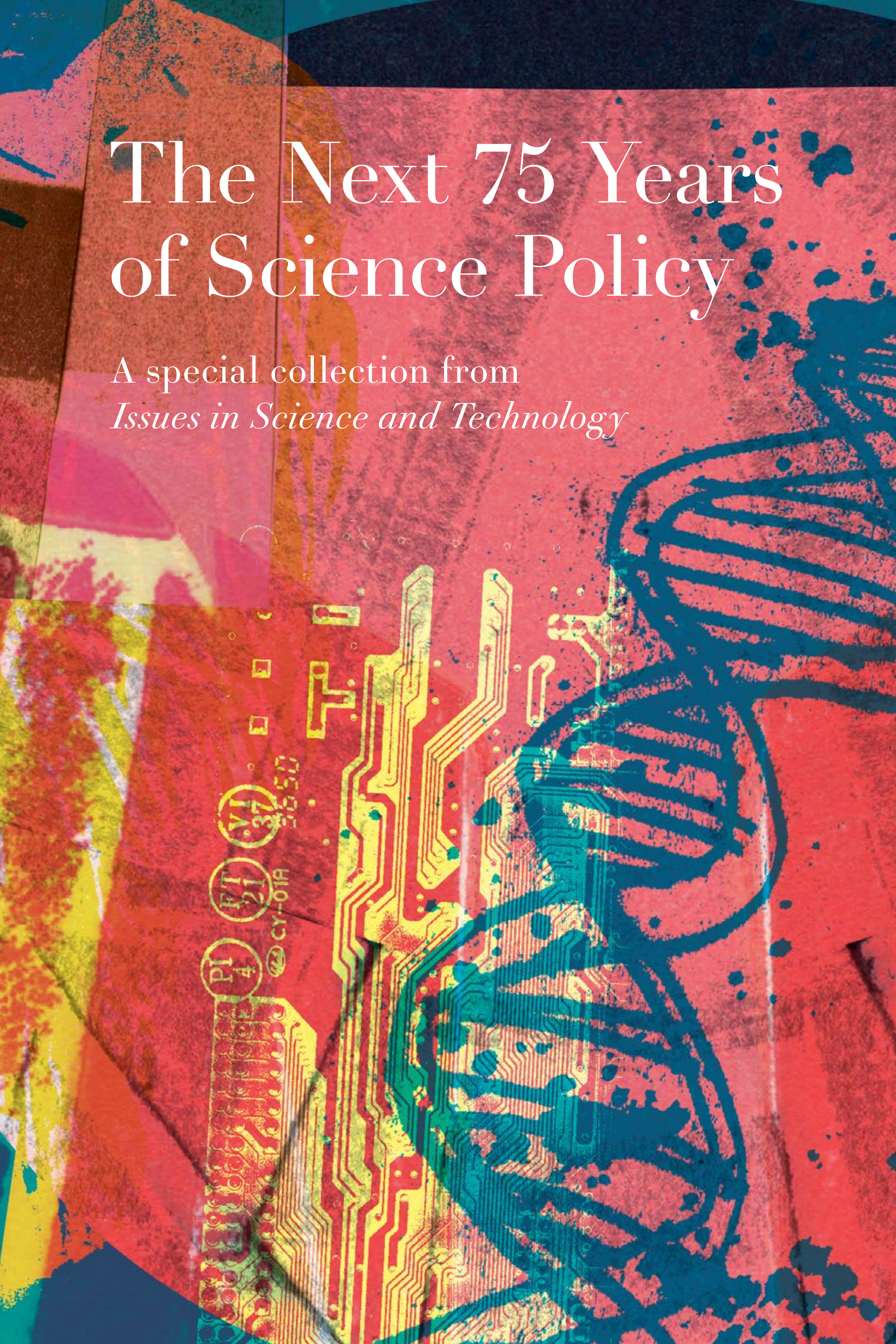

# The Next 75 Years of Science Policy

A special collection from
*Issues in Science and Technology*

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The Kavli Foundation

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# The Next 75 Years
# of Science Policy

# Table of Contents

359 SCIENCE PHILANTHROPY'S EVOLVING ROLE

# Foreword

In February of 2020, the National Academy of Sciences, with funding from the Kavli and Sloan Foundations, hosted a meeting upon the seventy-fifth anniversary of the release of Vannevar Bush's landmark report *Science, the Endless Frontier.* Bush's report is famously the blueprint that built America into a research powerhouse, but this meeting looked forward—to the new blueprints needed to accelerate and expand the outcomes of the endless frontier for another 75 years.

Since Bush's time, the world has changed significantly. Science is far more interdisciplinary, international, collaborative, impactful, and fast-paced than ever before. Even more importantly, science—both basic and applied research—has become the foundation and catalyst for economic development, national prosperity, community and individual health, and better quality of life. But challenges persist and new hazards lie ahead, as geopolitical risks threaten international cooperation and the flow of talent and stark inequities reveal pervasive flaws in power structures. Meanwhile, rapid environmental changes around the world make science ever more essential for understanding nature and our reliance on it—and charting a path forward.

In the spirit of envisioning blueprints for the next 75 years of science policy, *Issues in Science and Technology* developed this special collection of ambitious, challenging, and innovative proposals on how to structure the resources of science to enable the best possible future for everyone. Global leaders, philanthropists, policymakers, and early-career researchers alike shared their visions and expertise—creating a broad forum for the exchange of ideas about reinvigorating the scientific enterprise and accelerating and expanding the trajectory of the endless frontier. This book aggregates all of these contributions in one place to serve as a guide for evolving and rebuilding the systems of science for success in the decades ahead.

A common theme that runs across many articles is the need to fuel and maintain the talent pipeline to spur future discoveries. This includes transforming current structures in order to attract, support, train, and mentor the greatest diversity of talent in the United States, and also working to continue to attract talent from around the globe. These writers share a vision of science as an inclusive endeavor, starting in elementary school and extending to academic environments that welcome scientists from more backgrounds, experiences, and countries, while also inviting the public into the process of research.

Other themes include reimagining the role of research universities for the future, changing the culture of the research system to get the biggest impact from US investment, adopting more interdisciplinary and collaborative approaches to science, and taking full advantage of more diverse forms of funding and partnership. And, in the face of global geopolitical tensions, several essays propose new modes of international scientific collaboration.

But even the very best science enterprise will fail to deliver unless public policy is conducive to the translation of new knowledge into public good and economic competitiveness. It is more important than ever before that US leaders, scientists, and diverse communities engage to address the pressing issues of our time, including climate change, environmental degradation, healthy lifespan, biodiversity loss, unsustainable consumption of resources, and equitable development and opportunity for all in our society and economy.

We are grateful to all the authors who contributed their expertise to write the essays in this book, and to the sponsors who helped make it possible. We hope the perspectives expressed here help inspire the next 75 years of the endless frontier.

***Michael Crow**, Arizona State University president*
***Cynthia Friend**, The Kavli Foundation president*
***Marcia McNutt**, National Academy of Sciences president*

ROBERT W. CONN, MICHAEL M. CROW,
CYNTHIA M. FRIEND, AND MARCIA MCNUTT

# The Next 75 Years of US Science and Innovation Policy: An Introduction

In the future, science and technology will be called upon to address many challenges, from pandemics to climate change to food and water shortages to crises that cannot be foreseen today. Scientific research must be structured to meet society's needs.

Since the end of World War II, a particular conception of the relationship between scientific research and societal benefits has dominated US science and technology policy. As laid out in Vannevar Bush's seminal 1945 report, *Science, the Endless Frontier*, the federal government, by funding basic research at the nation's universities and independent research institutions, would generate both new scientific knowledge and the skilled practitioners needed to apply that knowledge to societal problems, thereby ensuring "our health, prosperity, and security as a nation in the modern world."

The vision at the heart of *Science, the Endless Frontier*—that society would benefit from new knowledge and should therefore support the generation of that knowledge—has been abundantly realized. Research conducted by America's universities and independent research institutions on behalf of the federal government has opened pathways to improved living standards, public health, and national security not only in the United States but around the world. However, science and the broader society in which science is embedded have changed radically over the past three-quarters of a century. Even as new scientific discoveries and new and innovative technologies have spurred economic growth and reduced poverty worldwide, wealth, learning, and opportunity remain available to far too small a proportion of humanity. The development of new medical treatments and procedures has extended life spans but has not prevented massive inequities in health care and health outcomes, as has been starkly revealed during the current COVID-19 pandemic. A central debate in the years after World War II—how best to structure scientific research to meet human needs—remains a work in progress in this world of accelerating change.

The seventy-fifth anniversary of *Science, the Endless Frontier*, combined with the particularly complex and turbulent events of recent years, has created a valuable opportunity to consider the science and technology policies we will need for the next 75 years. Scientific research today is much more complex, multidisciplinary, collaborative, and transnational—and often occurs at a much more rapid pace—than in the past. Researchers are studying a much broader range of issues, including problems that science-based technologies have exacerbated. China now spends approximately the same amount on research and development as the United States and substantially more than the countries of the European Union. Today, new knowledge travels rapidly around the world to institutions and to individuals who are ready, capable, and eager to apply that knowledge. The challenge for national governments is to develop and implement policies that enable countries to benefit from the assimilation of new knowledge to enhance productivity, national well-being, and new ways of doing things.

Universities and the federal funding of academic research are adapting to these and other changes, yet they still bear many hallmarks of an earlier age. Much of the research and teaching done in colleges and universities still occurs within disciplinary silos and adheres to the single principal investigator model, though this model can and does contribute ideas that serve as seeds for larger, more robust collaborative research efforts. Professors train PhD students to replace themselves despite a paucity of jobs and opportunities in academia. And an educational system designed to produce new scientists and engineers does far too little to help students in other fields gain an understanding and appreciation of science and the methods of science.

Science and technology will be called upon to address many challenges during the next 75 years and beyond, from future pandemics to climate change to food and water shortages to crises that cannot be foreseen today. At the same time, the great accomplishments of the past 75 years in extending life spans, reducing poverty, avoiding another world war, feeding a growing population, and connecting the world electronically provide a solid foundation on which to build. We will need every bit of knowledge, reason, and creativity we can muster to overcome the challenges of the twenty-first century. This means we must draw upon all of the determination and ingenuity available in society today. We must find better mechanisms for incorporating the public's outlooks and needs into research, while also reducing barriers to participation in the science and technology enterprise, to capitalize on the diversity of ideas and talent available across the globe. Nevertheless, we have every reason to believe that the human story will be one of continued progress made possible in large part by the application of new discoveries in science and technology to help solve human and societal problems.

## A guide to the future of US science and innovation policy

*Issues in Science and Technology*, with support from The Kavli Foundation, published this series of articles chosen for their potential to shape the next 75 years of US science and innovation policy. Under the series title "The Next 75 Years of Science Policy," the articles first appeared online in a dedicated space at issues.org. A diverse group of authors explored what is working well, what is not, and what needs to change.

This series of articles, intended to inform the future of science and innovation policymaking, appears against the backdrop of many recent reports on US science, technology, and innovation policy. While these reports differ in their emphases, they exhibit several common themes designed to steer science and technology policy in more productive directions. Ten reports spanning three years, 2019 through 2021, are exemplars. The degree of commonality across these ten reports is remarkable.

## A renewed emphasis on outcomes

Perhaps the most common of these themes is the call for much greater attention to accelerating the generation of new knowledge as well as the application of that knowledge to human needs. As the 2020 report *Competing in the Next Economy: The New Age of Innovation* from the National Commission on Innovation & Competitiveness Frontiers put it, "There are deficiencies in the US innovation ecosystem, barriers in developing and scaling new technologies, too many Americans locked out of the innovation sector due to inadequate opportunity, education and skills, and insufficient US leadership in the international developments that are setting the stage and rules for the next global economy."

To better assimilate new knowledge into products and processes that solve human problems, many reports have called for increased federal funding of what is variously called use-inspired basic research, outcomes-oriented research, needs-oriented research, societally responsive research, applied research, and translational research. The shared element is that such research not only increases scientific knowledge but is linked from the outset to practical issues. Such research, according to the 2019 report *Public Impact Research: Engaged Universities Making the Difference* by the Association of Public and Land-grant Universities, "clearly and directly connects the investment of taxpayer dollars to public benefit."

Of course the line between basic research carried out to understand nature and research motivated by the need for solutions to practical problems is blurred and changes over time. An outstanding recent example is the development of highly innovative vaccines to counter the SARS-CoV-2 virus. Less than a year elapsed between the genetic sequencing of the virus and the Food and Drug Administration's emergency authorization of vaccines that use messenger RNA to generate antiviral immune responses.

The long-standing debate over how to direct and structure research funding raises fundamental questions: How can increased funding for research best promote synergies between the advancement of fundamental understanding and the solution of practical problems? What institutional arrangements and incentives have proven most effective in achieving such synergies? How should public sector and private sector efforts best be linked for mutual benefit?

## Greater funding for research and development

Another common theme of recent reports is that the federal government is spending too little on research and development. The 2020 report *The Perils of Complacency: America at a Tipping Point in Science & Engineering* from the Committee on New Models for US Science and Technology Policy recommended that the federal government increase its funding of basic research from 0.2% of US gross domestic product (GDP) to 0.3%. The 2020 *Science and Technology Action Plan* from the Science & Technology Action Committee called for doubling total federal expenditures on research and development from 0.7% to 1.4% of GDP over five years. *Innovation and National Security: Keeping Our Edge*, a 2019 report from the Council on Foreign Relations, urged federal funding for R&D to be returned to its historical average as a proportion of GDP, implying an increase from about $150 billion to $230 billion annually (in 2018 dollars).

Economic analyses indicate that these funding increases would more than pay for themselves in economic growth, public health, and defense preparedness. Nevertheless, the funding increases proposed in recent reports are dauntingly large. Boosting federal R&D from 0.7 to 1.4% of GDP would increase federal expenditures by about $150 billion per year.

Policies designed to maximize the advantage to the United States of research funding would look different today than they did in 1945. What is the optimal size of overall research funding in the United States, and what proportions of that funding should come from government, industry, philanthropies, and university endowments? How can research funding from government be increased despite competition from other priorities? How does the science enterprise need to evolve and adapt, so funding increases translate into desired long-term outcomes?

## Balancing the risks and benefits of international collaboration

The United States has benefited greatly by fostering openness and international collaboration in science. The openness of the US innovation system has enabled researchers to stay at the frontiers of knowledge and has attracted to the United States international students and researchers who have made major contributions to the economy and society. The 2020 report *America and the International Future of Science* from the American Academy of Arts & Sciences states the common theme: “The benefits of international scientific collaboration for the United States and the world are substantial and growing and far outweigh the risks they can present."

But national security and intellectual property interests require that some controls be exerted on the international flows of information and people. As other countries—China in particular—have greatly increased R&D funding, science and technology capabilities, and research outputs, the United States is no longer in a dominant position. While US policymakers have a few options for influencing the actions of other countries, it is far more important that they turn their attention to determining how to "strengthen US innovation capabilities in a robust and sustained way," as stated in the 2020 report *Meeting the China Challenge: A New American Strategy for Technology Competition* from the 21st Century China Center at the University of California, San Diego.

Global competition for talent in science, technology, engineering, and mathematics—the STEM subjects—and increased difficulties in securing visas are also making it harder for the United States to attract international researchers. How can US policies best balance collaboration with competition? How can the United States continue to attract the best and brightest from abroad but remain secure? What are the best ways to control the flow of sensitive information without unduly restricting the openness on which scientific research depends?

## Developing a twenty-first century STEM workforce

Part of the social contract described in *Science, the Endless Frontier* is that federal support of university research would "encourage and enable a larger number of young men and women of ability to take up science as a career." The successful achievement of this goal was one of the greatest legacies of Bush's report. But the link between research funding and the preparation of a skilled workforce has weakened. Other countries channel much greater percentages of their young people into the study of STEM subjects.

Attracting, retaining, and developing more US STEM students requires a wide-ranging and comprehensive approach, including enhanced educational and training program design from childhood on, as well as attention to undergraduates and graduates through academic and career advising, mentoring, research and internship opportunities, financial support for students going into high-demand sectors, and transitional programs into professions. In general, STEM education needs to become more individualized, student centered, and holistic, rather than primarily representing the interests of the institutions involved.

The need to individualize can be seen particularly in the need to better support individuals who use science and technology in their jobs but do not have a bachelor's degree, a "critical, but often overlooked segment of our STEM-capable workforce," according to the 2019 report *The Skilled Technical Workforce: Crafting America's Science & Engineering Enterprise* from the National Science Board.

Likewise, at the graduate level, according to the 2018 report *Graduate STEM Edu-*

*cation for the 21st Century* from the National Academies of Sciences, Engineering, and Medicine, universities need to "shift from the current system that focuses primarily on the needs of institutions of higher education and those of the research enterprise itself to one that is *student centered*, placing greater emphasis and focus on graduate students as individuals with diverse needs and challenges."

A further challenge, as underscored by the National Science Board's *Vision 2030*, is that the members of groups underrepresented in STEM often do not get sufficient career development and opportunities, leading to marginalization and attrition. As *The Perils of Complacency* report observed, "If not addressed, this failure to attract historically underrepresented groups will continue to further hamper US efforts to strengthen America's STEM workforce."

The changes that are required at the university level are mirrored in structural and pedagogical barriers encountered by younger learners. Today, STEM subjects continue to be taught in K–12 and entry-level undergraduate classes mostly as collections of isolated facts with little real-world context. Classes typically fail to convey the rich interconnections among STEM subjects and between these subjects and the rest of human knowledge. Students, typically working individually rather than in the teams that characterize so much STEM activity, get little exposure to the creativity and innovation at the heart of these fields. They are more likely to get a sense of the dynamism of STEM subjects from experiential activities such as science clubs, math teams, and robotics competitions. Projects such as the Association of American Universities' Undergraduate STEM Education Initiative and the National Academies' Reshaping Graduate STEM Education for the 21st Century have proposed cultural changes to improve the quality of undergraduate teaching and learning and to prepare students to translate their knowledge into impact in multiple careers, respectively.

A major concern, reflected in many reports, is the need to attract more underrepresented groups, including women, to the STEM workforce by reforming the culture and structures of educational institutions. Among them is a recent call from a National Academies committee, in its 2020 report *Promising Practices for Addressing the Underrepresentation of Women in Science, Engineering, and Medicine*, for "systemic change in the STEMM [STEM plus Medicine] enterprise in an effort to mitigate structural inequities, bias, discrimination, and harassment that a substantial body of literature demonstrates significantly undermines the education and careers of women." There are also calls to address, at a fundamental level, the systemic barriers and intolerable behavior that lead to racism and sexism, as discussed in the National Academies of Sciences, Engineering, and Medicine's report *Sexual Harassment of Women: Climate, Culture, and Consequences in Academic Sciences, Engineering, and Medicine*.

What policy apparatuses can we use to incentivize, encourage, and retain all talent in STEM? What institutional changes are needed to ensure the workforce can develop needed skills and remain responsive to the changing needs of employers?

## Engaging the public in research

Despite the centrality of technology and the knowledge enterprise to American life, the public has few ways of influencing either applied or basic research agendas. Vast numbers of citizens are left out of the process of making decisions about everything from how research funding is allocated, to which issues are studied, to how new technologies are regulated—a problem that is particularly acute for disadvantaged groups and communities. While *Science, the Endless Frontier* implied that knowledge flows one way, from creators to recipients, we now know that knowledge creation and knowledge use are tightly interwoven and interconnected processes.

As Cristin Dorgelo, then with the Association of Science and Technology Centers, observed in *The Endless Frontier: The Next 75 Years in Science*, engaging the public in science requires building an infrastructure to harness the tools and the processes of answering questions and applying those answers in a way that addresses community priorities, not just the priorities of those inside the system. These tools and processes range widely, from developing scientific literacy, to citizens commissions, to laboratory open houses, to much greater outreach by government agencies.

The American Academy of Arts & Sciences' 2020 report *The Public Face of Science in America: Priorities for the Future* suggests several mechanisms to improve the connection between science and the public, including engaging the social and behavioral sciences in the effort. The practices of researchers also need to change to provide for transparency, trust, and the meaningful incorporation of public input into research.

How can the public provide feedback in the priorities of scientific research, including basic science? What mechanisms can be instituted to better understand the implications of science's applications in society? When might public engagement be valuable for actually helping to conceptualize research questions and choose methodologies? How can policy, such as criteria for awarding federal research funds, be used as a lever to encourage and support scientists to more meaningfully connect with the public?

## A groundwork for analysis

*Science, the Endless Frontier* appeared at a time of great optimism but also great uncertainty. A few weeks after the report's release, the atomic bombings of Hiroshima and Nagasaki occurred, ending World War II but radically transforming the environment in which future scientific research and technology development would occur. US troops, still scattered around the world, were beginning to come home, but new threats from the Soviet Union and its allies were already emerging.

Today's historical circumstances are vastly different yet no less precarious—and, in new ways, equally promising. The COVID-19 pandemic, the consequences of structural racism and pervasive inequities, new international tensions, the gathering crisis of climate change, and deep social divisions pose great threats but also provide unprecedented opportunities to disrupt the status quo and pioneer new approaches. Science and innovation policies will have a great influence on the issues that confront us. As such, those policies need to be guided by the best possible thought and analysis. The current tension between the potential of science and technology and the societal problems we face requires active deliberation among all stakeholders. We have laid out some of those issues here and have referenced recent studies that are germane to the issues at hand. The series of articles presented here will extend the discussion. We invite you to join us in exploring these issues and sharing policy ideas that will fuel our science and technology engine for the next 75 years and beyond.

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2

# Competing in the Twenty-First Century

BRUCE R. GUILE AND CAROLINE S. WAGNER

# A New S&T Policy for a New Global Reality

Globalized science and engineering capability has changed how innovation happens and who it benefits. US policies need to be reconfigured to respond.

Science and technology policy in the United States has a hubris problem. For several generations, the United States stood alone as the world's leader in research and development (R&D), without peer in scientific and technological achievement. But the quality and amount of research and technological innovation outside the United States has grown rapidly in recent decades. The United States is now one nation among many R&D-intensive nations. Complicating this picture, other nations have not simply cloned the US approach but have built their national scientific, engineering, and innovation capability on different models of relationships among government, university, and industry.

As the breadth and depth of global research have grown, academic scientists and engineers around the world have become linked in a dense global network, collaborating and sharing results in real time. This is a fundamental shift in the way humankind advances, records, and shares new knowledge.

The global networks of open, academic research overlap substantially and intermingle with equally robust cross-border networks of inter- and intracompany research, development, and commercial applications of new knowledge. This crossflow is another fundamental shift, one that has occurred in the way companies innovate and in the ways that nations capture societal and economic value from advances in science and engineering.

This new reality is neither well understood nor fully appreciated by the US policy establishment, which is overconfident that the country can regain its position as the dominant force in global science, engineering, and innovation. This belief, like the traditional argument that "more domestic R&D is always better," is outdated. Instead, policymakers must focus on capturing economic value from new scientific and engineering knowledge, whether or not it originates in the United States.

Economic value can be captured from global sources and integrated locally—but it requires deliberate actions, appropriate for the new situation. Just as national security depends on allies and alliances, so too must science and technology policy. US economic security and prosperity requires creating strategic international collaborations that take advantage of the strengths of other nations, and being a leader in negotiating international agreements on topics such as telecommunications technology, supply chain security, and antitrust law and enforcement.

## One among many, tightly networked to all

In the past, countries depended on the low mobility of researchers, inventors, and entrepreneurs to link R&D to innovation and innovation to wealth creation. When researchers were less mobile and less engaged in close collaboration with peers in other nations, new knowledge tended to be retained by institutions and the countries that housed them. From a national perspective, this arrangement had the benefit of aligning intellectual property ownership, early applications, and company growth with the location of the R&D activity.

The advent of the telegram, telephone, and a global mail system reduced the time it took for ideas to spread, shrinking the required time from years to months, then from weeks to days. But instantaneous, global collaboration was not possible until the rise of the internet in the 1990s, which enabled people to communicate in real time, collaborating as never before. The lowering of global barriers—including to international travel and cross-border personnel exchanges—came about as the result of several significant geopolitical changes, including the end of the Cold War, the rise of the European Union and relaxation of border controls across Europe, and the increasing wealth of China and other countries in Asia. These changes, taken together, globalized scientific, engineering, and innovation enterprises.

At the same time that global collaboration has become ubiquitous, the rest of the world has begun doing more research. During the 1960s, US public and private R&D investment accounted for almost 70% of the global total. Today, even though US spending has increased, US R&D is less than 30% of the world's total. Twenty nations now match or exceed US R&D intensity, with public and private R&D spending in these countries near or in excess of 2% of gross domestic product per year. In absolute dollars, China spends approximately the same amount on R&D as the United States. Furthermore, according to figures from the Organisation for Economic Co-operation and Development, China has nearly 2 million full-time equivalent researchers now, compared with the United States' 1.5 million.

Japan, Finland, South Korea, Israel, and Singapore were among the first to systematically increase their national R&D capability by sending scientists and engineers abroad, particularly to the United States, for training. These countries then brought researchers back to build domestic capacity that sought, in a focused way, to benefit their country's economic and military security. China has followed in their footsteps, at a quicker pace and at a larger scale, becoming a science and engineering powerhouse.

Simultaneously, US multinational corporations have established global networks of research laboratories, research university relationships, and talent recruitment efforts that partially decouple them from the science and engineering enterprise in the United States. Virtually every technologically advanced manufactured good is created by a production process (supply chain) that crosses national borders several if not dozens of times and draws on innovations from many countries.

Changes in the global distribution of advanced scientific and engineering capability have made it possible for small firms to have a handful of employees developing software in, for example, a half dozen different countries—a type of company whose existence was impossible a generation ago. These shifts in corporate R&D and innovation activities were triggered by the same technological and geopolitical shifts that drove the globalization of open science since the early 1990s. Stronger global intellectual property protections such as the 1994 Agreement on Trade-Related Aspects of Intellectual Property Rights have further supported these changes.

These converging historic trends mean that assertion of national leadership in quantum computing, genetic editing, artificial intelligence, or nanoscale manufacturing has little real meaning. Being first with new scientific knowledge or having a pioneering innovative company based in the United States does not guarantee success in domestic industry. Nor does it guarantee that the nation will capture substantial economic value from the new knowledge. In a globalized knowledge network, knowledge spreads so quickly and widely that being in "first place" is a notional distinction at best.

New scientific and engineering knowledge and innovation cross US borders in both directions—as part of commercial exchanges and collaborations—every day. Economic value cannot be captured by erecting barriers to the flow of knowledge or trade as the United States needs new knowledge and innovation from outside its borders as much as it needs robust US-based scientific and engineering capability.

Therefore, the goals and approaches of US policy regarding science and technology need to be reconfigured to promote economic prosperity and the national defense within the context of the irrevocable globalization of science and engineering. In simplest terms, policy needs to shift focus to capture economic and national security value from all innovation, whether or not it originates in the United States.

## Reconfiguring goals and mechanisms

For decades after World War II, the goals of national defense, economic growth, and competitiveness fueled considerable domestic public investments in developing and applying new scientific and engineering knowledge. These investments included increased public R&D spending, R&D tax credits, public-private partnerships, support for higher education, and policies to stimulate technology-based private sector innovation.

During the 2020 presidential campaign candidates, legislators, and think tanks generated a raft of proposals for new R&D spending, some of which are now being pursued by the Biden administration. Many of these proposals rest heavily on increased investments in domestic R&D to address perceived threats to US economic and national security from the technological and geopolitical rise of China. In the rush to address real geopolitical and international economic challenges, many of the current plans to increase domestic R&D engage in magical thinking, vaguely promising that investment in broad areas of science and engineering will somehow yield improvements in US prosperity and economic security.

US government investment in domestic R&D should not be abandoned or diminished; indeed, there are solid arguments that public investments in R&D need to increase to secure or improve the US national position in global knowledge networks. Merely spending more, though, is not enough to secure the economic future of the United States or to respond effectively to the growth and integration of scientific and engineering capability around the world.

To contend with this global reality, the United States needs a meaningful reconfiguration of policy goals and approaches. High-tech economic competition with countries that were "behind" the United States only a few years ago cannot be addressed with domestic R&D investments alone. Nor will more domestic R&D investment do much to counter vulnerabilities derived from supply chains based in other countries. Domestic R&D investments will also—absent reforms to US immigration policy—do little to keep capable and ambitious people from leaving the US to pursue careers elsewhere.

What this new reality means is that US policy regarding science and technology must become more like US national security policy, which depends on allies and alliances. Capturing the economic value from new knowledge and global innovation depends on creating strategic and mundane international agreements that help the US economy, both producers and consumers, to lawfully take advantage of the science, engineering, and innovation capabilities of other nations. In some cases, the US government will need to step up and play a leading role in negotiating bilateral and multilateral agreements, as well as setting norms for a wide range of activities that can include next-generation wireless R&D, privacy-by-design approaches to public health or social network data, antitrust laws affecting technology platform companies, and cross-border supply chain resilience.

The reconfiguration we are calling for includes:

1. Setting aside the notion that the goal of US R&D investment is to make the United States "win" every technological race and focus instead on capturing the economic and social value of new scientific and engineering knowledge, wherever it originates.
2. Expanding the US government support for tracking and monitoring research activity and output, regardless of where it occurs, and support for dissemination of that information to US-based companies and centers of research.
3. Implementing economic and regulatory policies, including international tax, antitrust, trade, and investment policies with an eye toward increasing the nation's ability to capture economic and national security value from new knowledge, wherever it originates.
4. Addressing national security vulnerabilities and risks in diverse areas (e.g., food, energy, and health, as well as traditional national defense) that arise from the new and broad dependence on global scientific and engineering networks.
5. Pursuing education and immigration policies that continue to attract R&D talent and skilled workers from other countries to the United States and to enable these individuals to stay here, while also increasing the number and improving the capacity of US-born scientists and engineers.
6. Establishing new types of strategic scientific and technological alliances with other countries around the globe, focusing first on natural allies among the liberal democracies.

These changes, along with other shifts in US science and technology goals and approaches, flow directly from acknowledging that our nation's economic security and prosperity in 2021 depends on S&T collaboration and exchange with other nations. This approach to innovation-based economic security is analogous to the manner in which US national security has long depended on alliances as well as the activities and capabilities of allies.

***Bruce R. Guile*** *leads the international working group on Global Innovation and National Interests at the BRG Institute.* ***Caroline S. Wagner*** *holds the Wolf Chair in International Affairs at The Ohio State University. This is the first in a series of essays authored by members of the working group.*

L. RAFAEL REIF

# How to Build Upon Vannevar Bush's "Wild Garden" to Cultivate Solutions to Human Needs

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In today's competitive environment, we cannot assume that curiosity-driven advances in science will someday be useful. We must also be pursuing questions targeted at needed breakthroughs.

Like many brilliant researchers, Vannevar Bush had a knack for raising the right questions. As we commemorate the anniversary of his groundbreaking *Science, the Endless Frontier* report and consider its lessons for us, we should be guided by Bush's forward-looking, probing questions at least as much as by his more time-bound answers. Many of Bush's specific proposals were altered or rejected outright, and some that were implemented are ripe for reassessment, but his questions remain as pressing as ever.

Bush started with a broad, fundamental query: What can be done to make the US population healthier, safer, more prosperous, and more comfortable in the postwar era? Then he zeroed in on the relevance of the areas he knew best and asked: What US research institutions and funding modes should be created, restructured, or adapted to enable the nation to succeed in the very different world created by the war?

Bush did not ask any questions that were premised on protecting the status quo. He advocated fresh thinking, not orthodoxy; when the report made waves in academic and political circles, he did not shy away from the controversy. It is only in retrospect that we fully appreciate his vision's enduring value.

In considering the challenges of our moment, Bush's farsighted questions about both outcomes and means should inspire us to take a clear-eyed view of the US research enterprise and to propose new approaches to confront the most pressing issues in today's world. Happily, unlike Bush, we do not have to build a system almost from scratch. But we also cannot simply take refuge in the comforts of the status quo and repackage familiar arguments for doing more of the same.

Compared with 1945, our current geopolitical circumstances are vastly different. Bush wrote, in part, that the United States could no longer rely on science coming from a shattered Europe; rather, he saw that the nation had an unprecedented chance to become the world's dominant scientific and industrial power after the war. Today, we face growing scientific and economic competition, particularly from a rising China that is also a military and ideological rival. Regardless of how one views China, its government, or its ambitions, there should be agreement that this new dynamic represents a fundamental challenge to the United States.

To meet this moment, we need to ensure that our federally sponsored research addresses questions that will enhance our competitiveness now and in the future. At the same time, we need better ways to usher more of those research advances into the marketplace. Our current system has many strengths: top research universities, a thriving basic research enterprise, an entrepreneurial ethos, prospering venture capital, but we must not allow these historical advantages to blind us to gaps that could become fatal weaknesses.

## Tackling the tough stuff

The United States has at least two areas of weakness that require attention. The first is that we have largely abandoned civilian *use-inspired* basic research: fundamental research specifically designed to solve practical problems. Organizations such as Bell Labs were once known for this type of long-term but targeted research. Most of the big industrial labs that performed this research have effectively vanished, and universities (and their federal funders) have tended not to pick up the slack. Instead, universities and federal agencies focus, by and large, on *curiosity-driven* basic research: research that is essential to our nation's long-term success, but that by itself is not sufficient to make us competitive in today's world.

What is use-inspired basic research? The Bell Labs work that led to the creation of the transistor and the semiconductor is perhaps the premier example. On the one hand, the research probed fundamental questions in physics and was recognized with a Nobel Prize. On the other hand, the research was targeted toward a specific, practical goal: replacing vacuum tubes, which were unreliable and too energy intensive. Our economy continues to benefit from Bell Labs' decades-old breakthroughs—but we cannot live off that technological inheritance forever.

There is no shortage of use-inspired questions we should be pursuing today. One example is developing algorithms that would allow computers to "learn" using less data. Our current data-intensive algorithms put the United States at a competitive disadvantage; China has access to more data than we do because of its larger population and its weaker privacy protections. One way to develop algorithms that need less data is to study how young children learn—an important and difficult basic research problem—with an eye toward giving computers some of that capability. Unlike computers, children do not need to see, say, a thousand cats to properly identify a cat. If we could make our computers' need for data similarly economical, we could vault past the competition.

In a competitive environment, we cannot assume, as Bush did, that curiosity-driven advances in science someday will be useful in some fashion. Instead, we must also be pursuing questions targeted at needed breakthroughs. Bush envisioned science as a kind of wild garden: individuals seeding ideas based on their intellectual interests with no overall design. We also need to see science as a kind of farm, where people work together to cultivate and advance selected ideas to address human needs. These two types of science need each other in order to advance and for our nation to thrive. Our current system does not provide the optimal balance between them.

The second gap is that the United States is not as good as it needs to be at getting "tough tech" ideas to market. Tough tech encompasses new products and processes that involve hardware as well as software—the development of which could create whole new fields. Such products can also help address pressing problems, such as climate change. Tough tech is often too risky and takes too long to mature to be appealing to angel investors, venture capitalists, and others who finance new companies. At the same time, the work is too far along the research and development path to qualify for government support. The result is that we miss the boat. Sometimes these companies instead get either financed by foreign investors or finally get developed and manufactured overseas (or both)—or they simply fold.

As a university president, I hear all the time about promising ideas that struggle for air in our current system. For example, there is the case of a professor with a brilliant new approach for grid-scale energy storage, but the path to commercialization would stretch beyond the typical five-year limit for venture capital funding. Or there is the potential approach to treating Alzheimer's disease that could not attract funding to get beyond the lab because of the extended timeline to develop the treatment.

It is no simple task to figure out how to create a system that would provide the funding that tough tech ventures need to survive. But we make it more difficult when ideology or hardened views about institutional roles are used to rule out proposals before they can be examined. Throwing around the label "industrial policy" is not a serious mode of analysis, regardless of whether the term is being used as a blessing or a curse.

Government, industry, and academia will have to work together to create new mechanisms to sustain tough tech companies long enough that their ideas can be fully developed and scaled. One approach we've launched at the Massachusetts Institute of Technology is setting up an independent entity we call The Engine, which provides technical assistance, space, and capital to support tough tech founders. But that's just one effort in one location. The federal government should be designing tax and funding policies to help more places experiment with more ways to get new companies off the ground.

These gaps in our system may seem like mere frustrations or peripheral problems now, but they can grow into fundamental failures, especially when other countries are working to benefit from our shortcomings.

## Legislative issues

As a nation, we have the wealth, the talent, and the creativity to get ahead of these problems; what we have lacked is the will. That is why I have been such a vocal supporter of the bipartisan, bicameral bill that is aptly named the Endless Frontier Act, which takes aim at some of the issues that I have discussed in *Issues* previously. The Senate passed the bill in June 2021 as part of the US Innovation and Competition Act to increase "investments in the discovery, creation, and manufacturing of technology critical to US national security and economic competitiveness."

Although the Endless Frontier Act is far from perfect and should be further refined, it gets the fundamentals right, and those have emerged from the Senate process intact. The bill would create a new Technology and Innovation Directorate at the National Science Foundation (NSF) that would be responsible for funding the use-inspired basic research our nation needs across a wide range of fields, and for related educational, tech transfer, and test bed activities. The measure would also authorize significant new funding for the effort: the new directorate's annual budget would reach $9.3 billion in fiscal year 2026, the last year of the bill.

NSF is the appropriate agency to anchor this effort: its portfolio has great breadth, the agency has deep experience working with universities as well as relationships with industry, and it has a deserved reputation for excellence. Beyond that, NSF works closely with universities, and universities educate students as an integral part of carrying out research. In the end, the source of a nation's strength is its people, and educating students in the latest technological areas is an essential part of becoming more competitive as a nation.

The House is also moving forward with an important and valuable effort through its National Science Foundation for the Future Act. This bill is more notable for its similarities with the Senate approach than for its differences. The NSF for the Future Act also creates a new directorate with new funding to address competitiveness issues (among others) through use-inspired and translational research. Both bills allow and encourage—but do not mandate—the new directorate to experiment with different project selection processes, and to experiment with different hiring practices to bring in well-regarded experts to run the new programs. The Senate bill, by comparison, explicitly mentions the Defense Advanced Research Projects Agency (DARPA) as a possible model for some programs; the House bill does not call out DARPA but gives NSF similar flexibility in implementing its research programs. The House bill permits all the directorate activities laid out in the Senate bill.

So then what are the issues that will need to be ironed out between the House and the Senate? Although this is not an exhaustive list, here are some matters that will require attention.

First is determining the scope of the directorate, including what broad issues should be within the directorate's purview, what kinds of research it should fund, and what technologies it should focus on. The House bill lists six societal issues on which the directorate can focus, including competitiveness; the Senate bill is focused primarily on competitiveness.

Competitiveness, I believe, is an overarching concern that will affect the nation's ability to deal with climate change, equity, and other important societal issues listed in the House bill. It is also an arena that is a logical extension of current NSF concerns and activities. Working on issues beyond competitiveness may be a worthy idea, if funding is adequate and the directorate can still be sufficiently focused. At the very least, competitiveness should be an initial priority for the new directorate.

Both bills could be clearer on what flavor of research the directorate will fund, while still giving NSF latitude to make scientific decisions and to adapt its plans to new or evolving needs. As already noted, at least one focus for the directorate should be funding long-term, use-inspired basic research targeted at problems with practical implications. The solutions to such problems typically demand teams with crossdisciplinary expertise.

Finally, the Senate bill includes an initial list of key technology focus areas, including broad topics such as artificial intelligence and quantum information sciences. Congress frequently provides this type of guidance to NSF and other agencies, and this guidance can be helpful in getting programs off the ground, as well as preventing misunderstandings and squabbling. The specific list in the bill might be refined or shortened, but it certainly should not be expanded; focus is of vital importance. The key technology focus areas will need to evolve over time, but they should not change frequently, as it will take sustained research in a focus area to make meaningful progress.

Congress will have to work out how to address racial and geographic equity Both bills appropriately have provisions intended to attract more individuals from underrepresented minority groups into science and engineering, as well as to assistschools such as historically Black colleges and universities that have large enrollments of students from these groups. These provisions are not only a long-standng matter of equity and justice; the United States will never be as strong and prosperous as it should be without drawing on the talents of all segments of our society.

Both bills also create new programs to help build the capacity of so-called emerging institutions—schools that participate in federal research programs, but that could expand the kinds of research experiences the schools provide to faculty and students. Some of these emerging institutions also have significant minority enrollments.

Such efforts, while focused on racial equity, will also serve to widen the geographic distribution of research funds. But more than this effort is needed. The geographic distribution of research funding was a subject of debate at NSF's founding, and the issue remains thorny.

The United States cannot reach its full potential if research and the resulting economic activity are confined largely to the coasts. Such uneven distribution also limits opportunities for many Americans. The question then is how to increase capability around the nation without diluting the focus on excellence and the concentration of resources that have enabled the creation of Silicon Valley in California, Kendall Square in Massachusetts, and other success stories.

The Senate bill includes important provisions to create economic winners around the country, perhaps most notably a Commerce Department program that would create regional technology centers and offer regional planning grants. The goal is to help move ideas from universities around the country into commercial production. Research work from anywhere in the country might have applicability that could spur growth in regional industries.

Other Senate provisions are more controversial. The goal of providing money that helps all regions is an appropriate one. But Congress needs to come up with a distribution approach for research funding that raises all boats, without inundating some boats with more water than they can handle or leaving some premier vessels high and dry. Congress should negotiate a way to build research and training capacity at more universities, without spreading money so widely or with so little focus that overall US capacity is weakened. No region of the country will benefit if the United States falls behind our competitors in research and technology due to funds being spread too thinly to make a difference. Likewise, the nation will be damaged if only a few regions prosper.

A final unresolved area of concern is national security. Congress rightly wants to be sure that the United States will be the prime beneficiary of taxpayer investment in research, and it's particularly concerned about China taking undue advantage of US researchers. Universities have been increasing their own scrutiny of engagements with Chinese entities. In 2019, for example, the Massachusetts Institute of Technology set up a new review process for research engagements with China, Russia, and Saudi Arabia, looking at their potential effect on US national and economic security as well as on human rights.

But we cannot become so concerned about standing in the way of China that we hurt our own ability to move forward. In the end, the most successful strategy for competing with China is having a robust research and technology system in the United States. Policies that create costly barriers to research—by unduly hindering open research, by making it harder to attract the best graduate students from around the world (most of whom remain here after completing their PhDs), or by alienating those who want to support US universities—will do little to hinder other nations but a lot to hurt ours.

These assertions do not mean that no additional policies are needed. Reasonable requirements to disclose foreign gifts and contracts; prohibitions on faculty engagements that create conflicts of interest; targeted limits on sharing research in narrowly defined, problematic areas—all these areas can protect the United States with sound, clear policies that provide useful guidance to universities. But if we impose broad measures that simply send the message that we are cutting ourselves off from the talent and ideas the rest of the world has to offer, we will limit our own ability to move forward. The worst situation for our national security would be producing nothing that anyone thinks is worth stealing.

You don't win a race by expending all of your energy on tripping up your opponent. Rivalry can spur innovation, but fear is paralyzing. Vannevar Bush was uneasy about the future, but his report's power came from his quiet confidence in US potential. We need to draw on that. We have plenty of cause for confidence. If we falter, it will be because we have become too set in our ways, too complacent, too unwilling to ask provocative questions, too worried about others' winnings and failings and not enough about our own. Instead, we need to build on our strengths.

Bush did not choose the name for his report lightly. He understood that seeking out frontiers takes gumption, vision, energy, confidence, and daring. In the end, his most important message to us may be to continue to embody those attributes.

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LAURA D. TYSON AND BRUCE R. GUILE

# Innovation-Based Economic Security

To benefit from today's globalized research and development, the United States needs to make science and technology policies an integral part of economic security.

The United States is at a crossroads in science and technology policy. Since the end of World War II, US government support for the creation and dissemination of new science and engineering knowledge has been justified on the grounds that it addresses health, environmental, and other major social challenges shared by nations around the world; fosters both national and global economic growth and development through innovation (and the development of innovation-capable talent); and strengthens national security.

Today, 30 years after the end of the Cold War and the invention of the World Wide Web, cross-border exchange and collaboration in science, engineering, and innovation is ubiquitous. The US share of annual global public and private research and development (R&D) expenditures is less than 30%, down from 70% in the decades following World War II. Cross-border collaborative research, personal exchanges and migrations, and international supply chains have fused much of the world's capability in science, engineering, and innovation into large, fast, dense, global networks. Every country, including the United States, now depends on knowledge and innovation from outside its borders for both economic prosperity and national security.

The rapid growth and integration of global capabilities caught the United States, long accustomed to being dominant in both science and innovation, off guard. The rise of China as a science and engineering powerhouse, as well as an overt economic and geopolitical strategic competitor to the United States, has alarmed US politicians and policymakers. Policy discussions about "decoupling" from Chinese science and engineering, and multi-billion dollar proposals for US government domestic R&D investment to achieve an ill-defined “win” in an innovation competition with China, ignore the reality of globally networked scientific and engineering capabilities and innovation processes.

When compared with policies for national security, which contain both goals and the means to reach these goals, the United States does not have a global science and technology strategy. Today, it largely responds to the actions and tech-based industrial policies of other nations (or coalitions such as the European Union). It is time for the US to adopt a new aim for science and technology (S&T) policy, that of achieving economic security through innovation, with a coherent set of organizing principles that allow the government to analyze progress, distribute resources, and coordinate actions.

## A non-strategy strategy

The American R&D and innovation system depends heavily on government for research funding, on universities as research performers, and on companies for development funding and innovation. For better or worse, there is very little orchestration. Rather, the US system depends on a loose collection of goals and principles for direction.

One way to understand how the system works is to look at where the money goes. In 2020, the US federal government spent approximately $164 billion on research and development, about two-thirds of which was focused either on health or defense R&D. The bulk of this government-supported research—probably exceeding 80%—is destined for open publication of results. Taking a different slice through the data on US government R&D spending, about $43 billion, or 26% of the total, can be characterized as “basic” research and predominantly curiosity driven.

The Departments of Defense and Energy, and agencies including NASA, the National Oceanic and Atmospheric Administration, or the National Institute of Standards and Technology, define their own mission-driven research needs and jockey for funding. Research funding agencies such the National Science Foundation and the National Institutes of Health also compete for funding, but the mission for such entities is the advancement of knowledge, the development of talent, and curing disease. While program managers in mission agencies exercise some direct control of research performed outside of government laboratories, the primary mechanism of strategic control (especially of university-performed research) by government is to make funding rich in some areas and lean in others.

Meanwhile, American companies spend about twice as much as the US federal government on R&D, though very little of that is destined for open publication and only a tiny fraction is basic research. The quantity of investment is both a testimony to the technological intensity of US industry and to the impact of government R&D tax incentives—one of the primary ways the government influences such private spending, albeit at arm’s length.

The patchwork nature of government influence over private R&D investment is revealed by considering activities such as capital market regulation, antitrust policy, data privacy laws, and environmental and labor market regulations. These have all evolved subject to a variety of policy and interest group pressures but without any central organizing principle with regard to their impact on national scientific and engineering capability. The same is true of most international economic policies and agreements such as taxation of foreign earnings and trade and investment agreements.

Thus, absent a coordinated science and technology strategy, the US approach to science, engineering, and innovation includes a wide variety of aspirations. These include the goals of advancing knowledge, economic growth, and international competitiveness, as well as the principles of public funding for defense, health, and curiosity-driven research. In addition, companies bear primary responsibility for innovation and the nation depends on a working, complementary relationship between government-supported research and private innovation to capture the social and economic value of advances in scientific and engineering knowledge.

This non-strategy, a tremendous success for the past 70 years, is now challenged by the globalization of public and private R&D capabilities and the approaches taken by other nations. Most R&D-intensive nations bias government R&D funding toward domestic industries other than health and defense, taking approaches that often include government-industry-university collaborations explicitly aimed at improving national performance in trade or strengthening a country's geopolitical and economic position.

### Recasting goals and principles

As the United States faces a new reality in the nature of global knowledge flows and innovation networks, a new approach is needed. To catch up and keep up, the United States needs to shift away from trying to use domestic R&D investment to "win" an international competitiveness battle and toward using S&T policy to pursue economic security, which means reducing geopolitical vulnerability in combination with improving economic growth and stability.

This simple recasting of the goal—to innovation-based economic security—opens up many possibilities that currently seem closed. For one, it motivates the country to find a better way to monitor the US and global S&T enterprise and, importantly, manage the inevitable trade-offs and fights among constituent groups as new resources are allocated to meet new goals. Second, it promotes working with allies such as the G7 nations, the European Union, and liberal democracies around the world in the name of shared economic security. Finally, it encourages a different and more effective evaluation of government actions such as expenditures on R&D, economic policies, and regulatory changes. These evaluations may consider how S&T affects the country geopolitically, in terms of economic growth, in the competitiveness of the United States as a location for company activities, and in consumer well-being.

There are (at least) six ways in which the goals and principles of US S&T policy should be recast to support innovation-based economic security:

**1. Move beyond insular "more is better" logic for domestic R&D.** With the exception of fairly narrow areas—such as the military, cybersecurity, or biosecurity—the results of US domestic research and innovation will become fully and quickly understood, and often applied, around the world. This argues forcefully that the US government should blend domestic R&D investments with cross-border R&D collaborations. Articulated as a goal, the challenge to US government entities is to blend domestic R&D investment plans with international collaborations to take advantage of S&T capability outside the United States. These need to be paired with institutional innovations to improve the country's ability to capture economic or national security value from scientific and engineering advances originating outside the United States.

**2. Address cross-border supply chain vulnerabilities as a matter of national economic security.** National economic security vulnerabilities related to mature industries are often a direct result of privately organized cross-border supply chains and their role in innovation. Consider, for example, the location and control of semiconductor manufacturing, which is determined by private companies. There is no obvious precedent for US government regulation or intervention with regard to cross-border supply chains to improve US innovation-based economic security. The tool set currently available to the government to address these issues resides almost entirely within the national defense enterprise, from the Committee on Foreign Investment in the United States (which has the power to limit some investments from abroad) to the Defense Production Act (which allows the government to dragoon private companies into public service). The goal of addressing cross-border supply chain vulnerabilities as a general matter of economic security may require new legislation. It also suggests that the executive branch needs to establish some non-defense standing capacity for early identification of vulnerabilities, perhaps a government entity that can trigger a reconciliation or supply chain reconfiguration process before a crisis develops.

**3. Make holding onto new, emerging, and technology-intensive industry activity a national priority.** Thirty years ago, "founded in the United States" meant that the country would capture economic returns—employment, taxes, profits, and consumer surplus—from US tech-based start-ups. Two global trends threaten this relative US strength. First, many non-US centers of tech-based start-up activity are gaining strength, from Shanghai to Munich to Tel Aviv. Second, three decades ago the phrase "multinational company" was synonymous with large companies, but the globalization of knowledge and talent networks now means that many small tech-based start-ups are multinational enterprises. As a result, even new industries invented and created in the

United States are less likely to stay in the country, whether because they are acquired by non-US firms or because business or technical opportunity leads them abroad earlier.

Of course, not all technology-intensive industries are start-ups. There are clear innovation and economic security benefits to the United States being the location of production in mature industries, such as many types of advanced manufacturing, with a deep and broad technical base. Location decisions of company activities are affected by many factors, including ownership, history, market access, taxes, regulation, and antitrust laws. But US S&T policy has a critical role, particularly in how the government supports domestic production activities through translational R&D activities and technical support (such as agricultural or manufacturing extension).

While not a comprehensive solution, a federal program to beef up US research universities' role in start-up and mature company retention may be the best available approach. Research universities have a proven ability to blend early-stage open research with a learning environment that can simultaneously support human capital development and entrepreneurial risk-taking. A federal grant program aimed at research universities that requests proposals to increase long-term retention of company activity in the United States would be a good first step. The tools available in working collaborations between the US government and entrepreneurial research universities—from intellectual property licensing preferences to incubators and university-adjacent, industry-focused R&D institutions—exceed those available to the government alone. With one eye on the models found in Germany's Fraunhofer Institutes, the Netherlands' Organization for Applied Scientific Research, and the United Kingdom's Catapult Centers, the United States should begin working to retain tech-rich company activities.

**4. Make the quality and flexibility of the US technical workforce an economic security priority.** The ability of the United States to capture benefit from domestic R&D and global knowledge networks depends on the quality and flexibility of the US technical workforce—from technicians, engineers, and bioscience professionals, to PhD researchers and tech entrepreneurs. From the perspective of innovation-based economic security, disparate policies—in particular, education, training, and retraining in science, technology, engineering, and math; immigration; and labor market policies—need to be understood, compared to approaches in other nations, and evaluated as a de facto US human capital strategy that will limit or improve the country's innovation-based national security.

In comparison to many other R&D-intensive nations, US federal investment in education and retraining is a mixed bag. On the one hand, US per-student spending for both secondary and tertiary students is much higher than the average among the 32 nations in Organisation for Economic Co-operation and Development. On the other hand, OECD data from 2018 show that US public spending on labor market programs (including unemployment benefits, training, and direct job creation), is second-to-last as a percentage of gross domestic product (GDP), with only Mexico spending at a lower rate. The US level of 0.25% compares to an average of 1.1% among the nations in the OECD data set, with countries including France and Denmark spending or exceeding 2.5% of GDP. Further, US federal and state incentives for private employers to invest in human capital are uneven at best and in many cases nonexistent.

On immigration, it is widely acknowledged that a significant portion of the US research and technical workforce came to the United States for higher education and stayed, collectively making a tremendous contribution to US economic security. Nonetheless, calls to give permanent residency to foreign students as soon as they graduate have not yet succeeded, so the United States continues to lose talent to opportunities elsewhere.

**5. Make S&T a permanent priority in all US government international agreements.** International economic, S&T, and regulatory agreements increasingly shape US domestic innovation and the nation's ability to capture economic value from innovation. While the government has made efforts to keep pace in some relevant areas of international agreements (e.g., intellectual property rights, research services as a component of trade in services, and foreign direct investment), the United States has fallen behind in areas such as cross-border data privacy and antitrust law.

This means the entire domain of US positions on, and engagement in, international agreements directly or indirectly affecting cross-border S&T collaboration and exchange is desperately in need of attention and coordination. As with other functions directly relevant to US economic security, responsibility for the relevant international agreements is balkanized among different departments and independent agencies. To advance US innovation-based economic security, the full range of international agreements affecting private and public scientific and engineering exchange and collaboration needs to be given concerted attention at a high level of the federal government.

**6. Create R&D alliances for economic security.** In the years following World War II, the United States helped build and manage stable national security alliances. In the twenty-first century, the nation must establish similar economic and innovation alliances as a bulwark against combined economic and national security threats arising from both strategic competitors and malign actors. The US should immediately focus on developing new multilateral sovereign-to-sovereign agreements for mutual protection against threats (to energy, food, health, or defense readiness) arising from exposures associated with global supply chains. Another priority should be agreements to contain new types of tech-dependent threats, especially those related to dual-use technologies such as artificial intelligence, cybersecurity, social media vulnerabilities, or biosecurity and public health. The June 2021 Research Compact among G7 nations is a good start.

New economic security agreements should not dampen economic competition among companies based in different signatory nations. Rather, the intent is to facilitate cross-border economic activity by agreeing on threat-reducing rules and protections governing economic activities, including the exchange and use of new scientific and engineering knowledge. In this regard, the United States has a large set of natural allies among liberal democracies.

The intent in forming these alliances is not to throw up immediate barriers to working with nondemocratic regimes. Economic security alliances allow countries with similar government structures, operating practices, and core values (such as consent of the governed) to work together freely even as they negotiate, perhaps with one voice, with nonagreement countries.

### Monitoring the enterprise and managing trade-offs

After decades of operating with very little orchestration, and in a world where the United States was dominant in science and engineering capabilities, the US government needs to change the way it coordinates S&T policy with economic and regulatory actions and international agreements that affect innovation-based economic security.

Responsibilities and operational capabilities important to innovation-based economic security are spread across a large number of departments and independent agencies. As such, the White House needs to reconcile and coordinate approaches and responsibilities—much as it is currently doing by addressing climate change as an administration priority. The most important, unfilled role is an integrative analysis and strategy process that can advise the president. A similar logic for strategy development and coordination in the White House supported the establishment of the National Security Council (founded in 1947), the Office of Science and Technology Policy (founded in 1976), and the National Economic Council (NEC, founded in 1993).

Given the histories, capabilities, and focus of these three groups, the NEC seems best suited to lead and coordinate government actions focused on economic security. No other extant group within the White House has the depth of domestic and international economic capability necessary to advise the president on the inevitable economic trade-offs. This includes understanding that some US S&T policy actions are necessarily in response to the industrial policies of other nations. The NEC has the credibility necessary to deal with the Departments of Defense, State, Treasury, and Commerce, and the office of the US Trade Representative on matters of economic security. Finally, most US government policies with inadvertent impact on private R&D and the advanced technology activities of companies are lodged in domestic or international economic policies; the NEC has the analytic capability to identify and recommend ways to shift economic policies to be supportive of company R&D and US value capture from technological advances.

Reconfiguring US science and technology policies, practices, and institutional relationships—at the pace necessary to catch up with changes in the world and the tech-based industrial policies of other nations—will be challenging and needs to start immediately.

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# For a Competitive Economy, We Need a Skilled Workforce

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The United States must make sustained investments in worker training and higher education to meet the shifting needs of a scientifically productive society.

As we imagine a science policy that can rise to the challenges of the next 75 years, worker training and education must be at the center of our efforts. America's workforce is central to our country's long-term economic growth and productivity. Labor force trends have changed dramatically over recent decades, while the need for highly skilled and innovative workers has grown, along with the need for workers with strong technical skills. Higher education institutions of all types must provide affordable and quality education to ensure these workers are available. Research universities are particularly important in educating people who will advance the boundaries of scientific knowledge. The United States must make sustained investments in worker training and higher education to make sure it can meet the shifting needs of a scientifically productive society for the twenty-first century.

## Workforce challenges

For much of the last 50 years, the US workforce has been growing. Multiple factors have been driving this change: the large Baby Boomer population moved into their working years; the share of women working for pay increased rapidly; and the United States welcomed a large number of new immigrants.

A larger workforce, by itself, can drive economic growth, and indeed that is what we have seen: since 1970, 25% of US economic growth has been driven by an increase in hours worked, largely due to workforce growth. The remaining 75% of economic growth has been driven by a rise in productivity, due to rising skills among workers, shifts in technology, and deepening capital investment. Of course, these changes are also fundamentally related to the workforce, since productivity improvements typically require higher levels of education, innovative research and development efforts, entrepreneurial skills, and intellectual curiosity, all of which are needed to produce new products and processes that change the ways we work and live.

Over the past decade, however, the United States has had to contend with a variety of workforce challenges. Some of these relate to changes in the availability of workers, due to shifts in the numbers of those entering or leaving the workforce. Many companies have complained that they find it difficult to hire the personnel they need at the skill levels required. Three trends, in particular, affect the number of workers available.

First is the aging into retirement years of the Baby Boomers—those born between 1946 and 1964. From the 1970s through the 1990s, Baby Boomers were moving from their teens into their most productive earning years. But in the past decade, members of this group have been retiring, working less, or perhaps working less productively as they face new technologies they understand less well than younger workers. While labor force participation among those over age 65 was slowly rising in the last 20 years, it has fallen during the COVID-19 pandemic and has yet to recover. One important consequence of this trend is a greater burden on current workers to pay for Social Security and Medicaid.

A second trend affecting the size of the workforce is that women's participation in the labor force has shifted in the past decades. After 50 years of steady increases in paid work, the percentage of women in the labor force grew from 38% in 1960 to 60% in 2000, but then stagnated after 2000 and has fallen during the pandemic, now standing at 56%.

A third trend is a reduction in the number of immigrants entering the United States, markedly reducing the growth of the workforce. US policy changes have severely restricted the ability of immigrants to get visas, even those who complete their education here. Some of the reductions in immigration are due to economic growth in other countries, such as Mexico, and to higher unemployment and slower growth in the United States, which make moving here for work less attractive. This shift in immigration affects industries that hire low-skilled labor, but it also affects industries that hire very high-skilled labor: indeed, the United States has historically attracted some of the most high-skilled workers who did not see opportunities in their home countries.

These three trends shaping the size of the workforce must be reckoned with. But the challenges facing employers in the United States go beyond the number of available employees. In many cases, the mix of worker skills has not matched employer demands. Ongoing trends have widened wage inequality, as demand for more educated workers has grown while demand for less-skilled ones has fallen, particularly in traditional manufacturing jobs that often paid relatively high wages.

Over the past 40 years, there has been a growing demand for very highly skilled personnel in engineering, technology, and health. Much of recent world economic growth has been due to the spread of new technologies and new products. Developing, marketing, and expanding these technologies requires a highly skilled workforce. Rising demand for this group of workers has driven up their wages. Furthermore, demand for them has increased around the world, so that they are now competing in a global labor market that values their skills. This fact is very evident in higher education, where our most productive scientists often get job offers from universities in both the United States and abroad.

While demand for highly skilled workers has grown, US demand for less-skilled workers has fallen. One factor driving this change is that new technologies have reduced the number of jobs for less-skilled workers through increasingly sophisticated robotics and automated processing. These changes have been reinforced by evolving international trade patterns resulting in jobs being shifted overseas. Over the past two decades, the opening up of China and other countries in Southeast Asia has presented many firms with production opportunities outside the United States that include a ready supply of lower-cost workers who are often willing to work long hours. The cumulative effect of these changes has been to reduce jobs and demand for less-skilled workers in the United States and to contribute to widening wage inequality.

Indeed, wage inequality has exploded. Adjusted for inflation, average wages among those with a four-year college degree or more have risen about 16% since 1979; but among those with only a high school degree, wages have *fallen* about 12%. These trends are particularly salient for men: indeed, men with a high school degree or less have largely lost access to jobs that allow them to be financially secure. In order to support their families, save for retirement, or buy houses, they need a spouse who is also working steadily. Meanwhile, relative wages among college-educated workers are higher than they have ever been, and particularly high among those with graduate or professional degrees.

These trends have been key to understanding racial wage gaps. Declining wages among less-skilled men have particularly affected Black men whose educational levels are lower than those of white men.

These trends also interact with gender inequalities. Women's college completion rates have risen much faster than men's. Since the 1990s, more women than men have been graduating from college, a trend particularly notable for Black women in contrast to Black men. The service-sector jobs in which women have often been employed are not easily outsourced to other countries, so women have not experienced as much of a rise in wage inequality by skill level as men have. This situation has meant that women's position in the labor market has improved relative to men, especially among those without college degrees.

These labor market trends have implications far beyond the world of work. Changes in wage inequality and wage-earning ability by gender have been linked to reductions in marriage, increases in opioid addiction, and deterioration in health and life expectancy among less-skilled men. A number of commentators link these shifts to rising political fragmentation and disaffection, particularly among those who have faced greater economic instability while watching (typically) urban and better-educated populations experience economic gains. And beyond the social implications, these labor market trends pose stark challenges for both basic and applied scientific research, technology development, and long-term economic growth.

As we emerge from the COVID-19 pandemic, we thus face a strained labor market in which employers are struggling to attract workers of all types. In the near term, this trend should particularly advantage some of those less-skilled workers whose wages have fallen in recent decades. But it remains to be seen whether the current labor market is anything more than a very short-run phenomenon.

### What should higher education be doing to respond to these challenges?

There are no easy answers to resolve these workforce and economic challenges. The United States needs a growing pool of high-skilled, highly educated workers, but it must find ways to provide stable employment at reasonable wages to all.

While addressing these challenges requires the involvement of many groups, institutions of higher education have an especially large role to play, since education is so important for the skills that today's labor market increasingly demands. These institutions range from community colleges to four-year colleges to research institutions that provide graduate training.

***Community colleges and less-skilled workers.*** Most workers will need more than a high school diploma to prepare themselves for long-term steady employment. But that does not mean everybody needs a four-year college degree. Both community colleges and vocational training schools provide technical training for many high-demand jobs. These are also the institutions that employers often work with to ensure a steady stream of workers with the specific training needed, and they are where older workers often turn for retraining.

As an entry point into many jobs, community colleges must seek to expand access and affordability—for younger workers acquiring an initial set of skills as well as for older workers seeking retraining. Graduation rates at community colleges remain too low. A variety of recent experiments have shown that retention and graduation at these colleges can be increased by smart institutional policies. While financial aid is important, it is only part of an effective strategy, which should also include academic coaching and proactive frequent contact with advisors, as well as attention to remedial course requirements.

In the long run, if we want to raise the wages of less-skilled workers, the surest way is to raise their education and training levels, giving them access to a wider range of higher-wage jobs in sectors of the economy where jobs are growing. But raising education levels is a decades-long process, and it will require more than adjustments to higher education pipelines. Also needed are improvements in urban and rural K–12 schools, which too many students leave having been poorly educated and unprepared for gaining higher-wage jobs or earning a community college degree.

In the short run, if economic trends continue to reduce jobs for less-skilled workers, raising wages for them is likely to require policies that subsidize earnings. For instance, we could expand the Earned Income Tax Credit for low-wage workers without children or provide ongoing child allowances for low-income parents. Expanding these policies to enrich income among less-skilled workers may be our best short-run option to stabilize their economic situation.

Of course, increased worker activism, through unions or other worker organizations, can also raise wages for less-skilled workers in certain industries. And in some areas such as health care—which will see demand increase for home health aides and nursing home assistants to care for aging Baby Boomers—the demand for less-skilled workers could increase in the future, thereby raising their wages. At the moment, as we emerge from the pandemic, a shortage of workers is raising wages in many lower-wage jobs, but that may be a very short-run phenomenon.

***Four-year colleges and online degrees.*** Four-year colleges and research universities remain key to training the skilled workers for whom demand is steadily increasing. Access to these schools for individuals from all income levels is important. But getting students to start college is only step one; they must then complete their degrees and graduate. A college degree opens access to jobs that provide substantially higher lifetime earnings.

Much of the public debate over access to college has focused on financial assistance. This aid is important, particularly for students from lower-income families. Too often, students and their families do not understand what is required to finance college or what types of assistance are available and are discouraged by the complexities of financial aid applications. Increases in Pell Grants and other mechanisms to guarantee access for lower-income students are essential to any higher education agenda for the twenty-first century.

Cost alone, however, is only one component of completing a degree. Good advising—both academic advising for coursework and career advising—is a particularly under-discussed issue in higher education. Advisors need to help students select courses, evaluate their interests and skills, and decide on a major. A targeted plan can speed time to graduation, which also reduces debt. Students who run up excessive student debt often take more than four years to complete their degrees because they were not effectively supported on a path toward completion.

Career advising is also important. Many students—particularly liberal arts majors—are unclear about what jobs their academic work will make available. And they often lack information about the financial implications of different degree choices. Career advisors should help students in their sophomore and junior years think about job possibilities and the coursework and internships they need to prepare for these jobs.

Expanded and high-quality online education can provide a viable alternative for highly motivated individuals who want to complete a degree or certificate. In 20 years, most major universities will be running extensive online courses along with more traditional residential education for 18-year-olds. Particularly for nontraditional students seeking to complete a degree program, or for those seeking professional credentials beyond an undergraduate degree, the demand for online education will continue to expand. Online learning provides flexibility to students, allowing them to complete coursework on demand, when they have the time for it. It is also likely that online education will become less and less focused on traditional degrees and more flexible with "mix and match" options. Schools may offer badges or areas of certification that students can complete with three or four courses. In that way, students can earn a more limited credential or combine badges into a traditional degree over time.

***Graduate research training.*** Graduate programs at research universities train the workers who keep the US economy at the forefront of innovation and discovery. Providing students with both the funding and the support to successfully complete their degrees at the graduate level is just as important as it is at the undergraduate level. It is crucial that we continue to attract both US and international students to US universities for this training. And we must change visa policies that send away highly trained students who want to work in the United States. We can't afford to lose this top talent to other countries.

Research universities are the primary source of basic research and innovation in the economy. Almost every new technology that has emerged in the past 40 years has had its genesis in scientific research done decades earlier. This research is typically purely exploratory, designed to explain how the world works rather than to develop any particular product. But it is often a necessary foundation that applied researchers in industry utilize when they look to develop new technologies or products. The basic research undertaken at universities is largely funded by the federal government. If we want to continue to stay on the front edge of technology in areas such as health, engineering, and data science, we must continue to grow support for basic research—as well as for the graduate student training that produces top-flight researchers.

## The future of higher education

Putting all of this together, what should higher education look like if it is to serve the needs of US science and society over the next several decades? Community colleges will hopefully be serving more students, with even greater flexibility to complete their training in person or online. Perhaps more of this training will be integrated into high schools, so that there is less distinction between a high school and a college course. I expect that what we now consider two-year associate degrees will increasingly become the equivalent of high school degrees in past decades, acquired as part of public education and free of charge to most students.

Four-year public colleges will continue to face challenges as state dollars for higher education are unlikely to grow and may well continue to decline. Furthermore, demographic shifts are reducing the number of high school graduates in many areas of the country. Some smaller schools—both public and private—will need to create partnerships with each other or even merge and consolidate.

Most four-year colleges—particularly the larger public schools—will offer an increasingly flexible set of options, providing both traditional residential college experiences and a host of online or hybrid options that allow students to move at their own pace. A four-year college degree may no longer be the norm. This change will hopefully attract more older students into completing degrees or acquiring additional credentials that advance their careers.

Least changed will be the research activities at major research universities. US universities have become the model for the modern research university, and this model continues to perform well, although it needs ongoing support for the increasingly interdisciplinary big science projects that will shape the future. Ongoing public investment in new knowledge is essential for the United States to remain at the leading edge of the global economy.

Many factors are important for economic competitiveness, of course. But among the most important are the skills and availability of a nation's workforce. For several decades, the United States benefited from a growing workforce with expanding skills, but that has been less true in the last 20 years. It will take explicit attention to this issue to ensure that the nation has the workers it needs in future decades.

This need means giving attention to policies that can enhance both the numbers and skills of workers, as well as the adequacy of their wages and benefits. We must make continued public investments in K–12 education and increase our investment in higher education to ensure access for all students. In turn, universities must do their part, becoming increasingly flexible in how they teach skills and provide credentials to a broader mix of students. Both the public and private sectors need to partner with universities to deliver the highest quality of education to their students.

To be sure, worker training is only one prong of any educational program for science policy over the next 75 years, but it is an essential one. There can be no science policy—and no science—without workers. We must commit today to training and supporting them for the generations to come.

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NORMAN R. AUGUSTINE AND NEAL LANE

# America on Edge: Settling for Second Place?

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The United States cannot afford to be complacent about the advancements in science and technology that are needed to power the economy, defend the nation, maintain public health, and combat climate change.

The United States is on edge in ways the nation has rarely experienced throughout its young history. The country's global leadership is being challenged in a rapidly changing and increasingly competitive world. Meanwhile, the nation's sustained complacency in dealing with long-festering domestic needs has weakened our institutions from within and placed in grave danger our leadership in the critical fields of science and technology—on which so much of our economy and security is based. America is at a tipping point, in short, and Americans are justifiably unsettled.

The country has faced existential challenges in the past—moments in history that shook its foundation—but has risen to the occasion under strong leadership. Four overarching challenges we face today require comparable leadership and response: competing with China, coping with climate change, maintaining cybersecurity, and combating and preparing for pandemics. There are many causes of the nation's current dilemmas, and their solutions will require exceptionally wise policy actions across a broad spectrum. But, as in the past, advances in science and technology (S&T) and research and development (R&D), driven by accelerated and focused investments, will be critical to success.

As presidential science adviser Vannevar Bush recognized more than 75 years ago in his pioneering report, *Science, the Endless Frontier*, efforts in basic research—funded primarily by the federal government—and overall science, technology, engineering, and mathematics (STEM) education will continue to be critical in the future. University-performed basic research, whether purely curiosity-driven or use-inspired, is of special consequence as its products include not only discoveries (made freely available to the world), but also science and engineering graduates, the engines of research and the transfer of knowledge and technology from laboratory to society. Because of the exploratory nature of basic research, progress requires freedom, patience, tolerance of risk, and sustained support. And since nature is global, even universal, basic research prospers best with international cooperation. US researchers need access to sites, facilities, and the best minds from across the globe.

The critical role of S&T has not gone unrecognized in other parts of the world. In 2008, for example, Wen Jiabao, former premier of the State Council of the People's Republic of China, wrote, "Scientific discovery and technological inventions have brought about new civilizations, modern industries, and the rise and fall of nations.... I firmly believe that science is the ultimate revolution." On May 30, 2021, China's president Xi Jinping was quoted by the *South China Post* saying, "Science and technology has become the main battleground of global power rivalry. Competition over cutting-edge technology has intensified to an unprecedented level. We must have a strong sense of urgency and be fully prepared."

Meanwhile, in the United States, the federal government has cut its investment in R&D over recent decades from 1.5% of gross domestic product (or 12% of the federal budget) to 0.7% of GDP (3% of the federal budget). The portion supporting basic research, as defined by the federal government, now constitutes only 0.2% of GDP—an amount roughly equivalent to what the US population spends every year on beer.

While surveys have shown that Americans are generally supportive of scientific research, that support has not prompted elected representatives to give research funding higher priority in government budgets. Too often, the public does not recognize how the products that pervade our daily lives were made possible by basic research that took place in a laboratory often decades before. Examples are ubiquitous: television, microwave ovens, stents, cell phones, laptops, GPS, meteorological and communication satellites, artificial joints, CT scans, all-electric cars, clean water, vaccines for polio and smallpox, a cure for hepatitis C, medications, jet aircraft, solar energy, and much more—including the mRNA vaccines for COVID-19.

More broadly, it is advancements in S&T that power the US economy, the foundation of the nation's ability to educate its people, provide quality jobs, defend itself, keep its population healthy, sustain social programs, modernize infrastructure, and combat climate change. China is now making many of these advances more quickly and convincingly than the United States and is reaping the rewards. To be sure, in today's interconnected world a responsible foreign policy with China is far more complicated than a race between two nations. All the same, it is clear that the United States cannot afford to continue on its current path of complacency.

## Differing trajectories

Comparison with China illuminates how deeply this complacency has taken hold in the United States. In many respects, China is in the midst of a revolution, managed by the central government and controlled by one political party with a membership of under 7% of the population. This revolution is focused on employing science, technology, and innovation to make China more prosperous, and its government is rapidly growing investments in R&D to provide the necessary new knowledge and tools.

Indeed, for many years China's leadership has been drawn from the ranks of engineers and scientists. In the United States, by contrast, only about 1% of the US Congress has degrees in science or engineering, and only two presidents—Herbert Hoover and Jimmy Carter—have had backgrounds in STEM. An education in science and engineering may not be vital to effective political leadership, but it does help policymakers understand the power and promise of S&T to propel a nation forward.

China's president since 2013, Xi Jinping, himself an engineer, has promised the nation's 1.4 billion people a share of the "Chinese Dream." China's middle class, once miniscule, is now roughly the size of the entire US population. China's ambitious infrastructure program—the Belt and Road Initiative, announced in 2013—comprises an investment of over $1.3 trillion to connect over 60 countries on land (the belt) and by sea (the road), stretching from East Asia to Europe and Africa.

China assigns a high priority to educating its people, but the gap in educational opportunities between rural and urban children continues to be large. In response, China is rapidly increasing its number of universities and colleges—now numbering more than 2,600, with a new institution opening every week—as well as the quality of faculty and the education provided. In the 2021 *US News & World Report* rankings of Best Global Universities, China had the second-highest number of the world's top 100 universities, after the United States. According to the 2021 *Times Higher Education* World University Rankings, Tsinghua and Peking Universities have now moved up in rank to join the top 25 in the world. China produces more than twice as many engineers and half again as many scientists each year as the United States, and the differential is rapidly expanding.

Moreover, under its Thousand Talents Program, China offers large financial and professional incentives to talented scientists and engineers from around the world to move to China. To date, the effort has not had a dramatic impact in the United States: STEM doctoral students from China attending US universities still have a high stay rate—currently about 83%—even with a difficult process for renewing visas and obtaining green cards. Similarly, recent surveys show that when researchers around the world were asked to what country they would prefer to move were they to leave their home country, about 57% answered the United States and only about 9% answered China. Still, there is no doubt that China is taking very ambitious steps to attract and retain STEM researchers, and countries that wish to compete must take this into account. The anti-China rhetoric that many political leaders routinely include in their statements is not likely to encourage young people to choose the United States as the place to study and establish their careers.

China's efforts are also reflected in its investment activities. Between 2000 and 2017, the country's domestic spending on R&D grew by an average of 17% per year, compared to 4% per year for the United States. Though China's economy has cooled in recent years, it is still making substantial investments in such critical fields as artificial intelligence, semiconductors, quantum information, high-performance computing, 5G communications, genomics, and renewable energy and energy storage.

These investments have paid off. Since 2011, the share of US-based smartphone companies and solar panel manufacturers in the global marketplace has fallen from 19% to 15% and from 8% to just 1%, respectively. Meanwhile, China has increased its share in these sectors from 11% to 58% in smartphone sales and from 35% to 67% in solar panel sales. China also holds the clear majority of market share of commercial drones (80% to the United States' 4%), lithium-ion batteries (projected 2800 GWh production capacity by 2030, to the United States' projected 500 GWh production capacity), and network infrastructure equipment (36% to the United States' 9%), led by the telecom giant Huawei. And while the United States still remains the leader in semiconductors (47% of the total, compared to China's 4%), many US companies do not manufacture these chips, but rather outsource their production to major overseas manufacturers.

The United States continues to maintain a lead in a number of key areas, but the margins are closing. China has now passed the United States in the number of Fortune 500 domestically headquartered companies. It has also overtaken the United States as the top merchandise trading partner among the world's nations. Of the 19 firms created in the past 25 years that are valued at over $100 billion, nine are in the United States and eight are in China. And of critical importance, China is projected to pass the United States in GDP not long after the United States celebrates its 250th birthday in 2026. Measured by purchasing power parity, China's GDP has already surpassed that of the United States.

To be clear, the United States still invests more in R&D than any other country. But China has been rapidly increasing its R&D spending and can be expected to overtake the United States within the present decade. And China is not alone in assigning a higher priority to investing in R&D than the United States, which now ranks ninth among Organization for Economic Cooperation and Development (OECD) nations, having fallen from second place in a few decades. In terms of the percentage of R&D funded by the federal government, the United States has fallen to twenty-ninth in the world. For a half century, the total US fraction of GDP devoted to R&D has remained stagnant, in spite of the increasing impact of S&T on everyday life. Lack of R&D investment is one of the reasons the United States ranks ninth on the Bloomberg Innovation Index. It ranks twenty-first in the number of professionals engaged in R&D per capita.

## Proposed actions

In light of these strategic disadvantages on the part of the United States, we believe the following measures are necessary—not only to compete with China, but also to repair the often self-inflicted damage done to our nation through neglect of public primary and secondary education and decreasing emphasis on S&T. While sustainable growth in federal investment in R&D, especially basic research, is necessary, increased funding alone will not suffice. We must also fundamentally change how we educate young people and how we approach immigration for work in STEM fields. Both increased financial investments and policy reform are urgently needed.

We recognize that federal discretionary spending will be under severe pressure in the coming decades. The Congressional Budget Office has estimated that expenditures already committed under current law for only two general budgetary categories—entitlements and debt interest—will equal total federal revenues by 2042, likely requiring either increasing tax revenue or borrowing to pay for science and nearly everything else the federal government does, from defense to infrastructure to social programs. And this projection does not account for increased federal spending due to COVID-19 or spending legislation now under consideration by Congress. Ultimately, funding decisions are a matter of priorities. We believe that, given the will, the leadership, and the potentially existential nature of the many challenges we face, the following proposed actions are both necessary and politically feasible. They fall into four major categories: increased and prioritized federal investments in R&D; reformed and renewed primary and secondary education; strengthened higher education; and expanded incentives for industry to invest and partner in meeting the nation's S&T goals.

***Increase investment in R&D.*** For many years the federal government provided about two-thirds of America's overall R&D funding, based on the understanding that the resulting discoveries, inventions, and technology were beneficial to the American people writ large. In recent decades, however, that share has declined to about one-fifth of the total. Industry, a clear beneficiary of R&D, has increased its share of national funding from about one-third to over two-thirds. But in the face of intensifying demands for rapid and more certain returns, industry has reduced its role in research while focusing on development, and in both cases, such results are proprietary and not shared with the S&T community.

This short-term focus has largely been driven by the fact that some 50 years ago, the average share of ownership in US publicly traded firms was held eight years before being sold; today that duration is four months. In recent years, half of US market capitalization has been held by firms investing less than their depreciation; 50 years ago, about 5% of market capitalization was held by firms pursuing such a strategy. Perhaps the most striking example of the impact of such practices is the home of the laser and transistor, the renowned Bell Laboratories, whose researchers garnered nine Nobel Prizes. Today, the remnants of that once preeminent US organization are owned by a firm in

Finland. Bell Laboratories, while perhaps the most prominent, was not the only major industrial R&D laboratory engaged in basic research; others included General Electric, Sylvania, Texas Instruments, Xerox's Palo Alto Research Center, Hewlett-Packard, IBM, DuPont, and many more. These laboratories received considerable funding from federal agencies as well as company investments. Even so, they could not be adequately sustained.

US political leadership has recently begun to recognize the peril that exists from current policies regarding S&T. The Biden administration, for example, has proposed large increases in R&D, and related legislation is currently being addressed by Congress on a relatively bipartisan basis. But such legislation, while extremely important, is only the beginning. Momentary infusions of funds have been seen in the past, such as the doubling of the National Institutes of Health budget under Presidents Bill Clinton and George W. Bush, or the Obama-era stimulus bill, all of which soon faded away. Meaningful progress will require a long-term, sustained effort—decades of steady annual real growth in funding R&D, particularly research, and higher education.

While the United States has steadfastly refrained from implementing what is commonly termed "industrial policy," at least on the scale of such nations as China, there are many examples of federal agencies' stimulating important innovation. SEMATECH, created in 1987, was a partnership between the Department of Defense and several US companies to help US industry compete with Japan in the critical semiconductor industry. The US Air Force invested heavily in the industry by purchasing highly sophisticated computer chips that were not then in commercial demand. The rapid growth of companies such as Control Data Corporation and Cray Computer Corporation resulted, in part, from the Department of Energy's needs for powerful high-performance computers to support its nuclear stockpile stewardship program. The United States has a history of investing federal money in selected industries, as it is now planning to do with artificial intelligence, quantum information, semiconductor chips, automation, and others. We would assert that there is a distinct difference between counter-free-enterprise industrial policy and the government's supporting select sectors of critical importance to the nation or strategically planning how to invest the taxpayer funds for which it bears a direct fiduciary responsibility.

### *Four Implementing Actions*

1. Sustain decadal growth in federal investment in R&D, especially in basic research:
    - Over the next five years, increase federal R&D funding from the present 0.7% of GDP to at least 1.1% and federal research funding from the present 0.4% of GDP to at least 0.8%, with the highest priority given to basic research—both use-inspired and curiosity-driven—largely carried out in universities and federally funded laboratories.
    - Sustain subsequent annual growth such that, within a decade, federal R&D funding reaches at least 1.5% of GDP, and federal research funding reaches at

least 1.2% of GDP, with the highest priority given to basic research.

2. Develop a national strategy for federal R&D, including an annually updated government-wide and agency-specific, five-year R&D plan submitted with each annual budget.
3. Fund federal R&D activities on at least a two-year cycle (as opposed to the current annual budget process) that includes these actions:
    - Create a capital budget for federal R&D (in order to evaluate and promote long-term investments).
    - Waive selected critical federal R&D activities from established government hiring, firing, and procurement regulations when deemed in the national interest.
4. Increase the share of federal funding devoted to high-payoff transformational pursuits, as compared with incremental gains and low-hanging fruit.

Growing federal R&D funding to 1.5% of GDP and federal research funding to 1.2% of GDP in ten years will require sustained real annual increases in the respective agencies' R&D budgets of 10% or more in early years, with even larger increases for research funding. Given all the other demands on the federal budget as well as concerns about the national debt, this increase is likely to be difficult. We believe, though, that these investment proposals reflect the magnitude of the national challenge and the urgent need to significantly alter the US trajectory in S&T by focusing on federally funded research. We note that 1.5% of GDP is below the peak for federal R&D funding during the Apollo program era, a time when funding for development vastly exceeded that for research.

While policymakers tend to place more emphasis on strategic areas where global competition is a particular concern, we also urge the federal government to dramatically scale up its investments in other fundamental research areas that industry is not able, or chooses not, to support. Important discoveries can come from the most unlikely research projects. The annual Golden Goose Awards, selected by the American Association for the Advancement of Science, provide excellent examples. Moreover, we believe that the nation should not cede its traditionally high standing in fields like astronomy and high-energy particle physics, but rather it should continue to be a global leader and key partner in these fields. While the need for the federal government to plan ahead and provide stability of support is not new, it is increasingly important given today's immense challenges.

Much budgetary emphasis in the United States has tended to be on near-term consumption as opposed to investment in the future. Congress focuses on elections every two years; business is concerned with next quarter's profits; investors follow developments by the hour—or less. One survey found that 80% of the chief financial officers of large corporations say they would cut R&D, advertising and maintenance rather than miss the next quarter's profit forecast. The federal government does not even have a capital budget, let alone a long-range plan.

Meanwhile, China is rigorously executing its fourteenth consecutive five-year plan. We believe that the United States must urgently adopt a longer-term planning process that includes an ongoing assessment of America's overarching S&T priorities in a rapidly changing global environment and examines the strategic importance of particular fields of science and engineering. For example, between 1970 and 2017, federal support for the physical sciences fell from 20% to 10% of federal research funding; yet much of the critical data and most of the materials and devices vital to advancing key technologies, including those used to carry out biomedical research and enable new medical diagnostics, treatments, and cures, come from research in the physical sciences and engineering.

***Reform primary and secondary education.*** There are many outstanding K–12 schools in the United States, and they produce some highly educated and talented young women and men. But too many young Americans, particularly in economically disadvantaged areas, especially minority communities, are not offered adequate educational opportunities and support. Overall, our public schools are simply noncompetitive by global standards, as illustrated by the low performance of American students in the international OECD Program for International Student Assessment (PISA) tests, ranking twenty-fifth in combined math, science, and reading scores. American students perform particularly poorly in mathematics, while the highest scorers hail from Beijing, Shanghai, and the Jiangsu and Zhejiang Provinces of China. Moreover, students from many of China's rural provinces perform at levels comparable with the OECD overall averages. In the National Assessment of Educational Progress, the United States' own standardized test, 59% of fourth graders rank as "not proficient" in math. By eighth grade, the "not proficient" group has grown to 66%, and by twelfth grade to 76%.

This enduring failure of US public education as a whole can and must end. The problem today is not a lack of funds: in 2017, US primary and secondary schools ranked high among OECD nations in funding per student. The problem is a broken educational culture that fails to prioritize content over process, that stifles creativity by restricting curriculum and methods, and that fails to realistically measure its performance. The United States places itself at a severe competitive disadvantage when the science and engineering workforce has only 13% underrepresented minority participation (although the group comprises 28% of the workforce) and only 29% female participation (although women represent 51% of the workforce and 58% of college graduates). This talent gap is particularly notable in the physical sciences, computer sciences, and engineering. Making the kinds of transformational changes necessary to improve public pre-K–12 education will be very difficult and take time, of which we have dangerously little.

### *Three Implementing Actions*

1. Federally fund preschool education for all children; voluntary out-of-school STEM-related programs; and continuing education opportunities, including sum-

mer workshops for public school STEM teachers.
2. Federally fund 10,000 competitively awarded four-year scholarships each year to US citizens to study STEM at a US university, with the commitment to teach at a US public school for at least five years upon receiving a degree. (Five years is the average duration in which US public school teachers currently remain in the profession.)
3. Implement merit-based pay systems and renewable teacher contracts (phased in to replace tenure) that provide for no-cost continuing education with a focus on subject content; and phase in a national requirement that teachers possess degrees in the core STEM subject they teach, with existing experienced teachers exempted from this latter requirement.

The need to dramatically improve US public primary and secondary education is not new, and there are no quick or easy solutions to the nation's inadequacies in STEM education. But we believe that these steps could help launch this transformation.

***Strengthen higher education.*** The situation that prevails in US higher education contrasts sharply with that of primary and secondary education. In what is arguably the most respected ranking of the world's research universities, the United States holds all top four positions and 19 of the top 25, including several public universities. However, American universities have in recent years been subject to enormous pressures from all sides including reductions in state funding, public resistance to rising tuition, inadequate federal academic research funding, growing costs of compliance with government regulations, public loss of confidence in the benefits of higher education, administrative burdens on the faculty, anti-immigrant political rhetoric that is likely to discourage foreign-born talent from learning and settling in the United States, and, of course, the devasting impacts of the pandemic. During the recent Great Recession, per student real funding at state universities was cut by 25% and has only begun to be restored.

Many studies and reports have drawn attention to the increasing burden on academic researchers and their institutions due to the accumulation over decades of research regulations, many of which are outdated and unnecessary. In addition, the lack of uniform rules and processes used by different federal research agencies adds additional administrative costs in both time and overhead. Because federal research funding has been stagnant for many decades aside from a few short-lived spurts, the quality of researchers and their ideas has steadily increased while success rates for proposed funding are low and the average grant size and duration are small. To maintain funding, researchers must write more proposals, which reviewers then have to assess and agency program officers have to process and prioritize. One survey found that faculty researchers are spending 44% of their research time dealing with administrative matters.

Competition, of course, is at the heart of the federal grant process, and expert peer review of unsolicited proposals has proved to be a strong method of ensuring excellence. But spending more and more time writing proposals rather than doing research and mentoring students is wasteful of talent, funds, creativity, and progress.

America's present leadership in higher education is possible to a considerable extent because of immigration of scientists, engineers, and mathematicians from across the globe. Indeed, it can safely be argued that not only America's research universities, but the nation's entire scientific and technological enterprise would barely function today were it not for immigrants, especially the large number coming from Asia. But the nation makes little effort to systematically retain talented individuals who come to the United States for college or graduate school and wish to establish their careers in this country. To the contrary, artificially low caps are placed on the number of visas that allow foreigners to work here, forcing United States-educated foreign-born graduates to take their skills abroad and concomitantly encourage US companies to move their research laboratories there as well.

As summarized by a 2020 report by the American Academy of Arts and Sciences: "In 2017, 42% of US S&E faculty were foreign born. Since 2000, 38% of the American awardees of the Nobel Prize in Physics, Medicine, or Chemistry were immigrants. Fifty-five percent of US start-up companies valued over $1 billion in 2018 were founded by immigrants, many of whom first came to the United States as science and engineering students. An openness to accepting immigrants and welcoming them into US society has been a major reason for the success of the US S&E enterprise, both in academia and industry."

To be sure, the question arises whether educating foreign-born individuals, in particular those from China, poses a military or commercial security risk. China has engaged in espionage, as have other nations, and will undoubtedly continue to do so. But there appear to be few, if any, cases of espionage involving faculty or students on US university campuses, although several academic researchers have been accused of inappropriate activities and have forfeited their jobs. In some other cases, faculty researchers have violated administrative policies by failing to properly disclose formal relationships with certain institutions in China or funding from the Chinese government, including its military. In other cases, faculty members did nothing wrong but lost their jobs anyway. In the past, suspected infractions of regulations have been handled by the federal agencies involved (e.g., the inspectors general) and by universities through normal administrative procedures that did not require intervention by the Department of Justice, except in cases where there was substantive evidence of violation of federal law.

There is little evidence to date that university research practices pose a significant risk to the nation's economy or security. To begin with, almost all university-conducted research is openly published, and relatively quickly, to maximize its public benefit and advance related research. Policies that broadly discourage foreign students from coming to the United States or make international research collaboration more difficult are likely to do more harm than good. The Department of Justice's "China Initiative," begun under the Trump administration, has unfortunately led to profiling and investigative overreach that has destroyed the careers of scientists never found guilty of committing a crime. The nation grappled with many of these same issues during the Cold War but concluded that basic academic research should be free of government restraints unless it is deemed “classified,” a position that was encoded in President Reagan’s National Security Decision Directive 189.

*Four Implementing Actions*

1. Restore, at least to 2001 levels, states’ real funding per student at public universities; repeal the tax on endowment gains of private research universities implemented under the 2017 Tax Cuts and Jobs Act; and double the maximum allowable size of Pell Grants.
2. Significantly reduce administrative burdens on faculty researchers by eliminating outdated regulations; establish greater uniformity in funding agency regulations, rules, and processes; increase the average size and duration of grants; and allow pre-proposals for researchers to receive quick feedback on the likelihood of their work being funded.
3. Universities should themselves investigate and resolve suspected research misconduct by university faculty, staff, or students (e.g., violation of disclosure policies). When federal funds are involved, funding agencies should conduct investigations except in the event there is discernible evidence of illegal activity, in which case regular government enforcement agencies should assume authority.
4. Universities should include broader impacts of faculty research (e.g., technology transfer from the laboratory to industry or other translation of discoveries to societal use) among the criteria for tenure in STEM fields.

US universities continue to be centers of intellectual activity and creativity and, as such, constitute a crucial national asset. They can play an increasingly important role in helping America meet the unprecedented challenges it will face in the coming decades, as long as they receive the necessary support and are allowed to maintain their historical independence.

***Incentivize industrial cooperation.*** US industry and universities have essential and complementary roles in helping the nation meet its needs. Industry is where innovation largely takes place, where the fruits of federally funded research—discoveries and new technologies—are further refined, developed, and applied to produce new products and services that people and institutions need and want to buy. Academic research is the vital element that enables the nation’s universities to produce the best scientists and engineers in the world.

But universities could even better educate students if there were stronger cooperation between companies and campuses, particularly in STEM fields. Barriers include current immigration policies that encourage foreign-born university graduates to leave the country, as well as tax laws and IRS regulations that discourage companies from investing in research and make it difficult for universities to form mutually beneficial partnerships. For example, existing US tax laws, remarkably, identify "long term" as one year. Collaboration between university faculty, students, and company engineers provides the opportunity to work in a transdisciplinary environment where many of the most important current breakthroughs are sought.

*Four Implementing Actions*

1. Provide green cards to foreign-born individuals receiving PhDs in STEM fields from US universities, as well as to members of their families; and increase the number of H-1B visas based on annual assessments of workforce needs.
2. Increase and extend corporate R&D tax credits, giving special attention to encouraging stronger cooperation with universities and federally funded laboratories; tighten regulations governing extension of patents; and remove barriers created by current tax laws and IRS regulations affecting universities.
3. Substantially increase federal tax rates on short-term capital gains; and substantially reduce tax rates on long-term gains to encourage investment in the future, accompanied by an expanded timeframe of gains affected by the laws and the number of steps in related tax rates.
4. Create a federally funded independent entity (comparable to the government-funded nonprofit venture capital firm In-Q-Tel in goals and operating practices) to promote both government and industry efforts to translate new technologies from researchers at US universities and federal laboratories to the US business sector. Such an entity would be not-for-profit, have an independent board of directors, and follow normal business practices rather than government internal regulation.

Some current federal policies work against US progress and future competitiveness. Immigration policies do not properly recognize that the United States must continue to rely on STEM talent from abroad if it is to remain a global competitor. Current tax polices encourage CEOs, directors, and investors to favor short-term gains over long-term investments. Readers may consider the proposal about capital gains to be outside the focus of this essay; however, it is offered here to highlight the fact that if there are few incentives for shareholders to be concerned about the longer-term future of companies in which they invest, there will be little reason for those companies to invest in such endeavors as research.

## The key role of international scientific collaboration

Looking beyond these four key areas, we must also recognize the pivotal role of international cooperation in fostering advances in S&T. Among the United States' greatest assets are our established alliances with other nations, and these relationships could prove decisive in retaining leadership in S&T as well as ensuring our nation's security. It is noteworthy that China and its three most significant allies—North Korea, Iran, and, putatively, Russia—have a combined GDP that constitutes only 17% of the world's GDP. Also, the recent crackdown by Chinese government authorities on several large technology firms that have fueled much of that country's economic growth raises questions about its future economy. By contrast, the United States and just two of its many allies, Europe and Japan, provide half of the global GDP. When democratic nations work in concert, they become a formidable force and provide a global opportunity that should be high among national priorities.

Furthermore, successfully coping with truly global challenges will require all nations, East and West, working together. We cite three examples of fundamental challenges that depend on R&D to a considerable extent for their solution and also require global cooperation, both in R&D and policy.

***Pandemics.*** Throughout the devastating COVID-19 pandemic, scientists from across the globe have put their regular projects aside and quickly come together, applying the results of decades of research in cell biology and disease to understand the virus and create vaccines in record time. Similarly, industry has quickly focused on vaccine development and production. None of this could have been accomplished were it not for the knowledge provided by many decades of basic research conducted in universities and federally funded laboratories throughout the world and made openly available through publication in peer-reviewed journals. The 2021 Lasker-DeBakey Clinical Medical Research Award went to two scientists, Katalin Karikó and Drew Weissman, for precisely this kind of early research.

Advances in the scientific understanding of infectious diseases such as COVID-19 and their origins, biological characteristics, societal impacts, treatments, and eventual eradication will necessarily require that nations, including China and the United States, work together—from laboratory bench to clinic to communities, small and large. There will be future pandemics, and they may be worse than COVID-19. All the world's scientific talent and understanding will be needed to cope with such events.

***Climate change.*** The earth's climate system is extraordinarily complex. Advances in scientific understanding of climate change and its impacts, including regional variations, will be necessary for effective mitigation and adaptation. The 2021 Nobel Prize in Physics went to Syukuro Manabe, Klaus Hasselmann, and Giorgio Parisi for their groundbreaking contributions to understanding such complex systems as the earth's atmosphere. In addition, a more aggressive program of research is needed to develop new carbon-free energy technologies; lower carbon emissions; and capture, store, and remove carbon from the atmosphere. The climate challenge is global, and the research to address it will require nations, including China and the United States, to share data and ideas and together explore new approaches. Geoengineering is viewed as a last re-sort; but if it becomes necessary, collaborative R&D involving experiments in all parts of the world will be essential.

***Cybersecurity.*** Market forces are driving the ever-increasing connectedness of everything in our lives: power grids, pipelines, banks, security systems, communications, hospitals, state and federal agencies, online commerce, the World Wide Web, and more. Of relatively recent origin is "the network of things"—physical entities linked together on a large scale by massive computing and communication systems. Such complex networks of hardware and software can potentially be highly vulnerable to outside interference and cascading malfunctions. As but one example: in 2003, a tree fell on a power line in Ohio and produced propagating failures that put 50 million people in the northeastern United States and southern Canada in darkness for up to four days. And that was an incident with no malevolent human intervention.

More recent events, such as the shutdown of the Colonial Pipeline by Russian criminals using ransomware and, in early October, the six-hour worldwide Facebook outage, are suggestive of the possibilities for disruption in an age when cars are in essence computers on wheels and people's door locks and thermostats—not to mention health records and bank accounts—are accessed from smartphones. When dealing with cross-border incidents, governments have few options other than cooperation, and that includes R&D as well as many areas of policy, including international standards and regulations.

The need for global cooperation in R&D poses something of a conundrum for the United States. While we must take bold steps to compete with China and other nations as new powerful technologies emerge and find application, cooperation is also vitally important in many fields of basic research, for at least three reasons. First, science in support of the common good is advanced by engaging the best minds with the best ideas and skills wherever people live and work. Second, some fields of science require expensive instrumentation—telescopes and particle accelerators, for example—that require sharing costs and use. Third, some research fields require access to specific geographical locations (e.g., studies of earthquakes or ecosystems) or to shared data (e.g., health information necessary to study pandemics, cancer, and other diseases).

## Time is short

Today's challenges threaten the economy, security, and well-being of all Americans. For many decades, the United States has been complacent, reaping the benefits of earlier investments and efforts—taking for granted that the country will continue to be the unchallenged world leader in R&D and applications, always making breakthrough scientific discoveries, inventing new technologies, improving opportunities for all, creating the world's greatest companies, maintaining the world's strongest economy. The rapid rise of China has demonstrated in stark terms that these assumptions are wrong, and business as usual is a sure path to failure.

There remains a brief window of time during which US leaders can take the necessary actions to reverse the downward trends described herein. For the benefit of all our children and grandchildren and future generations of Americans, we urge our political leaders to respond thoughtfully and energetically—and to sustain that response. America is on the edge, but as history has shown, the country can cope with challenges and emerge even stronger.

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ELLEN OCHOA AND VICTOR R. MCCRARY

# Cultivating America's STEM Talent Must Begin at Home

Only with collective commitment, effort, and focus can the country educate and develop the "missing millions" needed to push the frontiers of knowledge, keep our nation safe, and power the innovation economy.

For over seven decades, US leadership in science and engineering (S&E) has fueled the nation's economic prosperity and ensured its national security. The nation's S&E ecosystem, built on federally funded fundamental research anchored by the National Science Foundation (NSF) and other federal agencies, has catalyzed innovation and new industries, revolutionized health care, promoted peace, created the mobile digital world, and transformed nearly every aspect of daily life. Most recently, we have seen the fruits of this system in the tests, therapeutics, and vaccines we have relied on throughout the COVID-19 pandemic—lifesaving innovations made possible by investments in basic research carried out many years before.While these successes demonstrate the remarkable legacy of US S&E achievement, urgent action is also needed to ensure that the United States stays at the forefront of innovation. The most fundamental component of any such vision must be ensuring a steady supply of highly trained and creative scientists and engineers to develop the innovations of tomorrow. Talent is the treasure on which America's S&E enterprise and the nation's prosperity, health, and security depend.In an increasingly competitive world, we cannot take a supply of talent for granted. As the National Science Board (NSB) described in its *Vision*

*2030* report published last year, the US share of global S&E leadership is dropping as other nations, notably China, ramp up their research and development investments in areas such as artificial intelligence, quantum information systems, and hypersonics. At the same time, the growth of knowledge- and technology-intensive industries has increased worldwide demand for science, technology, engineering, and mathematics (STEM) talent, narrowing the pool of potential researchers and innovators who will work in the United States. If revolutionary scientific insights and technological innovations are to be made in America, then the scientists and engineers who imagine and create these insights and innovations must be developed and nurtured here in America too.

### The urgent need to cultivate domestic talent

To meet this challenge, the *Vision 2030* report embraces a two-pronged strategy of continuing to attract global talent and bolstering measures to produce domestic talent. The United States finds itself in a position not unlike the situation after the launch of Sputnik by the Soviet Union in 1957 and the subsequent passage of the National Defense Education Act (NDEA) of 1958. The NDEA contained provisions to ensure the development of domestic STEM talent in order to meet national security needs, given the sensitive nature of this work and the diminishing stream of scientifically trained immigrants at the time. As a direct consequence, many of the historic accomplishments that positioned the United States to be a global leader—in the space race and beyond—were developed by Americans hailing from every corner of our nation.

The COVID-19 pandemic and other recent events have made the need to cultivate domestic talent, in particular, even more urgent. For students in rural areas or from disadvantaged economic backgrounds, the educational disruptions created by the pandemic have exacerbated long-standing disparities in access to quality STEM education. Many students are affected by the digital divide: a lack of reliable access to the internet and computer technology severely impedes learning. The pandemic has also compounded the challenges faced by some groups in the S&E enterprise including women, underrepresented minorities, those caring for dependents, and early-career students and researchers preparing to transition to the next stage. Society has reflected over the past year on the systemic racism and inequities—including in the S&E enterprise—that continue to limit the participation and the potential of all Americans. At the same time, data show that S&E jobs, including those requiring STEM skills without a college degree, pay more and have been more resilient during the pandemic-related economic downturn when compared to non-STEM jobs.

Taken together, these facts mean that a business-as-usual approach to developing STEM talent will not be sufficient to develop the diverse and inclusive S&E enterprise that America needs in order to maintain its global leadership.

Demand for people with STEM skills and expertise keeps growing, driven by international opportunities and competition and by disproportionate growth in the number of jobs at all levels requiring those skills. As of 2019, nearly 21 million US workers with at least a four-year degree—about 14% of the total US workforce—say that their job requires a bachelor's degree level of STEM expertise. In addition, more than half of all STEM workers are part of the skilled technical workforce, with jobs that require STEM skills but not a four-year degree. Industry and the federal government both report that they are unable to find enough workers at all levels with the appropriate STEM knowledge and skills. This situation is likely to worsen as S&E work expands: by 2029, employment in STEM occupations is projected to grow by 8% compared with 3.7% growth in overall US employment, according to the US Bureau of Labor Statistics.

Still other data reinforce the pressing state of STEM education and the workforce in America. The NSB routinely partners with the National Center for Science and Engineering Statistics (NCSES), an independent federal statistical center housed within NSF, on its "Science & Engineering Indicators" report. The NCSES data illustrate that, even as STEM competencies become more essential in various lines of work, the United States is falling behind in educating its students in these fields. Despite continued emphasis on K–12 STEM education, US science and mathematics education at the elementary and secondary levels is mediocre relative to other nations. Since 2007, US student math performance has stagnated, while science performance is somewhat better and has improved between 2006 and 2018. Long-standing disparities persist in students' science and math scores across racial, ethnic, and socioeconomic groups.

A recent study showed that many students start out as "gifted" and "high achievers," but due to a lack of local investment in low-income school districts and access to resources like computers, after-school STEM programs, and mentors, these students become the "lost Einsteins." The study's researchers found that the innovation potential of the United States would increase four times over "if women, minorities, and children from lower-income families became inventors at the same rate as white men from high-income … families." This striking finding shows both the ethical and economic urgency of providing these individuals with the resources, support, and opportunities necessary to join and contribute to the domestic STEM workforce.

In higher education, some progress has been made in diversifying the racial and ethnic composition of S&E degree recipients, reflecting population changes and growing rates of underrepresented groups who earn postsecondary degrees. But the attainment gap across racial and ethnic minorities remains significant. There is a similar story for the workforce. Despite some progress, women and racial and ethnic minorities remain underrepresented in the S&E workforce relative to their proportions in the US population—and will remain "missing millions" for years to come unless there are vast improvements in attracting and retaining these individuals.

Furthermore, STEM jobs and innovation activities currently are concentrated in certain geographic areas. For example, 20 metropolitan areas are home to about half of workers in S&E occupations, but only 38% of employment in all occupations. At the same time, 80% of business R&D, which has averaged $325 billion annually over the past 10 years, is performed in just 15 states that account for 58% of the population. These same 15 states account for about 78% of patents produced. The United States needs to ensure that all Americans have access to quality, higher-paying STEM jobs that also enjoy lower rates of unemployment.

A different path is available to us, one that will create greater STEM opportunity across the country. It begins with cultivating diverse domestic STEM talent in every part of the country, across all demographic groups, income levels, and educational levels.

### How can the United States increase STEM skills and opportunities for all?

Congress and the Biden administration are considering historic levels of investment in the nation's S&E enterprise. This discussion also presents an opportunity to make historic investments in fostering the nation's STEM talent. Bipartisan support for new investment could simultaneously drive discovery and innovation and open doors for more Americans to pursue STEM education and careers. However, any new investment in the S&E enterprise must be accompanied by new and different approaches to attract and retain domestic talent and to address the interrelated elements of inclusivity, access, and affordability.

***Inclusivity.*** Attracting and retaining the missing millions will require broad culture change to promote inclusivity, especially around STEM education. Culture change includes welcoming students from a wide variety of backgrounds, experiences, and demographic groups and recognizing that they come with varying levels of preparation, personal circumstances, and motivations for their interest in STEM. Providing wraparound services such as mentoring, transportation, childcare, and career counseling can help more students finish their degrees and training. In addition, a student's STEM "spark" must be nurtured and encouraged, not subject to weeding out by classes that could disproportionately hinder underrepresented groups from pursuing STEM degrees.

As America's premier STEM talent agency, NSF is looking internally and externally at how the agency's policies, practices, and programs can help create a more inclusive culture in S&E. In 2018, NSF made clear that harassment will not be tolerated at grantee institutions and now requires these institutions to report findings of sexual harassment, or other kinds of harassment protected by federal civil rights laws, by personnel funded on NSF awards. In 2020, NSF Director Sethuraman Panchanathan established an internal Racial Equity Task Force to ensure that the agency addresses racial inequities and identifies and removes barriers to opportunities both internally for NSF staff and for the students and researchers NSF supports. The task force is examining its policies and procedures, including those related to grant proposal writing and development and the merit review process.

Furthermore, NSF's FY 2022 budget request more than doubles funding for INCLUDES, NSF's signature program aimed at accelerating the advancement of underrepresented populations in STEM by connecting individuals, alliances, pilot programs, federal agencies, educational institutions, and other entities in a network that serves as a model for intra-agency collaboration. The budget request also includes $20.5 million for the ADVANCE program, operating since 2001, to encourage institutions of higher education and the broader S&E community to enhance gender equity for faculty and academic administrators. As the COVID-19 pandemic has had varying impacts on individuals in the STEM research and education community, NSF plans to use a significant fraction of funds received from the CARES Act and the American Rescue Plan Act to help the groups most deeply affected.

In the first year of implementing *Vision 2030*, the NSB has focused in particular on the missing millions. The NSB issued a statement after the death of George Floyd, strongly calling for increased inclusion of African Americans in S&E at all levels, from the classroom to the research lab to the boardroom, with bolstered opportunities to participate, lead, and thrive. The NSB further committed to increased support for research at historically Black colleges and universities (HBCUs) and has encouraged NSF to build research capacity and technology commercialization at these institutions, which produce 30% of the nation's Black students who later graduate from S&E doctoral programs. The board has hosted external panels to highlight data and illuminate insights on such topics as the Black experience in STEM, COVID-19 impacts on women in STEM, and what the S&E community can learn from Hispanic, tribal, and other minority-serving institutions about supporting diverse students. The NSB continues to hold itself accountable by acting and advocating for more inclusive environments and by partnering with NSF to strengthen research training pathways, reduce barriers, and increase participation.

***Accessibility.*** To ensure that all K–12 students have access to a quality STEM education, the United States must address the persistent educational inequities that exist across dimensions of geography, race, and economic background. At the postsecondary level, it will likewise be important to make investments across the full range of institutions that cultivate STEM talent to ensure that the nation is reaching individuals of all races, ethnicities, and backgrounds in all parts of the country.

NSF's FY 2022 budget request reflects actions the agency is taking to ensure that more postsecondary students have opportunities to pursue STEM education and training. The proposed budget emphasizes artificial intelligence research, education and workforce development, and infrastructure activities at minority-serving institutions to increase accessibility for underrepresented populations. Increased funding for the Graduate Research Fellowship Program would support an additional 500 new fellows over the prior year, a 25% increase. Lastly, the proposed budget would establish a new NSF directorate to speed the translation of NSF-funded discovery to innovation. This would include building and expanding capacities for innovation around the country with Regional Innovation Accelerators that tackle use-inspired, solutions-oriented research across a range of technology areas.

Congress is also taking bold action to advance the agency's ability to develop domestic STEM talent. The House National Science Foundation for the Future Act, for example, proposes establishing multidisciplinary Centers for Transformative Education Research and Translation. These centers would help realize NSB's vision of furthering the broad adoption and use of NSF-funded STEM education research where it is most needed: in classrooms. The NSF for the Future Act also would support grants to advance research on teaching and learning at community colleges, which are critical access points for groups historically underrepresented in STEM and an important pathway into the STEM-capable workforce.

The Senate US Innovation and Competition Act (USICA) includes a provision for a pilot program to build research and education capacity at emerging research institutions, which includes many minority-serving institutions, in partnership with research-intensive universities. Such partnerships not only promote the exchange of ideas and new innovations, but also diversify the ranks of the S&E workforce, necessary for a competitive US research ecosystem. Only about a third of underrepresented minority students attend research-intensive universities, so such a program would help realize NSB's vision of engaging and retaining students from diverse institutions, races and ethnicities, and backgrounds in STEM. The USICA would also create a grants program to advance innovative approaches to support and sustain high-quality STEM teaching in rural and Indigenous schools, helping to ensure that individuals from all states have access to STEM careers. Such proposals seek to leverage NSF's unique strengths to address a critical national need. Finally, the recently passed Infrastructure Investment and Jobs Act will provide $65 billion for improving broadband infrastructure, which will increase access for the missing millions and help close the digital divide.

***Affordability.*** The *Vision 2030* report highlights the need for postsecondary STEM education to be more affordable. Several state or federal initiatives and proposals aim to address financial barriers to higher education, such as the Tennessee Promise, which offers high school graduates the opportunity to attend a community or technical college for two years free of tuition and fees. Louisiana recently enacted the MJ Foster Promise Program, which will offer grants to pay for education for high-demand, high-paying careers beginning at the state's community and technical colleges. At the federal level, making higher education more affordable for millions of Americans by providing two years of free community college, increasing the size of Pell grants, and expanding scholarships for future teachers could go a long way in attracting and retaining STEM students and building the workforce the nation needs.

## Next steps

The NSB will continue to collect and communicate data on the US and global S&E landscape and convene and collaborate across the national S&E ecosystem. The NSB will continue to advocate for innovative policies that help postsecondary education institutions attract and retain diverse talent and for applying research-based findings to improve teaching and education outcomes. The Board will enhance its focus on community colleges and minority-serving institutions because they are critical pathways for individuals from many underrepresented groups into STEM fields and careers. And although K–12 education is not NSF's chief area of focus, it is key to the development of STEM talent, and the board in its broader advisory role will continue to advocate for more, and more effective, STEM teaching in K–12 education as well as coordinated, concerted efforts at local, state, and national levels.

As for the NSB, because one-third of the members finish their terms every two years, each presidential administration appoints some new members. A diverse and inclusive S&E enterprise requires diverse and inclusive leaders. To reflect these values in practice, we encourage the Biden administration to ensure that new NSB members named in 2022 include S&E leaders who reflect the diversity of research interests, employment sectors, educational institutions (including community colleges), and lived experiences, races and ethnicities, and backgrounds of all Americans.

Building a deeper domestic bench of STEM talent to meet the challenges of the future will require all levels of government, educational institutions, community and nonprofit organizations, and industry to step up their efforts. Institutional change requires identifying and changing the policies, processes, programs, and practices that create or perpetuate systemic barriers to diversity, equity, inclusion, and access and selecting a diverse cadre of leaders who value an environment with those attributes. As members and leaders of the US S&E community, we know it is incumbent upon all of us to hold ourselves, and each other, accountable for progress in developing the next generation of diverse STEM talent. We must all work together to continue the momentum, to set meaningful goals, to collect data that will allow the measurement of progress, and to be transparent by making the goals, data, and progress publicly available.

We challenge everyone in the US S&E enterprise to value diversity, equity, and inclusion in your own practice. Reward institutions for creating and sustaining environments for diversity to thrive. Appoint people from diverse populations and backgrounds to decision making positions, elevating role models for the next generation of America's STEM talent. Be transparent as you set and work towards your goals. With this collective commitment, effort, and focus, the United States can educate and develop the STEM-capable workforce needed to push the frontiers of knowledge, keep our nation safe, and power the US innovation economy as envisioned in *Vision 2030.*

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# Reimagining the Research University

STEVEN W. MCLAUGHLIN AND BRUCE R. GUILE

# Greatness Thrust Upon Them: US Research Universities and the National Interest

The United States needs universities—some of the most fiercely competitive and proudly autonomous global institutions in America—to coalesce around national interests in economic prosperity and economic security.

In the 75 years since the end of World War II, the United States has steadily devolved a number of core civic missions to a decentralized system of state or privately chartered research universities. The nation depends on its research universities for the education of a research-capable, technically trained labor force that plays a key role in US technical entrepreneurship, industry, and government. The nation also depends on its research universities for innovations, a trained labor force for industry, and to create new knowledge that is shared with the world through open publication. This new knowledge serves humankind, of course, but is also an important aspect of US "soft power" in the world.

US research universities, fueled by research funding from the federal government, have performed admirably, delivering on these civic missions while providing social mobility for US citizens and immigrants alike. One unintended consequence of the tremendous success of the decentralized US research university system, however, is that the nation struggles to mount a coherent strategy to adapt to the rapid growth of science and engineering capability outside the United States and the integration of that capability in global networks.

National governments, including the US government, are responsible for international affairs, national security, and international economic relations. Other nations, most notably China, have placed technical talent development, the development of science and technology (S&T) capability, and industrial innovation at the center of their approach to geopolitics and economic development. In the context of our insular national history of research funding at universities and the S&T actions of other nations, business-as-usual research funding of US universities by the federal government is wholly inadequate to today's challenges.

In the more than 40 years since the "technology and competitiveness" crisis was first sparked by rising US imports of Japanese automobles and electronics, legislative debate combined with executive branch actions have created only marginal change. If the US research and innovation system is to adapt to rising S&T and innovation capabilities in other nations, then US research universities are crucial to the response. Our nation's research universties, lacking direct access to national levers of control (they do not vote, engage in political action, or control government budgets), have no choice but to lead by example and commit to building actionable consensus around a few essential areas of national importance. The nation needs some of the most fiercely competitive and proudly autonomous global institutions in the United States to coalesce around the national interests of economic prosperity and economic security.

Any such change will be an anathema to many academics, accustomed as they are to focusing on education, the advancement of knowledge, and the global good. But the reality is that regional and national interests in talent development and innovation for industrial development are already clearly articulated in the charters and founding documents of many leading US research universities. Coalesing around US national interests in economic prosperity and economic security does not require that universities abandon their core values of openness, academic freedom, and contributions to knowledge for the good of humankind. But it does require research universities to step back from their conventional calls for additional federal funding for curiosity-driven research. Instead, they should partner with government and industry to propel a revolution in how the United States integrates the core civic contributions of universities with national interests in economic security in the context of shifting international economics and geopolitics.

## Creating actionable consensus in areas of national importance

US government funding of open research at universities during the 1950s, '60s, and '70s drove their ascendance on the global stage. Today, the United States is home to approximately 150 universities with annual research expenditures regularly exceeding $100,000,000 per year. And depending on the ranking system selected, 30 to 40 of the top 100 research universities in the world are in the United States—more than in any other nation.

In most other nations, central government plays a more important role in direct university funding, regulation of educational institutions, information sharing among institutions, and even direct engagement in management and governance of research universities. The lack of central government coordination of US universities leaves a vacuum in policy approaches to economic security in our country.

Realistically, this vacuum will not (and should not) be filled by a new federal "Department of Advanced Education and Research." Rather, it needs to be addressed by consensus among those institutions with detailed understanding—and skin in the game—of the basic research, research-informed education, and research-for-innovation processes. As vehicles for the required consensus building, universities are in a unique position. It is not an exaggeration to say that US government research funding and US research universities evolved as a single organism over the past 70 years, sharing a set of values and norms constantly reinforced by a revolving door of employment between senior research and development (R&D) positions in the federal government and university faculty and leadership.

Working together with their natural allies in government, industry, and higher education associations, US research universities need to create consensus about important changes needed in the nation's S&T enterprise. None of these changes will occur, however, if university leadership defaults to calls for increases in federal funding of curiosity-driven research following historical patterns.

## Increase focus on research-informed education

The research activities of US universities have two direct outcomes: 1) they advance knowledge through research and publication, and 2) they educate and mentor students who, on graduation, carry those advances into diverse applications in the broader world. The former is important to humankind; the latter is essential to our nation's economic prosperity and security.

Although the United States lionizes the untutored or self-taught innovator in tech and business, university-educated researchers often are the limiting factor in national capacity in industries as diverse as biotech, artificial intelligence, catalysis, satellite applications, logistics, data science, animation software, and semiconductor manufacturing. Our national response to growth in science and engineering capability abroad desperately needs to include attention to development and retention of research-capable people at the cutting edge of knowledge across a wide range of existing and emerging fields of science and engineering.

Although there is not a one-to-one relationship between graduate STEM (science, technology, engineering, and mathematics) degrees and numbers of research personnel, there is evidence that the two are highly correlated. In the late 1990s, the United States led the world with more than 800,000 personnel engaged in research. By 2017, according to UNESCO data, the number of researchers in China was 1.7 million, exceeding those in the United States by approximately 300,000. This growth in research activity parallels the meteoric rise in doctoral-level STEM graduates in China (from 7,800 in 2000 to 34,400 in 2015). This is important because research personnel have an outsized economic impact, with large economic multiplier effects that create both unskilled and skilled jobs. As an example, Enrico Moretti's analysis of Apple's 12,000 mostly high-tech jobs in Cupertino, California, showed that they generate 60,000 additional jobs, 24,000 of which are for skilled workers.

The US economic policy establishment typically focuses on research funding, research results, and (in 2021) research security as endpoints in themselves; other countries are more ambitious. Most countries that have rapidly developed strengths in scientific and engineering capability have done so by investing in an industrial development strategy with explicit specifications for educating workers at universities. Thus the S&T policy of other nations—ranging from China and South Korea to Germany and many other European Union countries—has elevated the importance of industry problems in research funding, and thereby in human capital development, at universities.

Individually and collectively, US research universities need to step up to articulate and highlight linkages between taxpayer-supported, open academic research and US human capital. This is a critical and overlooked element of the argument linking public research investments to the current and future economic security of the nation. Similarly, US research universities play a unique and crucial role in attracting and retaining foreign talent. To continue this practice, universities should press the US government to establish national priority areas that fund foreign students and fast-track their H-1B visas or green cards.

Currently universities are joining calls for increased federal investment to develop and commercialize transformative, emerging, disruptive, or critical technologies, to name a few popular characterizations of advances in knowledge and application that have been identified as important. Although this leverages one strength and purpose of research universities, it pushes the most critical contribution of research universities into the background. Universities must shift to focus on how government funding for research can be reconfigured to drive a national agenda for research-informed education. This would include, of course, incentives for industry coinvestment in research at universities, again with a focus on advanced education.

As a vehicle for consensus building on this crucial national issue, the White House, via the Office of Science and Technology Policy, should immediately establish a standing forum on research for human capital development. This national function, operationally dominated by research universities, has not received analytical or policy attention commensurate with its national importance. The forum should solicit briefs on the topic, including specific arguments for what types of research should be funded to best support advanced human capital development, from universities and bodies as diverse as the National Science Board; the Departments of Defense (DOD), Energy

(DOE), and Commerce; professional societies; higher education associations; and, of course, industry.

Regular contributions from such a forum, timed to be considered as the administration prepares its budget or as Congress considers research-for-competitiveness legislation or budgets, would be an important complement, or alternative, to calls for federal investment in flavor-of-the-week areas of science or technology commercialization.

### Embrace industry-focused, university-based research and education

US research universities contribute to the country's economic prosperity and security through open (not proprietary), curiosity-driven research and talent development. This process is a wellspring that simultaneously feeds the high-tech, start-up economy and renews the technological capabilities of mature companies in the United States. The proliferation of university-based or university-adjacent incubators and innovation centers, and the colocation of corporate research laboratories or advanced technology operations with universities is the direct result of universities, US states, and companies seeing this process in action and building institutional mechanisms to take advantage of its momentum.

Government research funding—from the National Science Foundation (NSF), the National Institutes of Health (NIH), DOD, DOE, and other agencies—has historically played a pivotal role in the process of building human capital and new knowledge that emerges from research universities. But the biases baked into US government research funding over the past 70 years are now out of step with the nation's future needs.

This failure is apparent from the ways in which the availability of federal research money for defense, aerospace, energy, and biomedical topics have created and shaped the university-adjacent ecosystem. These research enterprises, often university managed, have crowded out other industry-focused activities that have emerged as robust industrial strategy in other nations. When the United States stood alone at the top of global science and engineering, the country's bias toward defense and medicine in government-supported R&D was not a problem. The dual-use spin-offs of US defense R&D—and of NIH-supported biomedical research—are legendary and continuing, but there is an opportunity cost.

In other nations, structured government funding outside defense, aerospace, and biomedical research—especially for public-private collaborative research and education in other industries—is much more important and presents a stark contrast to the US approach. Examples are national institutions of translational research and industry-focused, research-informed higher education such as the Fraunhofer Institutes in Germany or TNO in the Netherlands. There are also many one-off but long-lived, university-adjacent R&D activities that are industry focused with government support in other countries. Examples include the Advanced Manufacturing Research Centre at the University of Sheffield in the United Kingdom, the Taiwan Semiconductor Research Institute, and the French Institute of Petroleum.

The United States has many notable successes in industry-focused on-campus research—the MIT Media Lab or the Clemson University International Center for Automotive Research are good examples. But there is no substantial federal funding program specifically designed to solicit and fund proposals for industrial development-focused research and education activities at US research universities. An entrepreneurial professor with a good idea for such activity, generated internally or stimulated by industry partners, will often "shop" the idea to NASA, DOD, or DOE, or—if a plausible link can be made to curiosity-driven research—try to fit it into an NSF program.

There is widespread recognition that the US government's approach to industry-focused, university-based, or university-adjacent R&D and education enterprises has been an on-again, off-again affair, and at a small scale. In response, a handful of programs have tried to stimulate a start-up environment, including the National Institute of Standards and Technology's defunct Advanced Technology Program (later the Technology Innovation Program), as well as the Small Business Innovation Research and Small Business Technology Transfer programs and the National Science Foundation's Innovation Corps. But larger impact is not feasible with such limited approaches. An additional recognition of this failure can be seen in recent legislative proposals that create a new, permanent, and largely independent directorate of the NSF as well as a raft of new funding entities that mimic the structure of the Defense Advanced Research Projects Agency (DARPA).

We believe that a direct and first-principles approach to this national need calls for a new, independent funding agency unencumbered by 1) government missions such as defense or energy, or 2) a long history of supporting curiosity-driven research. Most importantly, this agency could match process to mission by drawing on the wide variety of proven domestic and foreign approaches to soliciting, selecting, funding, and managing industry-university research and education activities.

To rise above legislative wrangling and interagency turf battles, US research universities should lobby the the White House to ask the National Academies of Sciences, Engineering, and Medicine to undertake a design process for a new independent government research funding entity to focus on university-based, industry-focused research and education projects, programs, major facilities, and long-lived research institutes. Leadership and a substantial portion of the study committee membership should be drawn from the senior ranks of corporate research and human resource operations, preferably including individuals with direct experience in university research and education relationships. In addition, the group should investigate industry-focused research funding approaches used in other nations, such as the UK Catapult Centres, German Fraunhofer Institutes, the Dutch TNO, and similar operations in other technologically advanced countries. Finally, the group should carefully consider successful and unsuccessful examples of component strategies, including obtaining industry matching funding and personnel rotations between industry and universities.

Once there is a design, there will likely be foot-dragging from leading US research universities that perceive the initiative as a threat to funding and support for curiosity-driven research. Nonetheless, when we benchmark research-funding organizations in the US government against those in other nations, it is apparent that this a critical gap. Furthermore, US research universities can be both innovative and quickly productive in response to shifts in government research funding, which has been demonstrated by their long history of organizational innovation in response to changes in government mission-oriented funding.

### Align university international engagements with US national interests

Research universities, both in and outside the United States, are less and less campus-bound concentrations of talent and increasingly global, almost stateless, networks of faculty, students, and private sector researchers working to advance knowledge even while they address an environmental issue, create a business, change an industry, or cure a disease. This form of globalized research university activity presents tremendous opportunities for US prosperity and economic security. And it creates real vulnerabilities and risks.

Further, the government R&D funding establishment has given too little thought to the implications of the statelessness of US research universities, except to worry about research (e.g., intellectual property or dual-use technology) being stolen. This concern is shortsighted and fails to take into account the potential of US research universities as globalized entities that can be of crucial value to the nation in sharing the burden of economically important, near-term R&D—not just basic research—among nations and reaching out across national borders to learn and "capture" openly available frontier science and engineering knowledge of commercial importance from other countries.

Obviously individual US research universities must 1) maintain or improve compliance with US laws and regulations; 2) review existing research collaborations; and 3) participate actively in advocacy for, and help shape, research and education collaborations where there are likely demonstrable benefits to US national interests. Given recent history and the release of policy publications such as *Fundamental Research Security* by the JASON advisory group, there are very few US research universities that are not already fully engaged in the aforementioned activities 1 and 2.

Actions to date are, however, primarily defensive in nature: they help protect the security and integrity of the US university-based research enterprise, but they will not help the United States benefit from the more than 70% of global R&D that is performed outside the country every year. To take advantage of this rich new arena, US universities need a new playbook for international collaboration that includes a set of guidelines for cross-border collaborations and engagements that serve the national interest. Universities also need access to robust confidential due diligence about the nature and risks of any cross-border partnerships they enter into.

Most US universities rely on an underresourced internal committee process to determine whether a particular proposed collaboration is in the university's interest and consistent with its values. Even the most robust internal university processes do not have the authority or the capability to ask or answer rudimentary questions about conditions for international collaboration such as reciprocity, transparency, and national treatment. Similarly, US research universities would benefit from having access to a responsive, confidential, and impartial source of due diligence to evaluate proposed international collaborations.

These areas of weakness in US research universities are, of course, areas of strength in the US Department of State, which has long and deep experience in all forms of international collaboration and exchange as well as the national vulnerabilities associated with them. Through associations of higher education, universities should ask the US Secretary of State for help. The State Department—relying on its Office of the Science and Technology Adviser to the Secretary of State, the Bureau of Educational and Cultural Affairs, and the Bureau of Oceans and International Environmental and Scientific Affairs—should immediately launch an initiative to help develop voluntary guidelines for universities to explore international engagement and establish the capacity for due diligence on university cross-border collaborative activities, perhaps as a freestanding, not-for-profit entity. An essential aspect of this work would be to highlight and resolve, when possible, conflicting international collaboration guidelines among, for example, NSF, DOE, and DOD.

US research universities should also pressure legislative and executive branch leaders to reformulate federal funding regulations that limit research funding to domestic enterprises, because it is demonstrably in the national interest to do so. This regulatory change would mean that research universities should spend some of their credibility and political capital to shift the conversation in Washington, DC, so that investing in overseas basic and precompetitive research and related R&D infrastructure—especially in collaboration with economic allies—is seen as advancing US interests.

If US universities cannot find or develop a path to international R&D collaborations that demonstrably benefits not only the university but also the United States, they will be judged harshly by taxpayers and their representatives in both state and national governments.

## US research universities and the national interest

Whether or not they have sought it, US research universities play a role in the innovation-based economic security policy in our country that no other domestic institution, or set of institutions, can fill. But substantial change is needed: our nation has only a few years to make substantial shifts in research focus, funding, and approach to keep pace not only with China but also with an increasing number of nations that see R&D, research-informed education, and tech-based business as the key to geopolitical security and economic prosperity.

Although additional federal funding and collaboration will be required, the ability of US universities to innovate could shift the landscape quickly. Within a few years the United States could regularly adjust its support for university-performed research in a way that is explicitly linked to developing and retaining research-capable and technologically sophisticated human capital. Most US research universities could have growing, robust, university-adjacent, industry-focused research and talent development enterprises. And more federal government funding would be available for university-based cross-border research and educational collaborations, which would have demonstrable value to the United States.

If US research universities advocate for these changes, leading by example when possible, it would demonstrate their ability to embrace their essential role in and responsibility for keystone aspects of US economic prosperity and security. This approach does not imply that US universities adopt a nationalist stance, but it does mean that US national interests are given due weight in the actions taken by university boards of trustees, administrations, and faculties.

The future of US research universities is intimately entwined with US economic security in the new world order of globalized science and engineering. If the United States is to prosper in the coming decades, then the nation needs its research universities—in partnership with federal funding agencies, industry, and relevant associations—to rise to help the United States adapt to current geopolitics and international economic relations.

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TIMOTHY LIEUWEN, SETH MARDER, AND CHAOUKI T. ABDALLAH

# Imagining the Role of the Research University Anew

Research universities should envision themselves as partnership builders, connecting local communities, government, industry, and others to plan for and respond to the challenges facing society.

*The year is 2034, and a magnitude 8.2 earthquake has just hit southern California. The destruction is massive and widespread as the long-feared mega-tremblor races 100 miles up the San Andreas Fault from the Mexican border to San Bernardino. Virtually every building suffers significant damage, but thanks to some of the strongest construction codes in the county, less than half become dangerously unstable. Even so, many roads and highways buckle, and dozens or even hundreds of bridges collapse—cutting off many communities from each other. Meanwhile, the shaking blocks the flow of water from numerous reservoirs. An estimated 5,000 people die, and 50,000 are injured in the immediate aftermath, before the first aftershocks unleash further destruction.*

*It could have been worse. State and local governments, businesses, and individuals had been preparing for this tragedy for decades. They were joined in the late 2020s by a network of science and engineering hubs from a dozen research universities that had come together specifically to address and plan for the dominant challenges facing society—from the long-running disruptions triggered by climate change to more acute disasters such as earthquakes and pandemics. Because engineers had anticipated that normal communications networks would utterly fail in a mega-earthquake, for example, researchers at California State University, Stanford University, and the Georgia Institute of Technology had spent several years developing transponders that could be rapidly deployed via balloons lofted over stricken neighborhoods, allowing first responders to communicate with each other and the outside world.*

*Communication was nevertheless limited for average citizens in the 2034 quake, and California Institute of Technology, which, of all the network's universities, had focused the most on earthquake preparedness and response, was severely damaged, taking it offline. In a manner that had been well rehearsed in multiple tabletop exercises, the coordination activities normally performed by Caltech were distributed almost instantaneously throughout the network.*

*Meanwhile, in Los Angeles County, a 25-foot-high tsunami unleashed damage up to three miles inland from the coast. As a result, airplanes could no longer land at Los Angeles airports, water for much of the city was no longer potable, and power outages were significant. Fortunately, due in part to smart-grid technologies developed at the University of Colorado Boulder, roughly 50% of the city still had power. Low-cost solar thermal water purification systems originally developed by the University of Texas at Austin and at El Paso, the University of Arizona, and others for routine use in mid-income countries were airdropped to various centers in the city for widespread distribution. Thanks to a combination of solar energy, batteries, and microgrid technologies, those hospitals that were still structurally sound largely retained power and could treat patients, even in areas lacking power from the grid. Portable solar cells printed on lightweight solar tarps (developed at Stanford and UC Boulder in partnership with the National Renewable Energy Laboratory, Sandia National Laboratories, and the University of New Mexico) were airdropped into other areas, including south central Los Angeles, where power was more severely disrupted.*

*The situation was still a disaster, requiring a large all-hands response coordinated by federal and state governments. But contributions of the university science and engineering network played a key role in saving lives and recovering the region's essential functions.*

Nothing tests people, systems, and processes more acutely than a major crisis—as the present situation with the COVID-19 pandemic has shown over and over. Such pandemics historically "have forced humans to break with the past and imagine their world anew," as novelist and activist Arundhati Roy wrote in the *Financial Times* last year. They are what she called "a portal, a gateway between one world and the next." The world can expect more such crises in the future, as the above scenario illustrates. But with targeted, smart planning over the next few years, society can be better prepared to meet them.

The academic world is not immune to such disruptions. Decisionmakers have been forced over the past couple of years to reexamine long-held paradigms about conducting research and development, embracing those processes that have worked well while recognizing that universities can improve upon current approaches, in some cases at a systemic level.

Here we share some thoughts based upon our experiences working with a diverse range of stakeholders, from government policymakers to researchers in the laboratory, that may help universities more effectively leverage the talent in scientific, engineering, and policy communities to create a more resilient, inclusive, and agile research enterprise. We also propose one possible framework for creating such an enterprise—which we call the Network of Agile Science and Engineering Centers.

## The future of research universities

It is generally understood that modern research universities are complex organizations that are deeply interconnected with a range of stakeholders. These universities create knowledge, technologies, and jobs and enable economic development. They are integral partners with government, industry, nongovernmental organizations (NGOs), and the wider community. They are critical local hubs for innovation where students, start-ups, researchers, corporate innovation centers, and corporate offices intersect. They serve as anchor institutions within their communities and help to develop the next-generation workforce.

Like many research universities, and independent of the COVID-19 crisis, we at Georgia Tech launched a major study in the early part of 2020 that reexamined the role of research universities in society. The study considered the external forces to which these universities must respond, the problems they must address, with whom and how they should partner, and how they should be structured. We wanted to take a hard look at a basic question: Knowing what we know today, if we were to develop the university research enterprise from scratch, what would it look like? Our efforts were slowed by the pandemic, which also, and somewhat paradoxically, clarified the impact of global crises and brought to the forefront issues such as inequity of access and opportunity, the power and fragility of supply chains, and the need for well-coordinated scientific and engineering partnerships that can respond nimbly to rapidly—and sometimes radically—changing circumstances.

Meanwhile, a second group of us at Georgia Tech engaged in a more long-range strategic planning effort, with input from sectors beyond academia. The efforts of this group led its members to develop a specific concept for restructuring a part of the research enterprise via a highly coordinated group of centers of excellence based at individual universities and directed by a committee of academic leaders.

A core conclusion of our first study was that research universities have a responsibility to play a greater role in helping society address and plan for the opportunities and challenges that lie ahead—including, but not limited to, climate change, equity, health and aging, security, and strengthening democratic institutions. But academia must be more adaptable—or agile, in business parlance—to an ever-changing environment than it has historically been.

Four key takeaways emerged from this study:

***Organize around complex missions.*** As the COVID-19 pandemic raged, we were forced to reconsider our internal structures and processes, asking: How is the work done? Who and what are rewarded? How can research organizations tackle complex societal challenges and create new research directions; empower and support all Americans; combine research, technology transfer, entrepreneurship, corporate engagement, and economic development; and ensure compliance, security, and research integrity?

We can and must innovate in how research organizations are organized to execute their missions. Commercialization and licensing, interdisciplinary research, external partnerships, and other functions in the research enterprise all cut across many of the current departments and people in universities, and there are many possible ways to organize these functions. Continued effort, thoughtful experimentation, and sharing of best practices will be key to sustained improvement in research organizations. Possibly the two largest challenges that cut across all research universities are (1) creating effective approaches for organizing and rewarding transdisciplinary work and (2) developing approaches for apportioning resources and credit across the many contributing partners. In the language of sports, we must learn to reward the assists as well as the successful shots.

***Embrace arbitration over advocacy.*** The collective challenges we face as a society involve the complex interplay of policy, politics, finance, human behavior, history, science, and technology. Moreover, as has been self-evident in recent years, knowledge and science are easily politicized. Critical societal challenges and opportunities are coupled with deeply concerning trends in the national discourse: growing polarization in thought, increasing distrust in foundational institutions, and expanding distrust or cynicism regarding "experts." Indeed, an important lesson often lost on the research community is that *improved expert knowledge often does not clarify the path that seemingly rational people should take on a complex topic*—a subject explored at great length by Daniel Sarewitz. In addition, greater knowledge often does not reduce political controversy in areas where there is no consensus on values, such as abortion, use of fetal stem cells, or nuclear power.

Consequently, universities must institutionalize the cultures and processes to increasingly serve as, and *be perceived as*, honest brokers. Honest brokers, as described by political scientist Roger Pielke Jr., engage themselves deeply within the broader set of stakeholders to expand the scope and ramifications of policy options for decisionmakers while simultaneously educating the public and transparently advocating for critical and independent thinking. At the same time, academics should be extremely careful about engaging in advocacy—no matter how well intentioned—because it can so easily and cynically be dismissed by opponents as simply the voice of another special interest, thereby discounting the important role that subject expertise can play. Of course, most academics don't see themselves simply as advocates but rather as truth-tellers. Indeed, "speaking truth" is a clear role for experts, particularly in cases where there is low scientific uncertainty. However, many of the most perplexing problems facing society, problems in which subject matter experts can be helpful, involve high uncertainty as well as low societal consensus on values—where honest broker roles would be more appropriate.

***Form holistic, trusted partnerships.*** Universities are but one actor in seeking and implementing solutions to societal challenges, but they must become more integrated as trusted partners in the wider ecosystem of governments, companies, NGOs, and local communities. Corporate-university engagement is already shifting from ad hoc, one-off, problem-specific efforts to increasingly holistic partnerships organized around student recruitment, development of innovative solutions, research, and access to specialized equipment. The same approach must be more extensively implemented around holistic partnerships with cities, states, and communities, whether as anchor institutions, facilitators of educational advancement at the K–12 level, hubs of innovation with commercial potential, or strategic partners with industry.

Partnership models must also evolve from a collection of two-way partnerships to an interconnected network (as described in our speculative but realistic earthquake example above). Increasingly, research universities should envision themselves as conveners and partnership builders for local communities, government, industry, and other NGOs. Some of these partnership models and support structures, such as higher education and federal engagement, are well developed due to the successful implementation of ideas articulated by presidential science advisor Vannevar Bush more than 75 years ago. Others models, such as serving as anchor institutions for local communities and fully engaging with them, are less so.

A key conclusion from our study was the need for universities to define and better understand the social and economic ecosystems in which they operate when framing partnership opportunities. No university can be all things to all sectors. For starters, universities should strive for shared values and transparency around intellectual property and publishing as well as the impact on student education. Universities also need to consider how activities will be guided and reviewed to make sure they contribute to the overarching goals of a given partnership. Finally, a key conclusion of our analysis was that the kinds of interconnected partnerships we envision require an organization—including its structure, function, and roles—that is consciously and proactively designed around such holistic partnerships. In other words, don't just bolt a "partnership" office onto the preexisting research org chart.

***Organically integrate equity and inclusion.*** Equity and inclusion cut across the research university in multiple dimensions. Not only are equity and inclusion core values that reflect our foundational assumptions about the dignity and equality of all people; they are also key strategies for enabling more innovative approaches and better solutions.

Framing the appropriate research questions, bringing the full fruits of research and innovation to everyone in society, and engaging the full representation of humanity in the research enterprise will continue to require attention, monitoring, and new models to include more minds, all voices, and diverse perspectives. It is neither appropriate nor beneficial to focus only on challenges defined exclusively by university researchers. Instead, such researchers must engage those affected by the answers to help frame the research questions.

Thus, equity and inclusion efforts must be deeply integrated into the research organization and structure at all levels—rather than being just the responsibility of diversity, equity, and inclusion professionals. In addition, engagement must be built upon transparent and accessible data and information, enabling accountability and metric tracking. Finally, the values of equity and inclusion must be integral to how academia develops the structures, functions, and organizational constructs by which the research university is organized.

## Concrete options

In addition to considering new roles for universities, another group of colleagues at Georgia Tech, with input from other sectors, examined concrete options for future planning. This second study group began developing a specific concept for restructuring some of the research enterprise, which its members dubbed a Network of Agile Science and Engineering Centers (NASEC). Consisting of a highly coordinated group of centers of excellence directed by academic leaders, the proposed network would take a holistic approach to preparing for and addressing problems of critical global needs and developing rapid responses. It would address a wide range of issues including communication, supply chains, logistics, policy, regulation, information dissemination, scalability of approaches, and independent validation of approaches. NASEC's efforts would need to be coordinated, not only to save lives and ensure well-being in difficult circumstances (e.g., disasters), but also to work on longer-term issues that are critical to national interests and the future of the planet (e.g., climate change). Rather than attempting to predict specific disasters, NASEC would focus on efforts to mitigate their impact.

This Georgia Tech group also developed four guiding principles on which NASEC should operate for best results. These principles are based on extensive experience working within research networks or centers and observing the successes and inefficiencies of organically formed networks within the academy during the COVID-19 pandemic.

First, because the group is meant to be a massively interconnected network, there should be a high degree of communication and collaboration, both within the network and with a wide range of governmental and nongovernmental stakeholders. We suggest that such interconnectivity is essential because, in the heat of the moment, even when there is tremendous goodwill, there is not always clear coordinating of activities, sharing of best practices, or, perhaps most importantly, filtering out of less-than-best practices. We have observed such inefficiencies, which result in duplicative effects, while sitting on ad hoc panels and working groups that include industrial, government, and academic entities. In some cases, data were shared relatively widely, without clear definition of the assumptions and collection techniques required to validate or invalidate conclusions. This unclear communication can and did lead to confusion and uncertainty, which is problematic in the best of times, but truly unacceptable in crisis situations in which there is no time for the self-correction process that often takes place in the scientific research community.

Second, currently underserved communities must be active participants in NASEC, so that their voices are heard and their populations benefit from training in the network. Promoting socially just practices is not only the right thing to do; it also increases buy-in from underserved groups that have good historical reasons for being skeptical of major scientific and engineering endeavors.

Third, the network should adopt elements of frugal science and technology to ensure that populations with limited means—both locally and globally—can participate in the benefits of technologies and processes developed in NASEC. In other words, we need to find solutions that are both affordable and have the potential to be widely disseminated throughout the globe, independent of the wealth of the community affected.

Fourth and finally, the proposed network should help secure the United States' economic competitiveness and greater independence in the materials and manufacturing processes essential to the country's supply chain. During the COVID-19 pandemic, for example, there have been geopolitical and simple transport issues between the United States and China that created challenges for US companies in gaining access to masks and raw materials needed to combat the pandemic. This situation required US companies to pivot rapidly to retool manufacturing capacity toward making products such as ventilators, N95 masks, and hand sanitizer that directly affect the response to the pandemic. In addition, the lack of access to precious metals and semiconductors had indirect impact on production of goods and services that were important to both the pandemic response and the economic recovery that would follow.

## Back to the future

*The year is 2037. In response to the COVID-19 pandemic and other threats to US national and economic security, both presidential and congressional commissions made several key recommendations to address some of the long-term challenges facing the country. One such recommendation led to the creation, in the late 2020s, of the Network of Agile Science and Engineering Centers. In the period since its inception, NASEC became integrated into the fabric of our national resources, not only to respond to near-term urgent crises, but to play a role in addressing challenges playing out more slowly in the United States and globally.*

*NASEC trained a generation of researchers, first responders, policymakers, entrepreneurs, and educators in the United States with a holistic view of crises and a set of skills required to be an effective part of nationwide teams addressing them. Importantly, students and postdoctoral researchers in NASEC, as well as its more senior members, forged close personal ties during their time together. Consequently, important profession-*

*al connections and, critically, an appreciation of the multidimensional aspects of crises were developed through participation in NASEC activities. Armed with these insights, NASEC alumni, who remain closely connected through its active alumni network, were hired by numerous organizations in the public and private sectors and, because of their unique training, rapidly advanced to leadership positions in the institutions that employed them.*

*One reason for this success is that these professionals brought to their new jobs the guiding principles and values that underpin NASEC. Along the way, they also learned (or in some cases relearned) the importance of having excellent communication skills, an empathetic approach to problem-solving, the ethic to be constantly training for various scenarios, and the ability to prioritize and reprioritize responses in the face of chaos and external pressures from, for example, the media and politicians. Just as important, NASEC alumni have infused their agile, holistic approach into many organizations throughout the United States, establishing a foundation for more readily addressing new and previously unrecognized challenges as they arise.*

## Leading through the portal

COVID-19 was a serious wake-up call to the United States and the world. Society's response made it clear that many aspects of the national and global infrastructure were ill prepared to deal with such a crisis. Such a monumental disruption to people's health and economic and social well-being had an immediate impact and will continue to have long-term effects. This disruption has led the United States to reevaluate its overall response to various societal threats, both those that are naturally occurring and those created by humans. It was evident that although the nation had in place many entities and agencies—from the Federal Emergency Management Agency to national laboratories, nonprofits, and industry—working with state and local governments to address crises, more could and needed to be done to secure the country's infrastructure and population.

Research universities have unparalleled opportunities and responsibilities to serve an increasingly complex society: to develop innovative solutions, educate the next generation, and enable economic prosperity; to play critical roles as conveners, bridge builders, and partners; and to be indispensable, trusted authorities. Just as importantly, as has been made painfully clear during the COVID-19 pandemic, universities must continue to be agile in responding to largely unknown yet certain to occur large disruptions.

To quote Roy's article again, "[The pandemic] is a portal.… We can choose to walk through it, dragging the carcasses of our prejudice and hatred, our avarice, our data banks and dead ideas, our dead rivers and smoky skies behind us. Or we can walk through lightly, with little luggage, ready to imagine another world. And ready to fight for it." Research universities must lead the march through the portal, into a better world.

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### MICHAEL V. DRAKE

# Building the Diverse Health Workforce of the Future

Creating a more equitable, accessible, and inclusive health care system won't be easy, but we already know what works.

In the spring of 2020, as COVID-19 was beginning to spread rapidly in communities across the United States, medical personnel at the University of California, San Francisco, began to notice a trend. Many of their early COVID-19 patients were Latino and included significant numbers of health care workers and their families. The experiences of this first wave of patients illustrated a fact now widely recognized: communities of color have been—and continue to be—disproportionately affected by the pandemic. Individuals in these communities have been more likely to become infected, often due to jobs that could not be moved online. And due to a variety of factors, including preexisting health conditions and lack of access to health care, they have suffered especially profound health and economic impacts.

Although the pandemic has intensified awareness of these interrelated issues, they are of course not new. For too long in our country, racial discrimination and a fragmented and inconsistent health care system have contributed to adverse outcomes in communities of color. These effects are further compounded by a lack of diversity in the health professions. We know that individuals from underrepresented groups are less likely to be insured, less likely to have access to quality health services, and more likely to suffer and die from certain illnesses, including asthma and diabetes. The pandemic has amplified this existing inequality. According to recent research by the University of California, Los Angeles, Fielding School of Public Health, the rate of confirmed COVID-19 infections in California's nonwhite population has ranged from 1.5 to more than five times as high as the rate among white Californians.

An important contributing factor to these troubling outcomes is the fact that tens of millions of Americans live in geographic areas with shortages of health care providers and services. In California, these areas include the San Joaquin Valley in the center of the state and the Inland Empire in the south—two of the fastest-growing and most diverse parts of the state. During the pandemic, the combination of preexisting workforce shortages and skyrocketing demands for care has made it even harder for providers to deliver quality care to their patients.

Beyond these shortages, we must also confront the fact that our nation's existing pool of health professionals does not reflect the diversity of our communities. This lack of diversity hampers our efforts to treat and cure many of our fellow Americans, and—as the data show—has prevented us from responding as effectively and equitably as possible during the COVID-19 crisis. Research shows that a more diverse health workforce provides real benefits for patients, from better communication with doctors to higher levels of patient trust and satisfaction.

Today, we are still grappling with successive pandemic waves while looking ahead to a future with dangers that continue to evolve. As we move forward, it is clear that we must make sustained investments in programs and proven strategies that will reduce deep inequities in our health care system, support a more robust and diverse health workforce, and build a more resilient, equitable health care system for the future.

The good news is that we already know what works.

First, we must train and support more health care workers—especially those from underrepresented groups. Optimal clinical care depends on a wide range of health professionals working together—from physicians to nurses to pharmacists to community health workers.

At the University of California, we operate six innovative Programs in Medical Education (UC PRIME) focused on developing the next generation of physician leaders with specialized training in caring for underserved populations in rural and urban areas. In the 2020–21 academic year, 365 medical students were enrolled in UC PRIME initiatives, with 67% of them from groups underrepresented in medicine. In recognition of the programs' extraordinary success in the recruitment of students from underrepresented groups and steady focus on meeting the needs of underserved groups, the 2021–22 California state budget boosted funding for these programs while providing new funds to launch additional PRIME initiatives focused on Black/African American and Native American/American Indian populations. This collaborative effort among the UC system, the state of California, and community leaders—now thriving for 17 years and counting—can serve as a model for other professions and other regions across the country.

Second, academic health centers must establish and expand relationships with diverse institutions of higher education—including Historically Black Colleges and Universities (HBCUs), Hispanic-serving institutions, and tribal colleges—to further diversify the pipeline for educational programs in the health sciences. Since it was established in 2012, our UC-HBCU Initiative has helped 699 HBCU scholars spend a summer at UC campuses, conducting cutting-edge research with UC faculty. Many of these scholars go on to apply to UC graduate and health sciences programs and work in the health sector. These are important avenues for building relationships and trust with communities that are underrepresented in the health professions.

Third, universities must increase faculty diversity in the academic health sciences and other fields. We know that students are more likely to thrive academically and professionally when they have access to instructors from diverse races, ethnicities, and backgrounds who understand their experiences and perspectives. At UC, our president's and chancellor's postdoctoral fellowships provide support for outstanding scholars from underrepresented populations in all fields. Together with efforts that provide hiring incentives, mentorship support, and other resources for scholars and practitioners from diverse groups, we are making progress toward a faculty that better reflects the diversity of the communities we serve.

Finally, the pandemic has shown us that we must invest in building a broad and inclusive pipeline of health professionals that extends beyond the clinical workforce. The contributions of epidemiologists, virologists, veterinary scientists, and other health professionals—including the researchers who developed COVID-19 tests and vaccines—are critically important for building a strong and effective health care system in which a diversity of perspectives and approaches is reflected at every level.

The process of launching and expanding initiatives like these isn't easy. I have found that the common denominator in institutions that are successful in promoting diversity, equity, and inclusion is this: the people involved are intentional about their efforts. They have measurable, concrete goals. They have a method to achieve those goals. And they stick with it, regardless of budgetary, political, or other hurdles.

Ultimately, achieving systemic change will require not only ongoing commitments like these by individual institutions, but also meaningful partnerships across every sector of our society. Universities and academic health centers must work closely with elected officials, business leaders, and community organizations to ensure that these types of programs have the leadership, funding, and support they need to take root and flourish. In California, we are fortunate to have the support of the governor and state legislature in achieving these goals.

Across the country, many communities are making progress in addressing these issues. Yet the pandemic continues to show us just how far we have left to go. Actively investing in these priorities at the local, state, and federal levels will go a long way toward creating a more equitable, accessible, and inclusive health care system that truly serves us all.

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# New Frontiers for Innovation Policy

ERICA R. H. FUCHS

# What a National Technology Strategy Is—and Why the United States Needs One

To compete in the twenty-first century, the United States needs a nimble agency to catalyze technological innovation that delivers security, prosperity, jobs, and health—for all citizens.

Over the last half century, the global geopolitical balance of scientific, economic, and production capabilities has shifted away from US dominance. The United States is no longer in a singular position of global scientific and technological leadership, and China has become the largest producer and second largest market in the world. Meanwhile, we face equal or greater challenges than ever before on the home front, where economic inequality has increased, social mobility has declined, and political polarization is on the rise.

Unfortunately, at this moment of dual internal and external challenges, the United States' intellectual and institutional foundations are insufficient to develop ways that can resolve them. Leading experts have made different and often-conflicting proposals. Some advocate for slowing the progress and adoption of technology. Others argue for dramatically increasing funding of science and technology, including investing in regional innovation hubs to reduce inequality and increase jobs. On their own, none of these proposals are likely to fulfill experts' or legislators' multiple objectives for them—improving national security, increasing the number and distribution of good jobs, and succeeding in global trade.

Missing from these debates is the recognition that win-win technology choices do exist. That is, with the right incentives, it is possible to make strategic investments in technology that achieve multiple national objectives. For example, Christophe Combemale and his coauthors have shown that not all technology leads to wage and skill polarization; indeed, many of the technologies on today's critical technology lists may lead to better jobs for high school graduates and strengthen national security at the same time.

Likewise, in contrast to regional hub proposals that will require decades to supply the promised jobs, I have argued that equitably building the infrastructure of the future—smart high-speed transit systems, dynamic electric grids with renewables, and broadband internet access—will more quickly increase jobs in underserved areas, improve social welfare for all citizens (including health, energy access, and communications), and boost the productivity and resilience of industry. In addition, if this infrastructure is domestically procured, it could rebuild US manufacturing.

Unlike a firm, which has the single objective of profit maximization, a nation has multiple objectives, including national security, economic prosperity, and social welfare. Making transparent to policymakers where strategic win-win investments exist across these objectives will require building the intellectual foundations, data, and analytic tools necessary to inform such multi-objective decision-making. Acting across missions will require new government institutions capable of making such technical investments and delivering desired outcomes.

Although there has long been interest in the relationship between security and social objectives, and scholars have explored synergies and mapped trade-offs among environmental, employment, and other objectives, I am aware of no research to date that seeks to quantify trade-offs and win-wins across the full range of national objectives. US agencies and departments, including those in science and technology, typically have singular missions, such as defense, energy, transportation, commerce, and labor. These government bodies are excellent and should not be changed. At the same time, the current system leaves a hole whereby even with each agency or department perfectly fulfilling its distinct mission (say, defense, trade, or environmental protection), the country could still fail to fulfill its multi-objective role (say, for labor).

To foster win-wins across national objectives, a US National Technology Strategy Agency is needed to seed initiatives that fill gaps in the existing innovation ecosystem and to catalyze other agencies to bring their expertise to cross-cutting efforts. This new agency will need to simultaneously build the interdisciplinary intellectual foundations, data, and analytic capabilities to make win-wins transparent and inform its investments.

## What a national technology strategy is *not*

Building a US national technology strategy should not involve changing the basic structure of the departments and agencies we already have, nor should it involve imposing top-down coordination or locking the country into single technologies or policy objectives. Calls for a national technology strategy that involve top-down coordination, efforts to reduce "redundancy" across agencies, or attempts to "reduce inefficiencies" are misguided and could actually dampen innovation.

In fact, one of the strengths of the US innovation system is its diversity and redundancy. Scholars have long emphasized the importance of the diversity of the US innovation ecosystem, in which agencies and departments have different missions and can take aligned, complementary, or even opposing funding roles. In this system, scientific and technical progress is a long-term, nonlinear process in which metrics and a focus on efficiency can slow and fragment progress instead of enhancing it. The National Research Council beautifully describes how the US innovation ecosystem's mix of mission-based agencies helped create a revolution in computing: "By funding a mix of work in universities and industry, [the United States] was able to marry long-term objectives to real-world problems. And, by channeling its funding through a variety of federal agencies, it was able to ensure broad-based coverage of many technological approaches and to address a range of technical problems."

Another national technology strategy solution that is commonly proposed is creating reports with lists of critical technologies. While these reports are a useful step, they cannot be the central foundation of a robust US technology strategy. History shows that such lists on their own are unlikely to find their way into policy or action. Between 1989 and 1999, for example, the federal government identified critical technologies through a biennial National Critical Technologies Report to Congress, with input from multiple agencies, including the Department of Defense, Department of Commerce, Department of Energy, and National Aeronautics and Space Administration. Unfortunately, the reports lacked the follow-on necessary to link criteria to policies—never mind to coordinated policy actions—in a productive way. Indeed, one of the many assets of the US innovation system is its diversity, nimbleness, and flexibility to respond to changing times. Reports don't have this flexibility.

In addition, if a national technology strategy were about a single mission such as security, key win-win opportunities may be lost. Advanced semiconductors—which stand at the center of current US challenges in security, trade, and jobs—offer an example of the potential dangers of optimizing for only a single objective, rather than incentivizing technological win-wins across multiple objectives. For example, a policy aimed at maximizing national security and minimizing defense costs might take a three-pronged approach of funding innovations in hardware and software security, supporting chip fabrication in a series of allied nations, and funding advances in the next generation of computing (e.g., beyond Moore's Law). By contrast, a policy giving equal weight to national security and labor might increase incentives for foreign and domestic firms to invest in fabrication facilities in the United States. A policy that added equity might also increase incentives to locate those fabrication facilities in underserved communities, while investing in university electrical engineering programs in semiconductor hardware design and vocational program training in semiconductor manufacturing in those places.

Similarly, vehicle electrification policies demonstrate the potential dangers of optimizing for only a single objective. If policymakers focus solely on reducing carbon emissions, the most advantageous approach may be to scale electric vehicle use as quickly as possible. However, if they expand the objectives of the investment to include maximizing national security, prosperity, and equity, policymakers would need to find ways to quantify the value of domestic manufacturing of batteries (for jobs, security, and innovation); identify which citizens in which places will gain and lose jobs through the transition; assess the value of various levels of cybersecurity requirements for security, welfare, and learning; and determine how shifting the source of pollution from vehicles to energy generation sites on the grid (which disproportionately have poorer populations living near them) may decrease equity.

To overcome these obstacles, in parallel to mission-oriented efforts, the United States requires a nimble institution that can work within the existing mission-oriented innovation ecosystem and identify and act upon the opportunities afforded by win-win investments. Unfortunately, for both of the above examples, right now the government lacks the data and analytic capabilities to quantify and make transparent the implications a particular technology solution has for each national objective, the trade-offs different technology solutions present across multiple national objectives, and the potential self-reinforcing benefits of certain choices for subsequent decisions (such as making it more cost-effective to locate subsequent manufacturing in the same location in the future).

## Toward a national technology strategy greater than the sum of its parts

Correctly implemented, a national technology strategy must be about incentivizing innovation that offers outsized returns across national objectives, without undermining the strengths of our existing innovation ecosystem.

To catalyze such technology solutions, the United States should create a small, nimble agency that can research opportunities, fund strategic initiatives independently, and work across, coordinate with, and catalyze initiatives by the existing mission-driven departments and agencies. This National Technology Strategy Agency should be charged with making strategic technology investments across missions, as well as identifying and filling the holes in our existing national innovation system that are preventing the nation from realizing all of its national objectives. This agency must have an analytic arm and an executive arm housed within the same agency.

The agency will need sufficient money for its investments to be influential and to fund platforms of technology, but its budget should be sufficiently modest so that it is forced to engage and influence efforts in other agencies to have a larger impact. Based on lessons from the Defense Advanced Research Projects Agency (DARPA), Advanced

Research Projects Agency-Energy (ARPA-E), and Office of Technology Assessment (OTA), I recommend an annual budget of $3 billion for external seed funding, plus an operating budget of $500 million to employ 100 program managers and 100 analysts with an appropriate support staff and facilities. This level of funding would give the agency a budget and program manager staff roughly on par with DARPA (which today has a $3.5 billion budget) and an analytic team slightly smaller than that of OTA, which at its closing in 1995 had 143 full-time staff (augmented by contractors) and an annual budget equivalent to $52 million in today's dollars.

For the executive arm, the Semiconductor Research Corporation (SRC) provides an excellent model of how one entity with seed funding and political capital can amplify its impact by bringing multiple funding agencies together at the state and federal levels around a common mission. Unlike SRC, however, a National Technology Strategy Agency must act to forge a technology path across the missions of the existing agencies to meet the full multi-objective role of government. Public officials with embedded autonomy—deep knowledge of the technological, social, and industrial context—are most likely to get these choices right. As in DARPA, the executive arm should have a staff of rotating program managers brought in from academia, industry, and government who are the best and brightest in their fields, able to use the position as a stepping-stone to subsequent leadership positions in their careers. Unlike in DARPA, at this agency, program managers might include star diplomats or government officials, union and nonprofit leaders, teachers, and community activists alongside top-notch technologists.

At the same time, the analyst arm will need to provide transparency for policymakers and the new agency's program managers on the trade-offs present in different potential technical decisions for meeting national objectives. Given the current bedraggled state of the government's analytic capabilities, the analyst arm will need to develop new data and methods to perform systematic assessments of national and global technology and production capabilities. The analyst arm should have a stellar interdisciplinary staff of PhD-level experts in each technical field (65%–75% of its experts), as well as PhD-level economists, political scientists, sociologists, psychologists, and historians focused on applying their expertise to real-world technology policy problems. Similar to that in OTA, the full-time staff of the analyst arm of this new agency should leverage contracts with academic researchers to develop new data, methods, and analytic insights. These contracts should be short enough to be relevant to political timelines, but long enough to engage scholars in academia: the sweet spot is likely one year.

The full-time staff should then integrate the resulting academic insights and translate breakthroughs in data and analytics into regular government functions.

Funding academic research also plays the important role of not only bringing in stars to address the nation's challenges, but *creating incentives* for researchers in academia to work on real-world technology policy problems, which require integrating technical and social science expertise.

To ensure excellence and relevance, the agency must have an external expert advisory board with leaders from academia, industry, government, and nonprofits (such as labor unions or community activists). In addition, based on lessons from DARPA's Information Science and Technology Study Group, the National Technology Strategy Agency should have small, rotating, problem-specific expert advisory boards drawn from industry, academic, and community leaders as well as program managers. (Notably, OTA also had study-specific advisory boards.) These small study-specific advisory boards ensure that the analyst staff and academics are grounded in the science, engineering, industrial, and political realities of the problem on the ground. Subsequently, participating program managers make sure that the study's suggestions are acted upon.

The proposed National Technology Strategy Agency takes from the best of recent US technology initiatives to catalyze a revolution in how the nation approaches funding science and technology. By incentivizing technology paths with win-wins across missions and orchestrating initiatives across different mission-oriented players, it could amplify investments across agencies and departments to deliver on not just one but multiple objectives.

Finally, and perhaps most important for its longevity, the National Technology Strategy Agency has the potential to be politically popular, particularly if it is successful in raising the employment, equity, and welfare of all citizens. Built as described above, such an agency would also be capable of teaching itself and the nation how to push forward with continuous improvement to define the future, rather than merely respond to the past.

## Lessons from our national innovation system

***Catalyze coordination from the bottom up.*** A National Technology Strategy Agency should build upon lessons from past models that have been successful in catalyzing multiple entities to collaborate and co-seed technical initiatives. Calls for top-down coordination can misunderstand the complexity of the national innovation system and the ways that bottom-up coordination already happens within that system. In the semiconductor industry, SEMATECH, SRC, and the National Nanotechnology Initiative (NNI) offer examples of bottom-up coordination from very different stages of scientific and technology development.

SEMATECH was originally a 50-50 government-industry public-private partnership to promote near-term equipment upgrades to increase competitiveness with Japan. SRC is an industry-led public-private partnership that funds academic research three to seven years out to ensure research advances meet industry needs. NNI works to support and set priorities for more fundamental long-term research in nanoscale science and technology.

At SRC, industry leaders meet regularly with program managers from the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), DARPA, and DOE as well as state leaders to decide on funding directions and co-fund complementary agendas under a single SRC program umbrella. Likewise, NNI has facilitated working groups, an infrastructure network involving an integrated partnership of user facilities at 13 campuses across the United States, and centers to support the development of tools for fabrication and analysis at the nanoscale. It has also created NNI-industry consultative boards to facilitate networking among industry, government, and academic researchers, analyze policy impacts at the state level, and support programmatic and budget redirection within agencies.

***Fund solutions, not industries.*** A National Technology Strategy Agency must undertake policy tailored to technological and sectoral nuances, while explicitly avoiding policies that support industries. Policies focused on sustaining established firms or specific industries rather than catalyzing solutions to problems will fail to achieve important national objectives. For example, a challenge like the end of Moore's Law in advanced semiconductors will require enormous quantities of funding to solve, yet has implications for economic prosperity, national security, and social welfare. It would be easy to misallocate funding in an attempt to address this problem—indeed to misunderstand the nature of the challenge itself.

The system of developing silicon-CMOS chips (the kind of integrated circuit that underpins computing), which has flourished for 40 years, is coming to the end of its physical limits. It would be foolish to simply fund established firms to continue this soon-to-be-defunct trajectory. Instead, we should fund the advances in new material systems (beyond silicon-CMOS) to ensure computational capabilities continue to advance and that the United States leads in those advancements. Here, I am not proposing choosing technology winners; no one knows which innovation in beyond CMOS devices will be the solution. Rather, I am emphasizing the importance of spending our limited national dollars on the *right problem*.

***Think beyond moonshots.*** A National Technology Strategy Agency must avoid the lure of using "moonshots" as a one-size-fits-all solution. Although they've become increasingly popular, moonshots, competitions, or contests are unlikely to work well in all contexts, particularly where significant platform coordination is necessary. Consider, for example, the challenge of inventing the next generation of underlying transistor technologies. This challenge is an extremely difficult problem requiring advances in the underlying physics with implications for security, prosperity, and society. But trying to solve the problem through a moonshot or prize would be problematic. First, it requires coordination across the computing technology stack, including new chip architecture, new software, and new equipment. Therefore, it would be difficult for a single innovator or new entrant to manage this coordination, especially with such high uncertainty early on about which new technological solution would win. Second, the required capital investments are considerable—more than a billion dollars is likely needed even for a device-prototyping foundry. These considerations speak to a need for coordination, rather than individualized competition. Here, a government arm similar to DARPA, in coordination with other agencies and private industry, would be best suited to lead a technology revolution. Such an agency would be able to achieve the necessary coordination and overcome issues preventing private firms (new entrants and established corporations) from making the leap on their own, including fragmentation of technology trajectories, declining profit margins among established firms, and profitability of short-term solutions for other private stakeholders.

***Orchestrate outcomes without choosing winners.*** A National Technology Strategy Agency should take lessons from DARPA on how to successfully orchestrate technology revolutions. My research on DARPA demonstrates that, rather than forcing policymakers to choose between the extremes of free markets or the heavy hand of government to select successful technologies, DARPA offers a third alternative: embedded network governance. Program managers work to identify and influence new technology directions through constant contact with the research community. By understanding emerging themes and matching them to military needs, those managers then bring together discrete researchers, bet on the right people, stand up competing technologies against each other, and fund platforms (or "pyramids") of technologies to address interdependencies across components in the system. As they do their job, program managers maintain the bird's-eye perspective critical to integrating and orchestrating disparate research activities spread throughout the national innovation ecosystem to achieve military, scientific, and technological goals. This goal-oriented, program manager-level orchestration of technologists has led to technological breakthroughs as wide-ranging as the internet, mRNA vaccines, and artificial intelligence.

***Leverage the whole ecosystem.*** A National Technology Strategy Agency needs to leverage the entire innovation ecosystem, understanding the variety of models within it and the role each plays in advancing science and technology. While DARPA may play an important role, it plays only one role in this complex system.

Although DARPA is a model for funding and commercializing breakthrough technologies, it is not a model for funding breakthroughs in basic science. In medicine, the Howard Hughes Medical Institute has funded breakthrough discoveries in basic science by providing substantial funding to worthy young investigators with few restrictions. This open-ended approach contrasts starkly with DARPA's mission-oriented milestones and orchestration. Likewise, in the computing revolution, the Office of Naval Research made critical early investments in advance of DARPA.

Neither mission-oriented nor focused on the funding of eminent scientists, NSF has repeatedly come through on essential aspects of technology development. In the case of the internet, while DARPA funded the early breakthroughs, continued efforts sponsored by NSF to develop CSNET and later NSFNET (a program of coordinated, evolving projects linking university-based supercomputer networks to be able to share information and resources with each other) demonstrated the value of internetworked communication systems and led to the internet's eventual commercialization. With its funding spread among researchers at a wide range of institutions, generally universities, NSF also plays an important role in the broad scientific and technological education and dissemination of knowledge needed for the development and commercialization of revolutionary technologies.

Furthermore, the mission-oriented departments and agencies play a critical role in providing incentives to focus on and solve real-world problems. For example, given the centrality of computing to each of their missions, DOD, DOE, NASA, NIST, and NIH all played essential roles in the computing revolution.

***Invest in crossover capabilities.*** Science and technology investments have systemic implications and complementarities that, if invested in thoughtfully, could enhance opportunities to succeed across multiple objectives. My and my colleagues' research on responses to COVID-19 at the national and firm levels underscores the importance of national competencies in technology and production and the ways science and technology capabilities can reinforce each other across sectors.

On the one hand, national domestic capabilities can support a nation's ability to effectively invest in and rapidly regulate the introduction of new technologies. As just one timely example, DARPA was among the agencies that provided early funding for mRNA vaccines. This investment, coupled with the tacit knowledge of US manufacturers that had previously developed complementary intellectual property and domestic manufacturing capability, enabled the development and manufacture of Moderna and Pfizer-BioNTech's mRNA vaccines on a remarkably short timeline.

Likewise, where companies quickly and successfully pivoted into producing scarce COVID-relevant medical supplies, the centrality of US-owned businesses and the domestic manufacturing ecosystem was notable. US manufacturers already in the business of personal protective equipment (PPE) production (e.g., Honeywell, 3M, Prestige Ameritech) were able to leverage their intellectual property, sourcing networks, and domestic manufacturing capabilities in other sectors (such as aerospace and advanced materials) to rapidly shift to domestic manufacturing sites. US domestic manufacturers in other businesses, such as automobiles (e.g., General Motors, Ford, Tesla) and filtration materials (e.g., American Melt Blown and Filtration, Berry Global Group), were likewise able to leverage their substantial technical, sourcing, and production expertise to rapidly begin mask, ventilator, and melt blown material (used in facemasks) production.

On the other hand, a lack of national domestic capabilities can hurt a nation's ability to respond. Ongoing research by Alfonso Amaral and colleagues suggests that European countries without domestic manufacturers of ventilators struggled disproportionately in the regulation of new domestic entrants. Likewise, although some components of the domestic manufacturing ecosystem supported the US response, the dilapidation of the US manufacturing ecosystem also hindered some manufacturing companies attempting to pivot into producing badly needed medical supplies. Research by Nikhil Kalathil and colleagues suggests that, during the pandemic, small- and medium-sized companies could have been particularly responsive to the need for PPE and other protection at local dental clinics, nursing homes, and small hospitals. But these manufacturers faced problems including a lack of access to domestic sources of intermediate inputs, equipment that was largely built in China, and a lack of skilled workers to run, fix, and adapt equipment. They also faced information barriers and high financial costs of passing regulatory hurdles.

These examples show that an effective national technology strategy must attend to cross-cutting investment that spans sectors and layers of the national innovation ecosystem, while ensuring that there are no holes in critical domestic capabilities—whether in production or innovation.

## Toward a national technology strategy

The COVID-19 pandemic has highlighted deep global interdependencies in health and manufacturing as well as national challenges in racial, geographic, and income inequality and job safety. As the United States began attempting to respond to the pandemic, the nation found that we had undervalued various aspects of social welfare, including health and equity. We had also undervalued resilience and domestic manufacturing. We lacked the data to know who all our own manufacturers were and which of those could possibly help respond to the pandemic, never mind where bottlenecks might exist elsewhere across the globe. If our institutions continue to address only singular missions, such as national security without health or equity, these problems will be repeated, whether during the next natural disaster, the next pandemic, or the next war.

To build a stronger and more secure, prosperous, equitable, and resilient nation, we must create an institution that can design investments to realize all of legislators' objectives for them. With a National Technology Strategy Agency—whose mission is to identify technological solutions with win-wins across all of the nation's objectives and to leverage the complementarities across sectors and the systemic nature of investments in technology—we can create this future.

Jobs and equity are as central to our sovereignty and security as weapons. The last 75 years has demonstrated that, without a portion of government assigned to designing technology for win-wins across all national objectives, the impact of technology choices can be uneven, reducing jobs and equity for some while increasing productivity and wealth for others. But, done right, technology investments can address—and indeed have outsized returns in addressing—national security, economic prosperity, jobs, health, the environment, and equity. The United States cannot afford to get these decisions wrong. While the excellent existing departments and agencies will continue to fulfill their specific missions, we must act now to found the new institutions that will identify, catalyze, and orchestrate technological paths across our innovation ecosystem to ensure that our technology investments are designed to create security, prosperity, and welfare for *all* citizens.

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WILLIAM B. BONVILLIAN

# Encompassing the Innovation Panoply

As US science policy shifts toward a new model intended to stimulate economic growth, the country must create an institutional infrastructure for federal industrial policy.

US policymakers from both parties have long avoided "industrial policy," but a new set of drivers—competition with China, confronting climate change, and the COVID-19 pandemic—is forcing a shift in attitudes. These three challenges amount to a crisis that is likely to induce a major change in US science policy.

Following the Trump administration's vaccine development effort, the Biden administration and Congress have proposed a series of major technology initiatives that are moving the federal government toward what can only be called industrial policy. An injection of more than a hundred billion dollars over the next decade into targeted programs could completely revamp the model of US science policy that has been in place since the end of World War II.

Many high-income nations, including Germany, Japan, Korea, Singapore, and lately China, have long placed bets on industrial policies to accelerate their economic growth. By contrast, the United States, outside its defense and energy sectors, has taken only modest steps, largely aimed at the golden goose of free markets: innovation. Indeed, beyond a history of generous tax breaks to energy companies, civilian industrial policy in the United States has been mostly limited to research and development subsidies and tax incentives. This approach fits with a sense, in both parties, that government intervention should be used only to fix "market failure"—activities such as the provision of national defense or scientific research that, without government support, would not be provided by the private sector at levels considered equal to the national interest. Thus, the new direction of US industrial policy reflects a broader government intervention beyond R&D to support technological development from ideas to markets, including prototype testing, demonstration, and product introduction.

## Bush versus Steelman

To understand what industrial policy has done for US innovation, and the transformative steps legislators currently are considering, it is instructive to recall the policy debate that shaped our current research enterprise.

Vannevar Bush is widely considered the architect of American science policy. As President Roosevelt's de facto wartime science advisor, Bush created an integrated innovation system that linked industry, universities, and government agencies around projects that used research to gain an edge on the battlefield. It was textbook industrial policy.

Yet at the war's conclusion, Bush sought to return the reins of innovation to the private sector. In his famous *Science, the Endless Frontier* report, he proposed concentrating federal support on basic research, to be conducted at universities. In practical terms, Bush sought to establish an independent agency, a foundation, to centrally administer all federal research funding.

It is crucial to understand that Bush was no less brilliant an engineer than he was a policy entrepreneur; he grasped the power of simple ideas that captured the imagination of policymakers. His design for the organization of US research was undergirded by a mental model of innovation that Bush himself might have considered a caricature, but that was easy to present, to defend, and to use to garner political buy-in. Today it is known as the linear model of innovation. In Bush's design, the federal government injects funds for research on one end of the innovation pipeline, and after transferring that new knowledge to industry, the private sector shepherds it through subsequent stages of maturity—development, prototyping, testing, demonstration, and product implementation—all the way to the marketplace. Bush did see, from his industry and military experience, that the transfer of public research to private enterprise would be neither automatic nor unproblematic.

Like all policy proposals, Bush's design met political and practical challenges. His most formidable detractor was John R. Steelman. A professor of sociology and economics at Alabama College, Steelman was recruited in 1934 to the Department of Labor's Conciliation Service and soon became its director. In that position, he helped President Truman resolve disputes with coal miners and railroad labor. In 1946, Steelman became assistant to Truman, a position that in later administrations evolved into the White House chief of staff.

Bush's original proposal was passed by Congress in 1947. However, Truman vetoed the bill, not wanting the new foundation to exist outside control of the executive branch. At the president's behest, Steelman led a group of former New Dealers in producing a four-volume study of federal support for science, a much more comprehensive study than Bush's. The Steelman report proposed much more government involvement and funding for R&D, with far more emphasis on public funds for development. While Steelman placed the proposed funding agency under executive branch control, it was not to be the main actor; other federal agencies would fund development projects in addition to research aligned with their missions.

As the Bush and Steelman designs collided, political forces demanded a resolution, in no small part because science had become an instrument and symbol of hegemony between the Cold War superpowers. The National Science Foundation Act was finally passed in 1950, although the agency didn't receive significant funding until after the Soviet Union's launch of the Sputnik satellite in 1957. Although NSF was the brainchild of Bush, it never became the central hub of federal research he had envisioned. Rather, Steelman's decentralized model, including a modest-sized NSF and other, more generously funded research agencies, set the framework for the US federal research enterprise.

Steelman more than Bush may thus be the true architect of American science policy, except for one thing: Bush's linear model of innovation has remained firmly entrenched in the minds of policymakers. Basic research became the core focus not only at NSF but at other federal civilian science agencies. The linear model's intuitive appeal—that innovation is produced like a car or a toaster, along a conveyor belt of sequential stages—may be why this model continues to inform the role of government in science. It may also have kept policymakers from implementing full-scale industrial R&D policy. That may be about to change under the pressure of today's brewing crisis.

## Seventy-five years of piecemeal industrial policy

The US government has purveyed piecemeal industrial policy for at least three-quarters of a century. By far the most significant part of it has been channeled through the national defense apparatus, which built a series of innovation agencies and programs and linked them to follow-on defense procurement investments. Although these investments were justified in the interest of national security, many resulting technologies were "dual use" or "spillovers" that created new sectors in the civilian economy. These include space, nuclear power, computing, and the internet. Arguably, the fountainhead of postwar innovation is the generously subsidized defense innovation system.

Since the end of World War II, industrial policy approaches have occurred within four somewhat discernible periods. The first period firmly established defense industrial policy but did not do the same for civilian industry. The Cold War imbued a sense of national peril in the political class, which rushed to re-erect a formidable national security enterprise. This enterprise needed a technological edge, and, to that end, it included a defense innovation and production system modeled on the war mobilization effort.

Starting around 1950, the military worked to integrate key innovation actors—industry, university, and government—in service of the defense mission. The 1957 Sputnik crisis further accelerated the effort, leading to creation of the National Aeronautics and Space Administration and the Defense Advanced Research Projects Agency (DARPA), both in 1958. The Department of Defense (DOD) had low tolerance for uncertain timelines and outcomes, so it returned to the integrated wartime model, building a system that supported not just research but also development, prototyping, testing, and demonstration. DOD often created the initial market by becoming a major customer. In contrast, the civilian R&D agencies supported research only through early-stage development. This means that the United States has been running two very different innovation systems in parallel: a distributed and disjointed civilian system and an integrated defense system.

The second period was the era of competitiveness with Japan in the 1970s and 1980s. Japan's economy advanced in leaps with the modernization of its industrial production process, the total quality management revolution. Combined with just-in-time inventory and precision machining technologies, Japan seemed poised to outperform the United States in the full range of high-value-added manufactures. Although the United States remained the leading innovator, its industry was comparatively disadvantaged by a lack of government coordination of innovative activities and actors. Evidence of Japan's edge became apparent as its cars and electronics penetrated US markets, and the public and the political class attributed rust belt manufacturing declines to Japanese ascendence. US industry was forced to play catch-up as it climbed the steep learning curve to embrace total quality production.

In that period, the United States launched a series of novel policy attempts to try to help small firms and start-ups at the cutting edge of technological innovation grow and compete in global markets. These programs included streamlining technology transfer with the Bayh-Dole Act in 1980, which gave universities rights to patents that resulted from federally funded R&D, and the Stevenson-Wydler Act, also in 1980, which introduced similar incentives for federal laboratories. It also included the Manufacturing Extension Partnership to bring new processes to small manufacturers and the Small Business Innovation Research program to support small firms and start-ups in developing technologies from their research. Other policy initiatives sought to support those businesses seeking to gain a competitive edge via innovation. The programs included the Advanced Technology Program to support technology development at companies; SEMATECH to restore US semiconductor leadership through manufacturing quality and efficiency improvements; and the R&D tax credit to encourage companies to invest in research and development.

A third period, starting around 2001, comprised policy efforts to mitigate climate change through energy innovation at the Department of Energy (DOE). As implemented, the new policy translated into new offices and tasks added to the department rather than modifying its existing functions. The new elements included the Advanced Research Projects Agency-Energy (ARPA-E), expanded renewable energy programs, advanced manufacturing institutes, a Loan Programs Office for new energy technology projects, and Energy Frontier Research Centers. Regulatory programs were also expanded to drive technology shifts.

A fourth period has evolved in recent years around advanced manufacturing. When US manufacturing began relocating production overseas, old industrial towns never fully recovered their lost jobs and status. China arose in a remarkably short period in the early 2000s, displacing the United States in 2011 as the world's largest manufacturer. Simultaneously, US manufacturing experienced a steady decline. Manufacturing employment shrank by one-third between 2000 and 2010, and 60,000 factories closed as production shifted to China and other countries ready both to operate at a fraction of the labor cost and to introduce new efficiencies.

In response, between 2012 and 2017, the federal government created a network of 15 manufacturing innovation institutes (the sixteenth was added in 2020) called Manufacturing USA, supported by DOD, DOE, and the National Institute of Standards and Technology (NIST). Each institute was organized around a particular advanced manufacturing technology, ranging from 3D printing to photonics, digital production, and robotics. While past manufacturing policy focused on trade or tax incentives, the institutes aim to accelerate introduction of productivity-enhancing manufacturing technologies to enable the United States to better compete. They bring together industry and universities, with support from three federal agencies and from state and local governments. The institutes undertake technology R&D, offer shared equipment centers for new technology prototyping and testing, and provide education and workforce development programs.

The success of industrial policies over these four periods has sometimes been mixed. Take, for instance, the industrial policy programs motivated by energy policies: government-funded large-scale energy demonstration projects have a mediocre record. Projects such as the Clinch River Breeder Reactor, the Barstow Solar Power Tower, and two DOE-run synthetic fuel plants faced massive cost overruns because they failed to anticipate collapsing oil prices four decades ago. The projects conveyed only limited technology information to the private sector. In more recent years, there have been unsuccessful large-scale carbon capture and sequestration demonstration projects. The most visible recent setback occurred when DOE made a $535 million loan guarantee to Solyndra in 2011 to scale advanced solar technology. But the new technology could not compete with low-cost, subsidized solar panels put into the US market by Chinese firms, and Solyndra went bankrupt. This highly publicized episode was an embarrassment for industrial policy approaches and it serves, along with these other energy projects, as a useful reminder of their complexity.

## New industrial policies

A series of new industrial policy efforts is now taking shape. In size and scope, they are dramatically different from previous approaches.

The US government in 2020 abruptly shut down much of the economy to mitigate the impact of the COVID-19 pandemic. To adjust to the pain caused by these shutdown orders, stimulus packages were enacted, flooding the economy with an unprecedented $3 trillion in federal expenditures, with a follow-on $1 trillion infrastructure bill in 2021. The resulting industrial policy consists of a suite of initiatives, some funded through these stimulus actions. They include the following:

*Operation Warp Speed* (OWS) dramatically accelerated development and distribution of COVID-19 vaccines to within ten months, in contrast to the usual four to ten years required for vaccine development and approvals. Using multiple policy tools and authorities—including guaranteed contracts for production scale-up, flexible government contracting mechanisms, a diversified portfolio approach backing several vaccine technologies, extensive supply chain management, and government-organized transportation delivery systems—OWS delivered vaccines to mass markets in record time. It likely saved countless individuals from illness and untimely death. OWS is an example of industrial policy with unqualified success, a fact that underscores the potential of its approach.

*The CHIPS for America Act* was passed by Congress with bipartisan support in 2020. A $53 billion appropriation is now pending to finance new fabrication plants and foundries for US chip manufacturing. It will also support research, technology development, and scale-up programs in advanced chip technologies and strengthen manufacturing and production supply chains. The global share of US-produced semiconductor chips has fallen to 12% and, as the technology moves down the nanotechnology scale, US firms have lost technological leadership to Taiwan and Korea.

*The Endless Frontier Act* (now called the Innovation and Competition Act) passed the Senate in June 2021 and is now in conference with a comparable but narrower bill passed by the House. It creates a new Technology Directorate at NSF with a $29 billion budget for applied R&D in ten key advanced technology areas. The new directorate will fund University Technology Centers, which can include consortia with industry, and will also support testbeds and lab-to-market activities, as well as Regional Innovation Hubs that could help with scaling up technology advances.

*Demonstration projects for new energy technologies* were included as part of major infrastructure legislation approved in a bipartisan compromise. The projects include carbon management, clean hydrogen, renewable energy, nuclear energy, and critical minerals and materials. In addition to over $20 billion in funding for the demonstrations, the legislation creates a new DOE Office of Clean Energy Demonstrations.

*Strengthening domestic supply chains* was a focus of a major White House report in June 2021. The report examined four areas—pharmaceuticals and ingredients, advanced batteries, critical minerals, and semiconductors—and made recommendations for new policies as well as funding to secure supply chains in these areas.

These programs all meet a definition of industrial policy because they are governmental interventions beyond research. All face a major challenge of finding public support and political acceptance, and all go well beyond previous efforts presented as fixes for market failures. And while this is clearly new territory for US policymakers, simply bringing such initiatives into existence does not guarantee their success.

## A new institutional infrastructure

For these programs to be effective, they will require a network of new supporting and coordinating institutions—a type of institutional infrastructure that the United States has not previously attempted. Past industrial policy approaches outside the defense arena, particularly energy technology demonstrations, have sometimes failed precisely because of missing support institutions.

A review of the supporting infrastructure in defense R&D over the past decades, as well as what has been missing in civilian R&D, makes clear that three broad categories of mechanisms and support systems are needed to ensure an agency's capacity to carry out industrial R&D policy. First, there is aneed to build foundations to form strong projects and the talent base to implement them. Second, the country will need infrastructure to scale up these projects. And finally, policy initiatives will need support going forward. Understanding these three categories can help administrators at implementing agencies ensure they have the appropriate capabilities, while enabling them to signal to Congress and the White House that insufficient resources will likely lead to failure.

***Foundational elements.*** The first category of necessary infrastructure contains elements necessary to establish new projects, including connections to research foundations and a talent base. Industrial policy is not only about application; it must also effectively integrate the various tasks of innovation that, contrary to the linear model, are rarely timed sequentially. Ensuring research is plugged into innovation networks will be critical to ongoing and long-term applied efforts. OWS was the beneficiary of vital research work on mRNA and nanolipids that enabled rapid scaling up of vaccine production. Similarly, applied technology advances in semiconductors (per the CHIPS and Endless Frontier Acts) and DOE demonstration programs will require extensive foundational research.

Furthermore, outside of the defense sector, federal R&D and technology agencies typically lack experience in implementing industrial policies. In particular, these agencies lack trained and experienced managers to coordinate integrated portfolios from development to deployment. Program managers currently overseeing civilian research projects have an entirely different job: they judge scientific merit and promise independent from considerations of application and commercial use. In turn, in industrial policy programs, project managers are central nodes of innovation networks, articulating the work and simultaneously coordinating production of knowledge and commercial products. In the current system, program managers are virtuoso pianists; under industrial R&D policy, project managers are orchestra conductors.

For example, the team that created and then led OWS had a wide range of experience and expertise, including from the private sector and across different agencies. Complex DOE demonstration projects are another example, requiring expertise in project management, engineering, and finance. People with bureaucratic know-how and understanding of legal and contracting authorities could also prove vital, as OWS's use of innovative contracting demonstrated. Understanding regional innovation may be key as well, as illustrated by projects called for in the Endless Frontier Act. The point is that these kinds of projects require new skill sets: not simply R&D skills, but a panoply of tech development, tech scale-up, tech financing, and tech production skills. Outside DOD, this talent base is not in place, and it would have to be trained promptly to support the new programs.

***Scaling up.*** The second category of infrastructure enables agencies to scale up efforts to bring R&D out of the research stage to develop prototypes, verify technology, determine how to manufacture the product, and see where it fits into supply chains. In contrast to the foundational efforts, all scaling efforts must be integrated tightly with the private sector; none are like the famed Manhattan or Apollo projects with the government as the sole customer. Therefore, all will need strong public-private partnerships that open up markets.

Again, OWS provides a good example of close integration of the government with private sector vaccine makers, to the point at which government personnel were located at firms to speed regulatory understanding and review. To succeed, industry partners must be actively engaged and committed. Industry leadership is thus a significant aspect of successful industrial policy: pending legislation needs not only the buy-in of politicos but of industrial and financial leaders as well.

One of the first steps to scaling requires testing and demonstration to produce working prototypes. DOD, with its long-standing industrial policy approaches, builds testing and demonstration into its technology development programs, but civilian agencies often do not. Testing and demonstration are also crucial to commercialization. Firms and users will not be interested in a technology unless it is tested and proven. Testing and demonstration capability at DOE, for example, will be critical for the development and adoption of new battery, advanced nuclear, and renewable technologies, as well as industrial carbon capture and sequestration and carbon dioxide removal technologies. Testing and demonstration are built into the Endless Frontier Act, but their effective implementation should not be assumed.

Although the health science sector has a technology certification procedure through the Food and Drug Administration (FDA) approval process, there is no formal and fully accepted process for validating other technology. However, this mechanism is a very powerful innovation tool: FDA approval guarantees immediate market acceptance. FDA's preliminary step to full approval, emergency use authorization, was a technology certification that proved vital to the success of OWS in limiting the pandemic's effect, helping the adult population reach a vaccination rate of over 70%. As noted, no equivalent certification is available outside the health sector, but its utility suggests that comparable technology certification or validation mechanisms should be considered as the government pursues industrial policy approaches.

A particular weakness in most industrial policy programs is the lack of manufacturing integration. The new industrial policy must interface with national manufacturing, or innovation will suffer from supply chain insecurity. This is particularly hard given that US manufacturing productivity rates have fallen to historically low levels over the last 15 years, with plant and equipment investments declining in parallel. It's a catch-22 situation: industrial policy gives innovation a push with the intention of reinvigorating US manufacturing, but a vibrant manufacturing sector is the necessary pull for research-based innovation.

Building more supporting infrastructure is necessary in part because government-financed R&D will not be taken up by a still-depressed manufacturing sector. The government needs to boost manufactures to give its R&D programs a chance to succeed, but boosting manufactures is best done via innovation in production processes and technologies. What's more, while these initiatives focus on implementing advanced technologies, the United States is running a $191 billion (and growing) trade deficit in advanced technology goods. This imbalance suggests that the proposed advanced industrial policy for R&D programs will only achieve partial success domestically, with the residual effect realized in overseas manufactures. Consequently, renewed focus on manufacturing is critical for industrial policy to have its desired effect on the US economy.

Enhancing the US innovation system via industrial policy also means integrating it, bridging gaps between its actors, and establishing redundant routes to build supply chain resilience. Within such efforts, mapping supply chains itself seems a vital task for policy success. Such a mapping was pivotal to the success of OWS. It is already proving central to the effort to secure domestic supply chains for critical technologies and materials, and it will be required in semiconductors and for technologies targeted by the Endless Frontier Act.

***Support.*** Initiatives for industrial policy may grind to a halt unless financing is available for scaling up technology projects. A variety of financing mechanisms may be appropriate for different projects, including lending, guaranteed contracts, tax incentives, and procurement contracts for initial market creation.

Guaranteed contracts were crucial to OWS's ability to rapidly scale up vaccine production. The DOE demonstration program relies on authority from DOE's Loan Programs Office, as do the critical materials- and minerals-development efforts called for in the initiative to secure critical domestic technologies and materials. The semiconductor initiative uses investment tax credits as a financing tool to enable domestic fabrication plant and foundry creation. While the Endless Frontier Act does not specify a financing system, a section in the legislation calls for this authority. If advanced manufacturing is to be spurred as a foundational element for industrial policy initiatives, financing for new advanced manufacturing equipment, particularly at small and midsized manufacturers, will be needed. All these points underscore the importance of financing as a cornerstone of successful industrial policy initiatives. Creating a banking institution comparable to the Export-Import Bank for domestic manufacturing, with the private sector fully sharing the risk, may facilitate such financing.

The government cannot simply act as a technology development supporter. It must be an initial market creator, as it frequently is with new defense technologies, helping new technologies reach commercial feasibility scale. Federal procurement plays a massive role in the defense and health sectors: the accelerated vaccine procurement effort in OWS is a good recent example. The federal government can also apply its leverage over demand. For example, although defense production accounts for only a modest portion of total manufacturing output, a surprisingly sizeable proportion of manufacturers pursue (and obtain) defense contracts. Defense procurement could, in principle, require its contractors to adopt advanced manufacturing technologies by which they would help improve production efficiency and drive down federal costs. Effective use of federal procurement can also play a significant role in creating initial markets for new technologies in a number of areas, helping shape the demand that will be key for new technologies to scale.

Flexible contracting mechanisms go hand in hand with procurement approaches. The Defense Production Act, for example, provides authority for intervention into manufacturing supply chains to ensure the sufficient supply of goods critical to national security. This authority proved instrumental to the success of OWS in rapidly developing and producing vaccines. Application of this act is cited in the initiatives for DOE demonstrations and to secure critical technologies and materials. Another example of flexible contracting authority is the Other Transactions Authority, developed initially by DARPA to circumvent the lengthy standard federal procurement process and since applied by other agencies as well. These and other examples of flexible contracting authority could be key factors in the success of pending industrial policy.

## The task ahead

The United States has been undertaking industrial policy projects in the defense sector for a long time, and advances in aviation, space, nuclear power, computing, and the internet owe their inception largely to those policy efforts. On the civilian side, the government has been gradually undertaking more such policies in areas such as energy and manufacturing.

As a new industrial policy accelerates in response to the series of initiatives proposed by the Biden administration and Congress, we must change not only policy and outcomes, but also the way we conceive of the innovation system itself. The new policies are geared toward integrating the innovation system not as a linear production chain but as a network of interacting economic agents taking differentiated tasks of innovation beyond prescribed sequences. This has been called a "systems of innovation" approach, in contrast to Vannevar Bush's linear view of innovation as a conveyor belt. This new approach is a multidirectional system, not a one-way street, where technology development influences R&D as well as vice versa.

The new wave of industrial policy implies we must understand innovation in a more dynamic way, in terms of its components, flows, organizations, and underlying policies. In consequence, the proposed policy instruments target barriers and bottlenecks in innovation flows, with agencies engaging in "boundary spanning" to broker connections and implement solutions beyond their traditional jurisdictions. This will not be enough. We have long thought R&D was innovation, but we need to expand our perspective to encompass the full innovation panoply, from development through production and application. A concerted effort to build an institutional infrastructure to support industrial policy will be needed.

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SHOBITA PARTHASARATHY

# Innovation as a Force for Equity

Today's health innovation system doesn't benefit everyone equally. To change it we need to think differently about expertise, innovation, and systems for ensuring access to crucial technologies.

As we plan our science and innovation policy strategy for the next 75 years, we must work to center equity as a public value. Today, the United States is profoundly unequal, with 10% of households holding 76% of the wealth. The net worth of a typical white family is 8 times its Black counterpart and 5 times its Hispanic counterpart—and these disparities have not changed much over the last 30 years. Meanwhile, close to one half of all households in the United States have less wealth today than the median household had in the 1970s. Furthermore, the life expectancy for the wealthiest 1% of individuals in the United States is far higher than for the poorest 1%: 10.1 years more for women and 14.6 for men.

Historically, the US government has focused on policies designed to stimulate innovation in the hope that these policies would generate markets, produce macroeconomic growth, and provide access to new technologies. One of the first priorities of our nation's founders, notably, was to build a strong and predictable patent system that encouraged broad participation.

Over a century later, Vannevar Bush, director of the US Office of Scientific Research and Development, built upon this approach. His 1945 report, *Science, the Endless Frontier*, commissioned by President Roosevelt, encouraged the government to turn away from the mission-driven science that had supported World War II and instead trust scientific priorities to serve the public good.

In response, policymakers have made significant investments in basic scientific research through the National Science Foundation and the National Institutes of Health (NIH). Scientists guide the allocation of research funding through both priority setting and peer review. And the government largely has relinquished to universities and the private sector any intellectual property (IP) interest in the technologies that result from its funding in the hope that this will stimulate market activity. The assumptions are clear: innovation, by its very nature, is socially beneficial, and the government's role is to foster innovation through research, translation to the private sector, and a robust patent system. And by many measures it has been successful.

But innovation isn't benefiting everyone, and sometimes it amplifies inequality. Whether the internet or insulin, many people in the United States lack access to crucial innovations. Meanwhile, machine learning algorithms and many other technologies reflect and reproduce social biases, including racial biases. Better public policies, however, can help to address these problems and ensure a more equitable and just twenty-first century.

## Distinguishing innovation from health care

According to one review, between 1970 and 2009, government resources directly contributed to the discovery of 153 drugs and vaccines. But these diagnostics, devices, and treatments are often inaccessible to the most vulnerable. In some instances, they are extraordinarily expensive, making them unaffordable. Other innovations such as cancer screening technologies may be relatively affordable, but they are not distributed equitably. Some observers might argue that this is the fault of our decentralized, privatized health care system. But characterizing these as problems of health care rather than innovation is itself a political choice that is shaped by a circumscribed understanding of innovation that focuses solely on scientific and economic output. This choice has real costs for communities.

Patent policies and practices, for example, facilitate private sector efforts to build and maintain monopolies over inventions, and then charge extremely high prices for access. Consider the case of hepatitis C, which affects approximately 3.5 million people nationwide, of whom 20% develop severe complications that can require medication, hospitalization, and liver transplant. In recent years, the US Food and Drug Administration (FDA) has approved a handful of new drugs to treat the disease. The new treatments are quite effective, but because they are patented and there are very few options available, the companies can charge astronomical prices: from $84,000 to $95,000 for a 12-week regimen. This ultimately limits their use. And while the life of a patent is only 20 years, companies file multiple patents on different components of the drugs to extend their monopolies. One analysis found that for each of the top 12 grossing drugs in the United States, companies attempted an average of 38 years of patent life.

These problems aren't limited to the patent system. Agencies that fund research shoulder responsibility as well because, imagining that an unfettered marketplace is the primary way to distribute innovation, they refuse to assert their authority to influence markets. In 1980, the US Congress passed the Bayh-Dole Act, which clarified that universities could hold patents on the fruits of federally funded research conducted by their employees. Universities could now patent inventions at early stages and license them to companies, who would use additional patents, trade secrets, and proprietary tacit knowledge to strengthen their market position. Congress acknowledged, however, that there might be instances where patents might contravene the public interest. So Bayh-Dole established a "march-in" right that allowed the government to step in if the patent holder did not adequately commercialize the product, and force universities or small businesses to license the innovation to additional companies.

To date, however, federal agencies have never exercised this right. For example, NIH and Department of Defense (DOD) provided grant funding for the development of Xtandi, a prostate cancer drug developed by researchers at the University of California, Los Angeles (UCLA). UCLA patented the compounds and sold them to a Japanese firm, which markets the drug for over $129,000 per year per US patient—a much higher price than in other high-income countries. Despite efforts from civil society groups and federal legislators, DOD has refused to use its march-in rights. DOD argues that although the drug is costly, it is widely available—and therefore public health and safety needs are being met.

High prices aren't the only issue. Even when prices are reasonable, markets may still distribute innovation inequitably. This imbalance becomes even worse when supplies are scarce. At the beginning of the COVID-19 pandemic, both public and private sector laboratories across the United States rapidly developed diagnostic tests that could be used to identify people with COVID-19 who needed to isolate themselves to limit disease spread. But even as supply increased, tests remained scarce among marginalized communities despite their disproportionate risk of contracting and dying from the disease.

Again, some observers might argue that these sorts of problems are not the fault of innovation policy but rather the responsibility of markets or health care systems. But NIH itself acknowledged that vulnerable and historically underserved communities were not able to access COVID-19 diagnostics. In response, NIH created a research funding program (RADx-UP) to address this issue, suggesting that the agency itself recognized its role in and responsibility for the problem.

Unfortunately, programs such as these are reactive and ad hoc, and often focus on health care pricing and access rather than on the design of the technology itself. Policymakers and scientists could instead make systematic efforts to consider these concerns at the roots, when early-stage research is funded and patent rights are awarded. They could make technology design and development choices that maximize equity rather than, for example, market viability. Put simply, innovation and health care equity need to be relinked in our public policies.

## Treating socioeconomic conditions with molecules

Guided by scientists as well as market priorities, innovation-focused institutions prioritize mechanistic investigations that can produce generalizable conclusions and, ultimately, scalable commodities such as molecules or drugs. This focus, in turn, enables what some call "pharmaceuticalization," in which social conditions are turned into individualized, biologically based conditions that the private sector can fix through profitable technology. But this argument can be taken one step further.

By a) investing in research and interventions at the molecular level, b) viewing the marketplace as the primary route for technology to achieve the public good, and c) encouraging expansive patent rights, the US government currently enables the development of commodified solutions that are devoted to treating health problems once they emerge. Such medicalized interventions tend to be more accessible to already privileged groups. But addressing the root causes—including the built infrastructure, working conditions, or environmental pollution—are likely to produce the greatest gains for marginalized communities, and long-term benefits for the population overall.

Consider the example of asthma. Its cause is unclear and there is no cure, but many of the lung disease's triggers are external and specifically environmental, including air pollution, chemical fumes, and dust. It is also strongly associated with poverty. In general, more people are being diagnosed with the disease than in the past, but its prevalence is increasing more rapidly among historically disadvantaged communities of color. These communities are also likely to experience worse disease outcomes, including hospitalization and death. In response, governments have increased research funding, but research has focused primarily on genetic and biological mechanisms rather than on how to transform environmental and socioeconomic conditions necessary to prevent and mitigate disease. This approach fits with both the dominant concerns and approaches of scientists in this field as well as those of the private sector.

## Innovation left undone

The US innovation system has come to represent a narrow range of interests. Vannevar Bush argued that allocating grants on the basis of merit, as defined by peer review, would increase the likelihood of high-quality science and ultimately produce beneficial technologies as well as economic growth. Implementation of this approach, however, has skewed research. Most federal funding goes to a handful of universities in a few states. Harvard University, for example, receives more research funding than all historically Black colleges and universities combined. In addition, women, historically marginalized communities of color, and disabled scientists receive less funding than their white, male, able-bodied counterparts, despite recent targeted initiatives to better balance funding support.

The resulting demographic homogeneity has a real impact on innovation, by shaping the research questions reviewers define as important and the methods seen as appropriate. NIH, for example, is less likely to award R01 grants (grants of larger sums that are needed for a successful research career in the health sciences) to Black investigators than their white counterparts with similar educational backgrounds, training, previous grants, and employers. These researchers tend to investigate less-funded topics: their proposals often include topic words—such as *socioeconomic*, *health care*, *disparity*, *lifestyle*, *psychosocial*, *adolescent*, and *risk*—that focus on structural concerns and are less likely to lead to commercializable products. Meanwhile, the proposals that are most likely to be funded include topic words such as *osteoarthritis*, *cartilage*, *prion*, *corneal*, *skin*, *iron*, and *neuron*. Overall, the proposals least likely to be funded are associated with women and reproductive issues.

The consequences of these skewed funding choices, by the country's main funder of early-stage biomedical and health research, are significant. These choices are further reflected in a society-wide emphasis on mechanistic research, which is more likely to interest the private sector because it can be more easily patented and commercialized. The private sector is less interested in innovation at the community level, in public policy, or in infrastructure. This approach doesn't only limit our understanding of health inequalities, it perpetuates the false understanding that the solution to health problems lies in individualized, commodified technologies.

### Innovation that amplifies societal biases

In its deferral to the marketplace and reluctance to regulate, the federal government ultimately enables the development and entrenchment of harmful and even biased technologies. The history of the pulse oximeter reveals how this happens. Oximeters measure the amount of oxygen in the blood by calculating how much light is absorbed by human tissue; this technology has been crucial in evaluating patients during the COVID-19 pandemic. Skin tone, however, affects light absorption. When Hewlett-Packard developed the original oximeter in the 1970s, it took care to ensure its accuracy among varying skin tones by testing it among people of color and allowing it to be calibrated according to each individual.

But Hewlett-Packard eventually stepped away from this area of technology, and a small biotech company developed and patented a new version of the pulse oximeter that is now dominant in COVID-19 care and beyond. The new company did not test its device in a range of patients and used its patent rights not only to prevent others from developing devices but also to reject requests for information about its accuracy. This was permitted by the FDA, which has jurisdiction over pharmaceuticals and many medical devices, but focuses narrowly on questions of safety and efficacy. The Patent and Trademark Office (PTO) typically only considers whether a technology is an invention according to the law and what is previously known (i.e., "prior art").

It was only amid the COVID-19 pandemic, when an anthropologist called attention to the problem and a group of physicians conducted a study, that it became clear that the device systematically reported that Black people had a higher blood oxygen level than they actually did—which means they might have erroneously delayed seeking medical care to get needed supplemental oxygen. There have been no studies of the device's accuracy among other communities of color. The company has not responded to this issue, and although this device is regulated by the FDA, consideration of its potential racial bias is outside the agency's remit.

No regulator explicitly considered the needs of people of color in the FDA permitting process. And although patents are designed to publicize the technical workings of a device to encourage others to invent beyond it, here the FDA had effectively removed the incentives for others to test or innovate. The oximeter manufacturer was under no legal obligation to reveal its accuracy data. The pulse oximeter remains in common use and is still seen as an essential tool for monitoring COVID-19 at home. Its continued use, however, has likely led to delayed hospitalization and death among people of color around the world.

Some might argue that these issues are matters of regulation rather than innovation. But such a view unnecessarily constrains the policy levers available. As I discuss in further detail below, agencies that fund science could encourage their grantees to consider whether their technologies might exacerbate inequality and help them to develop more socially just designs. And policymakers might also reconsider the strength of IP protections—especially when they stand in the way of assessing the quality of a technology for all.

## Innovating for equity

To address these problems and prioritize equity, society needs to think differently about expertise, innovation itself, and systems for ensuring accessibility to crucial technologies.

***Reconsider who the experts are.*** On the subject of health, innovation policy customarily favors the knowledge of biomedical scientists and engineers, physicians, and industry representatives over that of patients, social scientists, ethicists, or historians. But taking equity seriously means ensuring that technologies reflect societal needs and priorities and are also rooted in the realities on the ground. Gaining that perspective requires involving scholars with a deep understanding of equity as well as the affected communities—particularly people in communities who have been historically marginalized—into the earliest stages of the innovation process.

At present, the public has little opportunity to influence innovation policy beyond electing the representatives who make laws and allocate research funding, and occasionally advocating positions through stakeholder organizations. Technologists and policymakers might argue that nontechnical communities lack the requisite knowledge and skills to participate in innovation policy, but this is incorrect. All people are experts in their own needs, lives, and circumstances. If policymakers, scientists, and engineers aim to improve community health, they must begin by understanding the knowledge and priorities of those within the community they seek to help.

Furthermore, in recent years there have been numerous efforts to engage citizens in discussions about highly technical issues. While the exact approach varies, studies show that with the help of background materials, community members are able to grasp technical details. Most are more than capable of questioning experts and building upon their answers. And through deliberative processes, they can offer extremely useful insights to guide policymaking. In the process, participants report that they appreciate exercising their civic duty and feel more engaged in the community.

Communities and social scientists should play a key role in setting priorities at agencies that fund research and at the PTO. These constituencies could be welcomed into advisory committees that are designed to make recommendations to leaders in the executive and legislative branches, about research needs and priorities as well as fostering innovation in the public interest. This participation includes existing advisory structures. The PTO, for example, convenes a Patent Public Advisory Committee on a quarterly basis with a membership that currently consists entirely of participants from the worlds of patent law and the tech industry. A more representative committee would provide the agency with a deeper understanding of the needs of the citizenry and specifically the health impacts of the patent system.

Furthermore, communities who are affected by policies should be involved directly in day-to-day decisionmaking at innovation policy institutions (such as NIH or the PTO), and should be given some authority in the grant review process. This idea is not new. In the 1990s, women with breast cancer, frustrated by the lack of medical progress in preventing and treating the disease, successfully advocated not only for increased research funding but also for the inclusion of patient voices in grant decisionmaking. They presented the argument that they, as people with the disease, offered a unique understanding of the disease experience and had the necessary expertise to evaluate the impacts of different interventions to address breast cancer. Today, they regularly participate in scientific peer-review panels. They also successfully convinced Congress to explicitly fund research into environmental causation, departing from NIH's customary focus on mechanistic investigation and commodifiable solutions.

Similarly, in the wake of the recent water crisis in Flint, Michigan, in which residents of the city drank and bathed in water contaminated with lead and bacteria due to the negligence of scientific, political, and policy leaders, researchers and funding poured in to study the effects and offer solutions. But Flint residents were wary: How could they ensure that researchers didn't replicate the racism and mistreatment of previous generations of scientific studies? And how could they make sure the community benefited from the research? As an answer, they created the Healthy Flint Research Coordinating Center (HFRCC), which must approve all research conducted in Flint. HFRCC often suggests changes to proposed studies that would align better with community concerns and context as well as ensures that benefits flow directly back to the community. In return, HFRCC helps connect researchers with funding opportunities.

Bringing communities into the PTO decisionmaking process would look somewhat different. There, citizens might inform technical examiners about the health costs of broadly written patents, or even remind them of colloquial understandings of novelty and invention. As an example, the European Patent Office has engaged citizens in both town hall meetings and scenario-planning reports. And it is easier for Europeans to register their grievances about specific patents in "opposition" proceedings.

***Reimagine innovation.*** Recognizing community and social scientific expertise is a crucial first step in remodeling our innovation system. But we also need to reimagine innovation itself, and the roles of funding agencies in fostering it. The current approach excludes categories of innovation that are likely to be particularly effective in promoting equity and inclusivity such as low-tech interventions and new approaches to public policy, built infrastructure, urban and suburban planning, and pollution prevention and remediation practices. It also fails to recognize innovation by people who have a deep and sophisticated understanding of their social worlds and strong incentives to fix them however they can, but who might lack formal technical training; this category includes nurses, maintenance workers, and individuals in low-income communities.

Research funding agencies can redefine innovation to center equity by spending substantial funds on truly interdisciplinary research that brings together the life sciences, engineering, sociology, public health, economics, and other expertise. This cross-cutting research should take social context seriously in both understanding disease causation and developing solutions to improve health outcomes. Consider, for example, efforts to prevent heart disease and stroke, diseases that disproportionately affect the Black community. Researchers have been working on a variety of solutions, including a mobile health app designed to encourage physical activity and nutrition. Some health experts believed that a properly marketed and distributed app would be useful because it would be commodifiable, could reach a tremendous number of people, and its quality could be controlled.

Interviews with the Black community, however, revealed the technology's limitations. Accustomed to being disrespected and even harmed by biomedical institutions, interviewees were skeptical of the app. And they revealed a serious barrier to exercise: the lack of safe and accessible outdoor environments in many urban areas. One app, in other words, was not enough to solve the problem. These limitations were revealed early on in development only because of the inclusion of diverse perspectives in the innovation process. This revelation could, with the addition of insights from experts in urban planning and environmental health, lead to more tailored technologies or projects focused on developing innovative infrastructural solutions that would ultimately improve people's health.

Another reform that could make equity part of early-stage innovation would be to require equity impact assessments as a condition of grant funding. Grant applicants already adhere to a variety of requirements, such as the National Science Foundation's expectation that funded projects have "broader impacts" that will serve society. Funding agencies could require applicants to explain how they will evaluate the equity impacts of their proposed project, and how they will address inequities reflected in or amplified by their intervention. This reform could include assessments of whether the design itself is equitable, whether it will be distributed equitably, whether affected communities were consulted in the development of the intervention, and historical analysis of how previous, similar technologies either exacerbated or ameliorated inequality.

Proper implementation of such equity impact assessments would require changes at the level of research projects, grant reviews, and agency staff and programs. To address the requirement, researchers would need to engage members of marginalized communities in their projects as equal partners while also consulting experts who have studied how innovation and equity interact. In their evaluations of equity impacts, they would also need both qualitative and quantitative data. Because of the promise of federal funding, universities would likely provide institutional support for these equity efforts. Agencies would need to diversify the expertise of their grant reviewers, and employ staff with the background to understand and evaluate the equity assessments, facilitate interdisciplinary and community partnerships, and help multidisciplinary research teams ensure their work benefits society. Ultimately, these equity assessments could transform the culture of innovation in a way that individual grant programs focused on diversity, equity, and inclusion could never accomplish.

Funding agencies should also establish offices for community-based innovation. For inspiration, we can look to the National Innovation Foundation in India, which was established by India's government in 2000 to strengthen "grassroots technological innovations and outstanding traditional knowledge." The foundation understands that much innovation takes place among those who are "knowledge rich" but "resource poor," and its first goal is to identify this work where it is taking place. To this end, it offers awards, grants, and loans to people who are developing technologies that might benefit their communities. It also takes special steps to find innovation at the grass roots, through yearly scouting trips to low-resource settings. This initiative, proponents argue, not only makes low-cost, low-tech interventions more widely available but it also empowers communities that traditionally have been marginalized by the innovation system to contribute.

Similar offices within US research agencies could identify and support traditionally unrecognized citizens who are engaged in effective innovation but whose work has traditionally gone unnoticed, and address barriers that may prevent them from applying for funding to develop their creative ideas. This work could embolden these communities to develop solutions that work best for their needs and reveal unheralded sources and types of innovation. Although these interventions might not be commodifiable or scalable like the technologies discussed above, they are more likely to be accessible to those who need them most. And because they are built from the grass roots, they will be more trusted and sustainable in the community.

***Create new systems for accessibility.*** Funding agencies, and the policymakers who guide their priorities, have emphasized the market as the primary mechanism for translating technology to society. Patents and other forms of IP play a key role. But while patents can stimulate innovation in some cases, they can also have an inhibitory effect. And IP can make technologies inaccessible, which is particularly problematic in areas such as health.

Policymakers can address these issues by becoming more sensitive to the circumstances where monopolies might conflict with the public interest, and using the tools at their disposal to resolve these conflicts. This approach could include suspending patents or requiring nonexclusive licenses under specific circumstances, exercising the government's march-in rights, or nationalizing the development of particular kinds of innovation. The PTO could also limit the scope of some types of patents. To create new incentives, the government could provide prizes to innovators who produce, or make substantial contributions toward, innovation that enhances equity. In return, innovators would not maintain any IP interest.

Finally, research funding agencies should create offices that identify and support non-market-based approaches to health innovation. Today, they focus primarily on facilitating the uptake of federally funded research by the marketplace, through technology transfer initiatives at both the national level and inside universities. But there is little investment in translating research that might improve, for example, built infrastructure; pollution remediation programs; or social, environmental, and health policies. These efforts would ensure wider accessibility to the fruits of federally funded research.

The changes suggested throughout this section could be implemented first in the new Advanced Research Projects Agency for Health (ARPA-H) proposed by the Biden administration. Modeled on the famed Defense Advanced Research Projects Agency, ARPA-H is designed to produce breakthrough advances for common diseases. The Biden administration's proposed $6.5 billion budget is a large and laudable investment, but for ARPA-H to further the administration's strong equity objectives, the program must foster innovation that is based in interdisciplinary and community-based insights and be transferrable beyond the marketplace.

## Bold, systemic change

For generations, scientists, engineers, and policymakers have assumed that the US approach to innovation would inevitably produce equity. But it has become clear that this is not the case, and many people are now advocating for policy change. We are now seeing not only new funding opportunities and programs but also experts in equity and justice positioned at the highest levels of agencies that fund science.

This is not enough. Inequality is baked into the US approach to innovation policy. Driven by scientists' and market priorities, the current approach emphasizes standardizable, scalable, and commodifiable technologies that are designed to work at an individual level rather than benefit communities or address much needed infrastructure failures or policy requirements. Sometimes, this personalized, commodified approach leads to crucial, lifesaving interventions. But often these interventions are inaccessible to the most vulnerable. Institutions involved in innovation policy invariably abdicate responsibility for this disparity. Meanwhile, our society's regulatory ambivalence means that there are essentially no opportunities to correct the social biases and blind spots that are embedded in technologies, ultimately amplifying structural inequities.

Ensuring that innovation policy truly serves all people requires bold, systemic change. We need to fundamentally rethink our understanding of innovation and innovators, upend our assumptions about relevant knowledge and expertise, and reimagine both the government's and the market's role in innovation. For the last 75 years, the "endless frontiers" of science have been defined too narrowly, by too few people, and with incorrect assumptions about the relationship between innovation and societal benefit. To ensure truly equitable progress, we need to leverage a diverse range of knowledge to determine which endless frontiers to investigate and how to study them.

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DAVID N. SPERGEL AND WILLIAM H. PRESS

# Innovation Is Not a Linear Race, It's a Dance Between Discovery and Use

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Investing more money in science is not enough to meet the challenges of the twenty-first century. We also must recognize a diverse set of approaches to scientific advancement.

One simple story that we tell about science is that basic research, driven simply by human curiosity, leads to discoveries, which enable applied research, which fuels the development of new technologies that then transform our lives and our economy. The operative metaphor of this simple story is that of a relay race, in which each runner hands off the baton to the next.

Another related, but equally simple, story starts with a lone scientist toiling for years to produce a profound insight that alters our understanding of the universe. The metaphor there is that of the long-distance runner.

This metaphor of a race, based on linear progression from insight to technology, is central to the way we talk about innovation in the United States. In no small part, that is because the compelling version of this story that Vannevar Bush told in 1945 led to the creation of the National Science Foundation, which has been a legendary success through the decades since. Still, a closer look reveals a history of advances in science and technology that is much less straightforward than these simple stories and metaphors would imply. The meandering path to success sometimes starts with a technological breakthrough and at other times with a fundamental breakthrough. The course of scientific progress is difficult to predict, and advances sometimes require insights from outside fields and inspiration from new challenges.

Now, with the perspective afforded by the COVID-19 pandemic, we can see unprecedented public, bipartisan, political support for ambitious new investments in science and innovation. Significantly, both the US Senate's proposed Endless Frontier Act and the House's proposed National Science Foundation for the Future Act embody a willingness—a desire, even—to boost innovation.

The proposed enhancements will be most effective if they both build on and preserve Vannevar Bush's vision and simultaneously nurture and support these more complex pathways to innovation. The most effective strategies for advancing science and promoting innovation will alter the metaphor: not strictly a relay race moving linearly from basic to applied science, but rather a complex dance in which science and technology are partners at every stage. Both the Senate and House versions of legislation increase our national investment in basic discovery-driven and curiosity-driven science. Both also put significant new investment into "use-inspired" science, in which uses include technologies with commercial applications as well as new tools for further basic scientific advances. The proposed legislation also includes investments in people, programs, and the building of new collaborations and institutions. In addition, the legislation requires attention to how these investments are allocated to increase diversity in the STEM—science, technology, engineering, and mathematics—talent pool and enable a broader geographical distribution of technology-driven economic growth.

Maximizing the long-term return on investments in science requires that we understand the rich history of the way ideas and solutions develop. Basic research can be curiosity-driven or use-inspired—or a combination of the two. And research that is not use-inspired may become so later. When François Jacob, Sydney Brenner, and Matthew Meselson discovered mRNA in 1961, they were working to understand the fundamental processes that are at the basis of life. Building on this basic discovery, in the 1990s Katalin Karikó had the vision that mRNA could be used to fight disease. Today, mRNA vaccines are protecting us against COVID-19 and enabling our society to begin to return to a new normal.

These unexpected stories of science and technology dancing together can be very clearly seen in the development of instruments, which is usually seen as applied research. Experimentalists are constantly pushing the capabilities of exquisitely sensitive instruments as they explore the very small, the very large, or the very rare. But these are not one-way innovations: these and other use-inspired advances have applications "back" to fundamental research, and also "forward" to the development of economically important new products.

Consider the story of the development of the internet. In 1989, Tim Berners-Lee, a British scientist working at the CERN particle physics laboratory, conceived and developed the World Wide Web to meet the demand for automated information-sharing between physicists in universities and institutes around the world. John O'Sullivan, an Australian engineer developing novel approaches for detecting radio pulses from neutron stars, had started inventing new ways to detect weak signals in the 1970s. Many years later, his Wi-Fi patents became the basis for technology that is pervasive in our daily lives.

And, as these stories show, basic science is not always leading the dance. Advances in technology can work "backwards" to stimulate the development of fundamental science and mathematics. Practical steam power, the revolutionary technology that launched the Industrial Revolution, came before—and stimulated—development of the theory of thermodynamics. Subsequently, this deeper theoretical understanding made possible more powerful and more efficient steam engines, and the later development of internal combustion engines and turbines.

Today, we can see a similar trend in industry's development of practical artificial intelligence—for speech and handwriting recognition, fraud detection, and commerce—that is now driving a more rigorous understanding of machine learning in academic settings. Meanwhile, the drive to understand the unexpected power of AI and machine learning is motivating theoretical computer scientists and mathematicians to explore the behavior of functions in new modalities like high-dimensional spaces. Standing in the midst of the rapidly changing field of machine learning today, one finds it difficult to predict where the field will have its greatest impacts.

Technology development can itself lead to serendipitous fundamental discoveries. When Arno Penzias and Robert Wilson discovered the cosmic microwave background, the leftover heat from the Big Bang, they were working to find something much more prosaic: the source of "sky noise" in AT&T's work on microwave communications. It's not a coincidence that they were working at Bell Laboratories, which to this day provides the historical prototype of the use-driven laboratory that explored scientific areas deemed relevant to AT&T's role in communication technologies. By giving its scientists and engineers the freedom to explore, Bell Laboratories is now credited with discoveries in radio astronomy, the laser, the transistor, the charge-coupled device image sensor, and the fundamentals of information theory—work that earned its alumni nine Nobel Prizes and five Turing Awards.

Just as there are multiple paths to discovery and innovation, there are multiple ways to support the science enterprise in its advance along these paths. The proposed legislation recognizes the importance of pre- and postdoctoral fellowships and traineeships that advance young scientists to careers of creative independence. It also recognizes the complementary roles of "big" and "small" science, and the importance of the complementary institutional jewels of our science enterprise, the research universities and national laboratories.

This deepened investment in science is essential for facing the challenges of the twenty-first century. However, increased spending is not enough. We must recognize that there are multiple paths of discovery and innovation, and multiple means for supporting such paths. This complex dance of science and technology motivates a national science strategy that supports basic research in both its curiosity-driven and its use-inspired forms, while also supporting applied research and, in partnership with private sector industry, translational research and development. To effectively advance innovation for society, we must support and enable a diverse set of approaches to scientific advancement.

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WILLIAM S. HAMMACK AND JOHN L. ANDERSON

# Working in the Penumbra of Understanding

A twenty-first century science and technology policy that works to solve society's problems must fully incorporate engineering's unique perspective.

At their core, science and engineering have different goals and thus different methods. As Theodore von Kármán, an engineer who received the first National Medal of Science in 1962, put it, "Scientists study the world as it is, engineers create the world that never has been." Engineers solve problems by creating artifacts or systems, often before scientific understanding is available and before the public has identified a need. And the practice of engineering is defined by process, not by one's field of study.

Understanding and enhancing engineering's unique process have become vitally important as the nation seeks to reimagine science and technology policy to solve important problems and drive economic competitiveness for the future. The recognition of engineering's distinctive processes should of course be integral to the planning of big initiatives like infrastructure investment, but it must also be brought to bear on the proposed new directorate at the National Science Foundation. We argue that, to understand what innovation means and how it can be harnessed for national goals, it is crucial to understand engineering's perspective.

## Distinguishing the scientific and the engineering methods

Perhaps the most distinctive feature of the engineer's perspective is the way knowledge is applied in practice. The method used by engineers to create artifacts and systems—

from cellular telephony, computers and smartphones, and GPS to remote controls, airplanes, and biomimetic materials and devices—isn't the same method scientists use in their work. The scientific method has a prescribed process: state a question, observe, state a hypothesis, test, analyze, and interpret. It doesn't know what will be discovered, what truth will be revealed. In contrast, the engineering method aims for a specific goal and cannot be reduced to a set of fixed steps that must be followed. In fact, its power lies exactly in that there is no "must." As mechanical engineer Billy Vaughn Koen has said, "The engineering method is the use of *heuristics* to cause the best change in a poorly understood situation within the available resources."

A heuristic, or rule of thumb, is an imprecise method used as a shortcut to find the solution to a problem. The idea is so old and pervasive that practically every language seems to have its own corresponding term: while in English we speak of the thumb, in French it is the nose, in German the fist, in Japanese "measuring with the eye," and in Russian "by the fingers." In practice, it's anything that can plausibly aid the solution of a problem but is not justified from a scientific or philosophical perspective, either because it doesn't need to be or because it can't be justified through anything other than results. The specialized skill, the defining trait, and the great creativity of engineering all lie in finding the correct strategy to reach a goal—selecting among and combining the heuristics that will lead to a solution, regardless of whether a deep scientific understanding exists.

One obstacle to leveraging this unique perspective in service of national science and technology policy is the popular notion that science discovers, while engineering applies. This perception—which, among other things, can lead to funding being directed to headline-worthy "breakthroughs" rather than toward real innovation—was aptly caricatured by Walter Vincenti in 1990. "Modern engineers," he said, "are seen as taking over their knowledge from scientists and, by some occasionally dramatic but probably intellectually uninteresting process, using this to fashion material artifacts." This traditional "linear model" of the relationship between science and engineering—popularized by Vannevar Bush's postwar manifesto, *Science, the Endless Frontier* (1945), the foundational document for federal funding of basic research—suggests that engineering is simply applied science. In this view, someone else observes and explains a phenomenon before an engineer uses it to create something.

But the truth is that engineering often *precedes* science. The nineteenth century provides a wealth of examples. Scientific observations in this period eventually led to a new scientific understanding of the world, from chemistry and medicine to electromagnetics and quantum physics. But before this new knowledge crystallized, engineers used principles from these subjects to change the world, as illustrated in a few examples. Chemists synthesized long rubbery molecules, but as they puzzled about the nature of those particles, Hilaire Bernigaud spun miles and miles of "Chardonnet silk"—the first synthetic fiber, better known as rayon. Similarly, scientists discovered that a current passed through cables could control a magnetic needle, a baffling phenomenon intractable to the theories of the time, while engineers built vast telegraphic systems under the ocean. And in 1873, Willoughby Smith observed photoconductivity in selenium while working on submarine cables. The phenomenon mystified physicists, but an engineer used the photoconductivity of glassy selenium to create a photocopier in 1938—some 30 years before scientists fully understood it in amorphous materials.

As these examples illustrate, to view engineering as applied science is to conflate the tool with the method. One might think that as science has progressed beyond the nineteenth century, it has steamrolled all uncertainty and replaced engineering's heuristics with firm calculations from first principles. In fact, nothing of the sort happens, because as scientific knowledge advances, engineering goes *beyond* that knowledge. The relationship between science and engineering is therefore complementary, synergistic, and essential. Scientific practice and knowledge offer engineers gold-plated, grade A heuristics that work better than those based merely on observation or long periods of trial and error; but this scientific knowledge does not explain how to design or create an artifact or a system. Scientists, in turn, use the products of engineering to investigate and discover.

## Engineering's goal orientation

Another distinctive feature of the engineering perspective is its focus on achieving particular goals. This orientation is exemplified in the invention and development of the cell phone. In *Cutting the Cord*, Martin Cooper lays out the vision he and his Motorola colleagues had that went beyond the science and technology of the time: that any person could talk directly to any other person anywhere in the world using a handheld device. Many technical barriers presented themselves, including limited basic scientific understanding of electromagnetic wave propagation in the Earth's atmosphere, lack of a built environment and of cellular networks with multiple users, and lack of the high-density integrated circuitry needed to miniaturize the phones themselves. But the Motorola team was not deterred by these challenges; they developed both the scientific understanding and the electronic components needed to produce the first prototype handheld device (the DynaTAC), with which Cooper made the first cellular call on April 3, 1973. Had these engineers waited for the relevant science to be known and the miniaturized integrated circuits to be developed, the emergence of cell phones and their descendant smartphones would have been delayed many decades.

Another example of the goal orientation of engineering can be found in a cutting-edge and still-evolving science of the last 50 years: molecular biology. Deciphering the code of life embedded in DNA opened a deep and rich mine of knowledge about how organisms work. As understanding deepened, scientists became interested in customizing enzymes, nature's catalysts, to tackle tasks beyond those assigned by nature. But complexity stymied progress: an enzyme is composed of roughly 500 amino acids, and there are about 20 different amino acids, which means there are $20^{500}$ possible combinations of amino acids of enzyme length—a mind-bogglingly large number, well beyond the number of atoms in the universe. While efforts to find new and useful combinations among the astronomical possibilities baffled scientists, Frances Arnold, a chemical engineer, created enzymes that reduce the environmental costs of producing fuels, pharmaceuticals, and chemicals.

Arnold determined that she needed enzymes that work under the conditions of an industrial process rather than those of their natural environments. To create these new enzymes, she pioneered the method of "directed evolution," which does not require a fundamental understanding of how the amino acid sequence encodes an enzyme's function. Her first engineered enzyme was synthetically evolved from a member of the group that enables humans to digest milk. These enzymes work well in the water-rich liquids of the small intestine, but when Arnold put them in an organic solvent called dimethylformamide (similar to paint stripper), they no longer "digested" milk proteins. To solve this problem, Arnold simulated evolution by creating mutated versions of the enzyme, changing an amino acid or two, and then testing their function. Most of these modified enzymes failed to digest the milk protein, but a few managed to succeed, at least partially. She selected the best new enzyme, created mutated versions of it, and tested again. After ten rounds of mutations and selection in increasingly higher concentrations of the solvent, she engineered an enzyme that worked in a harsh chemical environment almost as well as the original did in water.

Arnold's idea of directed evolution met resistance from scientists, who protested that her work wasn't science because it didn't contribute to the understanding of protein function. She responded that her goal was the engineer's guiding principle of "getting useful results quickly." When she accepted the 2018 Nobel Prize for Chemistry for this work, she elegantly stated a key attribute of engineering practice: "A wonderful feature of engineering by evolution is that solutions come first; an understanding of the solutions may or may not come later." That deep understanding of enzymes has yet to arrive: "even today," she notes, "we struggle to explain" how her evolved enzymes work. This is a clear reminder that as knowledge about the universe expands, an engineer will always be out front working in the penumbra of understanding, where advances move the borderline between certainty and uncertainty.

To work at the margins of solvable problems and step beyond current scientific knowledge is the raison d'être of engineering. To design something useful without complete scientific understanding signals that an engineer is at work. Engineers often don't wait until scientists thoroughly understand a phenomenon because the public cannot wait for science. In the absence of complete information, engineers for centuries have created structures, devices, and systems that revolutionized the world—ocean-crossing airplanes, lifesaving medicine, glass and steel towers, lithium-powered cell phones, cellular networks, and spacecraft journeying outside our solar system. All these and more were created by the most powerful problem-solving method available to humans: the engineering method.

Facilitating better connections between science, engineering, and technology will require making these aspects of engineering more evident both to the public and to policymakers. One reason they are not well appreciated is that engineering has been so successful. The hallmark of good engineering, after all, is often its invisibility: the public simply takes for granted that airplanes fly, furnaces and computer networks work, vaccines are safe, and buildings stay up. Another reason is that the linear model remains the prevailing mindset of most academic research. Venkatesh Narayanamurti has recently pointed out the ways this picture is "faulty," calling for the linear model to be replaced by a "combination of the scientific and engineering methods," with "neither leading but each strengthening the other."

Incorporating this expanded sense of nonlinear innovation with the knowledge that every engineering solution is unique can be the basis for a vision of science policy that nimbly adapts to solve society's greatest problems. The engineering method aims for a specific goal—an airplane, a computer, a cathedral—but it has no prescribed process and so there is rarely a tidy, orderly, and complete explanation of an engineered solution. A policy model that assigns funding to specific institutions or facilities may miss the uniquely creative tools that engineering brings to bear. The engineering method is best described as an attitude or approach, or even a philosophy of creating a solution to a problem; the same person can act as a scientist and an engineer on the same day.

## The murky meaning of "technology"

A final obstacle to leveraging the unique perspective of engineering, as Anna Harrison has noted, is that the word "technology" often subsumes and obscures the work of engineers. In fact, technology is the *result* of methods from both engineering and science as well as from business.

The historian Leo Marx has illuminated how the word blurs distinctions and nuance. What exactly do we mean by "railway technology," for example? We might mean the ancillary equipment—yards, bridges, tunnels, viaducts, signals, and miles of track—or the business office representing a large capital investment, or the specialized knowledge necessary to create the trains, rails, and telegraphs, or the institutional laws that mandate the gauge of the tracks or set standardized time zones. "When invoked on this plane of generality," Marx concluded, "the concept of *technology* … is almost completely vacuous."

The same might be said for the phrase "science and technology." A poor understanding of the unique engineering perspective generates unrealistic expectations of "science and technology" and risks a loss of faith in the whole science-engineering-technology enterprise. It can also insulate engineering choices from public scrutiny and understanding and thus lead to products and systems that do not serve the full population.

Artificial intelligence researchers Safiya Umoja Noble and Kate Crawford have shown how, in the absence of input from the social sciences, search engines can reflect embedded biases. As Noble explains, "We need people designing technologies for society to have training and an education on the histories of marginalized people, at a minimum, and we need them working alongside people with rigorous training and preparation from the social sciences and humanities." The social sciences are desperately needed to inform both scientists and engineers in order to avoid unintended consequences of their discoveries and creations—and to point them in the direction of social benefit.

## Engineering's value and future

For all these reasons, national policy must take much greater heed of what engineering has to offer, as both a distinctive method and a central component of innovation. Conceiving of engineering simply as applied science distorts the synergistic relationship of scientific knowledge and engineering practice, implying that engineers must wait for science to lead the way. In reality, engineering responds to wants and needs, not simply to the discoveries of scientists, and it often works at the cutting edge in a way basic scientists can't—leading the way well before scientific understanding catches up. A distorted view of engineering also works to obscure what makes the field so exciting and creative, which might dissuade the best and brightest from pursuing an engineering career and thus rob society of the next generation of creative innovators—engineers who are needed to confront local and global challenges such as mitigation of climate change, control of pandemics, avoidance of famine, and other yet-unknown needs. Any science policy for the next century must ensure that we continue to foster engineers who, as von Kármán put it, will "*create* the world that never has been."

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MELISSA FLAGG AND ARTI GARG

# Science Policy From the Ground Up

It's time to modernize the federal role in the nation's increasingly decentralized R&D ecosystem and unleash innovation at the local level.

The United States' system for federal support of scientific research and development emerged in the 1950s. Driven by the goal of building domestic STEM capability for meeting modern society's needs, the nation quickly established itself as the dominant force in R&D globally. By the 1960s, US funding, which was largely dispensed by the federal government, accounted for an astonishing 69% of global R&D expenditures, and American scientists ranked among the most prominent in the world.

Seventy years later, the global landscape has changed, reducing the primacy of the US R&D enterprise. In response, policymakers and influential thought leaders, alarmed that the nation has fallen behind, seek to shore up US leadership in R&D by increasing funding to federal science agencies while expanding their mission areas, leaving their core operational models intact. This approach, however, fails to account for a key development that is shaping R&D in the twenty-first century.

The American R&D ecosystem has become dramatically decentralized. The federal government now supports less than 22% of domestic R&D spending—and an even smaller fraction of the global total. Today, the country's innovation system is as vibrant as ever, but federal preeminence has changed. While the government remains a critical player, it is less dominant than it once was: federal agencies now support less than 50% of basic science funding, with the balance coming from business, philanthropy, and academic endowments, as well as state and local governments. This innovation system may appear messy and chaotic when compared to those of nations with top-down approaches to managing R&D—but it is also extraordinarily productive. At its best, this decentralized system incentivizes individuals and organizations to compete not only for the best ideas, but also the best solutions that the market will support.

Despite these shifts in the innovation landscape, federal science agencies still operate in a highly centralized manner. Decisions about which research areas to prioritize and which projects merit funding are made by program managers in Washington, DC, who inevitably apply a highly nationalized lens. Because most applications of scientific and technical knowledge require some localization to specific circumstances within a given community, this centralized approach favors research that is abstract and theoretical in nature. As a result, federally supported science has been less effective than it could be at helping American communities deal with long-standing and emerging goals and concerns, including clean water and sanitation for both rural and urban areas, increasingly severe drought and flooding, wildfires, crumbling infrastructure, increases in preventable chronic diseases, and the opioid addiction epidemic, among others.

To become the steward of a domestic R&D enterprise aimed at meeting the needs of the twenty-first century, the federal government must fundamentally re-envision its role, embracing the reality of the United States' decentralized innovation system and taking on an updated set of responsibilities. In addition to cultivating the development of cutting-edge scientific knowledge, it is time for the government to ensure the translation of that knowledge into solutions for local and regional problems prioritized by communities across America. This means adopting a more inclusive, bottom-up approach to selecting which questions get researched, as well as partnering to provide more regional funding and infrastructure for local innovation across the country. Making this shift will reinvigorate America's domestic capacity for innovation and unleash our talents to regain global competitiveness while improving the quality of life for people here at home.

## Embrace the chaos

Under the current system, even when the federal government decides to tackle socially relevant issues, it often lacks the processes to account for the local and regional aspects of national problems, limiting the direct applicability of research output. For example, while rural water sanitation problems plague multiple US communities, questions of target microbes, priority climate zones, and infrastructure solutions will be highly localized. Similarly, while the subject of climate change is high on the list of federal science priorities, myriad related concrete local problems badly need to be addressed today: wildfire control in California, rural sanitation challenges in Alabama, flood control in areas as diverse as New York City and Louisiana, drought-tolerant agriculture in Arizona, and sustainable fishing as habitat zones change in the Northeast.

The very mechanics of our centralized system pose significant barriers to exploring regionally important research questions, even when they're part of research priority areas such as climate resilience. Although some policy and advisory processes incorporate broad input when setting priority research areas at the top level, decisions about which specific research topics and questions get detailed in funding solicitations typically lie with a small number of federal program managers. Despite their best intentions, these national decisionmakers are ill-equipped to answer, and unlikely to articulate, highly localized questions on their own.

Meanwhile, an opportunity to connect Americans with our domestic research enterprise is being overlooked. If we want nonscientists to understand the value of federally supported R&D, they need to see it in their communities; they need to know it can and will be brought to bear on the problems that matter to them; and they need to know the scientists and engineers who are developing these solutions in order to trust the outcomes. We have models to draw from, most notably the US Department of Agriculture Cooperative Extension System, created in 1914 to help farmers, ranchers, and rural communities solve problems, leverage knowledge and technology, and create resilience. Although we still celebrate this program, we haven't modernized the model or extended it to other communities and scientists, and we are missing an opportunity to engage today's landscape of potential funders to support such local efforts.

To accomplish this, the federal government should leverage its unique power to convene, gathering diverse groups of people and organizations to work together to articulate, understand, prioritize, and support a broader range of questions and problems. By bringing states, localities, universities, national labs and other research institutions, industry, and philanthropy together, the government can move beyond simply funding research, to amplifying the impact of dollars spent by all the stakeholders. Through outreach and a new emphasis on engaging and convening a broad spectrum of Americans, the major science funding agencies can help build bridges between diverse stakeholders, empowering them to solve problems together; and they can help communities develop and sustain the talent and infrastructure needed to continue meeting new challenges over time. We applaud the National Science Foundation (NSF) for introducing such efforts, and we'd like to see them expanded, amplified, and implemented across the science funding agencies.

## Beyond profits and prestige

We want to be clear that we are not advocating to end federal support for foundational scientific research. Instead, we are calling for an additional focus to bring basic scientific results to life across the country by applying them to real-world problems. Currently, the US R&D ecosystem is largely driven by two goals: profits and prestige. The former motivates industry, which measures success in earnings and shareholder returns. The latter fuels academia, which counts success by publications in high-impact journals and federal grants. What are the incentives for innovating solutions to local and regional problems without clear profit or prestige drivers?

Even when institutions try to prioritize real-world outcomes, as often seen with philanthropic funders of research, they still find an R&D landscape optimized fordifferent incentives. Those incentives matter. Making research applicable to real-world problems takes time, people, and resources. And to do it effectively, we must recognize the difference between invention—developing a new idea published in a high-impact journal or protected with a patent—and innovation—taking an idea and applying it in novel ways to solve problems. Many of the incentives in ac demia favor invention and assume the next steps of applying those ideas and inventions to real-world innovations will be driven by other actors who are motivated by different incentives.

When the right incentives exist, the United States innovates extremely well—even if it doesn't always look nice on a flow chart. Consider, for example, the story of Apple's voice assistant, Siri. This technology was invented as part of research funded by the Defense Advanced Research Projects Agency (DARPA) and conducted at the nonprofit research institution SRI in the mid-2000s. The technology was then spun out and commercialized by a private company that was acquired by Apple in 2010. In other words, federal R&D funding for defense supported invention of a technology by a nonprofit research center, which was then developed by a for-profit start-up company that was then purchased by a large company, which later contracted with multiple suppliers. It took this chain of events and multiple organizations to put Siri's digital voice in pockets all over the world. Siri demonstrates the interlocking capacities—well outside of academic labs—necessary for invention to become innovation. But what happens when profits are not the goal, and therefore incentives are unclear?

To translate the science and invention it currently funds into innovations and solutions to society's problems, the federal government will need to learn how to convene and collaborate with the existing innovation ecosystem to bridge gaps and connect players. This process will require a cultural change that creates incentives beyond prestige and profits to get multiple players working toward beneficial outcomes. At the same time, the federal research establishment must acknowledge its role in creating today's incentive structures for academic science and take proactive steps to reshape them.

## Unleash problem-solvers everywhere

To start this process, the federal government needs to quickly change the incentives that discourage and even prevent scientists from working on local problems. These barriers exist at different levels and have individual as well as institutional effects. As one of the largest single sources of academic and basic research funding, the federal government has played a significant role in giving a global focus to the overall culture and promotion system for scientists and engineers. In applications for federal funding, for example, determinations of merit typically place a high value on the investigators' publications and prizes in globally recognized fora, while questions of community benefit such as NSF's Broader Impacts are often framed vaguely and evaluated inconsistently.

But these are not the only ways that federal support inadvertently diverts R&D capacity away from local communities.

Education is one of the core missions of our nation's taxpayer-supported public university system. Attending college to learn from professors who are also active researchers is an important way for nonscientists to gain direct exposure to practicing scientists and engineers, and it connects researchers to the communities in which they live and work. Nonetheless, university professors are allowed, and even encouraged, to leverage federal grants to "buy out" of teaching, further divorcing the federally supported research system from the people it is supposed to benefit.

Federal incentives also inadvertently create barriers that prevent communities from building local research capability and capacity. Today, most project research money cannot be used to support developing infrastructure or buildings—adhering to a tenet that funds should directly support research. But today's research often requires specialized facilities. As a result, the lack of federal funds for research infrastructure privileges wealthier states, regions, and institutions that can afford to build their own facilities. Though valuable, programs such as NSF's Established Program to Stimulate Competitive Research are insufficient to overcome wide structural inequities, which ultimately serve to deepen the divide between the rich and the rest.

While balance between research outcomes and facilities investment is needed, blanket restrictions on the latter limit the ability of regions to develop local capacity that could enhance their ability to solve local problems proactively. Broad access to research infrastructure allows ideas to be tested wherever they arise and both inspires and empowers more diverse bright minds to enter the research pipeline. One model for this kind of federal support is the Defense University Research Instrumentation Program, which funds research infrastructure and instrumentation. Developing locally operated research infrastructure can also provide benefits by, for example, providing access to local small businesses or aspiring entrepreneurs who need to test an idea. Sharing such benefits with the community builds trust and supports the economy.

Finally, the effects of the value system implicit in federal funding extend beyond the research it funds—sometimes inadvertently discouraging researchers from accepting state or local funding. As more than one university professor who has sought to conduct locally relevant, state-funded research has discovered, the institutional processes and practices that have developed around federal grant management can make accepting other forms of funding an onerous task, requiring herculean efforts to complete. In this way, federal incentives dominate institutional priorities as well as those of individual researchers—and may prevent them from conducting research that is relevant to the communities where they live.

To realize the benefits of STEM research for all Americans, we need to align more incentives in the research ecosystem toward helping society, not simply increasing global scientific knowledge. Not only do federal science funding agencies have the power to reshape the incentive structure for engineers and scientists; but doing so is a necessary step to ensure we have a robust STEM ecosystem capable of meeting tomorrow's complex needs.

## Creating a science culture that solves problems

There are several near-term changes federal funding agencies could implement to elevate the value of public service, local solutions, and local capability and capacity in our domestic science and engineering enterprise. One simple change would be making time spent doing direct community engagement, such as working with local government and/or community leaders, an allowable expense on a grant. More proactively, requiring a summary of direct community engagement efforts and beneficial community outcomes in grant-reporting requirements would begin to shift incentives toward local action. To elevate community concerns at the federal level, peer review boards and advisory bodies established under the Federal Advisory Committee Act should include members with diverse experiences including community engagement, local leadership, and small business. The Environmental Protection Agency's National Environmental Justice Advisory Council provides one example of how such a broad-based advisory body could be constituted.

Another opportunity for the federal government to take creative new approaches can be found in the problem definition phase itself. Too often our current system overlooks the importance of intentional problem formulation. Vaccines against SARS-CoV-2 provide an example. Our federal research support system rapidly mobilized scientists across the country toward the singular goal of developing effective vaccines. This effort demonstrated our domestic research enterprise's greatest strengths, but it also exposed one of our greatest weaknesses: failure to contend with the multifaceted challenges of on-the-ground innovation. In the case of vaccines, lack of trust in the health care system in some communities has slowed vaccination rates. If the problem had been formulated as one of achieving effective immunity through vaccination, rather than simply developing a vaccine, we might have identified these challenges early on and worked to develop broader solutions. In the future, a more human-centered, design-based approach to fully articulating problems could encourage both stakeholders and subject matter experts to map the entire problem space.

In the longer term, decentralization provides significant opportunity for the full range of R&D actors across industry, academia, philanthropy, states, and localities to fully engage in shaping our research culture. Today's American innovation ecosystem has many holes and mismatches. Scientists want to do societally relevant work, but cannot find institutional support. Communities and regions seek research-based solutions to their problems, but cannot marshal the needed resources. Policymakers at local and state levels try to navigate untested novel technologies as well as uncharted climate and health-related problems, but cannot find trustworthy technical advice. Philanthropies seek to fund solutions to long-standing societal challenges, but cannot align the multidisciplinary talent. These disconnects provide an opening for the many players outside the federal government to help bridge gaps to support a more responsive and inclusive research enterprise. And once engaged, this enterprise could take on new tasks.

With this mindset, for example, an independent organization could use digital technology to connect communities, researchers, and funders in new ways. Many researchers spend ever-increasing hours developing proposals to get funding for their laboratories. Simultaneously, many smaller institutions across philanthropy and state and local governments lack the resources to manage large calls for proposals and burdensome review processes. This situation results in both groups narrowing their pools of ideas and potential grantees. Creating an independent proposal marketplace that serves stakeholders ranging from states and localities to industry and philanthropy could expand opportunities for everyone. In such a marketplace, researchers could post white papers or proposals for their research ideas, and funders seeking outcomes could post their questions and problems. Even the most niche funders could search and find proposals aimed at their priorities. The marketplace could further incentivize the full diversity of research, encouraging a range from short-term and problem-focused proposals to longer term, high-risk research and allowing a myriad of specific topics and geographies. Such a single, streamlined process would respect the time and expertise of our researchers, funders, and citizens. It would also encourage the transparency needed to build a culture of consideration around how science can meet many different social needs.

Finally, the federal science agencies need to reshape the incentives that currently cast academia as the primary career path for serious researchers. Perhaps a place to start is by funding not only academic postdocs, but postdocs and fellowships across state and local governments, philanthropies, and industry. Currently, we train every graduate student for a career in academia even though it is no longer the most common career path. This process often leaves graduates feeling they have somehow failed if they opt out of that path. Instead, to ensure we proactively leverage our STEM professionals more effectively and compassionately, we should incentivize and enable careers that span the invention to innovation spectrum.

## What would Vannevar Bush do?

Many of today's proposals to reinvigorate R&D through increased federal spending are returning, compulsively, to the template put forth by Vannevar Bush in 1945. But Bush's true contribution wasn't his policy prescription for science, but his analysis of the landscape and context of 1945, coupled with his sense of which actions could be feasibly taken by government to effect change.

In his seminal report commissioned by President Franklin D. Roosevelt, Bush looked carefully at the research resources of the time, as well as the challenges the country faced: curing disease, securing the nation, and serving the public good. He emphasized that his recommendations were not a solution to all the problems he delineated, but rather a few targeted actions that government could feasibly take to fill research gaps that would have the greatest impact. As a result, Bush's recommendations centered on creating, from scratch, a sustained commitment to and infrastructure for government-funded research. His success in achieving this outcome is remarkable.

Today, an analysis of our R&D and innovation system will show that what's missing isn't federal funds for academic research or even scientific expertise within the federal government; what's missing is connective tissue between ideas, inventions, and innovations and the problems faced at local, state, and regional levels. We lack mechanisms and platforms for communities with problems to help set the research agenda. We lack pathways for bringing people together and taking research ideas from laboratory demonstrations to real-world solutions. If Bush were here today, he wouldn't ask why we aren't spending more on scientific research. He would ask why we are not using the resources at our disposal to solve our problems.

We no longer live in a world where top-down command and control approaches are effective. In fact, outside the postwar era, such a model has never been part of America's cultural history. Instead, the federal government must learn to make today's decentralized structure work in ways that unleash our energies and genius onto the many issues we face now.

Through strong engagement and leadership, we can find a way for science to reconnect with communities and provide creative solutions. This process will involve not only the federal government reimagining its role. It will also require industries to commit to responsibility to their workers and communities, philanthropies to collaborate as part of the ecosystem, academic institutions to invest in efforts that lift up the entire community, and individual scientists and engineers to see themselves as civic actors and participants in the communities they serve. Seventy-five years from now, we hope our present moment is remembered as the time when we decided to embrace our powerful, bottom-up, chaotic, and often wonderful system.

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WILLIAM E. SPRIGGS

# Stories to Work By

Narratives of technological inevitability often limit the tools society has at its disposal to promote equality and opportunity.

In Charlie Chaplin's 1936 film *Modern Times*, humans in a factory are reduced to adjuncts to a massive series of cogs and belts. Overlords bark commands from afar to a servant class, and Chaplin's hapless hero is literally consumed by the machine … and then spit out by it. In the film, the bosses have all the power, and machines keep workers in check.

*Modern Times*'s dystopian narrative remains with us today. In particular, it is still held by many policymakers who assume that increasing technological progress, whether mechanical or informational, inevitably means that ordinary workers will lose. This view perpetuates itself when policies that could give workers more power in times of technological change are overlooked, while those that disempower workers are adopted. If we are to truly consider science policy for the future, we need to understand how this narrative about workers and technology functions, where it is misleading, and how deliberate policies can build a better world for all.

In Chaplin's world—then in the depths of the Great Depression and on the brink of World War II—a bleak view of technology's impact on workers is not hard to understand. But the curious thing about *Modern Times* is that it was filmed after a revolutionary period of technological change in travel, mass communication, and medicine that *could* have ushered in an extremely optimistic age.

To see Chaplin's point of view, we need to understand that, unlike today's innovations, the new technologies of *Modern Times* were true discontinuities with the past. No one in the Civil War could fathom the future innovations of World War I—airplanes, poison gas, machine guns, radios. By contrast, infantry units in Afghanistan in 2019 would have called in air support from jets in almost exactly the same way that they did in Vietnam in 1968. Sure, we have cellphones and the internet, but 50 years ago, advertisements touted picture phones that very much resemble today's Zoom calls. Technologically speaking, the world changed more between 1865 and 1917 than it did between 1970 and 2020. Those innovations between the Civil War and World War I created what we think of as the modern era, when limits were shattered that reasonably should have ushered in a golden age.

But that's not what we see in *Modern Times*. When we watch Chaplin get pulled into the machine again and again, we are really seeing a narrative that proposes that technology is destiny for workers. Where did this narrative come from?

Answering this question requires appreciating the way technological advances are accompanied by profound struggles over who will reap the benefits of this change, which are played out in cultural narratives justifying new inequalities in society. Technological disruption creates battle lines between the old guard and new challengers, introducing opportunities for huge fortunes for some first movers. And with each technological transformation, new winners and new losers fight over the rewards as well as the story of why they won and others lost.

Consider how technology disrupted the theater. Musicians and actors who were previously paid for live performances limited to one location were suddenly in a world where their performances were made available endlessly at multiple venues. Should the musician be paid each time a record was played, or should the owner of the machinery that produced the record reap the profits? Should an actor continue to be paid for each performance, even if it is recorded and shown on many "stages" when films were shown worldwide? Or do the profits belong to the owner of the film, the projector, or the theater? That question galvanized Charlie Chaplin himself, and—with D. W. Griffith, Mary Pickford, and Douglas Fairbanks—he incorporated United Artists in 1919 to give more ownership to the actors than the producers of films. So *Modern Times* was both a product of this struggle between the haves and the new have-nots and a narrative about an ongoing social cleavage in which the brunt of this technological disruption fell upon workers.

At the time, rising inequality was often justified by exploiting race and gender stereotypes to explain that technology was making those defined as "truly skilled" better off and leaving behind those considered inferior. Thus, looking closely at how technological disruptions affected Blacks and women reveals a larger dynamic. Consider, for example, the hundreds of Black male college graduates who served in World War I as part of the US Army Signal Corps with the segregated 325th Field Signal Battalion. These men operated radio communications, a revolutionary technology that put them on the cutting edge.

But when they came home, as I've found in my research, none of those hundreds of Black men who had trained and served in the battalion got jobs involving telegraphy or the new technology of broadcast radio, which began to boom a year after the war ended. Much the way major Silicon Valley companies today employ disproportionately small percentages of Blacks, Latinos, and women, after World War I qualified Black veterans with skills were not hired for cutting-edge jobs.

At the same time, a set of narratives were crafted that explained why Blacks were not part of the technological vanguard. The elite universities that had once been hotbeds for abolitionists now reversed course and excluded Black students. Members of the economics field that emerged during this time, which we now think of as modern economics, openly argued that eugenics made equality inefficient. In 1899, the man who had been the first president of the American Economic Association described immigrants such as the Irish and eastern Europeans as "low-wage races," while other economists around the same time did research to demonstrate that Black workers were unproductive.

In film, D. W. Griffith's *The Birth of a Nation* (1915), which was credited with sparking the resurgence of the Ku Klux Klan, became part of an enduring cultural narrative about white supremacy. These stories didn't stay on the screen, but spilled over as white mobs massacred Black citizens and destroyed their homes and businesses in Tulsa, Oklahoma, over two days in 1921—a tragic escalation of the same hate-fueled violence that had poured out in Chicago, Omaha, Washington, DC, and dozens of other cities in 1919. This was the ugly historical backdrop to Chaplin's *Modern Times.*

Damaging narratives about which workers "deserve" to be winners in the new economy persist to this day, and the counterexamples of how Black and women workers profited from technological change are all but forgotten. Stories of how change unfolded in two industries—railroads and telephones—illustrate the complex factors that determine the effects of technological change and the important role of policy and narrative in determining whether the playing field is fair for workers.

### Working on the railroad

The first story, regarding railroads, shows the ways that technology, coupled with institutions and geography, can empower specific groups of workers. In the 1880s, railroads grew dramatically in importance as they hauled more passengers and more freight over more miles of track. In the South, Black men quickly came to dominate the ranks of firemen on steam locomotives. Dirty and hard, the job involved shoveling coal to maintain the heat of the steam engines. The fireman was viewed as a servant to the engineer, who was invariably a white man. But as the demand for rail services grew with the spread of America's manufacturers, so did the demand for rail workers. And this job that had once seemed dirty and unimportant grew to be vital.

Because rail workers organized and formed unions, this form of technological advance resulted in workers gaining meaningful changes. With unions came higher wages; unfortunately for Black workers, they also brought new mechanisms for exclusion—but only in some parts of the country. In the South, Black men proved too prominent as firemen to be excluded, whereas outside the South, Black workers could not protect that foothold and were rarely to be found in the engine car.

As the railroads expanded, their owners sought new technologies to make trains faster and more powerful—at the time, that generally meant bigger engines, which required more fuel supplied by firemen. From 1880 to 1900, the number of railroad firemen increased from about 10,000 to almost 50,000, according to US Census data. In the South, Black men formed a growing share of the industry, accounting for 15% of firemen in 1880 and 25% by 1920.

The invention of the diesel engine in the 1890s led to the first diesel engine trains in the 1910s, with wider adoption by the 1920s. Of course, diesel engines meant the job of firemen became superfluous, and the number of firemen peaked near 90,000 in 1920. However, unions protected the jobs of incumbent workers through strict seniority rules. Over time, the age of firemen skewed decidedly older.

After 1920, white firemen were able to slow the entrance of Black workers into the field, but a combination of technological and social factors led to an ironic reversal of fate for older workers. As the role of the firemen changed from one of servant to the engineer to apprentice engineer, the racial hierarchy shifted. Railroad owners agreed that only white men would be engineers, which meant that whites who rose through the ranks would shift to being engineers, while Blacks, unable to advance, would remain in the union.

Over time, Blacks in these positions accrued significantly more seniority than many whites—giving them the right to choose the most favorable train assignments, which led to disputes. Unlike other skilled Blacks who fled the South in the early migrations of the twentieth century, Black firemen had to stay in the South to retain their jobs and seniority. By 1940, their numbers were falling.

Many factors drove technological advancement in railroads, but they were shaped by institutions and by a rapid growth in demand that caused productivity to grow at faster rates. Unions made a difference in how the deployment of technology affected workers, and so did institutional geography. Workers were not displaced; instead, work opportunities diminished. And institutions—not skills or talents alone—determined who benefited from the changes. This is an example of a situation in which technology and institutional power enabled some workers to get higher wages, though partly by cutting out other workers.

### Operators adapting

The history of the telephone tells a similar story about how institutions, rather than skills or talents, came to distribute rewards to workers—some more than others. In the decade between 1894 and 1904, telephones increased exponentially, growing from 285,000 to 3.3 million. To keep up with demand, the industry was required to train operators at rapid rates. Initially, the job fell to boys, who had been deliverers of telegrams, but boys were not good at customer service, and the technology required a lot of virtual hand-holding. Between 1900 and 1910, some 100,000 operators were trained, and as the decade went on, it became a women's job. Another 100,000 operators were trained by 1920—an average of around 1,000 people a year, about the size of the graduating class of many American universities.

Since this was a new technology and the technology was proprietary, the telephone companies assumed full responsibility for training workers; in fact, the development of technology was so fast that operators had to be trained on both new and older equipment because some would be assigned to places where the newest technology was yet to be deployed.

To attract workers, companies made the job appear attractive and even went to the trouble of making short films that portrayed the training as fun for women. At the same time, as Venus Green writes in *Race on the Line* (2001), racial divisions remained stark: all the women shown in the promotional films were white. Prospective Black operators did not have to contend with discrimination from callers (who couldn't see them), but they were prohibited from working for AT&T, and within the corporate telephone exchanges where they worked, they were never side by side with white women.

As with the railways, demand for telephone service grew faster than the labor-heavy model could accommodate. Even the best-trained operators could handle only so many calls. By the 1930s, AT&T was already introducing technology to let customers dial directly without going through an operator—but the technology was so new that customers had to be shown educational films explaining how to dial.

Unlike railway workers, telephone operators had little success at organizing unions. It wasn't until the passage of the National Labor Relations Act of 1935 that independent unions successfully organized at the local level. The number of operators peaked at just above 200,000 in 1930, but slowing demand during the Great Depression coupled with the expansion of technology meant that by 1940, telephone operators' numbers had fallen.

But here is where the story of the telephone diverges from that of the railroads. The technology continued to improve, so in 1951, customers could call from coast to coast without talking to an operator. (To illustrate the value and convenience of direct dialing long-distance calls—and to encourage trust in the billing system—AT&T produced additional educational films.) But a combination of union power and rising postwar prosperity meant that even as automation increased, the number of telephone operators rose to just shy of 400,000 by 1950 and continued to edge slowly to a peak of only a little over that in 1970.

What accounts for the telephone operators' ability to hold onto their jobs? Initially, operators were still necessary because they kept handwritten records of calls and charges, including for reverse charges, collect calls, person-to-person calls, and overseas calls. But automation of domestic long-distance calls was accompanied by automated billing, in which the data was coded onto punch cards. Thus, a new set of jobs emerged to operate the computer peripherals and run computer programs to tally and print bills. While women lost jobs in the automating of billing, women were hired to run the new machines.

Ultimately, technology augmented rather than replaced telephone labor because the telephone company was a regulated monopoly: driving down costs while expanding service made technological advancement important. In the context of a rising middle class and expanding incomes, this example shows how workers can make gains when technology is driven to keep up with demand.

## Hidden stories

These stories reveal dynamics at play in our still-unequal society, where gender and racial stereotypes continue to shape contemporary narratives about who is "threatened" by technological change. But history shows that technology doesn't always trigger lower wages and permanent displacement for vulnerable workers, and it also reveals how we've failed to understand the times and ways that workers have benefitted. Interestingly, one of the most compelling films of the last decade, 2016's *Hidden Figures,* tells precisely that story, by showing how Black women mathematicians working for NASA benefitted from technological gains. When electronic computers arrived and could have displaced human workers, mathematician Dorothy Vaughan taught other women how to code the computers in Fortran. But, as the movie's title suggests, these stories are often obscured.

Another such hidden story is that of the Black IT workers who created the mystique of Prince George's County, Maryland, as one of the nation's wealthiest Black counties. Despite the often-remarked dearth of Black IT professionals in Silicon Valley, their numbers around Washington, DC, are quite high—recalling the historical concentration of Black railway firemen in the South. And as in that example, a confluence of events enabled the growth of a large skill pool of Black workers—in this case, federal contracting guidelines that encouraged Black-owned small businesses—which coincided with the rapid adoption of computing in the federal government.

Another insight from these historical stories concerns the role of education. Today's companies may point the finger at schools for failing to produce skilled workers, speaking of leaky educational pipelines. But in earlier eras of rapidly evolving technology, companies themselves trained their employees. This model was not unique to the telephone industry. Fully aware that it could not find engineers trained in the proprietary technologies and intricacies of automobile manufacturing, General Motors created its own engineering college in Flint, Michigan, in 1919; the college became Kettering University in 1982.

## Technology is not destiny

In our own era, we can still see the shadows cast by Chaplin's *Modern Times*. As in the past, massive technological advances, like the proliferation of the internet and the explosion of social media, might have led to a new golden age, with workers competing on equal footing for jobs around the globe. Instead, as we have seen, the failure of workers from underrepresented minority groups to enter high-wage jobs has been blamed on their backwardness, cultural unsuitability, or poor education. Meanwhile, the internet and social media have become powerful tools of those advancing division and organizing extreme hate groups while recycling the crude memes of a century ago to explain today's grinding inequalities.

In 2022, our struggle has less to do with technology itself than with the social norms and economic rules that determine who profits—and the narratives that justify the resulting growth of income inequality.

Recent changes in technology could have created broad societal benefits by improving efficiencies in everything from coordinating transportation to letting people control their own work schedules. Instead, much technology has been leveraged to avoid regulations: consider how Uber has skirted taxi regulations and how internet companies and other advocates successfully argued for many years that internet commerce should be exempt from local sales taxes, thus gaining unfair advantages over their non-tech-enabled competition. And using scheduling technologies that could have accommodated workers' desire for flexibility, companies have instead used the software to disadvantage workers with irregular schedules, disrupting their bargaining power and pushing wages down.

Describing this upheaval as the result of technology overlooks the political and economic choices the United States has made over the last four decades that have let minimum wages fall, weakened collective bargaining laws, and defined corporations' fiduciary duty as being to stockholders rather than workers and communities. These choices are reinforced by an economics profession that often disregards the role of institutions like unions and government, as well as the advantages management has over workers. The persistent argument that some workers are deficient and cannot attain high-earning jobs should be seen in its proper context of being used to gain political advantage and excuse massive inequalities.

By contrast, the fastest productivity growth on record in the United States occurred from 1946 to the early 1970s, when output per worker doubled. During that same period, child poverty fell at its fastest rate ever, as the real wages of American workers rose with productivity. Several factors played a key role in making this possible. Perhaps most important was the strength of the labor movement: unions bargained in the private sector for a broad and diverse set of workers, and minimum wages rose with other wages, ensuring an impetus to compete based on rising productivity even in lower-wage industries. These gains for labor were particularly consequential for workers of color. Unsurprisingly, the share of unionized Black workers was greater than the share of unionized whites, given that whites were far more likely to be managers and others outside bargaining units.

Among the policy choices that led to this period of prosperity were substantial federal government investments in education. The GI Bill of 1944 and the National Defense Student Loan program established in 1958 expanded help in paying for college, giving the US workforce the highest share of college graduates in the world and laying the groundwork for the Hewlett-Packards and Apples of today. And the 1990s saw the fruition of President Johnson's Executive Order 11246, which made federal contractors take affirmative steps to live up to the Civil Right Acts of 1964's nondiscrimination in hiring provisions. Also in that decade, the federal government began using its leverage to open state and local public sector jobs, which allowed Black college graduates to escape the confines of teaching in segregated school systems to become managers and computer programmers.

The postwar period was also one of renewed optimism, with rapid civil rights advancement, the end of legal segregation, and the extension of voting rights, along with the ending of overt codes of discrimination in the labor and housing markets. This is not to say the period did not continue to see significant disruptions from technology; many jobs were wiped out by greater productivity. In the railroad industry, construction of the interstate highway system, greater reliance on cars, and a new commercial airline industry meant the end of Pullman sleeping cars on trains, meaning thousands of Black men lost their jobs as Pullman porters. Productivity gains also meant the prices of many items could fall and, with rising wages, create a different landscape for labor. For example, the drop in prices for washing machines, clothes dryers, and dishwashers reduced the demand for domestic workers, displacing large numbers of Black women.

But at the same time, removing discriminatory barriers and investing in education meant those workers displaced by automation could make their way to better and higher-paying jobs. Popular culture shifted the dialogue as well—in sports, where Black athletes like Jackie Robinson were elevated, and on film. A half century after Griffiths's *Birth of a Nation*, Norman Jewison adapted John Ball's 1965 novel, *In the Heat of the Night,* into a driving commentary on southern racism, with a scene in which the Black protagonist slaps a wealthy white landowner in front of the local white sheriff.

Today's tales of pending technological dystopia—echoed in economics papers as well as in movies and news reports—blind us to the lessons we could glean from the massive disruptions of earlier periods of even greater change. Today the threat of AI is portrayed as revolutionary, and previous technological change as slow and inconsequential—but this was never the case. These narratives of technological inevitability limit the tools we have at our disposal to promote equality and opportunity.

The challenges we face today are far from insurmountable: technology is not destiny. Workers are not doomed to be Chaplin's victim of technology with one toe caught in the gears of progress. We have choices, and the central challenge of science and technology policy for the next century will be confronting those choices head on. Policymakers should focus on the fundamental tasks of shaping how technology is deployed and enacting the economic rules we need to ensure that technology works for us all, rather than only the few.

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REGINA E. DUGAN AND KAIGHAM J. GABRIEL

# Changing the Business of Breakthroughs

A new worldwide network of scientists and engineers is demonstrating how philanthropy can leverage a highly effective innovation model to solve urgent global problems.

History tends to turn scientific breakthroughs into stories of lone heroes in which individual researchers doggedly pursued a new discovery or charismatic leaders pointed to the horizon and made massive investments at scale.

What these accounts miss, however, is the reality that solutions to complex problems—and the resulting breakthroughs—more often require a network of diverse contributors with the capacity to drive the work toward a common goal. It isn't only about applying resources; it's also about creating the structures required to deploy those resources to facilitate such a synchronized effort. What's needed to achieve more breakthroughs faster are new ways of working that systematically stack the odds in favor of success.

A case in point has been the development of mRNA vaccines—arguably one of the most important scientific breakthroughs of recent decades. The trauma and upheaval of the past two years have laid bare how much work has to be done in health, equity, and care for the planet. These years have also revealed the difference a single breakthrough can make. Importantly, the pivotal decisions and investments needed to advance mRNA technology and shrink the vaccine development process from years to months were not made at an expansive federal science agency like the National Institutes of Health, in a global pharmaceutical conglomerate like Pfizer, or even by a swashbuckling venture capital firm.

The technology was seeded at a place purpose-built for breakthroughs: the relatively small government agency called the Defense Advanced Research Projects Agency (DARPA), operating with only 0.5% of the Department of Defense budget and a staff of about 250 people.

Few seem to remember the moment now. But we do, because we were there. At the time, we ran DARPA for President Obama. It was one year after the H1N1 pandemic, and he was determined to make sure another pandemic wouldn't catch America by surprise. Inspired by that, a clinical geneticist and young DARPA program manager named Dan Wattendorf came to us with two important questions:

> *What if a novel pathogen causes a global pandemic that forces the world to stand still, and we can't wait years for a vaccine?*
>
> *And what if mRNA injected directly into the body to elicit vaccine-level antibody production could dramatically shrink the standard timeline for vaccine development?*

It was 2010, a year when the world was still reeling from a deep recession, and most of the public and private sectors were unwilling to invest in such questions, much less make a bet on a once-in-a-century pandemic. Moreover, there were many people in the scientific community who contended there was simply no evidence it would work.

Wattendorf argued there was no evidence that mRNA vaccines wouldn't work and that if they did, someday it would matter. That day came ten years later.

These types of anticipatory decisions and investments are encouraged at DARPA, where programs are designed to intersect what is possible—albeit perhaps not yet proven—with what matters. By encouraging such "what if" thinking, DARPA fosters exploration and the subsequent actions required to create breakthroughs that provide new options.

We greenlit the program, and work began that year. At the time, Moderna was in start-up mode with a handful of people, and other performers were brought in to start working on delivery and scaling in parallel. Working all elements necessary to demonstrate a breakthrough is part of what DARPA does, because a demonstration at a sufficiently convincing scale is what changes minds. Such programs must move quickly to generate a sense of momentum, be agile enough to enable collaboration across disciplines and organizations, and work toward a goal that is bigger than any one individual so as to unite all involved in pushing past obstacles.

Although DARPA was designed specifically to serve US strategic interests, we are convinced that its model can be retooled to increase the number and pace of breakthroughs needed to address global challenges. Putting such an entity in place requires new approaches that go beyond national borders, beyond the boundaries of basic vs. applied research, beyond the life sciences vs. the physical sciences, and, perhaps most critically, beyond public vs. private funding.

## A model that stacks the odds

After the 1957 launch of the Soviet satellite Sputnik, President Eisenhower created DARPA to ensure that the United States would never again be caught unprepared by strategic surprise. The agency's model was an expressly new structure devised to facilitate seemingly impossible breakthroughs by providing the conditions that make such revolutionary advances possible. Notably, the enduring attributes of the DARPA model don't guarantee a breakthrough; rather, they are designed to improve the odds of getting one.

First, every program has an ambitious goal that is also testable and measurable, since it must be possible to tell if the program succeeds or fails. Program goals articulate and focus on a specific new capability or a specific problem that needs to be solved.

This clarity in the goal enables the second attribute: a coordinated network of diverse, multidisciplinary teams from multiple organizations, all working together to solve a problem they cannot solve alone. Importantly, it is rarely, if ever, true that all the expertise or all the advances needed to achieve a breakthrough are resident in one laboratory or organization. This network, crucially, is not static, but is agile and dynamic. Tasks change as progress is made or setbacks are encountered, and the team that set out to reach the goal may not be the team that achieves it. This attention to network effects contrasts with more conventional approaches that tend to fund individuals or small teams working in isolation.

Unifying these temporary project teams is a key responsibility for the program manager, who is central to the whole process. Just as an agile, dynamic orchestra of performers needs a conductor, the program manager pushes, encourages, clears obstacles, and synchronizes the entire effort both scientifically and programmatically. Inputs from the team are important, and collaboration is necessary, but decisions are made by the program manager to avoid groupthink, conventional wisdom, and conservatism that could stymie progress.

Finally, breakthroughs demand a sense of urgency, and a deadline provides it. DARPA projects are given three to five years to solve a problem or create a new capability. Such a timeline sparks a shared and celebrated impatience that forces the team to focus on the big advance and edit away paths that might make modest progress but fail to achieve the goal. In a three-year program, if two weeks go by without progress, you've already lost 1% of your time. That exigency tends to make people intolerant of unnecessary delays or process creep.

Over the past six decades, DARPA's model has proved itself again and again by delivering advanced technological breakthroughs, including miniaturized GPS, microelectromechanical systems technology, stealth technology, the internet, lasers, night vision, and autonomous vehicles.

## Catalyzing global problem-solving

It's abundantly clear that the looming threats of today, such as pandemics and climate change, don't recognize national borders. Much as Sputnik highlighted that business as usual wasn't sufficient to meet the needs of national security, business as usual is not sufficient to solve these big, global challenges.

Instead, it will be necessary to bridge gaps not only between disciplines and organizations, but also among national, governmental, academic, and commercial innovation systems. Such an effort in the global commons requires investment capital and independent leaders who can operate without the constraints imposed by existing national systems—a task for which philanthropy is well suited.

While it is difficult for governments to act globally and the private sector cannot bankroll health investments that lack clear financial returns, independent philanthropy can step into this void. And at a time when humanity is in urgent need of action, philanthropy can act quickly, without concern for election cycles or the lengthy process of realigning political will and global economic incentive structures. Independent philanthropy has the ability—even the duty—to actively hunt for the dramatic advances that current and future generations need.

In 2018, Wellcome, a storied global philanthropy focused on health, saw a need emerging for a new entity that could tackle huge global challenges in health. The leadership of Wellcome funded the effort, called Wellcome Leap, and launched it in 2020. Importantly, they hired an experienced leadership team and then gave us and our fellow team members the freedom to operate differently. We were given the mandate to create an agile, ambitious new organization with program goals, funding structures, risk tolerance, and timelines more like the DARPA model and less like conventional research activities. Such a system isn't always comfortable, and that was the point. If you want to build an organization that challenges conventional wisdom, you cannot be surprised when it challenges conventional wisdoms.

## Building dynamic networks

Like DARPA, Wellcome Leap stacks the odds in favor of breakthroughs. But to operate globally, we had to reimagine how some of the DARPA attributes—goals, networks, program managers, and deadlines—work in a global context.

The ability to build dynamic networks, not in one country, but across the entire global commons, started with what we understand in retrospect was a door-to-door grassroots effort. We spoke directly to university chancellors, chief executive officers, and nonprofit organization leaders around the world to give them the context of the network we wanted to build. We explained our hypothesis—that breakthroughs require a sense of urgency and momentum in a team—so we needed to get teams working.

We knew the biggest obstacle to speed and momentum was contracting. Therefore, we asked leaders of this new network to pre-sign a master funding agreement—not to secure an edge in selection or guarantee any funding, but to enable the rapid formation of networks of researchers. The pre-signed contract does offer a key advantage to institutions that are selected because it means that anyone in their organization could be funded and working in days or weeks instead of the usual months or even a year it can take to complete contract paperwork in other organizations. And if an organization is not a signatory when selected for funding, we ask them to sign as the first step in contracting. To date, all have done so.

We didn't know if such an approach would work, but within the first year, 21 organizations on six continents had signed. Today, the number of organizations has quadrupled to more than 80. The resulting Wellcome Leap Health Breakthrough Network is arguably the largest, most readily "activatable" network in the world, encompassing more than 650,000 scientists and engineers globally. This type of grassroots effort doesn't work unless the appetite to work in this dynamic way on a global level is already there: we simply found a way to facilitate it.

The excitement quickly bore fruit. When we made our first program announcement (about eight months after standing up Wellcome Leap), we received 164 proposal abstracts from 21 countries. For all subsequent programs since, we've seen similar and growing international interest and participation in proposals and, ultimately, in selections.

Wellcome Leap's commitment to clearing obstacles has allowed it to move at extraordinary speed. A mere 30 days after making the first announcement, we received abstracts. Within two weeks, we provided feedback and recommendations for submission of full proposals. Proposers then had 30 days after receiving feedback to submit a full proposal, and we made funding decisions 30 days after that. What this means is that while other models might take more than a year for a project to actually begin, we're off and running in under 100 days from the program announcement.

Another important attribute that Wellcome Leap shares with the DARPA approach is that we do not use a consensus-based peer review process that requires rank ordering. Instead, we evaluate every proposal's ability to contribute to the specific goals outlined in the program announcement. That is the benefit of having a specific goal in mind: it provides a point of view for decisionmaking. Each program director chooses specific program goals and activities using an analytic framework. Because the program managers put in the work to form this point of view, they have the conviction required to make confident selections and adjustments along the way.

Interestingly, we have also found that not requiring a consensus process creates more diverse teams, linking early-career researchers, established researchers, and researchers across the academic, nonprofit, and commercial spectra. Our method tends to elevate young investigators with new ideas that challenge the conventional wisdom in ways that consensus peer review does not—in part because it isn't necessary to have proof that new ideas will work before they try.

This kind of risk tolerance is, counterintuitively, facilitated by our use of contracts rather than grants. We can agree, together, to take a shot at something in year one. If it works, we can make the decision to fund years two and three. If it doesn't, we can shake hands and part ways with the knowledge that it was worth the attempt. Our firm belief is that this process also allows us to spend less time trying to make perfect decisions at the proposal phase. The proposal, after all, is not the work; the work is the work. This belief has the ultimate effect of suppressing "grantsmanship" and elevating the outcome—the breakthrough itself—as the measure of success.

### Choosing Pasteur's quadrant

Perhaps the single most common question we are asked about the model is not about the program construct or its execution, but how we choose a program in the first place. Wellcome Leap has an unwavering commitment to work in what political scientist Donald Stokes described as "use-inspired research" in his 1997 book Pasteur's Quadrant. Work in Pasteur's quadrant, exemplified by the microbiology research of Louis Pasteur, is mission-driven, designed to create a new capability or solve a specific problem. Unlike pure applied research, work in Pasteur's quadrant requires the simultaneous advancement of science to create a new solution. And unlike pure basic science, which is curiosity-driven but need not have a specific application in mind, work in Pasteur's quadrant needs a bold goal to focus the work and unite a diverse set of performers.

This commitment drives every Wellcome Leap program to the same kind of "what if" thinking of DARPA programs. And although the first six programs we've launched over the past two years differ in program goals and focus, they share the attribute of being grounded in creating new solutions. A few representative examples are the following:

> *What if we could cultivate human tissue so that no one had to wait on an organ donor list?*
>
> *What if we've been approaching the first three years of a child's cognitive development all wrong, and a new way would lead to healthier, more productive lives?*
>
> *What if the treatment of depression didn't have to feel like rolling the dice?*

Although no program has yet completed its full three-year timeline, early and emerging results are showing progress toward meeting goals in several areas. Work on 3D printing of kidney organoids is now sufficient to conduct early studies in animal models. Teams of commercial and academic researchers are collaborating on state-of-the-art data pipelines to feed new models of cognitive development. A project focused on understanding how diseases progress shows promise for dramatically increasing the speed of single-cell imaging from a weeks-long, process-intensive task using expensive equipment into an hours-long task doable on widely available gene sequencers. And a fourth project has demonstrated a 100-fold reduction in the dose—and cost—of mRNA-based monoclonal antibodies that can be used to treat viral infections.

## Transforming for the future

In the coming decades, science policy needs to transform and adapt to attend to the big questions facing humanity and with the urgency they demand. Some people will say this is too hard. Or they will argue that the scientific research community should simply do more of what it's been doing because that's safer. This kind of inertia is the enemy of possibility—it makes global challenges such as human health and climate change seem too big. It makes politics seem too small and the public too mired in a fog of distrust, disinformation, and deepening cynicism to believe in the ability of institutions to solve such problems.

To meet these challenges requires seeing beyond borders, disciplines, and barriers to begin actively changing the way science is done, as well as the way it's funded. At this time, independent philanthropy has the ability to do what others cannot: take an unconventional and optimistic view of what's possible in order to act on behalf of future generations.

Our team built Wellcome Leap to harness global collaboration and find solutions to humanity's urgent needs. But also to create something else we need: hope. We see multiple generations disillusioned by institutions that tell them to set their sights lower, temper their expectations, accept the way things have always been done. They deserve somewhere to put their efforts and their faith. That faith must be rewarded, not with promises but with progress—one breakthrough at a time.

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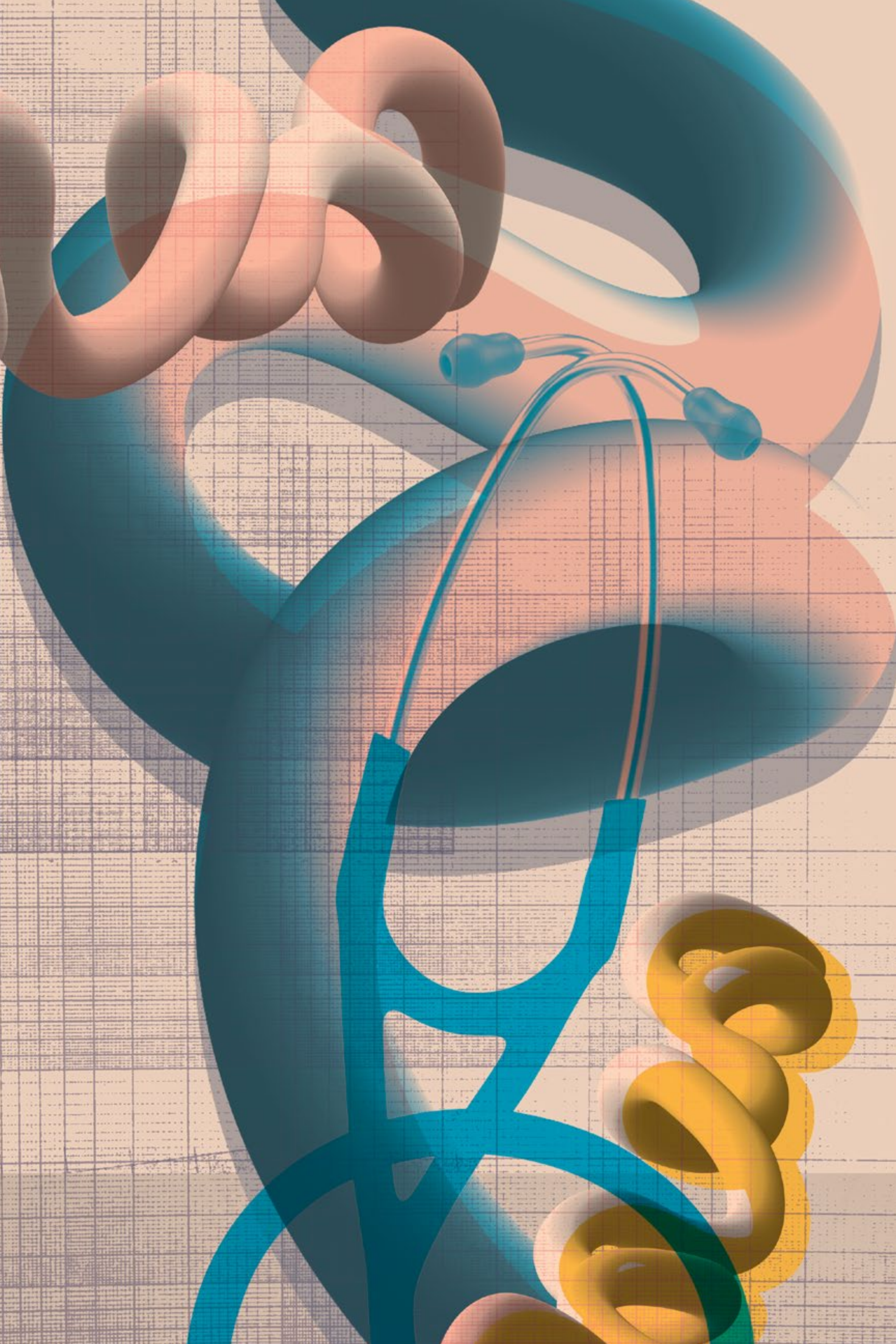

# Science in the Service of Society

LINDY ELKINS-TANTON

# Time to Say Goodbye to Our Heroes?

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To increase the speed and impact of knowledge creation, the United States must radically restructure research funding and resources away from big names—and toward our biggest questions.

In 2018, I gave a presentation to the visiting committee that advises the dean and the director of the School of Earth and Space Exploration at Arizona State University. The committee sat around the director's polished table while I talked about how we were changing academic culture. "We think it's important that every person who wants to, gets to speak in meetings," I said, explaining that shouting is rare and considered extremely bad form.

A committee member named Max interjected, "But you'll never solve any real problems if everyone is always polite. The only way to really solve things is to let people bring it all, what they really think, and hash it out. In engineering I've seen it over and over. People have to stand up and bang their fists on the table and shout at each other until the real answer is found."

For a moment I was speechless; I had been running large research units for six or seven years, and I was leading a significant NASA mission with a team of hundreds of people. The many team-building and decisional processes embedded in these leadership positions had left me with a clear sense of what a good team was, and it had never occurred to me that a person could think that shouting was a better process. I countered that shy people or junior people were unlikely to speak up, even if they knew the answer. Pounding on the table would silence them, rather than eliciting more opinions.

"But if people are saying what they really know and believe," Max replied, "there's going to be some heat to come with it."

How could he think pounding on the table was actually a way to solve big, complex problems, I wondered.

## The heroes of science

Since that meeting I have often thought about what the culture of pounding on the table means for the social model of science and engineering that we practice. Willingness to shout, willingness to assert, willingness to theatrically dominate others—all are still considered a sign of thought leadership in many scientific fields. But I have come to see it as a symptom of a much larger phenomenon that I call the "hero model" of science and engineering, which influences everything from who becomes a professor—and who gets harassed—to how we invent and what we discover.

This hero model describes the structure underlying most of the research done in the United States. In most academic institutions, the leading scholar in a given area of research is the acknowledged head of that group and has ownership of a pyramid of resources dedicated to his or her topic. These resources might include other professorships; staff, students, and their instructors; and curricula, buildings, and budgets. Thus a pyramid of resources is tied not to a topic but to an individual.

These heroes' pyramids are the building blocks of a much larger traditional academic and research structure in the United States that culminates in the $40 billion university knowledge creation enterprise. Heroes are the recipients of most US academic science funding; they are also seen as the moral leadership of their universities and even society at large. They are allowed extra-large voices on topics as varied as what knowledge should be created, how it should be funded, and how it should be adopted and regulated by society. Heroes advise presidents, talk to *60 Minutes* about the ethical use of gene editing technologies, and are often given sole credit for the extraordinary technological transformations of the last 75 years.

But to deal with the human and environmental urgencies of the next 75 years, we need a structure that can create knowledge where we need it and enable faster adoption of innovations. This revised structure must enable broader participation on every axis, including gender, socioeconomic background, race, nationality—and across disciplines. Now is the moment to reimagine research—for the greatest use of resources, the greatest use of all human minds, and the greatest progress into the most positive possible future.

To achieve these objectives, we need to understand that centuries of near-exclusive use of the hero model has driven away talent, squandered energy on empty disciplinary and cross-disciplinary competition, and allocated precious resources to the pursuit of fame. And as our labs have focused on incremental gains in knowledge, we've largely consigned the existential questions about how we can navigate toward a shared future to science fiction writers, not scientists—while failing to explicitly train scientists to think of the larger meanings and directions of their work.

It's worth asking whether the hero model is a good thing for taxpayers to underwrite. Should so much of our spending still be tied up in these structures? Vannevar Bush, the postwar architect of US science policy, posed in his 1945 *Science, the Endless*

*Frontier* an image of a government-led and funded research machine for fundamental discoveries. The report endorsed significant support for the experts and their pyramids. Bush and his committee envisioned a nation in which young people had open-door opportunities to rise in research, no matter the means or attitude of their family. What Bush and committee did not anticipate was the way the model would severely limit both research progress and training for early-career scientists.

Today's circumstances require optimizing the use of national funds, driving more directly toward key outcomes, and focusing scientists' attention on bigger existential questions. Breaking out of the old individualistic model opens up a new horizon, enabling greater and faster knowledge creation as well as radically more effective ways of educating students. This approach has been our aspiration at Arizona State University's Interplanetary Initiative, where we're exploring a new model of teams following "big questions."

Over the next century, we must create structures and incentives that support teams, knowledge goals, and societal outcomes rather than bolstering individual researchers themselves. And whether or not pounding on the table demonstrates that one's own answer is the correct one, the collective future of humankind requires that we hear all the voices at the table, not just the loudest.

Reorienting our focus from the hero model's "big people" to the consideration of big questions will address many of the challenges plaguing universities today: incremental, derivative, low-risk science; faltering funding; relentless focus on quantity of publication; irreproducible research; ongoing complaints of harassment; lack of diversity; an atmosphere that leaves students struggling with mental health; and (despite enormous funding outlays) an inadequately trained workforce in the STEM fields of science, technology, engineering, and math.

## Who exactly is the hero model for?

Leaving the hero model behind requires first grappling with why it feels so natural to most of us. Our research institutions have some of their roots in the early fourteenth-century writings of the Italian jurist Bartolus de Saxoferrato, who argued that academicians qualified as heroes under Roman law because they had endured three trials: during their schooling, examination by faculty, and public disputation (a formalized system of debate). Since then, universities have made progress by supporting scholars to become experts—think of the named chairs at historic European universities in particular, and the tradition of naming the entire research enterprise after its leader.

An expert is seen as someone who has consolidated knowledge in the service of society. In return, an expert is rewarded with both power and resources. This notion of heroic professors as part of the public good is so ingrained in the internal social contract of the university that it is rarely questioned. It's notable that even as the external social contract between universities and society has been scrutinized and questioned during the last decade, the role of principal investigators has largely escaped notice.

And although the professor-based research structure was intended to work in the service of society, the incentives for those professors changed long ago. By the end of the 1700s in German universities, argues historian William Clark, “the fame machine had taken control.” The fame machine made notoriety, rather than society, the focus of a professor’s work.

Today, professors still fiercely strive to keep their names prominent and protect the intellectual property of their specialization. And the more successful they are at appearing to be “thought leaders,” the more they are rewarded, while their actual service to society garners them very little. As a result, competitiveness is now a universal, pervasive condition of academic research. Researchers compete for funding, for the best students, for the publications with the highest impact factors, for space in the university, for media coverage, and for prominent lectures and awards.

And as competition for research funding has increased, fame’s value has only risen. Federal grant programs make awards to fewer than 20% of applicants and recent PhDs do multiple postdoctoral fellowships to be competitive for a permanent academic position. Fame is one of the few things that can assure higher funding rates, more successful student placements, and the invitations to write and speak that further perpetuate one’s reputation.

As the California Institute of Technology physicist David Goodstein has argued, science used to be limited by the scientists’ imaginations, but now it is limited by resources: funding and positions. This climate of competition incentivizes decidedly unheroic behavior by principal investigators. In a study of 51 research scientists, University of Minnesota professor Melissa S. Anderson and her colleagues found that scientists were doing strategic game-playing to entice competitors into dead ends of inquiry, failing to give credit to others, and pushing incomplete or preliminary publication in the pursuit of obtaining a higher number of papers.

What this behavior means for the society that underwrites these pyramids of resources is not only that money is wasted on bad research, but research progress is often confined to the small strips of real estate between the pyramids. Principal investigators assign their grad students to work on a small question adjacent to their pyramid, perhaps by applying a familiar technique to a new material. By design, this leads to incremental progress—which explains why corporations are often frustrated with academic partners who often are not trained to steer directly toward outcomes.

In some cases, of course, such meandering, incremental research yields results. As the biologist E. O. Wilson commented about his own exploratory scientific method: “When searching for a new phenomenon, try serendipity. Use precise but rough and easily repeated experiments to obtain some result or other, whether expected or not. The primary goal is to find previous unknown phenomena.… The best result of serendipity is surprise.”

Curiosity-driven research is known to bring such surprises and discoveries, but there is no reason to think that research directed specifically at a big question on the edge of our comprehension would be less likely to yield serendipity. And in the long run, a more focused orientation would have the benefit of driving the research enterprise toward higher impact discoveries.

## The hero and students

Students are doubly oppressed by the hero model: they are subject to the insular rules of their advisor's resource pyramid and they must compete with each other to become heroes themselves to attain tenure-track positions. To succeed, students must navigate an internal team culture and structure that is often opaque to outsiders, where bullying and harassment can proliferate. Even without such explicit abuse, students can be left on their own for years, leaving some to master the culture and thrive while others fall away in varying states of discouragement or bitterness. The culture further reveals itself in the way principal investigators wield possessive pronouns and proper nouns: "My" student, "my" lab, "my" team, and "The Smith lab" rather than "The Lab for Human Genome Research." Why do we need to personally own it all?

Personality-dependent careers are notoriously fragile: graduate students' intellectual and career progress is both inspired and profoundly limited by the knowledge, process, and kindness of their advisors. And tragically, the many postdocs who are unable to get tenure-track academic positions often believe they are failures—even though their eventual paths in government, industry, or elsewhere might in fact be far more valuable to our common future. By failing to prepare our students for productive lives outside of academia, our universities have reneged on their part of the social contract.

It's time for us to reexamine what our research structure is doing to higher education, our students, and the societies and economies in which we live—and to use that examination as an inspiration to create more equitable structures in which new people can be trained. This revised research structure should result in career success based more on a scientist's contributions than their charisma.

Although I am arguing that the hero model needs to be replaced, I am not advocating for doing away with expertise and deep disciplinary knowledge. The very concept of being an expert is a little-appreciated piece of human miraculousness: the long and winding path to inhabiting and assessing the far reaches of a field of knowledge produces a rare perspective on what knowing, itself, is. This position should not be accompanied, however, by freedom from the consequences for bad behavior. And if we want to broaden the knowledge of society, we must find ways to value the expertise of all—including the lay person, the postdoc, the uncharismatic, those who do not pound on tables. And for those of us now classified as heroes, breaking out of the role to do more socially engaged science can be a liberating experience—as I have been learning.

## Replacing heroes with teams to pursue big questions

To reach higher research and educational goals, we need to remove the barriers between disciplines, thus enabling transformational rather than incremental improvements in knowledge. To do this, we should focus on key questions, building teams of people from many disciplines to answer them.

NASA uses its matrix organizational model in precisely this way to focus project teams on highly aspirational goals such as designing and building a spacecraft to go to Jupiter's icy moon Europa. These project teams contain many brilliant individuals, and team cultures vary. Some teams have biased and exclusionary cultures reminiscent of *The Right Stuff*, Tom Wolfe's book about hotshot test pilots and future astronauts. By contrast, other team cultures are deliberately egalitarian, reflecting the need to value and listen to every voice when scanning for fatal design flaws, for example. In NASA's high-risk research environment, much more so than in a university lab, interdisciplinary teams train themselves to listen omnivorously in order to reduce risks and reach their goals faster.

In some ways, NASA's matrix model and the Interplanetary Initiative's model of asking big questions resemble proposals from the 1990s, when scientist Michael Gibbons and his colleagues called for a transdisciplinary, team-based, societally engaged research model that they dubbed "Mode 2" ("Mode 1" being the traditional, siloed disciplinary model of basic research). Although both the NASA model and the Interplanetary Initiative model make use of transdisciplinary teams to solve complex problems, the difference is that teams in our big questions model are built around a goal rather than a leader. I believe that this reorientation, which creates a uniquely deliberative team culture, is better at uncovering new ideas and making faster progress.

The best versions of the team model contain competition, but it is competition done right. That is, teams cooperate for outcomes while competing with other teams for funding and resources. Progress is monitored not on an individual level but on a team level.

In this, the teams bring people together to become more than a collection of individuals. When united in search of an external goal, team members strive to support each other rather than compete. And one of the peculiar joys of working in a high-functioning team is that it creates a richer and happier life for each member. Thus, this team structure can accomplish many social goals such as equal inclusion of diverse voices, support and growth opportunities for young investigators, and a reduction in harassment. These social goals seem out of reach or often are dismissed as irrelevant in the hero model.

## Identifying big questions

Before we begin building teams, we first identify big questions that need to be answered to make progress in a broad area of endeavor. At the Interplanetary Initiative, we start the process by bringing together 20–60 interested people to brainstorm.

But these are not just any people; we like to invite lots of different people. In 2017, our first year, we had deans, faculty, staff, graduate and undergraduate students, people from local corporations, service members from the Air Force, and private citizens from our community. All participated and many persisted fruitfully on the teams throughout the year. Since that first successful experiment, the mantra of "everyone is invited, all the time," has become embedded in our process—reflecting a conviction that everyone is an expert in what they view as important in society, and that drawing in their many perspectives makes us stronger.

The purpose of the convening is to find the sorts of questions that can frame big areas of inquiry. When we talked about exploring the future of human space exploration, for example, people volunteered their ideas of essential questions for a positive human space future, including: What social and political norms are necessary for lunar or Martian settlements founded by different nations or private entities? How can communications and location services be created according to a common standard for the Moon? How do we create more effective human–robot teams?

As the session goes on, we discourage the kinds of questions that reflect incremental thinking, and instead focus the group on purposefully asking big, critical questions. The goal questions are of vital importance and are the foundation of all the work that comes after.

Once we have a list of questions written on a whiteboard, we begin to discuss their merits one by one. Do any of the experts in the room think it's misstated, or already known? How vital is its answer, really? We end up with a collection of questions that have survived the process. By the time we've discussed them all, each person in the room has privately calculated that some questions are important and a few are an embarrassment. Interestingly, by this point there is not complete agreement on which questions are which, and thus there is no reason to talk about whether any might be dumb questions. For one thing, a question that seems "dumb" could well reflect contrarian thinking that might prove productive. When we are finished discussing all of the questions, we vote, with each person getting two or three votes. At the end, we have a short list of top questions to consider.

## Creating interdisciplinary teams

Once we've determined the questions, we set about deliberately building interdisciplinary teams. We start by inviting participants to volunteer into groups around the highest-voted goal questions. Each group is given an hour to decide on some concrete outcomes that would advance progress on their question and that could be accomplished with a year's work. Each team determines what disciplines they will need to work with to reach their goals.

All too often interdisciplinarity is a synonym for moving our disciplinary mountains closer together; or for hiring people who themselves are fluent in more than one discipline; or, in the third and perhaps saddest model, by taking a person from one discipline and assigning them to a different established disciplinary team, where they float as a kind of mascot.

In assembling our teams, we seek an interdisciplinarity that is egalitarian and question-driven, but still very much composed of experts in the traditional sense. You might think of the NASA project team, with engineers of various kinds, project managers, scientists, financial controllers, schedulers, graphic artists, and media managers. Each person's contribution is valued because each person's discipline is required for success in meeting the common goal.

Thus, interdisciplinarity is baked into these teams so that they not only produce results but also answer the goal question. Members are judged not by the usual outcomes—papers, grants, talks—although these do have their place, but by how well team members have addressed the central problem. This reward structure is absolutely crucial: interdisciplinarity needs to be owned at the highest level of the research organization and the culture must reward team outcomes rather than individuals.

At the end of the hour, each team has a goal question and a list of outcomes, which might include a white paper for a governmental oversight group, a prototype, or an event, along with the standard papers and talks. Then they outline other disciplines they need to reach their goal, and a facilitator helps them choose a leader.

Over the next two weeks, it's the team leader's job to make sure their team creates milestones for their year of work, drafts a budget to cover their needs, and finds the names of people in the necessary disciplines. We have found that if the team returns with the budget and milestones, they indeed have a reasonably effective leader, which is a requirement for progress. Currently, we select faculty members as leaders for the simple reason that they are already paid to do research and they are able to take on the fiscal responsibility of the seed money.

We then fund the teams with seed money, ranging from $5,000 to $60,000, with an average amount of $25,000. (One large pilot was supported by philanthropic funding.) Seed money can cover expenses such as some staff or student salary; undergraduate interns; and costs of materials, travel, and events. Though these funds will not usually cover even a graduate student's full salary, we have found that the money—along with the pure pleasure of being part of a team going after a big goal—has kept almost all the teams going all year.

The big questions model, which at first seemed risky, has proven itself extraordinarily effective. Of the 25 pilots we've selected over the past 4 years, 13 have launched successfully to additional funding or completion, 9 are continuing in our program on a mixture of seed and external funding, and 3 failed. This year alone we have 120 active team members and 20 outside partners.

We have lost no momentum in output. Our first peer-reviewed paper appeared only four months after our first pilot selection. What's more, we've increased the overall speed of innovation by moving more directly toward significant goals, including using our seed funding to build capacity that has allowed our projects to generate eight times the seed investments in follow-on federal and private grants and contracts.

One compelling measure of the projects' success is that our teams have pursued goals that do not fit neatly in the usual research enterprise, but they have leveraged their seed money to produce proof-of-concepts that enabled them to get conventional funding. One of many examples is Port of Mars, a multiplayer game designed by sociologists to gather data on human behavior in potential settlements on Mars; it recently received funding from the National Science Foundation. Another example is a pilot study of a speculative method to taxonomize and then design responsive space missions so that they can be repurposed and redirected after launch; this project recently received Department of Defense funding.

## A transformative culture

Over the years, I've thought about what makes our team process more effective—and more enjoyable—than the academic research model I was trained in. While the whole process contains purposeful changes from the standard model, I want to highlight two elements of the special sauce: project management and culture. These two components are where we leave behind the inward-looking hindrances of the hero model to embrace our larger ambition of serving society.

I've mentioned that each team in our process chooses a research leader, but that person is almost never an expert in team management, project scheduling, risk assessment, or financial management. (How many faculty are?) To remedy this missing expertise, we give each team a project manager who can provide the needed schedule, risk analysis, and budget framework, as well as performing the human resources functions that create standards of culture and process.

From the point of view of the research institution and funders, placing each team under project management protects the investment. Importantly, it also socializes the team for partnership with private organizations that expect budgets and schedules to be met. Furthermore, including a project manager keeps the team focused not only on answering the research question but also on the larger goal of delivering knowledge to society.

Within these professionally managed interdisciplinary teams, culture and team norms are discussed, and when the teams are willing, created. There is a pervasive idea in the pound-the-table pyramid that mannerliness is a sign of weakness, and only the weak require a discussion of culture. Culture, however, is elemental to creating speed and success for teams. Some NASA program directors and administrators have told me they consider team culture a main indicator of future success in mission teams, observing that an inclusive, listening team will overcome adversity and reach its goals whereas a secretive and ego-driven team will collapse under stress. Thus at NASA, effective team cultures are rewarded with hundreds of millions of dollars in funding. In this culture each person is valued according to their contribution rather than title. Being listened to, previously a hallmark and benefit only of being the hero, becomes the prerogative of every team member.

Project managers consciously shape team cultures in other ways. They encourage teams to solve challenges by creating a culture of "Yes, and…" rather than the academic reflex of "But…"—these teams achieve more and support their junior members to greater successes. In such teams, members form relationships that lead to trust, open discussion, and mentorship. Senior people connect with junior ones, enhancing, broadening, and cross-pollinating each other's networks. More mentors means better outcomes for students, who then have more options for a good fit with a mentor. A wider mentor pool also adds more perspectives to help trainees figure out career paths and research development.

After years of thinking about Max's comment about pounding on the table, I have a rejoinder: A culture of listening is transforming our work in every way, helping us meet our practical and social goals through interdisciplinary work as well as reengaging us in the social contract of educating students. There is simply no comparison. And there is no going back.

In the future, restructuring the US research enterprise to enable such teamwork could help the nation reach larger goals of transforming the pace of innovation and education. In my years of experimental research, I've observed how opening up our process to community observation, questions, and steering can strengthen the connections between the university and society. With this restructured model focused on rapid, directed progress not only on technological innovation alone but also on society's deepest commitments, it would be foolish to continue to spend all of our research dollars on the traditional model envisioned and instituted by Vannevar Bush more than 75 years ago.

Of course, I understand quite well the difficulties of leaving behind our old models of research. I, too, was trained in the heroic ideal. And back in January 2017, as we began our very first brainstorming session, I felt anxious. I stood at the front of the room welcoming people in, a little like the host at a party with a risky guest list of 50 and too few RSVPs. As each person came through the door, I felt a little lighter and the room began to feel different, too. When we started the process of determining our goal questions, the room changed again. People contributed ideas. And they were not just the usual vocal participants, such as the deans and senior faculty, but also undergraduates and our friends from the town. Soon we had dozens of relevant, aspirational, and important research goals. I had an unfamiliar feeling of having shed an academic persona and come together with a shared feeling of purpose simply as one inspired human being among others.

Over these years of experimentation with a team-based, externally focused research paradigm, I've felt my relationship to the scientific work I've been doing for the past two decades transform and accelerate. I used to love tackling the next challenge from my own pyramid of research resources. Now that feels more like a hobby and working with teams to pursue bigger goals has far deeper meaning. Sharing the excitement is infectious, and sharing the responsibility is relaxing. I feel this most of all with the Psyche mission, where a team of 800 people is preparing to send a robotic spacecraft to orbit an asteroid and learn about the first metallic solar system object humans have ever visited. I'm attempting be a servant leader, and my world feels more rational and meaningful as a result.

As scientists, we must ask ourselves whether we are solving the biggest and most urgent problems, and whether we are lifting up our colleagues and the next generation to do the same. The responsibility and the power to create change lies in our hands. We can imagine how to do research that more rapidly and effectively enables a more hopeful future—and by doing so, we can reimagine ourselves and our society.

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GOPAL P. SARMA

# Scaling Research Solutions for Society's Real Problems

To transform US research labs to better serve society, we need to bring in a new type of scientist who specializes in scientific operations.

The COVID-19 pandemic demonstrated that the US scientific community has the ability to surge to a higher level of productivity very quickly. Although the NIH–Moderna collaboration that jump-started the development of a safe and effective COVID-19 vaccine is the most visible example of this capacity, other institutions and collaborations accomplished similar leaps under the pressure of the pandemic. I had the great fortune of witnessing close-up a diagnostics effort organized by the Broad Institute of MIT and Harvard, that rapidly converted our genomics platform for COVID-19 testing, ultimately reaching a processing capacity of nearly 150,000 samples a day and testing over 20 million samples to date.

If such impressive accomplishments are possible, shouldn't our scientific institutions be capable of doing much more under ordinary conditions? With society's outstanding need for breakthroughs in science and technology for problems as far-flung as climate change, health disparities, and pandemic preparedness, doesn't science have an obligation to do more?

The scientific system's successes over the past 18 months have also spotlighted its failings: the fruits of US science and technology have benefited some groups disproportionately relative to others, with race, geography, and socioeconomic status being key determinants. To ensure that our scientific research benefits everyone in our country, we must get more innovation out of our labs and into our communities. This change will require not only producing solutions, but then rapidly identifying, scaling, and distributing them to the entire population.

One way to accomplish this kind of rapid scaling is to rethink the organizational structures of our research centers, specifically by staffing them with a new kind of scientist: a professional manager or operations specialist who can amplify the impact of research beyond disciplinary boundaries, thus expanding the scope of the organization. To transform the US research enterprise to better serve society, we should consider recruiting and incorporating these new types of scientists in research teams and more widely adopting their unique approach.

At the Broad Institute, our COVID-19 diagnostics effort built on existing organizational divisions that had already invested in industrial-scale laboratory facilities, software engineering teams building production systems for handling health data, and a diversity of industry partnerships. These innovative operations and teams—unusual for a research laboratory—are overseen by full-time professional scientific staff. With titles ranging from scientific adviser to alliance manager to director of scientific partnerships, at the Broad these organizational leaders—who often have extensive scientific training—work to magnify the impact of the traditional principal investigator (PI)-driven laboratory.

The initial challenge for COVID-19 testing was to reconfigure a licensed clinical laboratory that had been designed for DNA sequencing to handle viral diagnostics. Early during the pandemic, our equipment was adapted to detect SARS-CoV-2 at the rate of a few hundred tests per day. By taking advantage of a highly modular approach to automation—driven by the operational expertise of the organizational leaders—within six months capacity was scaled to more than 100,000 COVID-19 tests per day. And as the pandemic has continued, our professional scientific staff has played crucial roles in connecting with industry partners for logistic support to expand testing across New England. We have also launched new capabilities such as pooled testing and viral whole-genome sequencing for tracking the emergence and spread of SARS-CoV-2 variants.

For simplicity, we can call these organizational professionals *scientific product managers* (SPMs). This title has echoes of the role played by product managers in the software industry, where software teams are often co-led by a technical lead (i.e., a senior software engineer) who works alongside a product manager. The product manager is an organizational generalist, often a former engineer who also earned an MBA, whose responsibility is to deeply understand the product ecosystem, customer needs, and technical capabilities. They may also be involved in communicating with key leadership in finance, business development, sales, and operations to attend to the process of launching successful products. The product manager works closely with the technical team to set priorities, create product roadmaps, and establish timelines for implementation. As such, they are considered key organizational leaders in the tech industry and are highly sought after as CEO candidates.

In the context of a research organization such as the Broad, our PIs are analogous to technical leads, while SPMs are more like product managers. Of course, the "product" in this case isn't a singular entity such as Gmail, Spotify, or MATLAB, but rather represents a scientific research agenda. And in the broader context of a collaborative ecosystem of partners in tech, pharma, venture capital, and government, SPMs can play a vital role in creating a hybrid culture that blends elements from these disparate communities.

Employing SPMs makes many initiatives at the Broad resemble a fusion of industrial operations and traditional research laboratories. A good example is Machine Learning for Health (ML4H), where I lead strategy and operations. ML4H is a hybrid between the type of software engineering team you'd find at Google, Apple, or Amazon, and the type of clinico-genomic research group found at academic medical centers. For this project, our SPMs work on prospecting and vetting potential partnerships; identifying new software features that would benefit the research community; collaborating closely with clinicians and our technical team to plan and execute new feature roadmaps; liaising with counterparts in industry to facilitate large, multiyear, interdisciplinary collaborations. With SPMs on board, ML4H can invest in the production of tools, resources, and policies in addition to scientific publications—all while incubating and launching cross-institutional research.

Unlike traditional PIs who typically think deeply and intensely about a relatively small number of focused problems, our SPMs are flooded with information—much of it organizational and operational. They then use their extensive research training to shape decisions large and small, wearing the diverse hats of scientific leader, thought partner, tactician, and diplomat.

We have found that the best SPMs are generalists rather than specialists. General scientific knowledge, critical thinking ability, and strong communication skills are major assets that our SPMs use to overcome bottlenecks in the research process. Their roles take them from the macro to the micro, from strategy to execution, from vision to minutiae. As generalists, they can collaborate on research while also being embedded in finance, development, and communication offices to understand critical dimensions of science funding, budgets, and planning—all things that scientists are typically shielded from—but which often determine the success of an endeavor.

When we hire SPMs we look for highly trained scientists who have left academia for careers in finance, consulting, and advertising analytics as well as those who have done stints in industrial laboratories or in the wider academic ecosystem of science publishing or policy. Many of the skills that these scientists have gained during their diverse experiences are particularly valuable in scaling up academic science. By bringing these people back into university-based or university-adjacent research environments in operational roles, we can organically expand the scope of impact that our scientific organizations are capable of.

Scaling the model of SPMs to more labs would not be difficult—there are many highly trained PhDs and other skilled professionals available, and there are also good working models for training and integration. At Broad, the organization invests considerable resources into every worker. While some SPMs are hired into highly structured roles, others are given considerable latitude in shaping their own role and might be given the better portion of their first year to explore how the institution works. As participant observers, the trainees network within the Broad, speaking one-on-one with dozens of PIs, graduate students, postdoctoral researchers, staff scientists, administrative assistants, and other key colleagues, while writing white papers on internal strategy. They may speak with lawyers from tech transfer offices, local entrepreneurs, and venture capitalists to understand the potential for science translation, identifying key bottlenecks for their local ecosystem. SPMs rely on mentors to find their path and settle into a stable role. This model, or others, could be adapted by institutions looking to incorporate SPMs into their work.

Although the Broad had the benefit of being launched in the wake of the Human Genome Project and was created with substantial philanthropic support, other scientific ecosystems could take an alternative path to developing such nontraditional expertise. Universities, for example, could pool resources across multiple institutions and commit to collaborating with industry to identify and develop instrumentation, software platforms, or other standardized tools and processes that would otherwise not be incentivized. This approach would require that universities embrace not only the SPM model but also work across the research and development cycles at the highest levels. Finally, universities must make a significantly deeper investment into local scientific communication, education, and community building to ensure that this new institutional capacity is directed at problems that matter to society.

I believe that fully integrating a cohort of full-time professional staff into laboratories and research institutions could transform the current scientific landscape. Augmenting existing research institutions with additional operational capacity should allow traditional PI-driven laboratories to continue to be the productive intellectual engine they have been since the Second World War, but with greater impact beyond the institution's walls. And shifting the culture of our laboratories could encourage new models of science to take root, so that scientists are judged by their societal impact rather than mainly by publications. As this model becomes more the norm, we can expect to see faster innovation and a more rapid translational pipeline from new scientific insights to products, services, and policies that benefit society.

Although SPMs can transform the work of individual laboratories, we should aim higher, and use SPMs to incubate the development of collaborative ecosystems in US cities in an organic, grassroots way. Over time, SPMs could profoundly change not only the capacities of our research facilities but also the way these labs conceptualize their mission. As SPMs connect and network within their home institution and into the local scientific ecosystem to create collaborations, they could also work with finance and development offices to create new philanthropic strategies and propose corporate partnerships. Such transformative scientific ventures could go well beyond the traditional understanding of scientific research, allowing each city and each scientific ecosystem to find its own voice and take advantage of whatever resources and institutional capacities are available.

The impact of SPMs should not be exclusively technical in nature. In medicine and public health, for example, we might imagine full-time staff devoted to science communication and public outreach, working closely with community leaders at religious organizations, food banks, and homeless shelters to ensure that local needs are consistently being represented to university researchers and other thought leaders.

Conversely, these lines of communication can ensure that advances originating in universities are being translated into local action. And by establishing strong relationships well in advance of public crises, we can ensure that our research institutions can anticipate and more rapidly work to organically and equitably distribute the fruits of our research enterprise when called upon to do so.

The success of US science has been built on decades of highly evolved decision-making and a rich ecosystem of research institutions. Rising to the challenge of the twenty-first century will require that we continue this introspective tradition. As we confront unprecedented challenges as a society, we need to take a broader, more integrative view of research, and also incorporate serving the needs of our country as a fundamental metric by which we evaluate scientific success. To accomplish this expanded approach, we need to find ways to scale our work to reach more people more quickly.

Today, when we think about the words "scale" or "scalable," we think of the tech giants or unicorn start-ups that capture larger and larger numbers of users for digital platforms at a dizzying pace. We experience the weight of Facebook's awesome power over the news media, elections, and the global ramifications of its algorithmic tweaks and product decisions. We feel the visceral impact of Amazon's relentless march into one vertical after another: from books to groceries to cinema to the infrastructure of the internet itself.

What we haven't tried is scaling the impact of our research environments by creating cross-institutional science and technology ecosystems so that a similar immediate impact could be felt for the country's most pressing problems. SPMs offer a way to seed the development of such environments by connecting our cutting-edge research with our local communities and applying our nation's vast investment in science and technology more directly to making life better for more Americans.

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CHELLE GENTEMANN, CHRISTOPHER ERDMANN, AND CAITLIN KROEGER

# Opening Up to Open Science

More inclusive open science can help solve society's most pressing problems—and at a faster pace—but making it mainstream requires systemic institutional change.

The modern Hippocratic Oath outlines ethical standards that physicians worldwide swear to uphold. "I will respect the hard-won scientific gains of those physicians in whose steps I walk," one of its tenets reads, "and gladly share such knowledge as is mine with those who are to follow."

But what form, exactly, should knowledge-sharing take? In the practice of modern science, knowledge in most scientific disciplines is generally shared through peer-reviewed publications at the end of a project. Although publication is both expected and incentivized—it plays a key role in career advancement, for example—many scientists do not take the extra step of sharing data, detailed methods, or code, making it more difficult for others to replicate, verify, and build on their results. Even beyond that, professional science today is full of personal and institutional incentives to hold information closely to retain a competitive advantage.

This way of sharing science has some benefits: peer review, for example, helps to ensure (even if it never guarantees) scientific integrity and prevent inadvertent misuse of data or code. But the status quo also comes with clear costs: it creates barriers (in the form of publication paywalls), slows the pace of innovation, and limits the impact of research. Fast science is increasingly necessary, and with good reason. Technology has not only improved the speed at which science is carried out, but many of the problems scientists study, from climate change to COVID-19, demand urgency. Whether modeling the behavior of wildfires or developing a vaccine, the need for scientists to work together and share knowledge has never been greater. In this environment, the rapid dissemination of knowledge is critical; closed, siloed knowledge slows progress to a degree society cannot afford. Imagine the consequences today if, as in the 2003 SARS disease outbreak, the task of sequencing genomes still took months and tools for labs to share the results openly online didn't exist. Today's challenges require scientists to adapt and better recognize, facilitate, and reward collaboration.

Open science is a path toward a collaborative culture that, enabled by a range of technologies, empowers the open sharing of data, information, and knowledge within the scientific community and the wider public to accelerate scientific research and understanding. Yet despite its benefits, open science has not been widely embraced. One approach to advance open science adoption has been to ask scientists to take an oath or pledge that includes open science as a tenet; several of these pledges have been proposed (in 1999, 2013, 2017, and 2018), but none have been broadly put in practice. We believe this is because the commitment was focused on individual scientists rather than the framework and communities they work within. Open science pledges can only work where organizations are already fully committed and supportive. Even if an individual researcher wants to openly share knowledge, institutional policies and reward systems create barriers.

Although some institutions recognize the opportunity that open science provides for attracting a more diverse workforce and increasing collaborative networks and innovation, others continue to equate the sharing of knowledge with relinquishing a competitive advantage. This manifests in a range of institutional policies and workforce incentives. Some institutions are limited by what publication expenses they can cover for making articles open access, while those with large computer clusters may prevent their researchers from working in more open, collaborative, cloud-based platforms. Outdated institutional intellectual property policies often conflict directly with open-source software contributions and software development, and awards commonly recognize individuals rather than teams. From small annoyances to larger career impacts, institutional policies create friction that inhibits participation in open science.

This tension between individual and institutional incentives and the progress of science must be recognized and resolved in a manner that contributes to solving the great challenges of today and the future. To change the culture, researchers must do more than take a pledge; they must change the game—the structures, the policies, and the criteria for success. In a word, open science must be *institutionalized*.

## Open science is better science

A powerful open science story can be found in the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP), established in 1995. Before CMIP, with the internet in its infancy, climate model results were scattered around the world and difficult to access and use. CMIP inspired 40 modeling groups and about 1,000 researchers to collaborate on advancing modeling techniques and setting guidelines for how and where to share results openly. That simple step led to an unexpected transformation: as more people were able to access the data, the community expanded, and more groups contributed data to CMIP. More people asking questions and pointing out issues in their results helped drive improvements. In its assessment reports, the Intergovernmental Panel on Climate Change relied on research publications using CMIP data to assess climate change. As a platform, CMIP enabled thousands of scientists to work together, self-correct their work, and create further ways to collaborate—a virtuous circle that attracted more scientists and more data, and increased the speed and usefulness of the work.

While the increased volume of data was a sign of success, over time the community began to struggle to provide access to all of its data. The Pangeo open science community stepped in to help. Established in 2016 when a group of scientists began trying to address barriers to big-data oceanography, Pangeo was designed as an inclusive, open community of scientists and software developers to create an ecosystem where anyone could raise an idea or issue, with community members organically teaming up to contribute their unique skills. Pangeo scientists and software developers worked together to create a cloud-optimized version of the 800-terabyte dataset as well as open-source tools to help with analyses. Today, instead of spending three to six months downloading the CMIP data to a local computer and years developing analyses, model data are freely available on the cloud, and anyone can examine them in just a few minutes.

Open science communities such as these exist in many different areas of science, and they are helping science move faster and work better. But the type of knowledge-sharing and collaboration exemplified by CMIP and Pangeo must become standard, which requires institutionalizing these practices.

## Taking open science mainstream

Even as individual scientists and groups decide to be more open, they could still face institutional roadblocks. Organizations must therefore incentivize researchers to build inclusive, diverse research groups that facilitate true interdisciplinary work, remove roadblocks to collaboration, and foster an environment where knowledge is shared and scientists are trained with open science as a core principle.

Some communities are already working toward these goals, including the Fort Lauderdale Agreement in biomedicine and the Berlin Declaration on Open Access to Knowledge. There has also been a flurry of recent recommendations on how to advance open science from the National Academies—which has developed a toolkit, software, and a vision for institutional design—and from UNESCO. These reports lay out clear guidelines for institutions, universities, funding agencies, and scientists to improve how science is done and expand who can participate (e.g., through open-access publications).

The most important message from these reports is that all parts of science, from individual researchers to universities and funding agencies, need to coordinate their efforts to ensure that early adopters aren't jeopardizing their careers by joining the open science community. The whole enterprise has to change to truly realize the full benefits of open science. Creating this level of institutional adoption also requires updating policies, providing training, and recognizing and rewarding collaborative science.

***Update policies to support open science.*** Agencies and universities must update their software and data release policies so that scientists can work together quickly, effectively, and without fear. Institutions are too often mired in slow, cumbersome approval procedures that are incompatible with open software and collaborative science practices. For instance, while working at a NASA center, scientist Jane Rigby wanted to release a simple software tool to the public, a process, she laments, that "took five months and 38 pages of paperwork—to release 217 lines of nonsensitive code."

Although careful approval is necessary at some institutions and in some fields where sensitive material is handled, these roadblocks should be restricted to projects that deal with that specific information. A tiered or more nuanced approach to risk is needed. For basic science, openness should be the default, especially as agencies and universities work to update disclosure requirements to account for national security risks.

Updating such policies to speed software and data releases will expand contributions to open-source software libraries, increase sharing of code so that results are more easily replicated and extended, and open new pathways to collaborations. The American Geophysical Union is working with its communities to move the norms and culture toward sharing data and code as the default. As societies and publishers move toward more open science requirements, they are nudging institutions to adjust their policies. Once these policies have been changed, they need to be clearly and loudly communicated within organizations—otherwise the effects of the previous policies will linger, making scientists fear the paperwork of participating in open science.

***Provide training in open science.*** Although data science programs are increasingly being added to university programs and curricula, computational training should occur in tandem with training in best practices for open science. Understanding how to work in an open science framework is a skill that scientists and project managers need to acquire.

A global effort to facilitate scientists' move to more open practices requires investments in learning resources that teach how to practice open science, build and participate in inclusive teams, and acquire basic data science skills and knowledge. Grassroots efforts—Google Groups, posts on Medium, Jupyter notebooks—have been filling this gap but could be built on, updated, and extended by teams with representation from all stakeholders and communities. Such resources should be freely and openly available online to be available to teachers and working groups.

Training in open science should begin at the undergraduate level and be offered to scientists and managers throughout all career stages. At every level, researchers should understand how to do open science, and funding agencies should support these efforts and tailor them to their communities. Asking scientists to change involves work, but such work can be incentivized through curated tutorials with badges or credits, and participation in open science should be rewarded by funding decisions.

***Recognize and reward collaborative open science.*** We believe the hero scientist is a myth and that all science requires teamwork, even as the current incentive structure continues to reward individual achievements almost exclusively. This has remained the case despite the achievements of team science, as described, for example, in a 2015 report from the National Research Council: "Team science has led to scientific breakthroughs that would not otherwise have been possible, such as the discovery of the transistor effect, the development of antiretroviral medications to control AIDS, and confirmation of the existence of dark matter."

To truly recognize and value teamwork, the scientific reward system needs to be reconfigured from the ground up. Individual researchers must not suffer career consequences for openly sharing data, and funding agencies, hiring managers, institutions, and researchers need to consider everyone on a team as an actor. Only by moving toward a more inclusive, team-oriented model will science develop voices with different perspectives to challenge established beliefs and develop creative new answers.

Funding agencies should also review proposals with an eye toward their ultimate community benefits and open science activities. University performance evaluations, for their part, need to integrate documentation of community-building efforts and open science activities—including in hiring and tenure review—and assess how their policies should be revised. Professional society awards and fellowships could include open science in evaluations, and awards could recognize teams rather than individuals.

## Sustaining momentum for change

In September 2021, the National Academies Roundtable on Aligning Incentives for Open Science released toolkit elements designed to help organizations ensure that their incentive systems encourage open science. In October 2021, NASA announced a new $40 million, five-year mission, Transform to Open Science (TOPS), and declared 2023 as the Year of Open Science. TOPS' Year of Open Science jump-starts a suite of coordinated activities designed to increase the understanding and adoption of open science principles and techniques, accelerate major scientific discoveries, and broaden participation by historically excluded communities in science. In November 2021, the UNESCO Recommendation on Open Science was formally adopted by 193 member countries and includes priority areas of actions to advance open science.

This momentum must be sustained. Now that major organizations have provided valuable road maps, institutions, agencies, and research centers must be convinced to follow them. Action at the individual and team level can only go so far toward solving what is truly a systemic shortcoming. It is only through changing institutional frameworks that open knowledge, data, software, and resources can become the rule rather than the exception. Moving to open, inclusive, community-driven science is a powerful way to rebuild trust with the public while also accelerating scientific discovery.

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JIAYING ZHAO, YUEN PAU WOO, AND LORNE WHITEHEAD

# A Research Agenda to Get More People Out of Poverty

Attempts to reduce poverty through technical innovation and income redistribution have fallen short, but the right mix of programs could succeed in overcoming persistent poverty—and unleash productivity growth.

Today, far too many people live in poverty, even in high-income countries such as the United States and Canada. This situation hurts everyone. Poverty alleviation is not an intractable problem, but its politics have been unyielding. We argue that solutions can and must be found, especially because reducing poverty and inequality provides not just a greater sense of security, freedom, and dignity, but also, crucially, it unleashes human potential and creativity. In particular, research has shown that alleviating poverty increases cognitive bandwidth and frees up the intellectual power needed for productivity growth.

It has become increasingly clear that technological progress in free market economies will not eliminate poverty. It is equally doubtful that any one program of redistribution is equal to the challenge. But in principle, the right mix of policies could allow for some redistribution without detriment to economic productivity. We propose here a significant governmental investment in research to test various promising combinations of programs to lift the most disadvantaged people out of poverty while maintaining a vibrant and innovative economy.

We believe such research is an important part of considering the future of science policy because eradicating poverty is itself an important social goal. In addition, many current science and technology policy proposals attempt to deal with poverty and inequality either directly or indirectly. Thus testing and evaluating policy packages that combine some of those proposals should be part of the public research portfolio.

We call this approach *synergistic system design*, which involves combining known social programs into policy packages that interact beneficially, so that their advantages reinforce, but not their disadvantages. We argue that this approach has the potential to significantly reduce poverty and that the required investment can be justified by the resultant societal benefits.

## Innovation and redistribution redux and remixed

Even in high-income countries, poverty rates are disturbingly high. For example, using a metric called the Supplemental Poverty Measure, which adjusts the official poverty line by including other information, the Urban Institute projected that in 2021, one in seven Americans (13.7%) would live in poverty. In Canada, one in ten (10.1%) lived under the poverty line in 2019 (as defined by the Canadian government).

In our view, poverty in high-income countries is largely a problem of income distribution, not fiscal capacity. But it's hard to redistribute income without affecting a nation's productive capacity. The incentives and efficiencies necessary to generate a high gross domestic product (GDP) could be undermined by a poorly designed redistributive system that would keep all citizens out of poverty.

The US economy is a major example of the distribution problem. While its GDP per capita doubled over the last 50 years (in inflation-adjusted dollars), the official poverty rate remained unchanged. Arithmetically speaking, a small tax increase on that new wealth could have eliminated poverty entirely. Yet, political support for such a program is inconsistent and seemingly never enough to make it a national priority. Politicians have all but abandoned redistribution and have instead deposited their hope in technological innovation—reasoning that if innovation can deliver economic growth and constantly raise national income, all boats will rise with the tide. But the last 40 years have shown that more and more boats are sinking in no small measure because innovation tends to perpetuate and even exacerbate existing income inequalities. Importantly, we do not propose a return to the old recipes for redistribution; rather, we realize something new must be proposed, with the dual objectives of greater efficacy and improved political feasibility.

## A hybrid approach to tackling poverty

The synergistic system design that we propose can be illustrated with a simple example. Consider two ways local governments reduce automobile injuries: by encouraging seat belt use and by discouraging speeding. For either approach, a small enforcement effort provides a good return on investment, but with greater efforts, the rate of return diminishes. This means that it is better to share efforts between the two than to put all the eggs in one basket. Sharing efforts between different but related initiatives often yields a whole that is greater than the sum of the parts. That is the beauty of synergy.

However, synergistic solutions are not always easy to find because there are usually numerous possible permutations, many of which may not yield a net benefit. This is why we believe that a large program of antipoverty research should be deployed to find the most promising policy combinations and to design them to be as effective as possible. In addition to the necessary empirical research, mathematical modeling could help develop plausible hypotheses. There's good reason for optimism because synergistic design has worked well in other fields. It led, for instance, to significant improvements in medical treatments with drug combinations that offer net benefits not possible with an increased dose of a single drug alone.

Various policies for poverty alleviation have been tried, but rarely in combination. Here are five examples of policies that could be part of a carefully crafted combination for achieving overall benefits that significantly exceed overall cost:

> **Minimum wage.** A minimum wage boosts take-home pay for some employees, but it also has the potential to increase unemployment by making it unprofitable for employers to hire some workers. Many students of the minimum wage agree that it helps to mitigate poverty, but even they remain divided about its optimal level. What's more, proponents of the minimum wage agree that, on its own, it cannot significantly reduce poverty.
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> **Basic income.** This term refers to programs that provide each adult citizen with universal, unconditional regular cash payments to help cover basic living costs. Past and ongoing experiments have found wide-ranging benefits of cash transfers, including improving individual well-being and helping people start businesses, gain higher education, and take care of their health problems. Positive network effects observed included declines in crime and a migration away from other safety net programs.
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> **Negative income tax.** This policy is a way to increase take-home pay of the lowest earners, without forcing employers to pay a higher wage than they could afford for that employee in that situation. In a negative income tax experiment run in several US states between 1968 and 1982, workers below a certain income threshold received money. The results did show a small reduction in the labor supply, but the decrease was mostly driven by youth who opted out of work to attend school, which was probably beneficial overall.
>
> **Subsidized goods and services.** In this approach, the government provides free or low-cost basic goods and services. Generally, this policy is popular for collective services that may be impractical to monetize, such as firefighting, policing, and na-

tional defense. However, poverty mitigation may require direct subsidies to meet basic needs such as food or energy.

**Wage subsidy.** This approach is somewhat similar to the negative income tax, but in this case the government makes payments directly to employers to help subsidize employment costs. In turn, wage subsidies can encourage innovative organizations to create expanded employment opportunities while providing affordable new goods and services. A wage subsidy program could be made conditional upon the recipient firm's achieving and maintaining measurable targets for safety, diversity, equity, and inclusion. Subsidy payments could also take the form of nonrefundable tax credits. An example of synergistic design that should be tested is combining a basic income program for workers with a wage subsidy program for employers. In that approach, all citizens within a selected community would receive a basic income, with no required payback beyond regular income tax, and employers would receive a nonrefundable tax credit, making it affordable for them to hire employees with lower intrinsic productivity. The wage subsidy would encourage employers to offer a modest number of minimum wage positions to individuals who would not otherwise provide sufficient value to merit employment.

### Need for research to evaluate synergistic approaches

The proposed synergistic approach for solving poverty will require numerous experiments at a large scale in both size and duration. This experimentation is essential for producing reliable, replicable, and generalizable results. There is a growing awareness that use-inspired basic research, led by trans-sectoral teams, can be a powerful way to tackle difficult, complex problems. Those teams must include implementation experts and researchers who are pioneering new approaches to develop potent combinations of, in this case, poverty-reduction programs. Furthermore, since synergistic approaches blend numerous ingredients, a great many recipes could potentially be beneficial and therefore should be independently evaluated.

Yet another key consideration is to ensure that experimental antipoverty interventions operate for a long enough time to assess their impact on community culture. For example, it would be understandable to worry that a basic income policy, on its own, could gradually diminish the value that culture places on employment, even though short-term basic income experiments have not detected such an effect. This possible effect could be countered by another ingredient in the mix, as we suggested above. But that sort of dual-effect hypothesis needs to be carefully tested, at scale, over many years.

Overall, we need to better identify and understand three aspects of the issue: (1) the most cost-effective combinations of antipoverty interventions; (2) the optimal investments in these areas to achieve a satisfactory reduction of poverty; and (3) the means to communicate these discoveries in order to get buy-in from governments and the public.

### BASIC INCOME: LEARNING FROM EXPERIENCE

In the Manitoba Basic Annual Income Experiment that took place in Dauphin, Manitoba, in the 1970s, low-income families received an annual income guarantee between CAD 3,000 and 6,000 (roughly CAD 20,000 to 60,000 in today's currency). The experiment resulted in a significant reduction in hospitalization, specifically for mental health diagnoses and work-related injuries. Recently, the New Leaf Project was conducted to examine the impact of unconditional cash payments on individuals experiencing homelessness. In the project, a one-time unconditional payment of CAD 7,500 (equivalent to personal annual income assistance in British Columbia) was made to each of 50 homeless individuals in Vancouver, Canada; another group of 65 served as controls. The cash transfer was in addition to existing welfare benefits. The results demonstrated that the cash transfers led to significant improvements in recipients' standard of living, cognitive function, and subjective well-being. Notably, there were no increases in spending on alcohol and drugs. Somewhat surprisingly, the cash transfers actually produced net savings of CAD 625 per person per year because of reduced shelter use.

As a new pilot experiment in universal basic income, the city of Compton, California, launched the Compton Pledge in late 2020. The city provides up to USD 1,000 per month to qualifying families for two years, as unconditional, direct, and continuous cash transfers to supplement their existing welfare benefits. This pilot adds to a growing list of US cities (also including Stockton and Oakland, California) that are experimenting with basic income programs.

Canada may be able to adopt a basic income program without adding to its fiscal debt. For example, the Parliamentary Budget Office of Canada has estimated that a guaranteed basic income of CAD 17,000 per individual (or CAD 24,000 for a household) would cost CAD 88 billion in 2022–23, and that this amount could be financed entirely by the removal of certain tax credits and some social assistance programs that overlap with the objectives of basic income. The simulation predicts a 50% reduction in the national poverty rate and a reduction in hours worked of less than 1.5%. Importantly, even that encouraging analysis overlooks the medium and longer-term benefits of poverty elimination that are not captured by a first-order economic analysis.

## A window of opportunity

Now is an ideal time to vigorously test this synergistic approach to alleviating poverty. The COVID-19 pandemic has forced many governments, especially in high-income countries, to experiment with economic and social policies such as stimulus checks, reforms to employment insurance to recognize gig work, and recognition of low-skill work as high-value activities, all while testing the capacity of the state to underwrite social programs. With this expanded understanding of what is possible, we argue that the time has come to do the required research to develop practical synergistic solutions. Put simply, the risks associated with not doing this essential research would vastly outweigh the comparatively modest costs of advancing this significant research agenda.

We therefore call for major investment, with a consequent obligation for excellent planning, to devise the optimal blend of interventions—first for testing and then for implementation. There is no doubt that high-income countries have the resources to accommodate such an investment.

Consequently, we believe it is time for a massive, Apollo-scale research investment that combines basic and applied studies of large-scale interventions to establish better paths forward for overcoming persistent poverty.

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AMBER MACE AND JUN BANDO

# States as Laboratories for Science Policy Innovation

As California's environmental initiatives demonstrate, states can complement the federal role in generating science-informed legislation that addresses local problems while providing a model for national and international policies.

In 1932 Associate Justice of the Supreme Court Louis Brandeis first popularized the idea of states as laboratories for policy innovation and experimentation. In his dissent in the case of *New State Ice Co. v. Liebmann*, Brandeis wrote, "It is one of the happy incidents of the federal system that a single courageous state may, if its citizens choose, serve as a laboratory; and try novel social and economic experiments without risk to the rest of the country." This policy experimentation can generate effects that extend far beyond state borders, and in the case of science policy, it can deliver tangible results that are purposely customized to fit local needs.

Today the urgency of climate change, combined with intensified partisanship and gridlock in US federal policymaking, elevates the importance of states as laboratories of democracy. Through policy experimentation and investments in research and development, states complement the federal role in generating science-informed policies that benefit the nation and the world, meeting needs for public services that national governments typically cannot address, and providing visible evidence of the value of public institutions in the daily lives of their residents. In addition, as federal science priorities and funding levels have waxed and waned, states have taken more prominent roles in setting research agendas that generate long-term social benefits.

As leaders of the California Council on Science and Technology, a state organization that provides scientific advice to policymakers, we relate here how scientists and policymakers have worked together in our state to create the type of civic and political environment from which innovative science-based programs can take root and spread. Our track record in this endeavor also demonstrates why building science policy at state as well as federal levels increases the chances for future success.

## States as pathfinders

California has long been a leader in developing science-based policies with environmental aims. Although other states, territorial and local governments, and tribal nations have been pathfinders in addressing issues such as air pollution, energy use, and climate change, and in building resilience into public services and policies, they have not achieved California's impacts. As the world's fifth-largest economy and twelfth-largest emitter of greenhouse gases, California is comparable to a nation-state and thus its actions have far-reaching consequences.

What's more, California's long history of effective action on the environment has built a reservoir of public trust in science-based solutions. In particular, this enabled state leaders to mobilize the political will needed to pass pioneering climate legislation in 2006, which has been followed by other ambitious legislation.

Among the state's early environmental problems were vehicle emissions and tailpipe pollution. Smog in mid-twentieth century Los Angeles was so bad that schoolchildren were not allowed to play outside at recess during the frequent smog alerts. The combination of the federal Clean Air Act of 1970, state emissions regulations that exceeded federal standards in their stringency, and regional air quality monitoring led to a significant reduction of LA's smog while generating new commercial opportunities within an expanding green economy. The fact that the state was able to deliver noticeably cleaner air without hurting the economy helped to build a sense of trust among the general populace that environmental initiatives could deliver multiple benefits. As of 2021, 14 other states and the District of Colombia had adopted California's emissions standards, which remain more stringent than federal standards.

Similarly, California adopted energy efficiency measures in the 1970s that kept its per capita energy use flat for more than four decades while per capita consumption rose steadily across the nation. As Art Rosenberg, a physicist at Lawrence Berkeley National Laboratory, explained to then Governor Jerry Brown, the state could significantly reduce per capita energy use if it could find a way to make refrigerators and other appliances more energy efficient. He also suggested changing specific utility incentives. Once his suggestions proved successful, the so-called Rosenberg Effect became part of the state regulatory effort, which has vastly improved the energy efficiency of homes, appliances, vehicles, and other energy-consuming products in California over the past 50 years.

Building on these successes, in 2006 California became the first state in the United States to adopt a comprehensive climate program. Assembly Bill (AB) 32, the California Global Warming Solutions Act of 2006, required the state to reduce its greenhouse gas emissions to 1990 levels by 2020. Most notably this legislation and its attendant regulations were built on research done by scientists, economists, and sociologists at California universities. Indeed, the carefully designed local effort helped California meet the goal of AB 32 four years early, in 2016. Lawmakers followed up that success with Senate Bill 100, the California 100 Percent Clean Energy Act of 2018, which mandates that all of the state's electricity production be carbon neutral by 2040. While popular support has been mixed and largely divided along political lines, several statewide referendums have supported the moves, reflecting a broad public perception that these efforts are good for both the economy and communities.

These legislative successes did not happen in a vacuum. California has been the vanguard for effective climate action in large measure because of its deliberate focus on connecting science and policy with the investments to match. In addition to taking action on climate, for example, California voters have twice authorized major investments in stem cell research in 2004 and 2020.

More broadly, the state has invested in building a science and technology infrastructure that has enabled it to be a global leader in innovation and productivity. These achievements would not have been possible without the confluence of multiple factors. Among them: the creation of public university systems that have produced a well educated workforce by increasing access to higher education for every resident regardless of economic status; the implementation of research and development funding that exceeds that of most of the world's advanced economies; and a population of extraordinary diversity in race, ethnicity, culture, sexual orientation, gender identity, socioeconomic status, and lived experience. The result: California's policies have enabled industries in key sectors—including aerospace, biotechnology, energy, and software—to move quickly, generating tremendous revenue and social mobility.

## Building bridges

Of course having the necessary infrastructure does not, by itself, guarantee the meaningful adoption and implementation of science-based policies. Deliberate efforts to ensure substantive communication and collaboration between the scientific community and government officials are also required. Recognizing this need, a coalition of policymakers and leaders of scientific research institutions came together in 1988 to create the California Council on Science and Technology (CCST).

A state-level organization, CCST was established to provide scientific advice on public policy issues to the governor, the legislature, and other civic entities. Each year CCST embeds 15 PhD-level scientists and engineers as fellows in legislative and executive branch offices. The CCST science and technology policy fellows support policymaking while gaining experience in policy and leadership. The fellowship is a public-private partnership supported by the government of California, the Gordon and Betty Moore Foundation, and other philanthropists.

Part of what makes CCST so effective is that it acts as a "boundary organization," a term coined by political scientist David Guston. Boundary organizations convene and draw expertise from universities and nonprofit research institutions, the private sector, and government agencies to solve problems in ways that none of these organizations is capable of doing on its own. Distinct from lobbying or policymaking organizations in character, boundary organizations avoid advocating for specific political positions, agendas, or outcomes. Policymakers have many routes for accessing scientific advice, ranging from experts on staff, science advisors, investments in research and development, science-based fellowships, and partnerships with universities and national research laboratories that enable access to the state's deep bench of technical experts.

As an example of the benefits of embedding scientific expertise in government institutions, consider Tony Marino's work to reduce the risk of public utility accidents. As a CCST science fellow assigned to the California State Legislature, Marino led an analysis of the horrific 2010 San Bruno natural gas pipeline explosion that killed 8 people, injured 58, and destroyed 38 homes in a fire that burned for more than 17 hours. Following his fellowship, Marino remained on the legislative staff to continue work that uncovered gaps in public utility operating procedures, including poor construction and inspection practices as well as shortfalls in recordkeeping. His work led to the promulgation of new legislation that, unlike previous laws, strengthened the accountability of utility companies for safety procedures. This more careful approach is likely to improve public safety and disaster response by increasing transparency and accountability in public utility operations and infrastructure maintenance.

Marino's fellowship experience reflects one way that boundary organizations such as CCST can deliver societal value by training professionals to work at the nexus of policy and science, leading to enhanced communication between policymakers and technical experts. His subsequent impact demonstrates how these advantages are not limited to the fellowship year. Most of CCST's 130-plus alumni fellows continue to work in roles related to state policy, drawing on their experience in government to develop solutions that are not just science-based but also politically feasible. CCST is also working with the Gordon and Betty Moore Foundation and other philanthropic partners to export the CCST fellowship program model to other states, eight of which have created similar programs. An additional 12 states have programs in various stages of development.

## Planning ahead for a crisis

When crises strike, the activation of existing partnerships, together with engagement by boundary organizations, can facilitate collaboration at the speed of relevance. To enable this, governments, civil society, and the private sector need to build partnerships *before* disaster strikes. Partners should train together in tabletop exercises. These discussion-based scenarios can identify and address in advance any cultural, regulatory, or other constraints that could hamper rapid activation of a collaborative response. Early in the COVID-19 pandemic in 2020, for example, many California-based colleges, universities, and federal laboratories transformed their facilities to support diagnostic testing and to manufacture personal protective equipment (PPE). Despite urgent, widespread needs and critical shortfalls in testing and PPE, however, these same institutions struggled to secure required permissions to deliver support to local and state authorities. These potential roadblocks could have largely been foreseen.

Climate change, pandemics, and—in California—earthquakes, are well-known risks that allow for somewhat straightforward planning, even if preparation is increasingly complicated by their simultaneous intersection with other crises such as financial meltdowns, acts of terrorism, and war. But what about the problems with which society has only limited experience or that have not yet developed? Emerging and disruptive technologies, such as cyberattacks that disable critical infrastructure or perpetuate disinformation, increasingly present threats and vulnerabilities for the government, defense, and private sectors that should be considered in resilience planning.

To this end, in 2020 CCST began a new partnership with the California government, philanthropists, and academic research institutions to strengthen the state's disaster resilience. Among the goals are developing new mechanisms for rapidly delivering independent, evidence-based advice and framing transdisciplinary solutions to emergent and over-the-horizon policy issues related to disasters. This work is intended to strengthen science and policy linkages before there is a need, thus enabling effective and inclusive resilience planning and timely collaboration in support of crisis response.

## The biggest barrier is not lack of knowledge

Long-term policy planning that drives transdisciplinary and multisectoral solutions, targets actionable early interventions, and generates equitable societal impacts is crucial to driving and sustaining complex policy agendas. Rather than a lack of science and technical knowledge, however, the greatest barriers to implementing effective solutions to complex policy problems have often proved to be competing political objectives, economic disincentives, cognitive biases, and cultural values.

California's experience with wildfires illustrates the profound influence cultural values can have on environmental policies. Prior to European settlement, the land management practices of California's Indigenous peoples included the routine, deliberate application of fire to steward the land and maintain ecosystem processes. In contrast to Indigenous communities that had coevolved with fire, European settlers viewed fire as a threat and instituted fire suppression policies. While effective in the short-term, fire suppression policies are ecologically unsustainable.

California's recent catastrophic wildfires are in part the direct result of conditions created by 130 years of fire suppression policies. These policies have remained in place in spite of decades of calls by Indigenous communities, forest managers, and ecologists for changes in forest management and land use. These needed changes include vast increases in deliberate and targeted burning to restore lower-intensity fire regimes in California wildlands. To date, political will has been insufficient to invest in and deploy these critical interventions at the scale required, in large part because of mainstream cultural perceptions of fire as inherently harmful. Today cultural perceptions of fire are changing, in part because megafires have negatively affected every Californian and raised awareness of the shortfalls of fire suppression policies. Smoke exposure from wildfires is now a statewide and regional issue, as well as the primary source of wildfire-related mortality. Today wildfires—through smoke exposure—kill more people in cities than in areas that actually burn.

Although the full costs of wildfires to human health cannot be calculated, we know enough as a society to make changes in policy that could save lives and taxpayer dollars. CCST's 2020 report *The Costs of Wildfire in California* showed that many costs of wildfires (including impacts to human health and ecosystem services) are not fully counted. Yet even the subset of wildfire costs that are known have exceeded tens of billions of dollars annually in recent years. A growing body of research finds prevention and mitigation to be cost-effective, strengthening the case for investing more in holistic wildfire strategies that allow ecologically beneficial fires back on the land. As policymakers grapple with how much to invest in prevention and mitigation, this kind of independent advice, synthesized from multiple disciplines, is key to informing policy discussions.

### Unmet opportunities

Despite California's robust economy, its benefits have eluded many who live there. Trends in technology and automation, together with the COVID-19 pandemic, have disrupted the workforce and widened the gap between those who have access to the higher wage jobs that technological innovation delivers and those who do not. Meeting society's most pressing challenges in ways that broaden economic opportunity will require engaging the full range of talent in our society. California and other states should continue to prioritize building a workforce that is more diverse—one that resembles the general population—in science, technology, engineering, mathematics, and medicine.

States are particularly well-placed to develop a more diverse workforce and to seed investments in specific regions that lag in growth. California could, for example, increase investments to accelerate the transformation of Southern California's Imperial Valley into the "Lithium Valley." Such an initiative would promote growth in the renewable energy sector, creating jobs in an area with a majority Latino population that has historically experienced high unemployment rates. Focused investments would also build the foundation of a market that could increase US competitiveness in a battery industry that is currently dominated by China.

Of course, mining lithium deposits—found in the Imperial Valley's Salton Sea—raises questions of social equity and environmental justice tied to the health and well-being of local residents and workers. Integrating such questions of social equity in the development of public policies has become routine in many states, including California. Engagement with local communities to address these questions to inform public policies can have the added benefit of enhancing the social power of historically marginalized populations who are most affected by climate change and other environmental stressors.

## Looking ahead to the next 75 years

The next 75 years will challenge humankind in ways impossible to predict today. Regardless of how the coming decades unfold, global challenges—including climate change, pandemics, and other complex shocks—are likely to manifest more frequently and acutely, requiring national and subnational governments to build ever greater resilience in public policies and services. At the same time, geopolitical power shifts and a hyperconnected and increasingly polluted information environment are likely to magnify ongoing social and environmental challenges.

Will the coming decades usher in a resurgence of open democracies or the expansion of authoritarianism? Against a range of potential future scenarios, emerging technologies are likely to magnify tensions, disruptions, and global competition for technological superiority.

The future success of humankind requires embracing global interconnectedness and harnessing the best social, technological, and policy innovations, regardless of where they are created. Global society's well-being relies on the generation of innovative and effective policy solutions. California's highly experimental approach to policymaking and rulemaking, coupled with its flexible and adaptive implementation, has enabled state leadership to respond by making improvements, such as "greening the grid." Future policymaking and rulemaking in an increasingly uncertain world is likely to require even greater experimentation, flexibility, and adaptation.

Against this backdrop, the effects of state-level actions in democracies provide strong counterpoints to arguments for autocratic models. California is investing heavily in building climate resilience, including with a $15 billion package approved in 2021 to build resilience and protect communities from climate risks such as catastrophic wildfire, extreme heat, and sea level rise. As of 2021, 30 states in the United States, together with the District of Colombia and Puerto Rico, had set goals of at least a 75% reduction in greenhouse gas emissions or the generation of at least 75% of electricity production from renewable or combined renewable and clean energy sources. Additionally, more than 50 tribal nations in the United States have completed climate assessments and action plans.

Generating solutions to society's most complex problems will require expanded collaboration among state, territorial, local, and tribal governments; philanthropy; other segments of civil society; and the private sector. It will require greater investments in the boundary organizations that catalyze these collaborations. Progress in science-informed policy will also be contingent on repairing trust in science and in public institutions—a vast topic but one we recognize and highlight as vital to the preservation of democracy.

States have served as the laboratories of democracy for the first 246 years of the political experiment known as the United States of America. As the country looks to an increasingly uncertain future, states' bold policy innovations and experimentation will play a vital role in meeting the needs of their denizens, the nation, and the world.

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GERALD BERK AND ANNALEE SAXENIAN

# Architectures of Participation

How collaborative open-source software development increased the velocity of problem-solving in cloud computing—and what that suggests for innovation policy.

Silicon Valley's dynamism during the final three decades of the twentieth century highlighted the singular importance of social and professional networks to innovation. Since that time, contemporary and historical case studies have corroborated the link between networks and the pace of technological change. These studies have shown that networks of networks, or ecosystems, that are characterized by a mix of collaboration and competition, can accelerate learning and problem-solving.

However, these insights about networks, collaboration, and ecosystems remain surprisingly absent from public debates about science and technology policy. Since the end of World War II, innovation policy has targeted economic inputs such as funding for basic scientific research and a highly skilled workforce (via education, training, and/or immigration), as well as support for commercialization of technology, investments in information technology, and free trade. Work on national systems of innovation, by contrast, seeks to define the optimal ensembles of institutions and policies. Alternatively, policy attention is focused on achieving efficiencies and scale by gaining control over value chains, especially in critical industries such as semiconductors. Antitrust advocates have attributed stalled technological innovation to monopolistic concentration among large firms, arguing that divestiture or regulation is necessary to reinvigorate competition and speed gains for society. These approaches ignore the lessons of network research, potentially threatening the very ecosystems that could unlock competitive advantages. For example, attempts to strengthen value chains risk cutting producers off from global networks, leaving them vulnerable to shifting markets and technology and weakening the wider ecosystem. Breaking up large platform firms may likewise undermine less visible internal interdependencies that support innovation, while doing nothing to encourage external collaboration.

How might the public sector promote and strengthen important network connections in a world of continuous flux? This essay reexamines innovation policy through the lens of the current era of cloud computing, arguing that the public sector has a regulatory role as well as a nurturing one to play in fostering innovation ecosystems. Since traditional ways of conceptualizing antitrust regulations are unlikely to be effective in today's complex global innovation ecosystem, we argue that a policy agenda drawing on elements of industrial policy, as well as reconfigured competition policy, can help ensure that the organizational structures of complex technological projects balance competition with collaboration to foster, rather than stifle, innovation. What we propose is not new. In the early twentieth century, the progressive reformer Louis Brandeis worked with engineers, trade associations, companies, and government regulators to configure antitrust law so that it channeled competition from predation to innovation.

We think these lessons are relevant today and can inform a new suite of policy ideas centered around participation in today's decentralized ecosystems. Furthermore, understanding the architecture of these technology ecosystems suggests policy tools to accelerate innovation and improve governance—while providing lessons that can guide strategies to enhance public benefit in the future.

## The nature of competition in the cloud

Competition in cloud computing is currently focused on building an interconnected infrastructure that simplifies management of very large volumes of data. As the third wave of innovation in the commercial internet, the market structure of this phase differs significantly from previous ones. The first generation of internet innovation during the 2000s was led by engineers' and start-ups' development of networking standards and protocols to support a globally accessible internet. The second wave began in the 2010s when the focus shifted to scaling the computational capabilities of this network and building out complex software systems and platforms—a market that was eventually dominated by large firms. During this second wave, cloud computing services emerged alongside institutions enabling distributed collaboration in the development of open-source software. Today, as information storage, computation, and software continue to shift away from private servers to the public cloud, engineers in both large firms and start-ups are building the elements of a modern data infrastructure for the cloud. The goal in this third wave is a platform that facilitates data management and ultimately makes data more widely accessible.

The market structure of this era of cloud innovation is a complex combination of networks of engineers in start-ups, established technology firms, and nonprofit foundations. All are experimenting with the elements of a distributed data infrastructure that will support the collection, storage, transformation, analysis, and movement of data in and between clouds, enabling what is likely to be a fourth wave of innovation in which nonprofessionals, as well as professionals, have unprecedented and unfettered access to sophisticated data analysis and widespread application of machine learning.

The multifaceted structure and diverse possibilities characteristic of the cloud's ecosystem do not fit neatly into boxes labeled competitive and monopolistic or open and closed markets. Most recently, this simplification has generated a bifurcated public debate between two camps with opposing views on platform regulation. On one hand, some argue that innovation is a product of competitive markets that allow entrepreneurial entry and therefore recommend antitrust policy to constrain the market power of large firms like Amazon, Google, and Facebook. Opponents of this approach argue that the large firms have used their ample resources and scale to generate ongoing innovations that benefit customers and even start-ups. In this view, increased regulation would only hinder progress.

To gain insights into the organizational conditions for innovation and its implications for policy, we spent two years interviewing software developers, attorneys, entrepreneurs, foundation executives, and managers working on data transformation in the cloud. We found partial support for *both* views of innovation: today, progress is coming from both large firms and a new generation of start-ups. However, the evidence suggests that neither of the two policy prescriptions is appropriate. Attributing innovation to either the free play of competitive markets or the capabilities of the large platform firms overlooks the power of collaborative ecosystems that increase the pace and quality of technological change.

Cloud innovation is currently at a crossroads, with two possible organizational trajectories. One trajectory is based on a top-down and centralized model, with platform firms exercising power over start-ups; the alternative is more decentralized and open, with the large firms collaborating with start-ups as well as nonprofit institutions. This second, more open trajectory is supported by extended, cross-firm networks of developers and appears to accelerate innovation.

Our research suggests that competition policy, innovation policy, and industrial policy should be seen as complementary, particularly for supporting today's collaborative ecosystems. Moving beyond the old categories allows us to define a vision for policy that deliberately reinforces the dynamism we see in the cloud and to consider how to extend that model to other industries.

## A short overview of cloud innovation

Today's cloud has evolved on top of legacy structures that still influence its development. In the early 2000s, businesses purchased software and ran it on their own servers, while storing information and data on-site. In 2006, Amazon Web Services (AWS) began offering cloud storage and computing services that freed businesses from the demands of managing physical servers or running large, licensed software applications on their own machines. Other infrastructure providers like Microsoft Azure and Google Cloud soon joined the competition, supporting the rapid growth in the 2010s of cloud-delivery of software as a service for a wide range of businesses and consumer applications.

However, as late as 2015, data remained locked in proprietary and incompatible corporate systems, making it extremely costly for firms' employees to move, share, or recombine even their own data. Traditional data warehouse systems require expensive on-premises hardware, which means that data is maintained in proprietary formats and managed and processed by a centralized IT department. As the internet enabled an immense increase in the volume, velocity, and variety of data, these centralized systems could not keep up. Over the past decade, the constraints of these systems have inspired widespread experimentation, including a proliferation of start-ups building new tools and data formats to enable data storage and processing in the cloud.

The shift to a cloud services model has also contributed to a renaissance of open-source software. Open source, historically seen as a fringe movement of hackers opposed to proprietary software, is now in the mainstream of software development. The principles of open-source software haven't changed: the code can be accessed, used, modified, and distributed, commercially or noncommercially, by anyone under the terms of the license. But far from being a peripheral option, open-source technology is now widely adopted by firms in all sectors of the economy. For example, the Linux operating system, which originated with programmer Linus Torvalds in the early 1990s, today runs most of the internet as well the world's supercomputers and stock exchanges.

The ecosystem of cloud innovation thus has contradictory features: it is both competitive and collaborative, decentralizing and centralizing. It has been a boon to entrepreneurship, triggering a veritable "Cambrian explosion" of new data-related firms over the past decade. At the same time, data innovation in the cloud has empowered the cloud divisions of the biggest platform companies, including AWS, Microsoft Azure, and Google Cloud.

But the distinction between big and small players is less important than the contradictory trends—toward centralization and closure, on one hand, and toward decentralization and openness, on the other—that are shaping today's cloud ecosystem. The move toward closure can be seen in the application programming interfaces (APIs) that once facilitated open experimentation and development across different platforms, firms, and products, reflecting the distributed innovation of the early internet. Today's giant platform companies have abandoned that openness and diversity by restricting access to their APIs. In their drive to gain market share, they have also acquired promising start-ups and developed proprietary systems that limit the ability of newcomers to build on their platforms. Thus, market concentration and declining openness and interoperability became complementary.

At the same time, the market architecture of the cloud has elevated the open-source movement, which offers a model of increasing openness, even as it is institutionalized and integrated into the portfolios of the largest commercial firms. Importantly, the movement no longer sees itself in opposition to market-based systems, and technology corporations have embraced it. Microsoft reversed its vehement opposition to open source to become its largest contributor in 1999, and IBM purchased Red Hat, the leading open-source consulting firm, in 2019. Google is a close collaborator with the Linux Foundation. Today, open-source software is increasingly developed by, and integrated into, commercial enterprises. Open-source producers now generate significant revenues by selling not just support and services, but also proprietary or enhanced functionality or open-source tools. Venture capital firms now actively invest in open-source start-ups (including some $2 billion in 2019 alone) that compete aggressively against firms selling proprietary software, and analysts report a recent boom in open-source IPOs.

Perhaps most significantly for policy, innovation in the cloud is populated by a host of firms and institutions committed to open source. These institutions include non-profit open-source organizations such as the Linux Foundation, the Apache Software Foundation, the Mozilla Foundation, the Eclipse Foundation, and the OpenStack Foundation. Once primarily repositories for code, these foundations are now well-funded, professionally staffed promoters of their development model. The Linux Foundation, for example, is no longer focused solely on the Linux operating system. Instead, it is dedicated to helping "open technology projects build world class open-source software, communities, and companies." Unified by a shared recognition of the value of open-source development, the Linux Foundation community today includes more than 19,000 contributing companies and more than 540,000 developers. In short, global networks of open-source developers, communities, and foundations are central actors in today's innovation ecosystems.

## Litigating "strip-mining"

How are policymakers to understand this new ecosystem, with its many players and evolving business models, in order to create forward-looking governance that encourages innovation? To date, discussions of policy have largely been confined to antitrust litigation. Exploring this impending litigation can show how it both reflects and elides the true complexity of the cloud's innovation ecosystem, which cannot be accurately characterized by concepts of monopoly and competition.

One stream of antitrust litigation is focused on Amazon Web Services (AWS), which controls 33% of the $178 billion global market for on-demand cloud computing. AWS's business model requires massive investments in data centers located around the world to share the workload of data storage, computing power, and networking. AWS, along with other leading cloud providers, also offers platform (databases, web services, development tools) and software services on top of the basic infrastructure. In short, AWS has made solving its clients' hardest IT problems easy, and as it has gathered more customers, it has gotten even better at solving those problems. In 2020, AWS accounted for nearly 67% of Amazon's operating profits, and Amazon increasingly sees itself as a technology company rather than a retailer. By continually improving the quality and performance of its cloud services, AWS provides an important benefit that has strengthened the entire tech ecosystem.

If the growth of cloud computing has benefitted businesses, it has a more complex relationship with the open-source software community. AWS, like other cloud platforms, makes use of open-source code, including the Linux operating system, and has been a powerful driver of its adoption. However, AWS's primary focus is on increasing its customer base by achieving scale and perfecting internal competency, which both serves and threatens the entrepreneurial technology ecosystem. For AWS, innovative open-source software offers a ready path to expansion. In 2015, for example, AWS copied the open-source code for a pioneering search engine named Elasticsearch and integrated it into its proprietary cloud services offerings. Reportedly, AWS was soon making more money from the code than the software's creator, Elastic. Critics have charged AWS with "strip-mining" the open-source code that smaller companies have invested heavily in, making it harder for them to make money. AWS has countered that it is a "significant contributor and supporter of the open-source community."

Because their code is open source, database companies like Elastic have no recourse in intellectual property law for protection from such actions. In 2019, Elastic sued AWS for trademark violation because AWS also used Elasticsearch as the search engine name. That suit was jointly dismissed in February 2022, with AWS changing the name of its service. Several other database companies are also exploring antitrust suits against the cloud providers, and their leaders have testified about harmful effects of the dominant firms' market power before the House Subcommittee on Antitrust, Commercial, and Administrative Law. Advocating aggressive antitrust regulation, these companies charge cloud providers with erecting barriers to entry by making it impossible for independent firms to compete. In the coming years, this battle will be fought in the courts through private and public lawsuits, in Congress, and by states' attorney generals. Meanwhile, in an effort to prevent AWS from building commercial services from their code in the future, at least eight open-source database companies, including Elastic, have modified their licenses, making them so restrictive that they are no longer considered open-source by the community. In seeking to shift power from AWS, these efforts could diminish the vibrancy of the open-source innovation ecosystem because it will leave the centralized model intact.

## Understanding architectures of participation

Many developers who are committed to open-source software argue that resorting to litigation and adopting restrictive licenses will hurt the community by further centralizing control, reducing adoption of open-source software, and ultimately harming end users. Developing a data platform in the cloud, they insist, is far too big and complex a project for even the largest and most technically sophisticated companies. The alternative to litigation, they say, is building an "open cloud," with standards and services that are designed to be federated rather than centralized, leading to interoperable products and, ultimately, to the democratization of the use of data. This open cloud model contrasts with a more centralized and extractive system, in which companies build proprietary systems and can set de facto standards because of their scale.

However, the kind of competitive open system these developers envision is quite different from that imagined by antitrust advocates. Consider the way open-source advocates speak of the necessity of building "architectures of participation." In 2012, Marten Mickos, who had been chief executive officer of the leading open-source database company MySQL, described "a model for how to engage people with different ambitions, different mandates, different employers (or no employer at all), and different communication habits in joint projects that unpredictably but inevitably produce superior results." Such efforts, he said, have "rules of engagement that allow disagreeing people to let their work products agree. This is a system where the designer invites input from contributors. The result is an ecosystem that evolves faster than any individual initiative, resulting in a work product with fewer deficiencies." Importantly, Mickos told us, these organizational structures "allow [for] strong disagreement and intense competition that leads to progress without harm."

Although the open-source movement may at times sound utopian, there is significant evidence that the architectures of participation create high-quality and fast-paced innovation. The advantages lie in economies of code reuse, the intrinsic motivation of open-source developers, community reviews of code, and high rates of experimentation through the ability to fork the code (i.e., to use the source code from open-source software to create new software). What's more, the movement has in recent years worked to embed profit-making opportunities in the open-source ecosystem. There are also conversations about how to reduce the harms of creative destruction in the fast-moving open ecosystem—by, for example, ensuring that participants in open-source projects that lose in conflicts over standards remain viable enterprises that can still put their years of work to use.

Still, it's important to recognize that this is far from a simple story of open-source Davids versus large-platform Goliaths. Companies that rival Amazon in size are also devoted to building architectures of participation for an open cloud. The Google Cloud division, for example, is an active participant in the open cloud community. In a 2019 interview, Google's vice president of infrastructure, Eric Brewer, explained that open source not only accelerates innovation; it also ensures consistency across diverse users and platforms. Brewer said that Google Cloud is committed to "partnerships with open-source companies where they're helping us build a managed version of their product." The Google Cloud Platform collaborates actively with the Linux Foundation and shares revenue with its smaller partners.

Rather than using its market position to dominate smaller players, Google Cloud sees greater advantage in collaborating with them to accelerate innovation for the industry. To these ends, Google Cloud has forged partnerships with Istio, Databricks, Envoy, dbt Labs, and others. The outcome, noted Brewer, is faster improvement for software in the cloud: "We used to upgrade software quarterly," he said, "now we do it weekly."

One example of how this ethos works in practice is Kubernetes, a system Google developed to place data and applications together in "containers," so they can be deployed flexibly across users and platforms. In 2015, Google donated the Kubernetes code to the Cloud Native Computing Foundation (CNCF), a vendor-neutral home for fast-growing open-source projects that is a part of the Linux Foundation. Although the decision to open Kubernetes to the community was controversial internally, Brewer reported that Google engineers convinced senior managers that Kubernetes was more likely to stay on the technology frontier by collaborating with open-source firms, which would continue to contribute to its development. In a 2017 speech, he noted that the pace of innovation in the Kubernetes code after it was open-sourced was unparalleled: in 2017, there were 1,500 new contributors and 49,000 new commits (changes to the code). In 2016, he said, there was one commit every 33 minutes, and in 2017 there was one commit every 25 minutes—noting that the quality of products improved significantly with the higher level of contributions. The CNCF reports 10,000 new contributors to Kubernetes in 2021, for a total of 62,000 total contributors, and lists 243 companies as Kubernetes Certified Service Providers and another 57 as Kubernetes Training Partners.

For Google, this web of partnerships ensures that there is a community of expertise supporting Kubernetes—making it even more likely that it is widely adopted as a standard. The broader effect is to accelerate data innovation in the cloud. To be sure, Google, like AWS, remains an unequal collaborator and could exploit its power to dominate or purchase its partners. For this reason, we argue for antitrust limits on mergers and acquisitions and monitoring of partnership contracts.

Another key set of actors in the building of architectures of participation consists of the nonprofit and charitable open-source organizations. Funded with dues from corporate sponsors and, increasingly, with revenues from program services they provide, some—including the Linux Foundation, the Eclipse Foundation, and the Apache Software Foundation—have grown over the last two decades to become global curators of open technology ecosystems. They collectively house hundreds of open-source projects and provide a base for around 1 million developers worldwide to contribute code and to manage and scale technologies and communities. These developers are generally employed by member companies that see value in having their engineers contribute to essential infrastructure projects that the foundations host. The foundations tend to the developer community, ensure rapid feedback, clarify intellectual property rights, and deploy automation tools to ensure consistency and interoperability across applications and platforms. They also benchmark speedy problem-solving by measuring the pace of new contributions to code.

The dramatic growth and increasing sophistication of these foundations can be seen in the example of the Linux Foundation, which was established in 2000 as the merger of two small open-source groups committed to the business adoption and protection of the Linux operating system. With initial funding from 70 businesses including Hewlett Packard, Intel, and IBM, its goal was to be a vendor-neutral home that represented Linux with one voice. As founder and current executive director Jim Zemlin put it in 2007, "Microsoft spends a lot of money protecting its Windows platform.… we're going to do the same thing." The foundation has become an influential promoter and supporter of open-source software, with more than $124.5 million in revenue in 2019, some 1,200 corporate sponsors, and 150 employees.

The Linux Foundation also hosts and monitors precompetitive collaboration on software projects that members see as common goods—even though they may be competitors. It organizes projects and initiatives, hosts important subsidiary foundations, provides tools to facilitate all aspects of open-source development from crowdfunding and mentorship to security and a unified control center to manage the projects, and teaches developers to write more secure code, do better testing, formulate responsible disclosure policies, and manage intellectual property. Finally, aware of the risk of being captured by big corporations, the foundation has been careful to avoid dependencies by ensuring that no one of its business supporters accounts for more than 2% of its total budget.

The foundations play an important role in governance, creating the interoperability standards that support technology ecosystems necessary for an open cloud. These foundations differ from the original internet standards-setting organizations like the Internet Engineering Task Force, founded in 1986, and the OASIS consortium, created in 1993 to coordinate the process of writing detailed specification documents by engineers, lawyers, and managers. Those organizations have struggled to keep up with the pace of change in the now-global internet and are increasingly troubled by internal conflicts and domination by the largest players in the industry. At places like the Linux Foundation, software engineers collaborate to set the standards for critical open-source technologies; and they share and license these open standards and specifications across the global supply chains—allowing the code-based standards to evolve as technology shifts.

The profound role of open-source foundations is not fully recognized. As pillars of the modern technology ecosystem, they both incentivize and support innovation in the cloud. Their relationship with open-source users and contributors is self-reinforcing, so that the promulgation of standards draws more developers, which drives more firms to embrace open source, and so on. And as more users shift software services to the cloud, the role of foundations in ensuring the health and development of the open cloud will only grow more important. As we will argue below, it is critical for government to support the development of open-source foundations, not only because they speed and enhance innovation, giving platform companies an incentive to contribute to open source. They can also provide important resources for government regulators, as well as offer insights into the possible future of high-innovation ecosystems.

## Policy to build dynamic architectures of participation

Given the complexity and divergent trajectories of today's innovation ecosystems, how should public policy foster innovation and openness, and support the process of making data more accessible? Although we believe that antitrust policy has an important role to play, our research shows that it must shift its goals. Litigating strip-mining may help to realize traditional antitrust goals, such as lowering entry barriers and fostering competition. But it will not generate innovation or provide a usable model for innovation policy. Instead, antitrust and other policies should work to shift the incentives for large platform companies and their competitors toward participation in collaborative ecosystems.

Public policy should foster collaboration over appropriation—and partnership over the subjugation of independent companies. There are successful precedents for the use of antitrust law to achieve this goal. The AT&T consent decree of 1956 opened the door to collaboration by forcing AT&T to share its patents with outsiders. Similarly, in the 1980s, regulators created additional incentives for AT&T to collaborate by forcing it to interconnect its wired network with microwave telecommunications. And in the 2000s, courts nudged Microsoft toward openness by forcing it to open some of its APIs.

In the immediate future, we see three policy possibilities that could help reach these ends: enlisting open-source foundations in interoperability regulation; restricting mergers and acquisitions; and providing public investment in open-source institutions. Enacting such policies and evaluating their impact could lead to new policy frameworks to promote future architectures that speed innovation.

Business and government users, consumers, and software engineers all benefit when the internet is more open and interoperable. Communication is easier, innovation is faster, and work is more flexible. Over time, however, internet interoperability has decreased as powerful platform monopolies restricted access to their APIs. Interoperability regulation requires platforms to open their APIs to external developers, allowing them to build new products and services on top of platform services. Advocates claim that interoperability regulation achieves the traditional goals of antitrust measures. It fosters competition, entry, and entrepreneurship. As a result, interoperability regulation has risen to the top of digital policy agendas in both the United States and Europe.

More importantly, interoperability regulation can create incentives for large platform companies to move toward participation in open-source projects if it is implemented correctly. However, interoperability regulation is hard and technical, and antitrust history shows that it is successful only when government appoints a committee of experts to oversee compliance. In today's rapidly changing software environment, where standards evolve with code, interoperability will be best served by enlisting open-source foundations to government service.

Open-source foundations not only provide superior monitoring capacity; in tandem with appropriate regulation, they are ideally positioned to guide platforms toward participation in open-source projects. An example can be seen in the 2002 Microsoft consent decree. With Microsoft under pressure by the government to open its APIs, its cloud division, Azure, became the largest contributor to open-source projects by 2015, and, a year later, joined the Linux Foundation as a "platinum" member by paying a $500,000 membership fee. To be sure, there may be many reasons for Microsoft's shift, but our interviews suggest that the consent decree was instrumental in moving the company toward greater openness and interoperability.

The prospect of including the open-source foundations in monitoring and governance builds upon a long history of American administrative and regulatory agencies' enlisting engineering associations to assist with standard setting, regulation, and antitrust. Drawing on these precedents, in 2020 then-Federal Trade Commission commissioner Rohit Chopra and Lina Khan, a legal scholar who is the commission's current chair, advocated a turn from adjudication to participatory rulemaking. Advocates of new digital regulatory agencies to oversee platform behavior would also do well to include open-source foundations in their design.

Another way to use antitrust regulations to help build architectures of participation is to restrict mergers and acquisitions. While advocates see this as a method to lower entry barriers, foster competition, and sustain entrepreneurship, our research shows that restricting mergers may also create incentives for large platform companies to participate in, instead of exploit, the innovation ecosystem. Making mergers and acquisitions more costly will make partnerships and collaboration more attractive.

At first blush, our proposal may look like a distinction without a difference: whether the goal is competition or building architectures of participation, the means is the same. But the difference is profound because the criteria by which merger reviews are activated and evaluated after the fact are different. Where traditional antitrust measures limit market concentration, our proposal asks regulators to focus on how well merger restrictions foster productive partnerships and a decentralized and participatory ecosystem and how effectively they increase the quality and velocity of innovation. Moreover, because there remains a power differential between large platform companies and their partners, it is important to empower antitrust agencies to monitor partnerships and check abuse before it undermines productive collaboration.

Government has a nurturing, as well as a disciplinary, role to play in promoting architectures of participation, for both existing and emerging platforms. To create incentives for platform companies to partner, contribute, and collaborate, government can invest in open-source institutions. In the United States, where public investment is more likely when national security issues are at stake, open-source subsidies have already been justified to improve cybersecurity. The National Institute of Standards and Technology in the Department of Commerce is currently overseeing a program to bolster the security of the technology supply chain, including open-source software. Many engineers also advocate for including open-source foundations in the government's recent efforts to invest broadly in infrastructure. Strategic government investments in the open-source foundations could also help to reinforce their neutrality by adding to the diversity of their funding sources.

As the science policy community looks toward the next century of innovation, it would do well to pay attention to building and supporting more effective ecosystems and architectures of participation. The tools for this need not be built from scratch. A generation of research on the role of networks and ecosystems in fostering innovation and the historical experience of standard-setting associations and regulators in channeling competition from predation into innovation provide ample resources. And with these tools, public policy can be renewed to support the development of ecosystems capable of improving the velocity, quality, and democratization of innovation.

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SUSAN D. RENOE AND CHRISTOFER NELSON

# Creating a Science-Engaged Public

True public engagement must build upon current investments in communication, education, and outreach to seek community involvement in shaping the research enterprise.

The federal government has the responsibility to serve all people through its programs, policies, and funding. This means it must lead the way in the creation and implementation of programs for engaging the public with science, which can ensure everyone has the tools to learn about, engage in, contribute to, and benefit from the results of scientific research and technological innovation. Doing so necessitates a shift in thinking from a need for the public to *understand* science to a desire for the public to *engage* with science in beneficial ways. According to the American Association for the Advancement of Science,

> Public engagement with science describes intentional, meaningful interactions that provide opportunities for mutual learning between scientists and members of the public. Mutual learning refers not just to the acquisition of knowledge, but also to increased familiarity with a breadth of perspectives, frames, and worldviews.

Strengthening the public's engagement with science is critical because nearly every challenge society faces—from climate change to pandemic preparedness and inclusive economic growth—requires significant taxpayer investment in scientific research and technological development. Members of the public need to understand how their dollars are being spent, have the chance to shape and provide input on the implications of these discoveries, and ensure that solutions benefit their communities. Indeed, the federal government's commitments on equity, public health, and the economy will not be possible without greater engagement with science and technology. True public engagement must build upon current investments in communication, education, and outreach to seek community involvement in shaping the research enterprise.

Without efforts to engage all people intentionally and equitably in science and technology, the research community will end up perpetuating the systems and structures that have marginalized groups and individuals for centuries. In a world where science and technology affect every aspect of people's lives and society, creating a science-engaged public is essential to ensuring that all can fully participate in that society. In short, both the process and results of science must be equitable, and meeting that goal requires more people to be engaged.

One mechanism that ought to be central to this vision is a new national strategy for public engagement in science. National strategies are federal tools for facilitating targeted investments and outcomes across the US government. By coordinating the activity of federal agencies, in consultation with community groups and the private sector, these strategies have proven effective in directing federal resources, increasing practitioner capacity, and achieving public outcomes on topics as diverse as homelessness; science, technology, engineering, and mathematics (STEM) education; and federal data. They often include commitments to specific actions across federal agencies and include mechanisms for further interagency coordination as well as measurement and accountability. A national strategy on science engagement would mimic other successful initiatives by increasing agency coordination to document current practices, building a shared language around science engagement, and scaling promising practices across the federal government.

In fact, the foundation for such a strategy has already begun to take shape in recent years. In 2020, the Day One Project laid out a bold plan of action that a new presidential administration could take for making public engagement with science a federal priority. A new national strategy should include three key components: increased federal investments in public engagement tied to research funding; strong incentives and structures for federally funded researchers to engage the public in their research (including through partnerships with public engagement practitioners and organizations as well as community groups); and coordination between the public and private sectors to ensure complementary efforts and collaborative investments in public engagement with science and technology.

## Investing in public engagement

As with all national goals, strategic investment is paramount. To engage all Americans in science and technology and empower communities to solve problems, the federal government should work to ensure that federal agencies dedicate portions of their research development budgets to public engagement, while at the same time investing in capacity-building for federal agency staff, scientists, and community partners to scale effective models. In particular, the federal government should seek to expand collaboration between communities and federally funded researchers through proven approaches including community-embedded research, cocreated citizen science, and accessible scientific tools.

For example, the National Institutes of Health established the Community-Based Participatory Research (CBPR) program to support "collaborative interventions that involve scientific researchers and community members," according to the program description. These approaches facilitate better outcomes for both medical research and patients and support overall community health. Strong arguments have been made to expand CBPR approaches across the health care field, including psychology research. Beyond medicine, the National Oceanographic and Atmospheric Administration (NOAA) has funded dozens of community-centered approaches to addressing environmental resilience. Through NOAA's Environmental Literacy Program grants, the federal government has funded citizen science, youth education and leadership, community dialogues, and more in order to support education and engagement efforts that are grounded in science and advance community priorities.

New investments will build on programs like these and many others that have developed new tools, authorities, and programs that allow federal programs to gather input on science and technology from the public, collaborate with communities to advance shared goals, and source solutions to science and technology problems from a wider range of innovators. Bringing these existing tools and authorities together with new approaches in a national strategy will promote more efficient investment of resources—and ultimately provide more effective outcomes for researchers and communities.

Scaling federal investment in public engagement could follow the example of, and build on, the work done in the last 20 years to increase investment in and capacity for open innovation approaches. While some open innovation approaches, such as weather forecasting, have been around for more than 100 years, in the early 2000s, agencies began increasing their use of these approaches, specifically incentive prizes and innovation challenges, to solve difficult technological and scientific problems. The first systematic analyses of the use of these mechanisms were undertaken by private foundations and research firms, as well as independent government agencies, in an effort to characterize the work underway and the opportunities to scale. Starting in 2012, the White House Office of Science and Technology Policy began issuing an annual report to Congress on federal use of prize authorities in order to track both the financial investment and the growing capacity for engaging in these efforts.

Currently, there is no equivalent reporting on how much money the federal government invests in public engagement with science or a broad understanding of the capabilities agencies draw on to engage the public. Therefore, a national strategy must start with understanding the current baseline in order to identify specific needs and opportunities for increasing this investment over time.

## Incentives for public engagement

Beyond investment, however, appropriate incentives for public engagement must be integrated into multiple levels of federal science and technology policy. Again, the groundwork is already in place. All research grants awarded by the National Science Foundation (NSF) are now evaluated on both their potential to transform their field (intellectual merit) and their ability to have significant societal impact (broader impacts). For more than 20 years, the NSF Broader Impacts (BI) criterion has provided an incentive for researchers to engage the public in their research, and proposals submitted without BI sections can be returned without review. BI is viewed as an integral component of the proposal and figures prominently in reviews, providing a strong incentive for researchers to take public engagement seriously in their projects.

A national strategy for public engagement with science should leverage ongoing efforts to strengthen the current NSF BI criterion and infrastructure such as the NSF-funded Center for Advancing Research Impact in Society, and expand existing public engagement programming and proposal requirements in other agencies. Programs to broaden participation of members of underrepresented groups and to prepare the next generation of scientists currently exist in most federal agencies, but requiring all research proposals to include public engagement plans will necessitate intentionality and substantial infrastructure and support.

## Partnerships for public engagement

A final key component of the national strategy should be cultivation of public-private partnerships to develop complementary and collaborative investments in public engagement—including private companies, philanthropies, and community groups that are increasingly engaging the public in their scientific research and technological development.

The federal government should work closely with these groups in crafting this national strategy, using it as an opportunity to learn promising practices, highlight model approaches, and enlist collaborators for future efforts. This public-private collaboration must also include the practitioners who have experience in equity-centered, community-embedded research, as well as expertise in communications and engagement that develop the social, behavioral, and cultural fluencies required to build and sustain lasting relationships. A successful example of such a partnership is the Science Public Engagement Partnership (SciPEP), a collaboration between The Kavli Foundation and the Department of Energy's Office of Science. At its core, SciPEP works to ensure scientists are effective communicators and able to actively engage the public.

Currently, most community-centered public engagement in science and technology is being driven by nonprofit organizations, private foundations, and even for-profit companies working in areas such as environmental science and medical clinical trial participation. The knowledge, experience, and lessons gained in these efforts should inform development of a national strategy. At the same time, the federal government can partner with these groups to leverage their capabilities, expertise, and deep community relationships to demonstrate the impact of public engagement approaches and more rapidly scale up public engagement efforts.

## Implementing a national strategy

A national strategy would go a long way to building robust mechanisms for public engagement into our science and technology policy for the next 75 years. In the shorter term, we suggest the following immediate action steps.

First, the Office of Management and Budget (OMB) and Office of Science and Technology Policy (OSTP) should clarify existing authorities that agencies can use to engage the public in science and technology. To more equitably increase the public's engagement with science and technology, federal agencies may need to take new approaches to making grants, entering into contracts and cooperative agreements, and engaging in other innovations. In OSTP's role as a coordinator across federal science agencies, it should undertake a concerted effort to understand the barriers that agencies are facing and should work with OMB to help agencies clarify how they can work within their current authorities to increase their support of public engagement with science.

Second, OSTP and NSF should convene an interagency working group to explore applying lessons learned from the NSF BI criterion to public engagement capacity-building in other federal agencies that fund extramural researchers.

Third, the National Science and Technology Council should revitalize the Interagency Working Group on Open Science—established in 2013 to help make results of federally funded science more accessible to the public—and charge it with expanded responsibilities. A key assignment should be developing a formal national strategy for public engagement that includes commitments adopted by all participating federal agencies and is created in consultation with researchers, public engagement practitioners, and community members.

A national strategy for cultivating a science-engaged public will ensure that research discoveries are enhanced by the knowledge, expertise, and priorities of all people, including those from communities and groups currently underrepresented in the process and outcomes. Expanding who is engaged in the scientific process will ensure rigorous research and a transparent process, yielding results with the potential to be more readily used and valued by members of the public. Above all, it will further individual and community capacity and agency to use scientific methods and technological tools to explore, create, and innovate.

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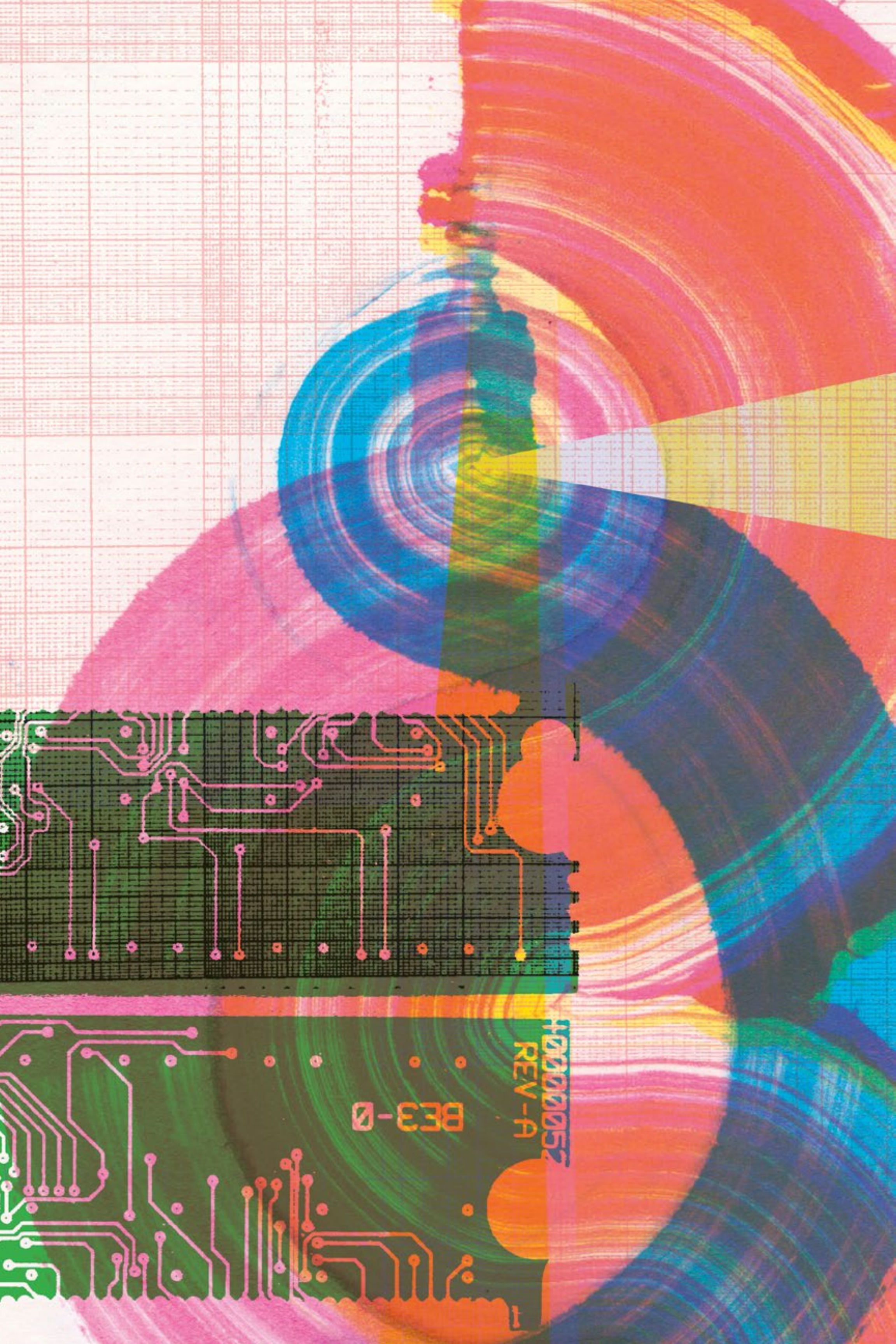
REV-A

# Creating Meaningful Diversity, Equity, and Inclusion

FREEMAN A. HRABOWSKI III AND PETER H. HENDERSON

# Nothing Succeeds Like Success

To expand underrepresented minority participation in science and engineering, we need to fund the institutions and programs that are already graduating diverse students.

In February 2020, the National Academy of Sciences and the Kavli Foundation organized a convocation marking the 75th anniversary of *Science, the Endless Frontier*, the landmark report written by Vannevar Bush at the end of World War II that advocated for a much larger federal role in funding scientific research. Speakers at the convocation highlighted the remarkable success of our nation's research and development efforts that resulted from the 1945 report. At the same time the convocation inadvertently highlighted a continuing challenge for the scientific community: lack of racial and ethnic diversity. With few African Americans or Hispanics in the audience and only two African Americans among the speakers, the participants did not reflect the diverse population of the United States.

Not long after the meeting, the United States was severely tested by three crises that would lay bare a deep racial divide in our country. The still-developing COVID-19 pandemic hit communities of color disproportionately, revealing significant health disparities. The recession that stemmed from the COVID-19 lockdown exposed racial inequities in the economy as well. Then the shocking death of George Floyd in May 2020 provided yet another example of racial disparities in policing and criminal justice—and catalyzed protests across the country by people of all backgrounds.

These deeply disrupting events converged to elevate the discussion of structural racism in a way we had not seen in this country for decades. Indeed, in the earliest days of the pandemic, the two of us found ourselves urging elected officials and health experts to disaggregate COVID-19 case and mortality data by race and ethnicity. That officials had not collected and published the data in this way at the outset indicated the lack of awareness or low level of importance they gave to issues of race at the time.

After the death of George Floyd and the ensuing protests, the nation's collective consciousness changed. Many individuals who had previously avoided conversations about race came to the table willing to have deeper discussions and take action in government, corporations, nonprofits, foundations, and the media. This shift created a moment when we as a country might "move the needle" on improving race relations and enhancing racial equity and inclusion—even against the backdrop of one of the most divisive US presidential elections in memory.

Can we make the most of this moment and enact lasting change, both in society and—more specifically for us—in the scientific community? Do we have the same sense of urgency about the inclusion of and success for those who historically have been marginalized that we have about battling COVID-19 or curing cancer? Can we channel this energy into an urgent, sustained, comprehensive, intensive, and coordinated national effort, such as that recommended in the National Academies of Sciences, Engineering, and Medicine in *Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads*, a 2011 report?

Inclusion is not just a matter of equity, although we should value that as well. We all benefit when we increase inclusion because we draw on the talent available in every group. When we have greater diversity of representation, we also have greater diversity of information, knowledge, lived experience, and perspectives—each of which enhances discovery and innovation. When the science and engineering community looks like the United States, we find greater trust in and support for that community across groups in the population.

We are encouraged by recent statements promoting inclusion from leaders in the federal scientific establishment. Eric Lander, director of the White House Office of Science and Technology Policy, argued in his first message after being confirmed by the US Senate, "To succeed, America will need to draw on all of its assets—chief among them, our unrivaled diversity." He noted that "science and technology have too often been unwelcoming or inaccessible to many Americans due to their gender, race, resources, or geography."

Sethuraman Panchanathan, director of the National Science Foundation, likewise in one of his first communications as director included diversity as an essential goal for the NSF. He articulated a vision that focuses on sustaining US global leadership in science and engineering by investing in strategic opportunities and creating a more inclusive scientific community.

Francis Collins, director of the National Institutes of Health, and his colleagues recently acknowledged that "structural racism has been a chronic problem in our society, and biomedical science is far from free of its stain." They have developed a new framework for NIH that includes "understanding barriers; developing robust health disparities/equity research; improving its internal culture; being transparent and accountable; and changing the extramural ecosystem so that diversity, equity, and inclusion are reflected in funded research and the biomedical workforce."

To move beyond a verbal commitment to greater representation and diversity, however, we will need to bring meaningful resources to science and engineering education and research, and make sure these resources are allocated wisely.

## At a crossroads

The Academies' 2011 *Crossroads* report examined the dimensions of racial and ethnic underrepresentation in science and engineering and articulated a set of promising solutions across the science, technology, engineering, and mathematics (STEM) pathway, beginning with K-12 education and then extending to undergraduate, graduate, and postdoctoral education and training. The committee urged a priority focus on enhancing undergraduate education for prepared underrepresented minorities who sought to major in STEM. The committee called this the "low-hanging fruit" because so many who are prepared and interested in science end up switching majors and leaving the field—often because of an educational culture that focuses on "weeding out" students instead of supporting their learning and success. This culture, in fact, leads many white and Asian students to leave science as well, although it has a disproportionate impact on minorities who are underrepresented in STEM: women, persons with disabilities, Blacks, Hispanics, and American Indians or Alaska Natives.

The *Crossroads* committee recommended several strategies to try to increase underrepresented minority success. First, funders and universities should draw on lessons learned from successful models and apply these practices to develop programs that provide students with academic, social, and financial support. Second, faculty and academic leaders should focus on course redesign, especially for introductory courses in the sciences, to support the success of students rather than weeding students out. (This recommendation was echoed in other reports, including one in 2012 by the President's Council of Advisors on Science and Technology.) Third, the NSF should create a targeted program to support the hiring and advancement of minority faculty in science, technology, engineering, and medicine modeled on the highly successful NSF ADVANCE program for gender equity, which has increased the representation and success of women faculty in STEM for the past two decades.

Since 2011, we have written articles—in this journal, the *Proceedings of the National Academy of Sciences*, and *The Atlantic*—updating the data in the *Crossroads* report. With each new piece, we have provided a fresh look at the issues and urged greater action by federal agencies, foundations, and higher education institutions. But here we are 10 years later. Have we moved the needle? Regarding diversity in doctoral education in the natural sciences and engineering, the answer is "not much."

While African Americans make up 13% of the US population, Blacks who were US citizens or permanent residents in 2011 when the *Crossroads* report was published earned just 2.2% of all new PhDs awarded by US universities in the natural sciences and engineering. That figure increased—if you can call it that—to 2.3% in 2018. Similarly, while Hispanics comprise 18% of the US population, those who were US citizens or permanent residents earned 2.9% of all new PhDs awarded by US universities in the natural sciences and engineering in 2011, a figure that increased to 3.7% in 2018.

We have seen somewhat more progress in the social and behavioral sciences, although there is still plenty of room for improvement. Blacks as a percentage of new PhDs in these fields increased from 6.2% in 2011 to 7.0% in 2018; Hispanics as a percentage increased from 6.0% to 7.9% during that period.

Here, we focus on the natural sciences and engineering, fields that have proved resistant to change. We are further concerned because there has been some erosion of progress in racial and ethnic diversity in these fields at the bachelor's degree level. We cannot make progress at the doctorate level without progress at the undergraduate level, which prepares students for graduate and professional study.

The percent of new bachelor's degrees awarded to African Americans has been flat in the biological and life sciences (it was 6.7% in 2008 and 6.8% in 2018). In the earth and physical sciences, the numbers were also relatively flat (at 5.6% in 2008 and 5.4% in 2018). In that same time period, the percentage of bachelor's degrees has declined slightly for engineering (from 4.7% to 4.3%) and for mathematics and statistics (from 5.3% to 4.9%). Of note, the percentage for African Americans has dropped more significantly for computer science during these years, from 10.8% to 8.9%.

The natural sciences and engineering present a different picture than the social sciences, where there has been some movement. According to NSF data, the percentage of new bachelor's degrees awarded to African Americans has increased slightly for psychology (from 11.2% to 12.2%) and for the social sciences (from 10.2% to 11.2%) over the same period of 2008 to 2018. In these fields, the percentages are nearing parity with representation in the US population.

## Learning from successful institutions

We do not have to accept stagnant or downward trends in STEM diversity at the undergraduate level. Several institutions have demonstrated how we can increase the numbers and support the success of underrepresented minorities such as Hispanics and Blacks in the natural sciences and engineering. As shown in Tables 1 and 2, institutions that have prepared undergraduates for doctoral study include historically Black colleges and universities (HBCUs), high Hispanic enrollment institutions (HHEs), minority-serving institutions (MSIs) and predominantly white institutions (PWIs). We should learn from them and build on what they have accomplished.

For Blacks, the top baccalaureate institutions of doctorates in the natural sciences and engineering include HBCUs such as North Carolina A&T State University (Greensboro), Howard University (Washington, DC), Florida A&M University (Tallahassee), Spelman College (Atlanta), and Xavier University of Louisiana (New Orleans). Non-HBCU institutions that are top baccalaureate institutions for Black doctorates in these fields are the University of Maryland, Baltimore County (UMBC, where both of us work), University of Maryland (College Park), University of Florida (Gainesville), Massachusetts Institute of Technology (Cambridge), and the University of North Carolina at Chapel Hill.

For Hispanics, the top baccalaureate institutions for doctorates in the natural sciences and engineering are—by far—the University of Puerto Rico (Mayaguez) and the University of Puerto Rico (Río Piedras). Other top institutions with high Hispanic enrollment are Florida International University (Miami), University of Texas at El Paso, and the University of Texas at Austin. Non-HHE institutions that are top baccalaureate institutions for Hispanics in these fields are the University of Florida (Gainesville), Massachusetts Institute of Technology (Cambridge), University of California, Berkeley, as well as UC Davis and UCLA.

As we have written previously, including in *Issues*, we at UMBC have had significant success in preparing African American undergraduates who have then been accepted to our natural science and engineering graduate program and earned their doctoral degree through our Meyerhoff Scholars Program. This program, established in 1989 with support from Robert and Jane Meyerhoff, recruits top minority and majority students in mathematics and sciences who have demonstrated a commitment to diversity in STEM. We instill high expectations in these students, including the goal of doctoral study. We provide financial support so students can focus on their studies, as well as build community to provide a sense of belonging along with vital social and academic support. We encourage students to study in groups and develop faculty allies who bring students into their research, reinforcing learning and promoting identification as a scientist.

Since 1993 more than 1,400 students, predominantly underrepresented minorities, have participated in the program and graduated from UMBC with a bachelor's degree in science and engineering. Most of these alumni have continued on to graduate or professional programs, earning 359 PhDs (which includes 66 MD-PhDs), 180 MD or DO degrees, and more than 300 master's degrees, primarily in engineering and computer science. Another 340 alumni are currently enrolled in graduate or professional degree programs. According to NSF data, UMBC is the number one baccalaureate institution for African American undergraduates who go on to earn PhDs in the natural sciences and engineering, as well as doctorates in the life sciences, mathematics, and computer science. According to the Association of American Medical Colleges, UMBC is the number one baccalaureate institution for African American undergraduates who go on to earn MD-PhDs.

To appreciate the success of this program, one must also understand the work we did simultaneously to change our institutional culture. As we have found, an institution's culture—reflected in its values, norms, and priorities—can enable or block meaningful change. To support the success of the Meyerhoff program, we also worked to change the attitudes of leadership, faculty, and staff about teaching, learning, and student success.

Many at our institution originally assumed that academic quality—particularly in science and engineering—could be measured by how rigorous a class could be, even if that meant a high number of students earned lower than a C grade or even failed. Over time, we changed the goal from weeding out students to supporting their learning and success while maintaining academic rigor. We discussed the data on student success, named the problem, created new goals, cultivated allies, and empowered change agents among staff and faculty. These conversations were difficult but led to simultaneous efforts to increase student completion (i.e., six-year graduation rates) and redesign courses (especially introductory courses) across departments to support student learning and success. Over the past 30 years, our six-year completion rate has doubled and the gap in completion rates between white and Black students has disappeared. The success of the Meyerhoff program and these institutional changes reinforced each other.

## Investing in success

A 2021 article in *Science* from a diverse group of high-profile scientists outlined several key steps to increasing broad representation in the scientific workforce. Among other recommendations, the authors urged Congress to establish and fund an interagency National Science and Engineering Diversity Initiative (NSEDI) with coordination and support from the White House Office of Science and Technology Policy. The NSEDI might, they wrote, require funding of "at least 10 billion dollars for several years—a substantial sum but only about 2% of national spending (public and private) on research and development and less than 8% of the federal government science budget."

These and any other funds that target increasing diversity should be allocated judiciously. We have enough data from the past decade to show which institutions have a proven track record of graduating underrepresented minority students who go on to doctoral programs. HBCUs and HHEs have already demonstrated their value in this endeavor, but so too have other institutions that graduate a substantial number of Blacks and Hispanics who go on to earn PhDs. Thus, financial resources should flow to institutions that most successfully contribute to greater diversity—regardless of institutional type.

Funders could provide these institutions with resources to create new Centers of Excellence for STEM Diversity, for example, that would pursue the goal of doubling the number of African American or Latinx undergraduates who earn a bachelor's degree in the natural sciences and engineering and are prepared to go on to graduate programs. Such a goal is demonstrably within reach.

If the top 30 baccalaureate institutions for African Americans (listed in Table 1) were to double the number of graduates they produce who go on to earn PhDs in the natural sciences and engineering, we would see a 31% increase over one decade in the numbers of African Americans with advanced degrees in these fields. If the top 30 baccalaureate institutions for Latinx students (listed in Table 2) were to double the number of graduates they produce in these fields who go on to earn PhDs over 10 years, we would see a 43% increase overall in the number of Latinx PhDs in the natural sciences and engineering.

Several institutions have already doubled or even tripled their number of science graduates from underrepresented minority groups. For example, 15 African American alumni from the University of North Carolina at Chapel Hill went on to earn PhDs in the natural sciences and engineering from 2002 to 2006—the equivalent of 3 per year. Just a few years later, between 2010 and 2019, nearly 60 African American alumni from UNC Chapel Hill earned PhDs in the natural sciences and engineering—the equivalent of 6 per year. Meanwhile at UMBC, we went from 5 graduates who earned PhDs in the natural sciences and engineering per year to nearly 15, almost tripling our numbers. Similarly, the University of Florida nearly tripled its number of Latinx alumni earning PhDs in the natural sciences and engineering, from 8 to 23 per year, moving them into fourth place, behind the University of Puerto Rico's Mayaguez and Rio Piedras campuses and the University of Texas at El Paso.

Nothing succeeds like success**.** Institutions receiving money to create new Centers of Excellence for STEM Diversity should draw on the most promising models to develop their programming. For example, the Howard Hughes Medical Institute provided some of the funds used by Penn State University and the University of North Carolina to adapt the Meyerhoff program to their own campuses. New programs funded by the Chan Zuckerberg Initiative at the University of California, Berkeley, and the University of California, San Diego, are also adapting the Meyerhoff program at their campuses. Howard University's Karsh STEM Scholars Program is a Meyerhoff-like program at an HBCU. Substantive interaction among science faculty within and across these institutions has also been crucial to their success. Support for networking across campuses that are innovating and making a difference allows faculty and staff to have conversations about challenges they are facing and communication about what works. We cannot emphasize enough the importance of sharing information in this way—sharing that can be ad hoc and informal or more formal and involve meetings and conferences.

One practice that needs to be more widely adopted is to provide financial scholarship support to underrepresented minority undergraduates in science, technology, engineering, and medicine. The scientific community understands well the importance of providing financial support for graduate students; we should also support undergraduates to allow them the opportunity to focus on academics instead of working part-time outside of school—a major distraction that reduces the time available for studying, learning, conducting research, interacting with peers, and developing as a scientist.

The transition from graduate school into their careers is another period when underrepresented minorities can need support and benefit from greater attention. Many years ago, we assumed that universities would quickly hire minority graduates with advanced degrees. This has not turned out to be the case. Indeed, many of these new graduates flounder at this transition point and end up leaving academia for positions in industry, nonprofit organizations, or government. While they might achieve personal success in these other sectors, we as a nation are missing out on the opportunity to increase faculty diversity and benefit from the contributions of these researchers to academic science and engineering.

As a start, educational institutions can help bridge this gap by taking stock of some of their own practices. For example, faculty should not merely act as advisors but also be champions for their underrepresented minority students—connecting them to faculty career opportunities and strongly supporting their applications. In addition, institutions should implement policies that encourage their departments to engage in broader, more equitable faculty searches. With better processes, search committees can cast a wider net, broaden the applicant pool, and create welcoming environments for applicants during the recruitment process. At UMBC, we have developed the STRIDE program to help departments and search committees improve their diversity hiring practices and overcome implicit bias. We have found greater adoption and follow-through on diversity goals when majority group faculty provide this training to their majority group colleagues.

## Looking forward

Producing scientists is about more than increasing the numbers. It is about changing attitudes and transforming the lives of people. It is about showing our society what is possible when we invest in the talent of all our youth. The most poignant recent example is that of Kizzmekia Corbett, an African American immunologist who is now on the faculty at the T. H. Chan School of Public Health at Harvard University. Corbett grew up in rural North Carolina, came to UMBC as a 17-year-old, was a Meyerhoff Scholar, earned her PhD at the University of North Carolina at Chapel Hill, and worked at the NIH as a postdoctoral fellow. She continued her career at the National Institute of Allergy and Infectious Diseases (NIAID), where she worked on vaccine development.

Few, if any, people have asked, “Has a Black woman ever created a vaccine, anywhere in the world?” Today all one needs to do to understand how success changes attitudes is to watch the faces of little girls and young women when they hear Kissmekia Corbett talk about leading the NIAID team that created the mRNA technology that is central to the COVID-19 vaccine. The message is clear: investing in young people, replicating best practices of effective programs, and committing substantially more money to support Black and minority scientists can indeed move the needle and also tackle fundamental scientific and public health problems for humankind.

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**Table 1**. Top 30 US baccalaureate-origin institutions of 2010–2019 Black doctorate recipients in the natural sciences and engineering, by institutional control, 2018 Carnegie classification, and HBCU status

| Rank | Baccalaureate institution | Institutional control | 2018 Carnegie classification | HBCU status | 2010–2019 Black S&E doctorate recipients |
|---|---|---|---|---|---|
| | All Black science and engineering doctorate recipients[a] | na | na | na | 8,095 |
| | From US baccalaureate-origin institutions | na | na | na | 6,833 |
| | From foreign baccalaureate-origin institutions | na | na | na | 1,053 |
| | From unreported baccalaureate-origin institutions | na | na | na | 209 |
| 1 | U. Maryland, Baltimore County | Public | Research-high | No | 146 |
| 2 | North Carolina Agricultural and Technical State U. | Public | Research-high | Yes | 129 |
| 3 | Howard U. | Private | Research-high | Yes | 125 |
| 4 | Florida A&M U. | Public | Research-high | Yes | 111 |
| 4 | Spelman C. | Private | Baccalaureate | Yes | 111 |
| 6 | Xavier U. Louisiana | Private | Masters granting | Yes | 90 |
| 7 | U. Maryland, College Park | Public | Research-very high | No | 88 |
| 8 | U. Florida | Public | Research-very high | No | 86 |
| 9 | Morgan State U. | Public | Research-high | Yes | 83 |
| 10 | Jackson State U. | Public | Research-high | Yes | 81 |
| 11 | Morehouse C. | Private | Baccalaureate | Yes | 74 |
| 12 | Hampton U. | Private | Research-high | Yes | 72 |

| | | | | | |
|---|---|---|---|---|---|
| 13 | Southern U. and A&M C., Baton Rouge | Public | Masters granting | Yes | 69 |
| 14 | Tuskegee U. | Private | Masters granting | Yes | 65 |
| 15 | Massachusetts Institute of Technology | Private | Research-very high | No | 63 |
| 16 | U. North Carolina at Chapel Hill | Public | Research-very high | No | 59 |
| 17 | Florida State U. | Public | Research-very high | No | 56 |
| 18 | Georgia Institute of Technology | Public | Research-very high | No | 54 |
| 19 | U. Illinois, Urbana-Champaign | Public | Research-very high | No | 53 |
| 19 | U. Michigan, Ann Arbor | Public | Research-very high | No | 53 |
| 21 | Tennessee State U. | Public | Research-high | Yes | 50 |
| 22 | CUNY, City C. | Public | Research-high | No | 44 |
| 22 | Louisiana State U., Baton Rouge | Public | Research-very high | No | 44 |
| 22 | Oakwood U. | Private | Baccalaureate | Yes | 44 |
| 25 | Clemson U. | Public | Research-very high | No | 43 |
| 25 | North Carolina State U. | Public | Research-very high | No | 43 |
| 27 | Rutgers, State U. New Jersey, New Brunswick | Public | Research-very high | No | 42 |
| 28 | Alabama A&M U. | Public | Masters granting | Yes | 41 |
| 28 | Cornell U. | Private | Research-very high | No | 41 |
| 30 | Prairie View A&M U. | Public | Masters granting | Yes | 40 |

HBCU = historically Black colleges and universities; na = not applicable; S&E = science and engineering.
[a] For the purposes of this table, science and engineering includes health sciences and excludes psychology and social sciences.
NOTES: Includes only US citizens and permanent residents. Institutions with the same number of doctorate recipients are listed alphabetically. SOURCE: National Science Foundation, National Center for Science and Engineering Statistics, 2019 Survey of Earned Doctorates, Special tabulation (RTI, May 2021).

**Table 2.** Top 30 US baccalaureate-origin institutions of 2010–2019 Hispanic or Latino doctorate recipients in the natural sciences and engineering, by institutional control, 2018 Carnegie classification, and HHE status

| Rank | Baccalaureate institution | Institutional control | 2018 Carnegie classification | HHE status | 2010–2019 Hispanic S&E doctorate recipients |
|---|---|---|---|---|---|
| | All Hispanic or Latino S&E doctorate recipients[a] | na | na | na | 10,894 |
| | From US baccalaureate-origin institutions | na | na | na | 9,607 |
| | From foreign baccalaureate-origin institutions | na | na | na | 1,075 |
| | From unreported baccalaureate-origin institutions | na | na | na | 212 |
| 1 | U. Puerto Rico, Mayaguez | Public | Masters granting | Yes | 577 |
| 2 | U. Puerto Rico, Río Piedras | Public | Research-high | Yes | 333 |
| 3 | U. Texas at El Paso | Public | Research-very high | Yes | 241 |
| 4 | U. Florida | Public | Research-very high | No | 233 |
| 5 | Florida International U. | Public | Research-very high | Yes | 181 |
| 6 | U. California, Los Angeles | Public | Research-very high | No | 175 |
| 7 | U. California, Berkeley | Public | Research-very high | No | 161 |
| 8 | U. Texas at Austin | Public | Research-very high | Yes | 157 |
| 9 | Massachusetts Institute of Technology | Private | Research-very high | No | 155 |
| 10 | U. California, Davis | Public | Research-very high | No | 152 |
| 11 | U. California, Irvine | Public | Research-very high | Yes | 135 |
| 12 | Texas A&M U., College Station and Health Science Center | Public | Research-very high | Yes | 132 |
| 13 | U. California, San Diego | Public | Research-very high | No | 126 |
| 14 | U. Arizona | Public | Research-very high | Yes | 121 |
| 15 | U. New Mexico, Albuquerque | Public | Research-very high | Yes | 118 |
| 16 | U. Miami | Private | Research-very high | No | 103 |
| 17 | U. California, Riverside | Public | Research-very high | Yes | 97 |
| 18 | U. Puerto Rico, Humacao | Public | Baccalaureate | Yes | 90 |
| 19 | Cornell U. | Private | Research-very high | No | 87 |
| 20 | New Mexico State U., Las Cruces | Public | Research-high | Yes | 86 |
| 21 | Stanford U. | Private | Research-very high | No | 82 |
| 22 | U. California, Santa Cruz | Public | Research-very high | Yes | 81 |
| 23 | Florida State U. | Public | Research-very high | No | 77 |
| 24 | U. Texas, San Antonio | Public | Research-high | Yes | 73 |
| 25 | U. California, Santa Barbara | Public | Research-very high | Yes | 71 |
| 26 | Arizona State U. | Public | Research-very high | No | 66 |
| 27 | U. Illinois, Urbana-Champaign | Public | Research-very high | No | 65 |
| 28 | U. Puerto Rico, Cayey | Public | Baccalaureate | Yes | 64 |
| 29 | U. Central Florida | Public | Research-very high | Yes | 63 |
| 30 | Rice U. | Private | Research-very high | No | 60 |

HHE = High Hispanic enrollment; na = not applicable; S&E = science and engineering.

[a] For the purposes of this table, science and engineering includes health sciences and excludes psychology and social sciences.

NOTES: Includes only US citizens and permanent residents. Includes only institutions in the US. Institutions with the same number of doctorate recipients are listed alphabetically. SOURCE: National Science Foundation, National Center for Science and Engineering Statistics, 2019 Survey of Earned Doctorates, Special tabulation (RTI, May 2021).

WAYNE A. I. FREDERICK

# There Can Be No Innovation Without Diversity

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For society to advance, we need solutions and upgrades that work for everyone without leaving anyone behind.

The various vaccines against the virus that causes COVID-19 could prove to be among the most important medical innovations of this generation, for reasons that extend far beyond the scientific and technological advances underpinning their creation. As they were being developed, the United States was experiencing a new wave of racial reckoning. The confluence of George Floyd's murder and the recognition that people of color were being disproportionately affected by the pandemic prompted widespread soul-searching to uncover past mistakes and chart a course to do better by these communities in the future.

As a direct result, biomedical companies placed greater emphasis on diversity and representation among participants in the clinical trials for the vaccines than has been seen at practically any other time in US history. Increased attention was also given to ensuring that lower-resourced communities and people of color had access to the vaccines, which remain the best tools available to protect individuals from the novel coronavirus and to empower society to move past this crisis.

To be sure, society floundered on both accounts. The participation of African American people in many COVID-19 vaccine trials still fell short of the almost 13% of Black Americans in the general population, even as many experts advocated for having people of color represent an even higher proportion of participants due to the outsized toll the pandemic had taken on these communities. In addition, many Black men and women, particularly those who lived in predominantly African American communities, did not have equal access to vaccination—especially as the vaccines were first being distributed. Philadelphia, for example, reported in April 2021 that its Black and Latinx residents were receiving the vaccine at around half the rate of its white population.

Despite these shortcomings, society has made progress on these fronts. Prior to the pandemic, most clinical trials only included around 5% Black participation on average. Diversity in COVID-19 vaccine trials was dramatically better: 9.8% of the Pfizer trial participants were Black and 9.7% of the Moderna participants were Black. And after initial setbacks, vaccine access improved dramatically for communities of color.

In thinking about the legacy of the COVID-19 vaccine, it is imperative to consider its social impact as much as its scientific ingenuity. Technological advancements will always be governed—either enhanced or restrained—by the context in which they are deployed. Inventing new and improved methods for creating vaccines won't stop a global pandemic if people can't or won't get vaccinated. Improving telehealth capabilities means little if patients do not have reliable internet connections or devices to support remote appointments. And generating new life-saving medications will only ever amount to theoretical benefits if people can't afford them and insurance won't cover them.

True innovation requires simultaneous improvements to social infrastructure and societal values. Real innovation cannot be accomplished without an emphasis on equity and justice. Actual innovation requires a diversity of voices and perspectives at all operational levels, including the scientists in the laboratories who develop these new approaches, the physicians who leverage these technological advancements, and, most importantly, the people who benefit from them. Otherwise, studies show, the course of progress is often hampered by groupthink and pursuing only the "safest" avenues of research.

Thus, unfortunately, true innovation is almost impossible in large swaths of American society as it exists today. There is too little diversity and representation in professional ranks and too much segregation in the general population. So often Black and white communities live in separate and unequal worlds, even if they happen to live in close proximity. In Washington, DC, for instance, the life expectancy for Black men living in Ward 7 and Ward 8 is more than 20 years less than for white women living in Ward 3, only a few miles away.

## One pathway to greater innovation

Fortunately, as greater emphasis is placed on diversity, science is becoming more diverse. But there is much distance to cover and many milestones to reach before medical advancements can benefit all people equally and amount to real medical innovation.

Although the health care inequities experienced by African American patients are complex and multifactorial, the relative scarcity of Black physicians helps to explain a significant source of the difference. Black Americans represent 13% of the national population, yet only 5% of doctors are Black—a pernicious disparity that has hardly changed in US medicine for over a century.

Unconscious bias is rampant in the medical establishment. Black patients often struggle to receive pain medication because white health care providers discount or dismiss their discomfort. They are frequently blamed for their problems in ways that white patients are not. A missed appointment is perceived to be a sign that they do not take their health care seriously, even if the reality is that they were unable to take off work to make the appointment or did not have adequate transportation to make it on time.

Research shows that Black physicians provide better care for Black patients, focus on researching and solving problems that primarily affect African American communities, and display greater cultural sensitivity in dealing with a diversity of patients. Introducing more Black doctors into the medical ranks would not only enhance the care patients receive but would also help reduce some of the prejudice that has permeated the profession.

The first step to diversifying an industry is to diversify the pipelines that feed into it. Ensuring Black students are better represented at the highest levels of higher education will ensure that Black men and women stand a greater chance of entering into careers in the in-demand fields of science, technology, engineering, and mathematics (STEM). But for many aspiring Black doctors and scientists, medical or graduate school is often unattainable because they cannot afford the long-term salary deferment or the exorbitant cost of a postgraduate education.

Although Black communities and institutions have talked about the importance of diversity in the medical profession for years, the urgency of cultivating Black physicians started receiving more widespread recognition only recently. In September 2020, Bloomberg Philanthropies donated $100 million to the four historically Black medical schools. The gift was intended to help increase the number of Black doctors by reducing the debt burden experienced by Black medical students.

Training more Black doctors is a straightforward process. More Black Americans want to become doctors than end up completing—or even beginning—their schooling. So those Black individuals who have the talent and the drive to become doctors need to be connected with the resources required to bring their aspirations to fruition. With more support from institutions such as Bloomberg that can reduce the debt burden and provide resources as Black students make their way through medical school, this essential profession can become even more diverse.

Greater diversity is needed throughout the medical research enterprise. Society needs more Black scientists, more Black researchers, more Black research administrators. According to a 2019 report, 40% of Black students who start STEM studies switch out at some point in their educational careers. It is imperative that Black students are encouraged and motivated to stick with STEM.

For Black men and women to reach the pinnacle of a STEM professional career, they must be engaged from a young age. At Howard University, we created a middle school right on our campus focused on math and science. From an early age, we are familiarizing students of color with the STEM discipline and encouraging them to continue their STEM education and pursue STEM careers.

Howard accounts for more Black PhD students than any other university in the country. We developed the Karsh STEM Scholars program to cultivate the next generation of Black STEM pioneers. We accept high-performing students into the program their freshman year and support them as they pursue STEM PhDs or MD/PhDs. Members of our first graduating class completed their undergraduate degrees in spring 2021 and are matriculating to some of the most competitive PhD programs in the country.

As the battle with the coronavirus pandemic and the COVID-19 variants continues, the biggest front of the war is taking place between members of society rather than between society and the virus. Vaccine hesitancy has replaced vaccine accessibility as the biggest foe society is facing in inoculating the public against the ravaging forces of the virus.

We spent time, money, and resources developing the vaccine—but not enough time, money, and resources ensuring that people would get it. Technological advancements are doomed to fail if there is not a diversity of people and perspectives at the table where the ideas are generated and the plans are conceived. For our entire society to advance, we need solutions and upgrades that work for everyone without leaving anyone behind. To truly find innovation, we must first realize diversity.

Diversifying the medical establishment, diversifying government, diversifying science and technology will all lead to better outcomes—not just for people of color, but for society as a whole.

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MEGAN E. DAMICO, SHARON A. RIVERA, JACOB B. RUDEN,
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# Expanding Science Fellowship Opportunities

Federal agencies must do more to ensure that prestigious fellowships for science graduate training are awarded in a manner consistent with larger goals of equity.

Famed astronomer Amy Manizer, physicist Eric Cornell, economist Steven Levitt, and Google cofounder Sergey Brin all have at least one thing in common: early in their careers, they received fellowships from the prestigious National Science Foundation (NSF) Graduate Research Fellowship Program (GRFP), which, in the words of the program's homepage, "recognizes and supports outstanding graduate students." Since the program was established 70 years ago, more than 60,000 GRFP fellowships have been funded, including 42 Nobel Laureates and more than 450 members of the National Academy of Sciences. Receiving a prestigious fellowship can aid the recipient's path to completing a graduate degree. It can also serve as a springboard to a successful and productive career. According to the GRFP website, "the reputation of the GRFP follows recipients and often helps them become life-long leaders."

Although it is well-known that the majority of doctoral students (around 81%, according to the most recent data) are trained at the highest-level research universities as categorized by the Carnegie Classification (known as "R1 universities"), GRFP awards go even more disproportionately to students at these institutions. A 2014 evaluation of the GRFP program revealed that, of PhD completers, nearly 95% of GRFP recipients attended R1 institutions. In more recent years, the distribution of GRFP fellowships across institutional types has remained unequal, with 31% of fellowships going to students at just 10 institutions.

There may be various reasons for this distribution, including the prevalence of certain fields of study at different types of institutions and the accessibility of those fields to students from different backgrounds. But GRFP and other prestigious fellowships are designed primarily as awards for individuals judged to have excellent potential, not for specific research projects (although a research proposal is part of the application). Such talented students will be found at all types of institutions. We suspect that one reason such fellowships are awarded disproportionately to students at R1 universities is because those institutions tend to have more resources and may do more to help prepare students to apply. However, "suspect" is as far as we can go: even basic data are lacking.

The disproportionate number of prestigious graduate fellowships awarded to students at a small number of universities is an overlooked part of a well-known problem. Prominent voices in the science policy community have spoken out about the need to increase the geographic and demographic diversity of the science, technology, engineering, and mathematics (STEM) workforce. Leaders have put forth concepts such as "missing millions" or "lost Einsteins" to describe those who have been excluded from STEM. More equitable geographic distribution of research funding could promote local economic and health benefits, and has recently garnered increased congressional attention.

Although federal fellowship programs like GRFP may be relatively small in the number of students they fund—most federally supported graduate students in STEM receive research assistantships—they loom large in the culture of science. Thus, they tend to reinforce a narrative that scientific excellence is defined by the school a graduate student attends, their adviser's prestige, or the level of access they have to grant writing workshops and other resources, which perpetuates an inequitable system that overlooks many qualified applicants. Agencies such as NSF must do more to make certain their fellowship programs are serving the larger goal of STEM equity, including collecting and reporting better data, ensuring that applicants at all institutions have training resources, and experimenting with other ways to equalize the fellowship process.

To better analyze fellowship programs and determine how to make them more equitable, federal agencies must work harder to collect data. In researching these fellowship programs, we were repeatedly stymied by a lack of data. Although the GRFP makes available a list of all awardees and honorable mentions by institution and field, data on applicants are lacking. With success rates of 12%–16% over recent years, it is important to have a better understanding of the full applicant pool in comparison to the awardees. For example, one proposal to make GRFP awards fairer would involve limiting the total number of applications per institution. However, assessing the utility of such a proposal is difficult without data. The most recent full evaluation of the GRFP program that we are aware of is from 2014. Beyond making available more complete data about the applicant and reviewer pools—including, to the extent practicable, demographic characteristics, institutional characteristics, and geography—we believe the program should undergo more regular evaluation, perhaps every two or three years, and that this information should be made publicly available.

A second area that the NSF should address is providing guidance to applicants. The R1 universities are classified as such in part because of their robust research infrastructure, and students from these institutions who wish to apply for fellowships often have special resources at their disposal. Some research universities offer fellowship workshops or boot camps for students and may provide additional financial incentives for students to seek fellowships from sources outside the institution. Many such institutions have fellowship recipients and experienced advisers on campus available to help graduate students with the application process. For example, Columbia University, a private R1 institution, has a multitude of grant writing support systems, including a semester-long grant writing course, workshops held several times a year specifically for the NSF GRFP and National Institutes of Health (NIH) F31 fellowship applications, access to personal review of application material by experts, and peer support systems.

In contrast, in the experience of one of us (Damico), the University of North Carolina at Greensboro (a public R2 or "high research activity" doctoral university, according to the Carnegie Classification) provides no grant workshops, support groups, or even announcements about graduate fellowships, including the NSF GRFP. While these examples are anecdotal, they paint a picture of inequity in institutional grant writing support that is likely true more broadly. Because this issue is not well documented, it remains a mystery where exactly the need lies for more support at other institutions and how successful support systems can be applied to meet the needs of students at other universities. We strongly encourage NSF and other agencies with selective graduate fellowship programs to investigate disparities in grant writing support and take steps to increase access to quality support across institutions. Data indicate just how helpful these programs can be to funding success for scientists of all levels, including graduate students. For example, a study from the University of Maryland, Baltimore County, surveyed students before and after a mentoring program that included a workshop series designed to inform them about best practices when applying to the GRFP. The survey data showed that participation strongly improved their knowledge of the process and expectations, as well as their confidence in being able to write a successful fellowship application after the program. Federal agencies could design and disseminate their own grant writing programming to students interested in applying to these fellowships, which could fill the gaps at institutions that are unable to implement their own programming and help level the playing field for all applicants. Providing this information in a virtual and free format would also help alleviate accessibility issues due to money, time, and travel resources.

Beyond collecting and releasing more data and providing application preparation training and support, agencies should experiment with other ways to make the fellowship process more equitable. Two specific ideas include adding a “funded pending revision” decision category to fellowship award decisions and taking steps to anonymize reviews.

One problem for students who lack institutional support is that their fellowship applications may be rejected with little feedback and there is often no chance to submit revisions until the next application cycle. For applicants to the GRFP, the stakes are even higher: beginning in 2017, the program changed its rules to allow students to apply only once. A change that could ease some of these burdens would be to establish a new category for competitive proposals, perhaps called “funded pending revisions,” that allows some applicants the opportunity to incorporate reviewer feedback to strengthen their submission. A similar concept, “accepted pending revisions,” is used by some scientific journals. Such a policy could both broaden the awardee pool and allow students to learn from the process.

Another area for investigation is reforming the GRFP review and selection system—a process that has been described as “dysfunctional”—to create clearer standards for judges, track accountability, and ensure the diversity of reviewers. For example, both NIH and NSF have experimented with anonymizing peer review, but should do additional work to understand the role of bias in review and learn whether anonymizing can help further diversify the pool of awardees in their prestigious fellowship programs. Along with anonymizing the process, agencies should continue to take steps to broaden the reviewer pool, specifically including reviewers from a variety of institutional types, which could also help in building support programs at these institutions. The NIH Center for Scientific Review has recently committed to “diversifying and broadening” its reviewer pool and will be regularly updating data on reviewer demographics. NSF is also exploring how best to attract “an untapped reviewer pool” and remove “barriers to scientists serving as reviewers,” according to an interagency policy group working on the issue. For the GRFP specifically, NSF accepts volunteer reviewers, which could affect the types of applicants selected. More research to understand the factors that make individuals more or less likely to review could help broaden the pool of reviewers. In addition, as we suggested earlier, data on the reviewer pool should be reported and made part of regular program evaluation.

Pursuing a doctoral degree is a difficult endeavor for many reasons. A recent brief from the National Science Board, for instance, describes financial barriers that hinder doctoral students, especially those from first-generation and lower-income backgrounds. Prestigious fellowships are one way that federal agencies can ease the way for promising students and increase their potential for longer-term career benefits. At a time when so much attention is being paid to STEM equity, differences between institutions in research infrastructure and resources should not be what makes one student more excellent than another. Who knows how many more future STEM leaders are out there, hoping the federal government can help unleash their full potential?

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GILDA BARABINO

# Building a Just and Fair Scientific Enterprise

The culture of science itself must change to fully reach untapped talent, enhance knowledge creation, and ensure the health and well-being of the nation.

Even before the COVID-19 pandemic, the need to make equity a central principle in science was obvious. The scientific community has long discussed the need to go beyond the narrow definition of science as the pursuit and application of knowledge to solve technical problems in order to support the idea that science must start and end with people, society, and the planet.

It has become quite clear that, to fulfill this responsibility, scientists who are accustomed to asking "How would we do that?" must begin to ask more complicated questions such as "Should we do it?" and "Who might be impacted?"

Part of what this requires in practice is changing the institutions where scientists are educated to welcome students from all backgrounds—and that will mean changing the academic environment, the curriculum, and the cost of education. I am going to argue that significant changes to policy and practice are necessary to empower science and engineering to better serve society, but I'm also going to argue that the culture of science itself must change to fully reach untapped talent, enhance the scientific enterprise, and ensure the health and well-being of the nation.

This affirmation may come as a surprise in an essay about policy, but problems in the culture of science are an often-overlooked explanation for the lack of progress not only in addressing society's concerns, but also in creating a more diverse science, technology, engineering, and mathematics (STEM) workforce. Five decades of interventions and substantial investments have failed to produce parity among racially minoritized people and women in STEM—in part because insufficient attention has been paid to identifying and addressing those systems and behaviors that, though hidden, have debilitating outcomes.

It is also part of the culture that scientists and engineers themselves often serve as gatekeepers in controlling who is recruited, accepted, and socialized into the profession. As the sociologist Cheryl B. Leggon says in her 1995 article on the impact of science and technology on African Americans, "who does science is important for who will do science." Further, the social and political contexts of science can't be ignored, as they influence who studies, what is studied, how studies are funded, how findings are applied, how power dynamics affect the academic and research enterprises, and ultimately how science impacts society.

If the scientific enterprise made equity a central tenet of the way science is done, the future could be dramatically different—and better—than the world as it exists now. In this future, the face of the scientific enterprise is reflective of society, and neither skin color nor street address is a barrier to entry. The cornerstone of this vision is that education is a right, as well as an investment in the nation. Early quality education would be universal, as would access to enabling technologies such as broadband. Lifelong education would include literacy in science, liberal arts, engineering, social science, and critical thinking, and opportunities would be equitably distributed.

In this future, science is user-oriented, collaborative, responsible, and purposeful. Societal challenges and solutions to them are the work of scientists. But "scientists" would be broadly and inclusively defined, informally and formally trained, and they would come from academia, industry, and the community. All would be fully engaged in making a difference in everyday lives.

A just and fair scientific enterprise will require a humanistic approach to create equity in society. This change must occur at individual, institutional, and systems levels, as well as along the entire scientific career path, guided by the humanity that connects us. Because of the central role education plays in ensuring health, mobility, and well-being, educational reform is critical to this vision.

Simply put, the nation's learning institutions must reorient themselves toward a mission of justice and must use that reorientation to shape institutional culture, policies, practices, and behaviors. That vision must inform concrete actions. Olin College of Engineering, where I am the president, has been committed to achieving gender parity among incoming students since its founding in 1997, and it has achieved that. Intentionality drove the desired outcome.

Likewise, science and engineering institutions must embrace a mission of helping students succeed and creating broadly educated, curious citizens. This involves ensuring literacy across a broad range of subjects and skills: not just STEM but also humanities and the arts, social sciences, and critical thinking. In addition to engineering fundamentals and technical skills, students need values and attitudes to lead a purposeful life and responsibly apply engineering for the good of society.

What does this mean in practice? At Olin, we see ourselves as a cause (not just a college) dedicated to educational transformation and public good. We achieve our mission through team-focused learning tied to solving real-world problems. Faculty and students see themselves as collaborators in learning. And starting with the admissions process, the whole community uses storytelling as a vehicle for forming and changing communities. Our goal is to transform engineering education by partnering with our students and other organizations to explore, develop, and share new educational approaches and environments that realize our vision of a world in which engineering is for everyone.

Finally, and crucially, we deliberately create a sense of belonging for everyone at the college—so that students, faculty, and staff all see themselves as vital parts of a learning community. We pay attention to equity and parity in gender and race from student admissions to faculty and staff hiring and retention. Policies for retention and recognition of faculty are explicitly aligned with the values of diversity, equity, and inclusion, allowing for innovative promotion practices, variable responsibilities, and flexibility in the demonstration of scholarship and impact. Our faculty are expected to demonstrate excellence in three overlapping areas: developing students, building and sustaining the college, and achieving impact outside the college. This, I believe, is an example of how institutions can shift their focus to distributing opportunities, rather than limiting access to them.

Institutional policy changes to promote equity and diversity are a first step in the larger task of reforming the system of scientific knowledge creation. American communities support the scientific enterprise through their tax dollars, but they do not benefit from its innovations equally. To remedy this, and truly transform all communities, institutions of learning must inclusively educate historically underrepresented groups who can bring their own perspectives, experiences, and interests to bear on problems of social significance. As the education leader Shirley Malcom wrote back in 1996, the situation requires more than policies; only structural change will create the transformation that is necessary.

And a significant part of this structural change must occur within the culture of science itself. It is time to look inward, taking account of the hidden behaviors, systems, and practices that play a role in limiting progress and advancement for racially minoritized groups in STEM.

Perceptions, stereotypes, and lowered expectations are all too familiar to students, faculty, and practitioners who are members of marginalized groups. This system of "weeding out" is a form of gate-keeping that works at all levels—from early childhood education, as documented by the economist Raj Chetty in his work on lost Einsteins, to faculty members who subtly insinuate that students of color should seek another major. It also extends to who is perceived as faculty and who is not.

In my own engineering training, I did not see faculty who looked like me, and I was acutely aware of others' perceptions of what an engineer looked like. When I began my academic career, my first set of students initially did not perceive me to be a faculty member. On the first day of classes, I arrived early to the assigned room, wrote my name and the course name on the board, and waited for the students to arrive. Nearly 10 minutes in, I heard students in the hall and even observed a couple poking their heads in, but no one entered. Finally, I stepped out of the classroom and asked the students if they were there for Chemical Engineering 1421. They said yes, but the instructor had not arrived. They seemed shocked when I told them that I was the instructor. Later that week, when I tried to place a book on reserve for the course, the student worker at the library testily replied that only faculty could place books on reserve.

From my experience, the innovation system often renders members of underrepresented groups and their contributions invisible or undervalued. Experiences like mine are not unique; indeed, they are well documented in the literature. One potential explanation for this lack of visibility is what the psychologist Isis Settles and her coauthors describe as "epistemic exclusion": "an experience in which faculty of color are deemed illegitimate members of the academy, and thus their scholarship is devalued."

Epistemic exclusion can manifest in myriad ways. Here's one I'll share. During a time I was carrying out an active research program while also leading diversity, equity, and inclusion (DEI) efforts for my institution, I learned I had been left out of a newly formed research collaboration in my area of expertise. When I asked a colleague why, I was told they thought I was only doing DEI work. Being pigeonholed like that has happened to me throughout my career and, I am sure, to countless others. It is yet another conundrum faced by members of racially marginalized groups: being seen when there is service work to be done—sometimes referred to as a cultural tax—and being unseen when it is time for collaboration, recognition, and promotion.

It is interesting and troubling that, as an African American woman at a near solo status in my career, I could be simultaneously hypervisible and invisible. It reminds me of the protagonist's opening declaration in Ralph Ellison's *Invisible Man*: "I am an invisible man.… I am invisible, understand, simply because people refuse to see me.… When they approach me they see only my surroundings, themselves, or figments of their imagination—indeed, everything and anything except me."

We should not underestimate the links among invisibility, identity, and recognition. As the writer and educator Christopher Emdin has explained, assimilation to white norms and the pressure to leave one's ethnic identity at the door—which is the case in science—stymies creativity and expression, challenges identity, and disadvantages ethnic minority students.

Another factor that plays a role in our invisibility is small numbers of racially minoritized women and men at science institutions. Often referred to as "the small N problem," the lack of disaggregated data disproportionately centers majority experiences, rendering invisible the specific experiences of marginalized groups and contributing to further marginalization. As the education specialist Tia Brown McNair and her coauthors point out in *From Equity Talk to Equity Walk*, gathering appropriate data also demands a robust process by which practitioners make sense of the data to inform their actions.

At a systemic level, this exclusion effectively limits innovation for the nation as a whole. The number of inventors in the United States could be four times higher if women, underrepresented minorities, and individuals from low-income families became inventors at the same rate as white men from high-income families. Those who do "get through the gates" often find their innovations discounted and have less successful academic careers—a challenge described as the "diversity-innovation paradox" by the computational sociologist Bas Hofstra and his colleagues.

What's more, this system inevitably restricts the *type* of invention and innovation that is produced. In a recent report in *Science*, the researcher Rembrand Koning and his coauthors confirmed the inventor gender gap and demonstrated that, for US biomedical patents from 1976 through 2010, "patents with all-female inventor teams are 35% more likely than all-male teams to focus on women's health." They point out that who invents affects who benefits from inventions. Because women are less likely to obtain these patents, important discoveries are lost.

I know firsthand the particular insights, expertise, and passions diverse researchers bring to the innovation system. When I chose to study sickle cell disease for my doctorate, part of my motivation was that I wanted to use engineering principles to solve a problem in medicine and I wanted to solve a problem that disproportionately impacted African Americans. Even as a graduate student, I knew there was a real intersection among race, health, and politics; that nexus has been a strong driver for me throughout my life's work. Many more people like me, who are motivated to give back to their communities, will find solutions to society's most complex problems if they are provided the right opportunities.

I have shared these examples from my own career because I believe that, together, scientists and institutional leaders need to see the culture of science in full, acknowledging what is hidden. But I also want to focus attention on another overlooked process that is embedded in science's system: the phenomenon of the invisible hand.

It is the invisible hand that can open doors, tap shoulders, guide and position, and, in many other ways, shape career pathways for those fortunate enough to be a member of the majority or normalized group, the most resourced group, or the group in power. This phenomenon is all around, frequently—sometimes inadvertently—acknowledged. Once, for example, an individual on an all-male panel at a leadership program I was attending stated that he had never applied for any of the administrative roles he held throughout his career, including his current position as senior vice provost. According to him, he was tapped for each one by another man. In his remarks, he gave no indication of realizing that others could rightly perceive him as a beneficiary of "opportunity hoarding"—gaining privileges because of access to an insiders' network not available to everyone.

Although it's tempting to believe that hard work is the key determinant of getting ahead and that social factors don't matter, such myths of meritocracy and color-blindness themselves serve as powerful gatekeepers. In reality, structural inequalities often tend to reward those who are already privileged. Left unchallenged, the myth perpetuates power imbalances and inequities, stifles innovation, and puts the entire scientific enterprise at risk.

The scientific enterprise must move beyond these myths to make science an endeavor in which everyone who does the work belongs, and no one has to give up their various self-definitions to take on the identity of scientist or engineer. Science should be a place where people bring their whole selves. And when we hold a mirror to ourselves, our institutions, and our systems, science's reflection should be representative of our society, our cultures, our communities, and our values.

To build the optimistic future I envision for humanity, scientists must first look inward. Leaders and educators must recognize that who does science determines who will do science, as well as defining the kinds of questions that will be asked and the kinds of problems that will be solved. In order to truly transform science to meet the complex challenges that society faces, both institutions of learning and the culture of science must begin to change, embracing the goal of a just and fair scientific enterprise as a cause to guide our actions today.

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SHIRLEY M. MALCOM

# The Limiting Factor of *The Endless Frontier* Is Still a Human One

In science policy circles, making science more inclusive and diverse has not received the attention it urgently needs. To remain a leader in innovation, the United States must diversify its science, engineering, and technology workforce.

Vannevar Bush's *Science, the Endless Frontier* report has been invoked, quoted and misquoted, poked and dissected many times since its release in the summer of 1945, often to highlight its influence on science policy and its call for federal funding to be directed to the research enterprise through the nation's universities. The report bears rereading—not only to appreciate Bush's vision, but also to consider how that vision has been tested as it met the societal and political realities of the past 75 years. And, reading it with a different lens, I have found the report compelling for its messages on education and talent development, causing me to reflect on Bush's general failure to envision how diversity, equity, and inclusion apply within that endless frontier.

In rereading the document, I was struck once again by the fact that Bush gave equal billing to setting up the infrastructure to support research and to addressing what one might call "people issues." One of the four advisory committees that Bush established was devoted to talent discovery and development. This 14-person, all-male committee considered many approaches, including drawing talent to science via scholarships for promising students and mobilizing talent through the education of returning veterans. Both of these worthy paths would carry hidden barriers to diversity in science, technology, engineering, and mathematics (STEM). The extraordinary expansion of higher education that resulted from the GI Bill, for instance, almost exclusively benefitted male veterans, with schools generally preferring to admit male students and many women's colleges admitting men for the first time. At the same time, students and veterans of color saw their opportunities restricted by limited access to high-quality K–12 education and the racism of Jim Crow laws mandating segregation in education and elsewhere.

Nonetheless, at least one member of the committee, James B. Conant, a chemist and president of Harvard University, saw the inextricable link between the advance of research and the development of talent. In the report, Bush quotes Conant's statement that "in every section of the entire area where the word science may properly be applied, the limiting factor is a human one. We shall have rapid or slow advance in this direction or in that depending on the number of really first-class men [*sic*] who are engaged in the work in question.... So in the last analysis, the future of science in this country will be determined by our basic educational policy."

Today, the United States faces new technological and geopolitical challenges, but the limiting factor is still a human one. Women and persons who are Black, Hispanic or Latino, and American Indian or Alaska Native remain consistently underrepresented in STEM fields for reasons that are manifold, complex, and structural. Efforts to date have been insufficient to address the roots of these issues. In science policy circles, the human resources challenge of research rarely receives the attention it urgently needs and deserves for the United States to remain a leader in advancing the next generation of science. The country is not always guaranteed to have easy access to talent from elsewhere; other nations are strengthening their own research and innovation capacities, while the United States has restricted policies for who can and cannot enter.

At a time when China's growing number of scientists and engineers poses a challenge to US competitiveness, the country needs to embrace its diversity as an important advantage. The United States is uniquely positioned to bring the varied cultures, perspectives, and lived experiences of its population, especially when coupled with America's ability to attract top talent from around the world, to solving problems and propelling science forward. Leaders and funders of US science should embrace this "diversity dividend" that sets the United States apart. Realizing the nation's scientific potential will depend on finally adopting necessary—and long-overdue—systemic changes to its institutions that will allow it to build and foster a robust talent pool, leading to a more diverse STEM workforce.

## A STEM workforce that does not look like the country

The potential talent pool for science and engineering is diverse and becoming more so every year. In 2021, the resident population of the United States aged 17 and under was about 50% white and 50% nonwhite. Women made up nearly 60% of the college-enrolled population.

However, this diversity is not reflected in STEM fields. The majority of US citizens and permanent residents who received bachelor's and master's degrees in science and engineering in 2019 were white; 69% of doctoral degree recipients in those fields were white. Black, Hispanic or Latino, and American Indian and Alaska Native students are vastly underrepresented in STEM degrees. For women of color, these disparities are even more apparent, and they carry over to the workforce. The precarious position of underrepresented minority scientists and engineers was highlighted by their experience during the COVID-19 pandemic, which disproportionately affected women and underrepresented minority students as they pursued STEM education and employment.

For decades, the US research enterprise has relied heavily on international talent to conduct graduate and postdoctoral research. The highest reported recipients of research assistantships are temporary visa holders. According to the National Science Foundation's Survey of Earned Doctorates, in 2020, 39% of US science and engineering doctoral degree recipients were foreign citizens with temporary visas. In 2020, temporary visa holders earned the majority of doctorates awarded in engineering (59%) and in mathematics and computer sciences (59%). This reliance on early-career international researchers is counterproductive to the nation's interest when these scientists then face restrictive visa policies that force them to leave the United States. In any case, as more countries invest in and expand their own research and development spending and science enterprises, and as the United States is increasingly seen as an unwelcoming environment for immigrants, there is no guarantee that the currently high percentages of foreign-born PhD graduates who intend to remain in the United States will be sustained, posing risks to the future of US science.

## How barriers to diversity limit the endless frontier

US higher education desperately needs to bring about the equitable system necessary to compete in a world that has changed significantly since Vannevar Bush's time. Despite nearly a half century of calls to diversify STEM, today the institutions that are more accessible for students from lower socioeconomic backgrounds and underrepresented minority groups—such as two-year colleges—tend to be underfunded and poorly linked to STEM career pathways.

Students from underrepresented minority populations also encounter other barriers. Attending predominantly white research institutions is often challenging, whether in STEM or any other field. Aside from facing overt and covert barriers to entry, imagine undertaking the difficulty of a STEM education while being made to feel unworthy, unwelcome, isolated, and out of place in the community of scholars.

Students from these groups who are able to enter graduate education face additional significant barriers in comparison to their white counterparts: they are more likely to carry higher levels of undergraduate debt and are more likely to accumulate additional graduate education-related debt, even in fields like computer sciences and engineering that are known for providing a debt-free doctoral education. The kind of funding students receive matters because the value of research assistantships (which, according to the Survey of Earned Doctorates, support a third of all science and engineering doctoral students) goes beyond the money—they also carry attention and mentoring opportunities. Yet Black doctorate recipients, independent of field, are less likely to report research assistantships as sources of support and more likely to indicate using their own funds to pursue their research interests. In the most recent Survey of Earned Doctorates, even when field is held constant, both cumulative and graduate educational indebtedness is higher for underrepresented minority graduates than white and Asian graduates, with the highest levels of all for Black students.

All of these barriers to increasing the diversity of scientists also limit the frontiers of science by restricting the types of scientific inquiry that the United States supports and pursues. Stanford University chemist and inventor Joseph DeSimone once said that "it's kids who came out of poverty who think first about the cost aspects of what they invent. I see that affecting technology at a big scale—you're always looking for someone with a different idea." Bringing such talent into STEM professions can support culturally responsive technology and innovation, and it also reduces US dependence on international sources of talent, builds community prosperity, and reduces income and wealth inequality.

### Systemic change, but not enough

Fifty years ago, in the wake of the movements for civil rights and women's rights, many institutions mounted small-scale efforts to recruit women and those from minoritized communities into science, engineering. and medicine. But after nearly a century of programmatic barriers to participation in STEM, the efforts were hit or miss at best. For women in medicine, for example, early initiatives included removing the quotas that barred them. Interestingly, removing those "do not enter" signs in the early 1970s led, over time, to women making up more than half of those enrolled in medical schools today. However, this representational parity does not translate into power parity since the policies, processes, practices, and cultures of the systems in which women study, from which they graduate, and in which they work have not been transformed. It is still expected that women will change or adapt to fit the system—as was made clear by the monumental 2018 NASEM report on sexual harassment, which showed that women still do not feel equal, safe, and seen in STEM fields.

Signed in 1965, President Lyndon Johnson's Executive Order 11246 attempted to address discrimination. The order required equal employment opportunity and affirmative action by federal contractors in recruitment, hiring, training, and other employment practices, a move that spurred many industry leaders to mount and support initiatives to build the STEM talent base. Universities, colleges, and nonprofits generally responded by establishing small-scale efforts intended to introduce students to careers, counsel them on coursework to take, and offer them educational experiences that would prepare them to succeed in higher education and beyond. Yet little changed in the institutions themselves. And instead of pursuing strategies that would help all students succeed, most institutions of higher education created "shadow projects" to enable students to navigate the system as it already exists, never questioning that a more effective strategy might be to fix the system that failed too many otherwise capable students. After five decades of supporting such small-scale intervention programs, higher education institutions need to shift the target to fixing the system to remove barriers to success for all.

*The Endless Frontier* report proposed to solve the "people problem" by providing scholarships to attract students and spur talent development in STEM, observing correctly that funding was a barrier for most students' college attendance in the late 1940s. The amount and mix of federal support for STEM higher education changed over the ensuing decades, expanding in the post-Sputnik days and shrinking in the 1980s with a change in all aid from grants to loans. Subsequent shifts of institutional aid from need- to merit-based support have created further barriers to students from minoritized populations who are frequently from low-income families and are disadvantaged by an often-segregated and less-than-stellar K–12 education. Compounding these challenges, changes in the structure of aid require that many students hold jobs while in school, taking away critical time to engage in intellectual pursuits, activities, and opportunities available to those with financial security.

Today's limited scholarships and support not only fail to deliver *The Endless Frontier*'s promises to disadvantaged students; they also undermine other efforts to bring these individuals into academia. At the graduate level, low levels of financial support are particularly limiting for underrepresented minority students, who often enter the workforce rather than taking on further study because they lack a family financial safety net. And in families with no history of graduate education, students can struggle to justify incurring debt for more education rather than supporting their families. As a result, students who could become the very sort of faculty member that many of them have never seen are likely to look at the sacrifice in time and salary required to join the professoriate and consider it a bad bargain.

Society loses when it fails to make the science and engineering talent pool inclusive. The loss of talent is not the only problem that exclusion introduces; it also results in a loss of innovation. The business researcher Rembrand Koning and his coauthors documented that "women's biomedical inventions are more likely than men's inventions to focus on women's needs." Researcher Fiona Murray, in an article in *Science*, points out that innovators focus on problems that they see around them. She highlights the example of Patricia Bath, an ophthalmologist who was struck by the difference between the incidence of blindness she saw as an intern as she traveled between the eye clinics at Harlem Hospital and Columbia University. Bath, an African American woman, created many sight-saving programs and the field of "community ophthalmology." She also created a new device and method to remove cataracts, the laserphaco probe, that could make this critical care more accessible to the communities she served. To be competitive in the global economy, and to be whole as a society, the United States cannot afford to lose innovations like hers—or the innovators themselves.

## Supporting institutions that foster diversity

It is important to recognize that historically Black colleges and universities (HBCUs) play an outsized role in educating students at the bachelor's degree level who then go on to obtain PhDs in STEM. The same is true of high Hispanic-enrolling institutions. Unfortunately, these schools continue to be undervalued and receive significantly less support than they merit. To capture the full diversity of America's talent, these schools should be supported and emulated because they successfully attract and train diverse STEM talent. Leaders of these schools understand the necessary large-scale, structural changes that are key to building institutions that can support all students, not just some. Only by transforming government agencies, colleges, universities, and related components of the STEM ecosystem will the United States be able to capture the benefit of the different perspectives and experiences that flow from diverse voices needed to ensure a strong future for the scientific enterprise.

The successes of minority-serving institutions and initiatives demonstrate that it is time to stop relying on experiments without first putting into practice protocols that researchers and administrators already know to be effective. For example, there is a robust bank of discipline-based educational research that demonstrates the value of improving the quality of introductory courses by using active learning, reducing hyper-competitiveness, acknowledging and supporting student identity, and building a sense of belonging in the field. Centers for teaching and learning, which allow faculty to experiment with new teaching methods informed by research, already exist on many campuses and could help faculty members hone the skills necessary to engage students from diverse races, ethnicities, and backgrounds in their subjects. Faculty resistance to such educational training is often mentioned as a reason not to insist upon it; but the pandemic showed that necessity can spur many actions that people might otherwise resist. Furthermore, all research institutions could benefit from learning from minority-serving institutions about how to support student success and welcome all the identities that students bring. I urge the scientific community to seize this moment to have discussions about the quality of instruction and about how institutions can assume an asset-based rather than a deficit-based approach to students of color.

Similarly, two-year colleges represent unique assets in the STEM talent ecosystem, given their focus on affordability and access. These schools offer unique opportunities for learners, as well as for the scientific enterprise, which could use this system to identify people with STEM talents. These institutions must be supported and connected, so that they become genuine on-ramps to STEM degrees for the students they serve.

It is clearly time for action on diversifying STEM, but this is also a time for reflection. Why, despite decades of discussion, has so little progress been made? More than 50 years ago, Robert K. Merton coined the term "the Matthew effect" to describe how eminent scientists receive the most credit for innovations and how advantage accumulates. (The term is based on the Bible verse "For whoever has, to him more will be given, and he will have abundance; but whoever does not have, even what he has will be taken away from him," Matthew 13:12.) The Matthew effect is often cited to explain the current system of advantage for major research institutions and the faculty stars within them. But it takes more than that to understand why there are currently no HBCUs among the highest ranking (R1) research institutions. Almost all HBCUs were established after the Civil War, and only a small number were included in funding under the first Morrill Act (1862). Although the second Morrill Act (1890) supported the establishment of public Black colleges, it allowed states to perpetuate educational segregation and systematically underfund education for Black students. Private HBCUs did not enjoy the largesse of big donors to support research ambitions. Largely situated in the Jim Crow South, these institutions struggled with deliberate underinvestment by their home states. Small and underresourced, they were not prepared to handle the influx of Black veterans who were eligible for and sought entry with support from the GI Bill. In 1994, tribal colleges received investment, but ultimately there has never been a major investment in either them or HBCUs that would enable them to become R1 institutions. The absence of a high-level research infrastructure in these institutions results in the loss of a potentially substantial network for addressing issues that differentially affect communities of color.

The pandemic has shined a spotlight on how failure to study these important issues through a lens of racism and race-awareness can affect society as a whole. Recognition of the way COVID-19 affected communities with health disparities has dovetailed with a reckoning about why highly qualified Black scientists are not funded at rates commensurate with their research grant application rates. One analysis judged that they want to study the "wrong things"—their own communities. Such research can receive a lower priority score when funding decisions are made. A researcher friend of mine described an invention by four of his Black women students: a "virtual traffic stop" at which no one, neither police nor driver, has to leave their cars. It doesn't take a lot of explaining to see why this invention might have been seen as a positive social good. So understanding how the Matthew effect has sent resources to the richer schools and how the development of HBCUs has been constrained also reveals who controls the research and innovation agenda.

## Avoiding a "tremendous waste"

When I consider the myriad ways that the US scientific enterprise has failed to diversify, I am reminded of a quote from *Science, The Endless Frontier:* "There are talented individuals in every segment of the population, but with few exceptions those without the means of buying higher education go without it. Here is a tremendous waste of the greatest resource of a nation—the intelligence of its citizens."

The United States will not realize the "diversity dividend" without mindfulness in the choices of decisionmakers: requiring that researchers demonstrate the presence of diverse teams; asking major research universities to embrace partnerships with institutions with which they do not usually partner; investing in research and business development from diverse teams. Efforts must be made to find and develop talent where it is—including at two-year colleges and in workplaces. A shift in thought is required to see diversity as an advantage rather than a deficit.

And for the big institutional research powers that emerged from Bush's vision? It may be important to temper the Matthew effect with the Luke principle (based on the Bible verse "From everyone who has been given much, much will be demanded; and from the one who has been entrusted with much, much more will be asked," Luke 12:48). Institutions that have been the major beneficiaries of public investment in research and development over the last eight decades have an opportunity, indeed an obligation, to enable a future characterized by inclusion that delivers on the excellence and innovation needed to address the next 75 years of challenges.

Imagining science policy for the next 75 years requires embracing a broader vision of who will do science and engineering and who will invent the future. The pandemic has raised awareness of how a failure to study these important issues through a lens of racism and race-awareness can affect society as a whole. And the lessons for the future are clear: scientists, engineers, and medical professionals must look more like US citizenry. True competitiveness means recognizing and using the country's diversity as an innovation advantage, harnessing the diverse perspectives that offer better ideas, better solutions, better science, and better and more inclusive technology.

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### RORY A. COOPER

# Making Scientific and Technical Careers More Accessible

Science and medicine have not traditionally been welcoming for people with disabilities. Here's how to make them more inclusive—and bring greater creativity, new perspectives, and fresh talent to these fields.

I entered college prior to the passage of the Americans with Disabilities Act of 1990, when much of the world was a daunting place for people with physical disabilities, despite previous laws and regulations having made marginal improvements to public accessibility. I decided to pursue engineering studies not knowing that people with disabilities rarely pursued careers in science, technology, engineering, mathematics, and medicine (STEMM), and that when they did, their chances of employment were poor.

Seeing astronauts land on the moon and watching the animatronics in Disneyland inspired me—just as my years in the US Army awoke a passion for public service. By vocation and inspiration, engineering seemed to me the best way to make a difference in the world. Armed with optimism, ambition, and a healthy dose of ignorance about the barriers before me, I earned three degrees in engineering, culminating in a PhD.

In many ways, I had found my home in engineering: engineers and people with disabilities share an inclination for practical problem-solving. This inclination, paired with a "let's find a way" disposition toward difficulties, can become a transformative force. While aspects of science and engineering are by nature difficult, these difficulties are also what make STEMM careers attractive. And, in that light, making these fields more accessible to people with disabilities should be a natural fit. Additionally, among the many benefits to making STEMM more accessible as well as inclusive is that it would ensure that creativity, new perspectives, and fresh talent are available to address the challenges facing the world and its inhabitants.

But STEMM fields are not actually home to many people with disabilities. Even though the Centers for Disease Control reports that nearly 25% of the population has some form of limitation in performing daily activities, the National Science Foundation reported in 2019 that among STEMM doctorate holders under age 40, only 5% have disabilities. What's more, scientists with disabilities not only have higher unemployment rates than other scientists, they also have higher unemployment rates than US workers in general. Scientists with disabilities are more likely to be working in non-science fields than those without disabilities. In very important ways, science is failing scientists with disabilities.

Since its inception, the Americans with Disabilities Act (ADA) has been a groundbreaking civil rights law that has lowered many barriers and created pathways for integration and participation for people with disabilities. The ADA has positively impacted society at large not only by enabling greater inclusion, but also because many of the accommodations created or installed for people with disabilities have improved life for nearly everyone. For example, speech-to-text and text-to-speech applications, texting, and closed-captioning are now widely used because they benefit many people and businesses. Curb-cuts in sidewalks that make it possible for motorized wheelchairs to move from sidewalks to crosswalks were first championed by disability activists and have now made cities more navigable for everyone.

Despite these widespread advances, people with disabilities are still nearly invisible in STEMM disciplines. And, more discouragingly, they are also overlooked within STEMM inclusion initiatives and activities. It is not uncommon for young people with disabilities to be guided away from STEMM fields after they complete middle school, which may limit their ability to pursue and attain a degree in college. To fix this and make inclusivity in STEMM a widely valued goal, it will be necessary to create deliberate pathways that can lead all students to success—ranging from extra training for teachers to create curricula, to making classroom facilities more accessible, to alternative methods of learning skills.

One hurdle is that disabled students often don't "see themselves" in STEMM careers, which could be addressed by exposing all students to role models that have disabilities. There are already some programs in place to accomplish this. For example, the US Patent and Trademark Office has created materials for schools called the Inventor Collectible Card Series, which features patent holders from diverse backgrounds and demographics. These cards are popular and effective at educating and motivating diverse populations of young people.

But motivation alone is not enough: it has been reported that when students with disabilities participate in labs and field work activities, they are often placed in the role of notetakers and observers rather than as active participants. The National Science Foundation's INCLUDES initiative is building a broad network of individuals, institutions, initiatives, and federal agencies to bring about a systemic shift with tools that support greater inclusion.

Several colleges and universities have been making a difference in the lives of people with disabilities and should be used as models to create broader inclusion. The Experiential Learning for Veterans in Assistive Technology and Engineering (ELeVATE) is a program established at the University of Pittsburgh with support from the National Science Foundation and in cooperation with Student Veterans of America. The program has helped wounded, injured, and ill military veterans to earn college degrees and become successful in new careers in industry, government, and academia. The ELeVATE program has been replicated in some form at several institutions and has become sustainable through support by private, corporate, and foundation donors.

Another promising model is the Cloud Lab at Carnegie Mellon University, which is creating a futuristic automated biology and chemistry lab that can be accessed from anywhere in the world through a software interface. This approach has the potential to increase opportunities for people with disabilities because not only could they use accessible software interfaces, but they would also be able to live and work wherever there is an adequate support system. And by accommodating scientists with and without disabilities, and allowing them to run their experiments in the same manner, cloud labs could make scientific employment hinge more on intellectual capability and creativity than on a person's ability to run experiments at the bench.

Building an inclusive environment does not depend on advanced technology, however. Since 1948, the University of Illinois at Urbana-Champaign has been a leader in training students with disabilities in STEMM fields. The school offers a comprehensive array of adaptive sports and recreation services, on-campus accessible housing with nonmedical assistance, and facilities designed to reduce barriers to a full array of opportunities inside and outside of the classroom and labs. Their Disability Resources and Education Services are among the most innovative and successful in the country.

Labs, field work, and computing resources are essential to both a STEMM education and a successful career. Unfortunately, they are also three of the most significant barriers for accessibility and inclusion of people with physical or sensory impairments. The architecture, layout, and furnishing of laboratories must become more adaptable and inclusive, which will require deliberate work. In many cases, lab activity accessibility can be achieved with creativity and simple changes such as powered height-adjustable work benches, computer-controlled scientific instruments, and even small robotic arms.

Field work is a difficult problem to solve because it often necessitates spending time outside the lab at "dig sites," on biological or ecological reserves or scientific ships, or other unpredictable environments. But even here, people have successfully deployed both technical and hybrid accessibility accommodations. For example, ruggedly designed wheelchairs can be used in off-road environments, and motorhomes or camping trailers can assist with accommodations. In some situations, drones with cameras can be used to address accessibility. "Trained human assistance" could be employed, for instance, by an undergraduate intern assisting a graduate student as their eyes, ears, or hands. In medical fields, it is possible to learn anatomy and clinical skills by combining computer models with hands-on investigation by a human assistant guided by a person with limited hand or arm function. With creativity and some extra effort, many activities can be made accessible. For example, in the field of space and planetary geology, field work is often focused on data sets that can be made accessible to people with various impairments.

Finally, it goes without saying that access to computing resources is essential, because STEMM work has become nearly impossible without the use of computers, specialized software, websites, and, in most cases, databases or data sets. Although accessibility of computing and information resources is codified in US law, there remain many gaps, sometimes due to legacy systems or because decisionmakers are unaware of both the barriers to and benefits of making computing and data sharing broadly accessible. This process can take a variety of forms—such as hardware alternatives to keyboards or mice, or specialized software such as speech-to-text or text-to-speech. While there are many challenges to making computing and software accessible, some of the bigger ones include creating video and image content that is accessible and useful for people with visual impairments and optimizing data interpretation tools for people with visual impairments, especially for those with both visual *and* hearing impairments. Another challenge is making computer-aided design tools and software that provide alternative graphing and charting tools for interpreting data with dynamic tactile displays. All of these challenges to accessibility can be overcome and, when they are, have been proven to benefit a larger group of society.

Impairments are very personal and unique, so it is critical to work with people with disabilities to determine approaches that will make activities inclusive and accessible for them as individuals. As an undergraduate student prior to the passage of the ADA, I was fortunate enough to learn from professors and fellow students who were supportive and creative, and believed that inclusion and accommodations were engineering challenges that aligned with the university's philosophy of "learning by doing." We met each term to decide how best to ensure that I could participate to the fullest extent possible. As a manual wheelchair user with use of my arms, most of these accommodations involved being sure that equipment and tools were accessible from a seated position. However, two important lessons emerged: first, communication and teamwork made it possible for me and students with other disabilities to be included. And second, with creativity and will, most of the accommodations for me and other students were and remain possible for only modest cost and effort.

To provide greater opportunities, some important structural barriers for inclusion of people with disabilities in STEMM need to be removed. A substantial portion of the potential student and professional employee population of people with disabilities requires assistance from another person to complete essential activities of daily living—dressing, eating, personal hygiene—which is frequently paid for through private insurance or a state or federal program. To get these benefits, recipients often must prove their income is low—and the limits are often lower than, for example, the stipends provided to many graduate students. This creates nearly insurmountable barriers for people who are working to get an advanced degree of the kind often required for a STEMM career. In addition, once a person becomes employed, this benefit may be revoked, forcing people to pay out of pocket, which effectively lowers their income relative to their peers. For full inclusion of people with disabilities in STEMM, structural changes are needed in how personal assistance is provided and how income is determined.

Earlier this year, the National Academies of Sciences, Engineering, and Medicine held a series of listening sessions called Leading Practices for Improving Accessibility and Inclusion in Field and Laboratory Science, during which panelists described multiple ways to remove barriers to inclusive environments for disabled scientists. Among the suggestions was valuing disabled scientists for their perspectives and paying them for the work they do to change the institution, rather than expecting them to do the work for free. Another point raised in the discussion was that STEMM is arguably the area with the greatest potential for growth in career opportunities and also the most underrepresented domain among people with disabilities.

It is clear that the attitudes of teachers, professors, administrators, and employers must adjust to adopt and internalize the belief that accessibility and inclusion are beneficial to all parties. STEMM students and professionals with disabilities bring unique and important skills, perspectives, and experiences that enhance both learning and work environments.

At the same time, building an inclusive STEMM community that welcomes people with disabilities is a moral principle and a basic human right. Representation cannot happen if a portion of the population is continually excluded from an appropriately accessible education that leads to good careers. Inclusivity is, above all, an affirmation of democracy. It may come with some cost, and society may not see the returns of those investments immediately, maybe only over decades. But it's still worth the investment.

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150°

# Educating Tomorrow's Scientists and Engineers

SHERYL SORBY, NORMAN L. FORTENBERRY, AND GARY BERTOLINE

# Stuck in 1955, Engineering Education Needs a Revolution

The "pipeline" concept has long kept people out of the field of engineering. It's time to address the needs of today's digital, diverse, global, and rapidly changing society.

In May 1952, the president of the American Society for Engineering Education (ASEE), S. C. Hollister, appointed a committee to look at the state of engineering education in the United States. The 1955 report, now commonly referred to as the Grinter Report, brought about a sea change in the training of engineers and became a foundational document for engineering education that still has a significant influence on engineering curricula at the undergraduate and graduate levels. After Grinter, theory replaced practical hands-on work. And this approach has changed little in the intervening decades. Over the years, we educators have done some tinkering around the edges, such as adding in a capstone design project, or replacing Fortran with other programming languages—but the basic structure of the curriculum remains unchanged even though our students can now find information on their phones that might have taken us hours to track down in the library.

Engineering education seems stuck in 1955. Our system of engineering education needs to address the needs of today's digital, diverse, global, and rapidly changing society. Additionally, the COVID-19 pandemic brought to the surface several problems in the training of engineers that have festered for too long: racial and social disparities, elitism in academia, and the pervasive practice of locking students in or out of engineering pathways as early as elementary school.

It is time that we as educators take a long, critical look at our values and curricula to ensure that we are preparing students for careers that exist today and for future careers. To ensure that we are attracting and retaining a diverse pool of learners to our programs, we need to examine what we are teaching and how we are teaching it. Are we expecting our students to solve types of problems that inspire them to continue to pursue a career in engineering and change the world for the better?

We also need to look at what we include in our courses and be willing to omit topics that are no longer relevant. Or, as it was phrased in the 2004 National Academy of Engineering's (NAE) consensus study report, *The Engineer of 2020,* we must avoid the cliché of teaching more and more about less and less until we are teaching everything about nothing.

We also need to recognize that the current generation of students is not content to address social justice and equity issues only in their private lives, separate and distinct from their work. To engage students, we need to demonstrate the relevance of engineering curricula to their concerns. For example, we must find ways to rectify the biases embedded in engineering products such as automated water faucets that do not recognize darker skin or facial recognition systems that have uneven performance because they have been trained on predominantly white and male faces. Engineering needs to become a field that can adapt to and serve the social projects embraced by current and future generations.

To be clear, we are calling for a sea change along the lines of the one that followed the Grinter Report, but with an eye on the world's needs in the century to come. This transformation must begin with a deliberate effort to build an inclusive and collaborative engineering community that spans disciplines, gender, ethnicity, race, and sexual orientation. To do that we have to reassess the content and nature of both precollege outreach and undergraduate education to build interest in and preparation for the study of engineering. In step with this assessment of the curriculum and outreach efforts, we must also evaluate our expectations of engineering faculty and reimagine the structure of how we train engineers.

## Teach problem-solving rather than specific tools

As former US secretary of education Richard Riley noted: "We are currently preparing students for jobs that don't yet exist, using technologies that haven't been invented, in order to solve problems we don't even know are problems yet." We have many modern tools at our disposal, but instead of assigning messy problems that would require the synthesis of concepts from multiple disciplines, applying logical boundary conditions, and examining outcomes to make sure they are reasonable, we assign problems that could be solved with a slide rule. These are easier to grade and explain, but they are not all that realistic or inspiring. And they are not really representative of the type of problems engineers may encounter in their working careers.

The field needs more programs that provide integrative, hands-on problem-solving. Although programs such as cooperative education and structured summer internships provide industrial experiences for undergraduates and makerspaces provide on-campus hands-on opportunities, we believe more is needed. Most of these programs are optional, meaning that only a self-selected portion of students participates in them. To integrate experiential learning into the curriculum will require more deliberate effort on the part of educators.

Likewise, we need to examine and discard some of the canonical ideas in engineering education. Instead of forcing our students to memorize the intricacies of the chain rule in taking derivatives, would it not be better to teach them to use mathematics to model physical phenomena, to question numbers that magically appear on their calculator readout, or to know when to apply the chain rule and where to look it up when needed? Some professors have advocated breaking calculus' grip on the engineering curriculum. (In current curricula, it is often faculty in the mathematics department who determine who gets to be an engineer.)

As ASEE's 2020–2021 president, Sheryl Sorby convened a task force to consider curricula as a tool for the transformation of engineering education. This framework includes identifying structural racism and inequalities and suggesting possible remedies while integrating cognitive, affective, and kinesthetic domains of learning to prepare students to have more expansive perspectives when approaching society's problems.

## End the "pipeline mindset"

The pipeline analogy, which suggests that young learners join a pathway of knowledge acquisition that ultimately results in an engineering degree, has impeded efforts to diversify engineering. A pipeline has only one entry point and one exit point. If a student enrolled in the wrong math class in seventh grade, or if her high school didn't offer advanced math courses, she will find it difficult to become an engineer. Few seventh graders have engineering on their radar, yet their choices in what classes to take could shut them out of engineering—unless they're willing to go back and enroll in remedial math courses to make up for their lack of foresight as a 12-year-old. This is not an attractive proposition for most. What if the tenacity of students who arrive in our engineering programs without the benefit of such foresight was recognized and rewarded instead of punished?

It is widely acknowledged that engineering educators have designed curricula meant to keep people out. The curricular structure is rigid, with long prerequisite chains and few free electives. For example, all of our students are forced to take three semesters of calculus—even though the vast majority don't really need that. In a sense, students are subjected to one to two years of academic hazing before they are allowed into "the club" of professional engineers.

Worse, engineering education promotes competition at all levels, even though social science demonstrates that this doesn't motivate everyone. Projects and exams are designed to be so hard that many students fail, which is described as "character-building." This approach is a symptom of a pervasive belief that every engineer should experience failure of some sort as a university student, which is justified by claiming "rigor"—and this rigor allows us to continue to use our curricula as a cudgel to keep people out. We might say that we don't have a weed-out mentality, but we certainly perpetuate a weed-out system.

Not only are engineering curricula often unattractive to women and students of color, but they also fail to prepare *all* students for their future careers. How many creative problem-solvers, who would have become excellent engineers, have been driven from our programs over the years? How many potential inventors and entrepreneurs have not been inspired to join our ranks? How many out-of-the-box thinkers have been lost from engineering due to the rigidity of the engineering curricula? The true loss of human talent from engineering disciplines is impossible to calculate.

### Recognize the humanity of engineering faculty

Engineering faculty are under ever-increasing pressure to excel at all aspects of research, teaching, and service. Yet the situation has dramatically changed from 50 years ago when the prototypical faculty member was a man with a wife at home to manage responsibilities such as the house, errands, childcare, and eldercare. Now all faculty members must juggle these responsibilities, sometimes alone, along with their day jobs.

Universities have a responsibility to make the myriad tasks more manageable. Rather than expecting each faculty member to be superlative at all tasks, we should more explicitly view departmental faculty as team members with different focuses among teaching, research, and service so that the team as a whole functions at the desired level. We must recognize that a strict timeline for gaining tenure may be contributing to an exodus from universities, particularly for women. In other words, universities need to revamp their policies for faculty promotion and tenure.

### Emphasize instruction

We must build on the broad agreement that teaching is crucial to preparing and retaining future generations of engineers. We can do this by developing measurements of effective teaching as well as rewards. Currently, it's commonly perceived that promotion depends on research, rather than on one's effectiveness as a teacher. As the 2009 NAE report *Developing Metrics for Assessing Engineering Instruction: What Gets Measured Is What Gets Improved* notes, this perception may be especially true at research universities, which confer the preponderance of engineering degrees annually. But one reason this perception persists is that despite well-established methods for measuring research productivity, the metrics for teaching, learning, and instructional effectiveness are much less well-defined and broadly implemented.

While "best teacher" awards exist on many campuses and within many professional societies, they typically serve to recognize a very few exemplars. What they fail to do is provide specific guidance and assistance in enhancing the effectiveness of teaching across all faculty. There is a need to develop a schema for instructional skills development that can be implemented both within individual campuses and across campuses within engineering disciplines. Moreover, this system must be incorporated into the training of future faculty—similar to how they are now taught the skills for research. ASEE has formed a second task force aimed at recognizing and rewarding faculty for their instructional prowess.

### Make graduate education more fair, accessible, and pragmatic

Crucially, we need to rethink the labor relationship between graduate students and faculty advisors. We must eliminate the attitude critiqued by National Academy of Sciences president Marcia McNutt at the 2020 Endless Frontier Symposium, whereby graduate students are regarded as "indentured servants" subject to the petty whims of their supervisors.

In this vein, graduate programs in the United States need to be more accessible and attractive to domestic students, including populations currently underrepresented in engineering. To welcome these students, we need to acknowledge the harm done by artificial barriers to admission that have little correlation to graduate student success. The need to be more creative in preparing and accepting domestic students is reinforced by the reality that international students are increasingly choosing to either stay in their home countries or to study at schools outside the United States because these other engineering programs are perceived as more welcoming politically, socially, and economically.

The structure of graduate education should shift to better reflect the increasingly collaborative nature of modern research. Most radically, this could include joint dissertations, whereby two or more individuals collaboratively write one dissertation that serves as the culminating document for all involved.

The training of engineers has been influenced by the Grinter Report for 65 years even though the report's stated purpose was to provide direction for the "next quarter century" only. The report moved the pendulum from hands-on, practical training to the side of theoretical and science-based engineering. We believe it is time to move the pendulum in an entirely new direction—toward a more humanistic approach to engineering. By focusing on the students themselves, we can graduate more balanced engineers who are prepared for the world as it is today and for the future.

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ADRIANA BANKSTON

# Great Science Begins with Nurturing Early-Career Researchers

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Graduate students and postdocs endure long hours, low pay, uncertain employment, and inequitable conditions. To foster future innovation, we must build an environment where they thrive in all aspects, including mental health.

I grew up in an academic family, hanging around research labs and even attending scientific symposiums. As a child I would sometimes sit in my European grandparents' laboratory perusing research dissertations from their students. I knew that my grandparents valued the next generation of scientists tremendously because they often worked long hours to provide students with meaningful training opportunities. My grandparents instilled in me a curiosity for science and the desire to have a positive impact on the world.

With this in mind, I pursued a PhD in biochemistry, cell, and developmental biology at a US university. It became clear during graduate school and then postdoctoral training that the more I progressed in my training, and the more pressure there was to produce results, the less time I had to focus on my own well-being and mental health. While conducting research in the laboratory as a graduate student and then as a postdoctoral fellow, I struggled to meet all the demands placed on my time and ultimately my mental health suffered; what's more, I knew it would take many years for my research even to see the light of day. My fellow PhDs and I were all overachievers, and the competition was palpable both within and outside of the laboratory. I knew that in the long term it would be a battle to stay afloat in this environment, and my instincts were supported by a 2014 study that found there was only one tenure-track job for every 6.3 biomedical PhD graduates.

Although I remained interested in the discoveries I could make as a young scientist, I reverted to what my grandparents had taught me about scientific research and the training of students. I started exploring how the scientific enterprise could be centered around creating an environment where early-career researchers can thrive. As a former trainee, I have worked to address the power dynamics in universities from the bottom-up, but now I have shifted toward a top-down approach by appealing to federal agencies and influencing legislation at the national level to support graduate students and postdoctoral researchers in the university system.

The large number of science graduate students and postdocs in the United States are a result of Vannevar Bush's foundational vision that he outlined as presidential science adviser. In 1945, Bush suggested using scholarships and fellowships to educate promising students and connect science to society while developing the nation's knowledge base. That model has thrived in the United States and has been used as a template in other countries.

But today the focus on early-career researchers feels diminished. With federal funding, graduate students and postdoctoral researchers make up a significant part of the academic science, technology, engineering, and mathematics (STEM) workforce, particularly in the field of biomedicine. Yet their needs—a basic standard of living, workplace protections, the training and mentoring necessary to find employment in academia and industry—are not adequately addressed by policymakers, funders, and universities themselves.

To put early-career researchers at the center of the scientific training experience, several interlocking steps are necessary. Reforms are needed to the way that graduate students and postdocs are paid, trained, mentored, and prepared for employment so that their needs are met and they are equipped to contribute to society. In addition, the issue of mental health among early-career researchers needs to be addressed—both studies and anecdotal evidence suggest this is a significant and urgent problem.

Even before the disruptions of the pandemic, multiple studies suggested that the mental health and well-being of the country's early-career researchers is at risk. In 2018, an often-cited study published in *Nature Biotechnology* found that graduate students and postdocs had six times the rate of mental health problems compared with the general population. This study included nearly 2,300 doctoral and master's degree students from 26 countries found that 40% of those surveyed reported moderate to severe anxiety, and nearly 40% had moderate to severe depression. A 2014 University of California, Berkeley, study evaluated 43%–46% of graduate students in the biosciences as depressed based on their responses to a survey.

In 2019, *Nature* surveyed over 6,000 PhD students worldwide from a variety of scientific fields and found that 36% of them had sought help for mental health issues. These mental health issues are "driven, in part, by the immense pressure on academic scientists to win funding, publish, and land jobs in a brutally competitive market," Katia Levecque, then a postdoc and now an assistant professor at Ghent University in Belgium, told *Nature*.

The COVID-19 pandemic appears to have further exacerbated the stresses experienced by research trainees. A 2020 study funded by the National Science Foundation surveyed 3,500 graduate students at 12 US public research universities in the summer of 2020 and found that, of those surveyed, 32% had symptoms of post-traumatic stress disorder, 33% had moderate or higher levels of anxiety, 34% had moderate or higher levels of depression, and 67% experienced low well-being. More than one quarter of these students also indicated some level of food or housing insecurity, or both.

It is clear that more data are needed to fully assess the severity of students' mental health-related issues, how these issues vary among research disciplines, and how they impact other aspects of life and work for early-career researchers. Aside from these urgent mental health issues, early-career researchers also experience significant challenges arising from the academic system itself and their relatively powerless position within it.

Because there are many more trainees than available academic positions, hypercompetition is a symptom of the system—a system that is in "perpetual disequilibrium," wrote Bruce Alberts, Marc W. Kirschner, Shirley Tilghman, and Harold Varmus in an article on the subject in 2014. This pressure-cooker atmosphere has multiple negative effects on trainees, who report working very long hours, being anxious about publication, and feeling that their job prospects are limited if they do not contribute to work published in high-impact journals.

Anecdotally, this stress adds up. "Maybe being told day in, day out that the work you spend 10+ hrs a day, 6–7 days a week on isn't good enough," wrote one young researcher to *Nature* in a post on Twitter, is part of the problem. Another complained of "indentured servitude with no hope of a career at the end," particularly when it comes to finding a job in academia.

Whether or not the stress of this hypercompetition precipitates a mental health issue in an individual, the need to find a career outside of academia can be extremely difficult for some researchers. A study that interviewed 97 postdocs from across STEM fields at five major US research institutions found that 20% faced an "existential" crisis as they came to realize that they would not be able to get academic jobs. First-generation students, students from underrepresented groups, and foreign-born students often face additional physical, emotional, and psychological challenges and stress in this transition to nonacademic jobs.

Additionally, many postdocs face low pay. Postdoc salaries vary widely, with an annual median pay of $47,500—though some make minimum wage. A 2019 study found that women tended to make less than men in some parts of the country. Such relatively low pay, and its inequitable distribution, can discourage anyone from a disadvantaged background—as well as those with families to support—from pursuing advanced research opportunities. This self-exclusion leads to a further weakening of diversity in science, which handicaps the STEM workforce.

Another hurdle for early-career researchers is the informal "mini-me" aspect of current postdoc training. Today, faculty members mentor trainees to follow in their footsteps into academia, but there are rarely any formal resources available to help trainees transition into nonacademic (e.g., industry) positions, which are more available. This lack of structure is further complicated by the increasingly long periods of time that individuals spend in postdoctoral training.

A 2021 study of STEM graduates from 1950 to 2013 found that during the study period, the time required to get a STEM PhD has increased from 5.8 years to 8 years. A postdoc position, on average, adds another 2.7 years to this training time—and this extended period of academic limbo ultimately reduces average lifetime earnings. Finally, the power dynamics of the current training model put early-career researchers at a disadvantage, sometimes leading to sexual harassment and bullying, particularly for women in science. This issue is described in the National Academies of Sciences, Engineering, and Medicine's 2018 report on sexual harassment in academia, which concludes that the organizational climate is the single most important factor in determining whether sexual harassment is likely to occur. Although some efforts have been made to increase transparency around laboratory environments, this is another instance where cases are often underreported, and more data are needed to illustrate the full extent of the situation. Change regarding sexual harassment and bullying in academia will require a policy of zero tolerance and accountability not only at the university level but also in the wider ecosystem of science and research. At multiple levels we are failing to support the next generation of scientists. Not only is this deficiency hurting early-career researchers, but it is also diminishing the pool of individuals who have been trained to innovate and solve the problems of society. We need to invest now in scientific talent and shift the culture of science to one centered on graduate students and postdocs. They are the future of the scientific enterprise. Supporting the needs, including mental health, of trainees requires policy changes to shift the environment in which they work.

The training system itself needs reform, which will require policymakers, funders, universities, and individual researchers to act together. With other colleagues, and under the auspices of the Future of Research (a nonprofit focused on early-career researchers), I have previously outlined several important steps. These include:

- establishing transparent salaries and benefits;
- creating clear guidelines and timelines for PhD and postdoctoral training;

- offering career and professional development resources;
- requiring that academic mentors are trained in their responsibilities;
- facilitating peer support; and
- creating a system where early-career researchers have multiple mentors.

Beyond these baseline changes, however, there is a need to take action to create a more positive and welcoming environment for trainees so that they thrive, rather than merely survive.

Funding agencies should reward universities that demonstrate positive environments as a result of studies showing their early-career researchers are thriving. Evidence of attention to these researchers' mental health and well-being should be conditions for principal investigator (PI) grant funding. In this manner, demonstrated attention to mental health and well-being will result in professional rewards for both early-career researchers and faculty members. In addition, legislators should direct federal agencies to fund programs that reward mental health support for graduate students and postdocs via their PIs' grants, or provide professional development funding supplements as outlined in this recent STEM pipeline amendment.

Universities are another key player. The National Academies' 2021 report on mental health recommends that universities create the necessary infrastructure by which faculty can support early-career researchers, develop mentor training programs, and enact policy changes to accommodate the mental health needs of trainees. These policy changes could a) allow for activities that support trainee mental health to be considered in faculty promotion and tenure decisions; or b) provide faculty with financial assistance to cover mental health services for their graduate students and postdocs. Performing regular assessments of the campus climate could help establish and maintain such initiatives in universities.

Mentors themselves play a powerful role in determining that campus climate. One of my favorite examples of a positive environment is that of the Horsley Laboratory at Yale University, whose PI, Valerie Horsley, clearly states that both good science plus personal growth and mentoring are key values in her laboratory. The lab has created a handbook, which is publicly available, that describes and provides examples of these values.

In addition, a constellation of other groups is advancing an agenda to change the status of mental health on campuses and in laboratory spaces. Nonprofits such as Dragonfly Mental Health are surveying the present landscape with the goal of motivating universities to enact change through research studies, consulting services, and supportive networking sessions. A survey from the Council of Graduate Schools also addresses the need to include mental health training in orientation sessions for new faculty members, and to prioritize mentoring as central to how early-career researchers are treated in laboratories. My hope is that these multiple efforts build a climate on campus and in research laboratories that provides early-career researchers with the resources needed to become a positive force in the world. It is a moral as well as strategic failing to view training and well-being for the nation's future scientists and innovators as an afterthought on the way to making great scientific discoveries. As my grandparents' experience taught me, the path to great science is through caring for and nurturing the people who do it.

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ALBERT P. PISANO

# A More Effective Innovation Practice

Practice-focused innovation centers could help the United States translate federally funded research into tomorrow's essential technologies.

To compete in the global marketplace, the United States needs to ensure government-funded breakthroughs in science and technology are translated into new and established business ecosystems. I refer to this type of innovation, which is initiated in academic research labs and moves into industry, as "pull through." The United States now faces a trillion-dollar question: How does the country accelerate innovation pull through and also build and rebuild industrial ecosystems to bring that innovation into society while creating jobs here?

My answer is: with practice. By practice I mean practically oriented work that directly builds on basic research funded by the US government. The nation's students and young researchers need more—and better—places to practice the concepts they are learning about to prepare to create pull through. Practice is not merely additional work, but the sort of work that extracts practical uses from new scientific insights, particularly technological applications and their commercialization. Practice thus entails transdisciplinary collaboration and knowledge integration to develop multiple proofs-of-concept into commercially viable products. I should remark at this point that practice, so conceptualized, is not a silver bullet. But it is, I believe, a crucial element that is currently lacking at US research institutions—even though the model has previously proved itself in enabling the US chip design industry during the 1980s.

To create a more integrated innovation ecosystem, one that starts in academic settings and leads into the marketplace, the federal government should create a nationwide network of collaborative environments dedicated to practice and designed to target technology areas of strategic interest to the United States. I propose we call these collaborative environments innovation centers for the practice of platform technologies.

A network of such dedicated research test beds, each devoted to a strategic enabling technology such as artificial intelligence, vehicular autonomy, gene editing, and future wireless technologies, can ensure that the United States remains on the cutting edge of such technologies, not only in the research, but also in their translation to societal use—creating both jobs and value here at home. Making these test beds into truly open innovation platforms will reduce the barrier to entry not only for people but also for innovative ideas.

Each practice-focused innovation center should be set up as a public–private partnership to bring industry, academia, government, and the Department of Energy's national laboratories together around a single technology. This infrastructure needs to be "neutral territory" where researchers can interact with one another and with technologists who are working on related issues in industry, government offices, and national labs. The innovation centers will replace simply meeting at conferences and sharing results and would aim to empower US-based researchers to engage in mutually beneficial large-scale precompetitive collaborations, including the crucial practice of technology integration in real-world conditions.

Importantly, the innovation centers should be accessible to young researchers across the nation and not be limited to the tight circles of people who are directly funded by any specific research grant. The infrastructure should enable students who want to work in fields of strategic national interest. Such people will bring with them not just the technical talent but also the motivation and networks necessary to persist.

Access to the practice of technology fulfills a deep need in today's students who earnestly want to see their work make a difference in society. Creating places that train scientists to translate their ideas means that the next generation of graduate students and postdoctoral fellows will enter the US workforce with both specific technical training and more expansive practical perspectives. The alumni of these centers will be more likely to integrate their innovations into the fabric of the industries that hire them. At the same time, inculcating a practical orientation on newly minted researchers ought to realize greater value from US government-funded research expenditures in basic science, engineering, and technology.

## Practicing the wireless technology of the future

The wireless technology of the future provides an opportunity to look more closely at how such practice-focused research infrastructure could work. The United States still leads in many of the areas of fundamental wireless research: the radio frequency coding modulation community in US universities is just one example. But as Paul Jacobs, the former CEO of Qualcomm, has pointed out, there are no longer any large-scale wireless technology infrastructure companies in the United States.

This deficit means that while the United States is funding and creating some of the most advanced research for tomorrow's wireless technologies, the country does not have the full suite of commercial ecosystems necessary to move the funded-by-taxpayers, world-class wireless innovations into US wireless industries. Thus, the nation is not capturing enough of the value created with its research endeavors.

Here is where practice-focused research infrastructure for future wireless technologies could not only create pathways for commercialization and the rebuilding of US industry but also build safeguards to privacy and security infrastructure. The innovation centers would provide virtualized platforms that would allow a nationwide network of researchers from academia, industry, and government to interact in open, disaggregated modern architectures. One of the benefits of such collaborations would be unprecedented opportunities to demonstrate user equipment interoperability at "open hardware interfaces," which are, by definition, standardized interfaces between hardware components created to ensure components from different manufacturers can talk to each other. Creating interoperability is crucial to making commercially successful components, but innovation centers would also be able to determine the privacy of security standards underlying this function. Thus the innovation test beds could create both data security and economic security at the same time.

This emphasis on open hardware and interoperability is not a new idea. In fact, the same strategy was employed at the beginning of the internet. Open innovation allowed a myriad of new hardware and software companies to enter the field, as well as stimulating a large number of application software packages; the architecture of the system encoded values of openness and flexibility that grew out of the culture that created them. Many of the early internet pioneers are still active in the computing field. Their expertise could be invaluable as the nation builds out this infrastructure.

Practice-focused research infrastructure centers would have the overarching goal of guiding innovation along a path that leads to more players being able to enter the wireless industry. In the absence of this national infrastructure, however, the threads that could be woven into game-changing wireless communications technologies will remain separate or poorly knit together, causing a delay that will put US leadership in the future of wireless in the global marketplace at great risk. By contrast, innovation centers can create an environment where the technology, the architecture, and the business models can more quickly evolve and emerge in parallel.

## We have done this before

Building nationwide research infrastructure that supports education and fuels new industrial ecosystems is something we as a nation have done already—at least in part—in different ways. In the early 1980s, for example, MOSIS (Metal Oxide Semiconductor Implementation Service) began as a program funded by the Defense Advanced Research Projects Agency that empowered researchers from across the country to get involved in designing and using integrated circuits. According to *MOSIS: Present and Future*, a 1984 report by some of the creators of MOSIS, the program's main function was "to act as a single interface between a geographically distributed design community and a diverse semiconductor industry. As such an interface, MOSIS has significantly reduced the cost and time associated with prototyping custom chips and custom boards."

In short, MOSIS enabled researchers from around the country to tap into a shared infrastructure and knowledge base. In this way, MOSIS democratized complementary metal-oxide semiconductor (CMOS) chip design and manufacturing and helped to ensure that the United States led in this chapter of the microelectronics revolution—in terms of fundamental technologies, the applications that grew out of CMOS technologies, and the innovation workforce that was central to it all.

As CMOS fabrication technologies advanced, so did the facilities and capabilities available to MOSIS users as the MOSIS hardware infrastructure kept evolving. When MOSIS metaknowledge exposed product gaps in the marketplace, companies formed to make the most of these opportunities. In this way, successive generations of graduate students and postdocs from around the nation got practical experience with CMOS chip design. These young researchers became the innovation workforce that brought the promise and potential of this platform technology to many different industries in this country. This phenomenon yielded new companies in multiple industries and a growing US workforce with practical experience that went on to both advance the technology and develop applications based on CMOS technologies.

MOSIS provides a fruitful example of the power of a virtualized innovation tool and the huge value that can be captured by empowering young researchers to gain practical experience with platform technology development and applications. Without MOSIS, most of these young researchers would not have been able to directly explore the use of CMOS technology. In addition, the demand would not have been there for the ancillary companies that sprang up to support and further develop the nation's growing interest in CMOS technology. Furthermore, MOSIS is a useful example for highlighting something that a national network of innovation centers for practicing platform technology *will not be*: to some extent, MOSIS served to pick CMOS as the winning integrated circuit technology.

In contrast, the new innovation centers for the practice of platform technologies will not pick winning technologies. Instead, each innovation center will provide neutral territory and essential technological and tech-policy ecosystems where breakthroughs in areas of national importance can be evaluated. At each center, implementation, integration, interoperability, and security issues can be explored. Winning technologies will emerge from this environment of precompetitive collaboration and experimentation, where researchers from academia, industry, government, and national labs are all at the table.

## Federal funding to protect the US research enterprise

New federal funding is critical for setting up and maintaining the nationwide virtualized research-for-education infrastructure at the core of these practice-focused innovation centers. Additionally, these new investments will serve to amplify the positive outcomes from the well-recognized virtuous cycles that emerge as traditionally funded US research teams move back and forth between fundamental and applied research projects. It is vital that policymakers preserve funding for both fundamental and applied research in all disciplines as researchers move forward with building out practice-based research infrastructure, with the aim of embedding these innovations (and their value) in the society that has funded them.

Built correctly, these practice-focused research ecosystems will create rich, dynamic virtual platforms with physical roots. They will create opportunities in which students of all levels as well as seasoned researchers in industry, government, and academia can interact. The nation will possess networked, virtualized research infrastructure that is specifically designed to encourage learning and engagement through practice. This vision is a blueprint for a more equitable and prosperous future in which anyone across the country has entry points to practice creating innovations. Moreover, policymakers will have found ways to build and rebuild America's innovation-driven industrial ecosystems. This is practice as policy.

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AYANNA HOWARD, CHARLES ISBELL, AND RAHEEM BEYAH

# A Moonshot for Every Kid

The exclusion of diverse people from engineering and computer science is a blind spot in US national security—and one the nation must work to fix.

The demographics of the United States are changing, but these changes are not reflected in the diversity of students pursuing degrees in engineering and computer science. Meanwhile, more than 700,000 computer and math jobs than existed in 2020 will need to be filled by 2030—far outpacing the number of degrees currently awarded.

The intersection of the country's growing dependence on technology with a clear shortage of STEM (science, technology, engineering, and math) talent is fast becoming a national security issue that must be addressed urgently.

In an April 30, 2021, speech, Secretary of Defense Lloyd J. Austin III emphasized that sophisticated information technologies, including quantum computing, artificial intelligence, and edge computing, will be key differentiators in future conflicts. The United States risks not having enough talent to drive innovative STEM research, development, and deployment in the coming years. It is imperative that people of color and those from other underrepresented groups become part of the STEM enterprise—not only to advance emerging technologies critical to maintaining American leadership and national security, but also to ensure that new technologies and their potential implications are developed with the needs of diverse communities in mind.

You might think of this as a replay of 1957's Sputnik moment, when the United States suddenly realized the need to invest in science education to avoid losing the space race with the then-Soviet Union. Today, by contrast, the country must make an unprecedented investment in diversifying STEM fields to help protect democracy, citizens' quality of life, and the overall health of the nation.

To nurture the talent that can help keep the country safe through the next 75 years, we propose a three-pronged approach that changes the way gatekeepers influence the field, makes more advanced high school courses and college support available for all students, and provides opportunities for young people to build confidence that they can solve real-world problems. These steps are designed to ensure that increasingly diverse voices and minds are represented in engineering and computer science and can thus contribute to solving our ever-evolving efforts to keep the country safe and secure.

## Understanding the deficit

Although the demographics of the United States are shifting significantly, with Americans identifying as Hispanic/Latinx rising from 12.6% of the US population in 2000 to an estimated 30.2% in 2050, Hispanic/Latinx and Black students remain significantly underrepresented among those who receive both undergraduate and graduate engineering degrees. Gaining greater participation from these groups could not only increase the workforce to maintain a competitive edge, it would bring broader representation to the deployment of future technologies.

There is general agreement that the problem of underrepresentation begins early—in K–12 education. Among high schools, a status of separate-but-not-equal has been a persistent problem. Access to advanced math courses in high school varies according to a student's race, ethnicity, and socioeconomic status; a 2016 study noted that "just a third of high schools where at least three-fourths of students were Black and Latino offered calculus." Given that math is traditionally seen as a gatekeeper course for college STEM majors—the highest math course a high school senior takes has a major influence on both college acceptance and college choice—it comes as no surprise that, at the college level, these disparities continue in engineering and computer science.

But inequities still exist even when Black, Hispanic/Latinx, and Indigenous students attend K–12 schools that have programs specifically for advanced students. Since 1998, only 2% of Black students and 3% of Hispanic students have been enrolled in gifted and talented programs in US public schools as compared to 4% of white students and 6% of Asian students.

Differences in math skills and test scores for those in different demographic groups do not explain this gap in enrollment. Rather, the race of their teachers accounts for the difference: Black students are referred to gifted programs at significantly lower rates when taught by non-Black teachers. This pattern may be rooted in the ways a teacher's race influences expectations of the students he or she teaches. One study concluded that when evaluating the same Black student, white teachers expect significantly less academic success than do Black teachers. These findings suggest that, by extension, if the engineering and computer science college professoriate does not fully represent the demographics of the students they teach, the same result is likely when it comes to student success and expectations.

In other words, engineering and computer science departments in colleges and universities are also a part of the problem. Just as systemic inequities persist in the K–12 educational system when it comes to STEM, related inequities appear at the college level. Although Black, Hispanic/Latinx, and Indigenous students are just as likely to identify STEM areas as a desired major when entering college, their average completion rate for STEM degrees is not on par with their peers from other racial groups. Among the factors identified as contributing to this gap are struggles in introductory math courses and the mental stress of navigating an environment that feels unwelcoming.

In this way, college-level inequities extend and magnify the inequities of math education, gifted education, and reduced expectations in high school. While many observers claim that higher education shouldn't be expected to fix the problems of K–12, it may follow some of the same inequitable practices as well as introducing new challenges. As engineering academics trained to solve complex problems, we can and should do better than make excuses for the status quo.

## An urgent agenda for change

Diversifying STEM is not merely a question of shifting pedagogy; it is an urgent necessity in our technologically fluid landscape. With nearly every aspect of life being tightly coupled with artificial intelligence, cybersecurity, and complex engineering systems, the United States cannot afford to sit back and wait for a computer science-based crisis to hit. The country is already witnessing the rising potential for such a catastrophe, with malicious attacks on energy facilities, hospitals, and cities becoming more frequent.

When the Soviet Union launched Sputnik in 1957, the United States embarked on rapid educational reform to regain technological ground in the space race. The National Defense Education Act of 1958 provided federal funding to "insure trained manpower of sufficient quality and quantity to meet the national defense needs of the United States." Subsequent transformations in science and engineering education trained new generations of engineers and scientists who continued to power the economy through the dot-com boom of the 1990s.

But, this time around, will the education system be able to train engineers quickly? If the country can't even retain the population of college and university students already interested in engineering and computer science, it's unreasonable to expect better during a crisis. Is it wise to wait until a triggering event puts a spotlight on the deficit of STEM talent as a national problem?

We argue that universities must recommit now to their fundamental mission of focusing on the public good and providing for the needs of society. Universities must ensure that they institute an engineering and computing educational transformation that provides every interested mind an equitable seat at the table.

To bring about necessary changes quickly—by meeting the needs of today's diverse students and preparing them to enter the STEM workforce—requires three significant changes. These changes constitute a push-pull strategy to remove barriers caused by widespread educational inequities and biases, while motivating students to stay in the field by empowering them to solve global issues. First, STEM education needs to eradicate expectation differences (or at least the behaviors associated with them) among gatekeeper courses, faculty, and advisors. Secondly, the system must increase the availability of math and science courses to accelerate learning to overcome inequities present in students' pre-college preparation. Finally, science and engineering curricula must be focused on experiential opportunities, so that students gain a sense of confidence in their use of knowledge to solve real-world problems.

***Programs to eradicate expectation differences.*** There are two ways to eradicate expectation differences: either change perceptions, or change people. To change perceptions, studies have shown that having resilience in the face of academic and social challenges is essential for success. For example, researchers have provided clear evidence that students who believed that intellectual abilities were qualities that could be developed—versus qualities that were intrinsic (i.e., the "born an engineer" syndrome)—had greater course completion rates in difficult math courses. Importantly, this finding held up whether students inherently believed intellect and resilience could be learned or were taught it. In other words, establishing programs that embed psychological interventions and train faculty and advisors in fostering these can-do mindsets among future engineers and computer scientists can be an effective step on the path toward eradicating expectation differences.

A second pathway to eradicating expectation differences is to ensure that the demographics of faculty and advisors better correlate with student demographics. Studies have found that engineering departments that awarded more bachelor's degrees to women African American/Black undergraduate students than other departments did were more likely to employ more African American/Black women faculty (and vice versa). One national initiative that is attempting to solve the representation problem is the National Science Foundation's NSF INCLUDES (Inclusion Across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science) program, which focuses on enhancing US leadership in discoveries and innovations by increasing participation of individuals from traditionally underrepresented groups in STEM education and careers.

***Increased availability of courses to accelerate learning.*** Because of gaps in their high school curricula, many college students struggle in their sophomore year when they take their first discipline-specific engineering courses. Although it's long been common for engineering colleges to host summer bridge programs for pre-first-year students to enrich their experience as they matriculate into engineering majors, we believe this is insufficient. In addition, initiatives should be more specific to the needs of students and more supportive throughout the entire school year to accelerate learning and overcome inequities in pre-college preparation.

One such effort was launched in the summer of 2021 for rising sophomores in the College of Engineering at The Ohio State University. Its ACCELERATE (Academic Enrichment and Career Development for Undergraduates) program was conceived as a combined academic and experiential enrichment program designed to address knowledge gaps especially among historically underrepresented students in engineering and to support students' progress through the engineering curriculum. Similarly, the Georgia Institute of Technology's Challenge program is a five-week summer residential program that helps "prepare incoming first-year students for a successful college career by equipping them to address the 7Cs: computer science, chemistry, calculus, communication, career development, cultural competency, and community service."

However, as we examine the quality and type of courses universities need to offer to overcome existing inequities, educators must go beyond the one-and-done mentality. One summer experience, one remedial calculus course, or one extra hour of tutoring—as helpful as they are—is likely not enough to eradicate years of educational injustices.

***Experiential learning opportunities.*** Learning through experience involves the process of hands-on learning or learning by doing. When students are learning the basics of programming, for example, they  read about code grammar or syntax; but unless they are personally plugging away at it, compiling and debugging, laughing in relief as they finally discover that missed semicolon, they really are not in a position to learn effectively. Collaborating with the US Department of Defense's National Security Innovation Network (NSIN) is one path for providing experiential opportunities to students based on solving real-world problems. NSIN is focused on solving national security problems by collaborating with academic partners such as Ohio State and Georgia Tech. In 2020, a group of five biomedical engineering students at Georgia Tech collaborated with NSIN to find ways to test the effects of battlefield blast exposure on and its correlation with traumatic brain injury.

No longer is an unprecedented investment in diversifying STEM fields simply something that would be nice to have; rather, such investment addresses a looming workforce need and national security issue. Disparaties in matriculation and especially graduation rates of students from underrepresented groups in engineering and computer science pose a major risk to national welfare. If engineering is to continue its mission of creating new technologies, businesses, innovations, and solutions to address the world's problems—and help solve them before they become full-blown crises—educators must act now to invest in all potential future engineers and especially those from underrepresented groups who have not previously received the broad range of support they need and deserve for success.

The moonshot we are proposing is quite simple: give every kid a fair shot, regardless of zip code or skin color. It is not only the right thing to do, it's also critical to the security of our nation.

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DARRYLL J. PINES

# Democratizing Engineering for Every High School Student

Offering engineering classes to high school students can empower them to create change in their local communities and encourage them to pursue careers in the field.

One of the greatest and most enduring strengths of the United States has been its ability to attract global talent in science, technology, engineering, and mathematics (STEM) to bolster its economic and technological competitiveness. To this end, the White House recently announced new actions and pathways for international STEM scholars, students, researchers, and experts to contribute to innovation and job creation efforts across the United States. But it is also crucial to recognize the importance of increasing and training the domestic workforce of scientists—especially engineers. The nation's current STEM shortages within research, development, and innovation communities cannot be addressed solely by attracting more global talent.

Indeed, the United States is facing a crisis in its K–12 pipeline. According to data from the National Student Clearinghouse Research Center, the percentage of US high school students enrolling directly in college in 2020 showed an "unprecedented" decline of between 4% and 10%. And while the US Bureau of Labor Statistics predicts STEM jobs will grow twice as fast as other occupations by 2029, research continues to show high school students have declining interests in STEM fields.

The gap in the US STEM pipeline is exacerbated by the large proportion of international graduates who either return overseas or work for foreign companies that compete with US companies. According to the 2020 Industrial Capabilities Report to Congress, China is producing eight times as many STEM graduates per capita as the United States (despite its population being four times as large)—and the trend continues to worsen.

This geopolitical dilemma requires a three-pronged response. First, the United States must make continued investments in basic scientific research. Second, the country must expand the pipeline of diverse STEM graduates. And third, engineering must be a requirement for every high school student. Together, these policies are an urgent national imperative.

With a growing number of high school graduates who are first-generation immigrants, from underrepresented minority populations, or both, it is abundantly clear that the nation's interests are best served by fueling the K–12 pipeline in ways that encourage more high school students from diverse backgrounds to pursue engineering programs. But how do educators inspire these students to discover engineering as their calling? Most students have a basic understanding that engineers "design and build things," but possess an extremely limited sense of what engineers actually do. Aggravating matters further, many students are intimidated by the math requirements and never consider the profession for themselves.

One successful approach to expanding the K–12 pipeline is the National Science Foundation-sponsored pilot program Engineering For US All (e4usa), which seeks to bring engineering principles, skills, and design experiences into the high school curriculum. As the National Science Foundation's Don Millard puts it, e4usa attempts to "democratize engineering for every high school student." The program's novel 30-week curriculum requires only high school algebra as a prerequisite and focuses on four major themes: discovering engineering, engineering and society, engineering professional skills, and engineering practice.

Several features of this program make it worth emulating. No prior knowledge of engineering is required and any teacher can be trained to deliver this first-of-its-kind engineering course. Students are empowered to create change in their local communities through exposure to problems that are personally meaningful or associated with society's grand challenges, including sustainability, clean water, and human health. Teaching techniques engage students in the creativity of engineering early in their education. Research has shown that consideration of differences in how students learn has a marked impact on student retention. And if universities can retain first-year students through completion of their engineering degrees, the number of engineers graduating in a given year could increase by as much as 40%.

After three years of implementation, e4usa is now in 50 high schools in 19 states, plus Washington, DC, and the US Virgin Islands. It has helped over 3,000 students across the United States. The demographics of the 2021–2022 cohort is approximately 42% underrepresented minority and 43% female and nonbinary genders. By every measure, this program is expanding the pipeline of diverse high school students interested in pursuing STEM degrees. Surveys of the first-year cohort showed 52 out of 82 participants going into STEM degree programs at either two-year or four-year schools. In addition, students can receive credit and placement at seven colleges and universities around the country.

Besides changing high school curricula, educators must also work to convince students of all backgrounds that pursuing an engineering career is not only possible but also deeply rewarding. The engineering of mRNA vaccines, for example, was performed at record speed and remains a wonder. When Kizzmekia Corbett, a leading coronavirus researcher and an African American woman at Harvard University, talks to young high school women, the first thing she wants them to know is that if she—raised in a tiny Southern town—can perform the groundbreaking research that led directly to the development of the Moderna COVID-19 vaccine, then so can they.

These stories make a difference. The girls hang on her every word as Corbett explains that she could never have imagined completing her undergraduate degree at the University of Maryland, Baltimore County, working as a research fellow at the National Institutes of Health, and then joining the faculty of the Harvard T. H. Chan School of Public Health—before seeing her research successfully harnessed by Moderna to create a life-saving medical intervention in a global public health emergency. Incredible stories like Corbett's highlight how government investments in basic scientific research fuel the pipeline to future discoveries.

The COVID-19 pandemic has showcased the need for greater STEM investments and for a diverse workforce trained to develop new interventions, new processes, and new materials. Fortunately, Maryland's political leaders understood early in the pandemic the need to leverage the combined expertise of science, medicine, and engineering via formation of the COVID-19 Task Force. Thanks to this advice, the governor and state legislature have the enviable task of deciding how best to invest approximately $2.5 billion, the largest surplus in its history, after years of structural deficits. The next round of vaccine breakthroughs or game-changing technology may well come from a student who grew up in a small town or underprivileged community but who participated in a program like e4usa.

These engineers of the future will need the ingenuity of Nikola Tesla, the scientific insight of Albert Einstein, the creativity of Maya Angelou, the determination of the Wright brothers, the leadership abilities of Bill Gates, the conscience of Eleanor Roosevelt, and the vision of Martin Luther King Jr. The nation's economic competitiveness, military strength, public health, and standard of living depend on these values—and growing the domestic engineering workforce is an essential step to making this future possible.

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BERONDA L. MONTGOMERY, FÁTIMA SANCHEZNIETO,
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# Academic Mentorship Needs a More Scientific Approach

Research into mentorship demonstrates that supporting the next generation of brilliant minds takes collaboration, innovation, accountability, and rewards.

For an aspiring scientist, intentional support and guidance through effective mentorship can make a career. For that same scientist, negative mentoring experiences—whether well-meaning but neglectful supervision or intentional bullying or harassment—can break a career. University-based scientific education and research depends heavily on established scientists shaping the next generation of brilliant minds, but currently it does not recognize that kind of labor in the way that it rewards publications and successful grant applications. In fact, it is surprising how little attention is paid to the support and guidance of early-career scientists—who heavily contribute to writing grants, doing research, and publishing results. As a community and a culture, academic science must shift toward prioritizing training and mentoring as much as it does the conduct of research. Accomplishing this shift will require deliberate changes to future science policy at all levels to make the development of early career scientists a national priority.

Decades of research into how to make mentorship successful and productive for the careers of aspiring scientists have not been systematically put to use, with the amount and quality of mentorship left to individual principal investigators (PIs), who typically receive little or no mentoring training. Funding priorities reflect this lack of emphasis: for example, only 3% of total National Institutes of Health (NIH) funding in 2020 went to grant mechanisms that specifically required mentorship and training plans. At the National Science Foundation, although grants supporting postdoctoral scientists require a mentoring plan, accountability structures for them are limited. To support the next generation of scientists and build a stronger, more competitive, and more sustainable research enterprise, academic and funding agency leadership must integrate fundamental and celebrated aspects of scientific research—collaboration, innovation, accountability, oversight, and rewards—into the practice of academic mentorship.

Today, mentorship is largely an ad hoc activity, with institutions delegating responsibility to graduate training programs and the PIs of individual research groups. This entrenched, informal system revolves around each scientist's individual commitment to mentorship and personal experience with past mentors. The uneven way the enterprise handles mentoring is reflected in the way the word itself is used (and misused) in various contexts. Often, the word "mentor" is used to refer to the PI who is running a student or postdoctoral researcher's laboratory, even when the true nature of that relationship is merely supervisory or managerial. Lack of a consensus understanding of the approaches to mentorship, the responsibilities involved, and the standards for practice translates into many established scientists and programs claiming to understand and implement mentorship, with relatively few doing so in ways that are intentional and informed.

*The Science of Effective Mentorship in STEMM*, the 2019 report on mentoring in science, technology, engineering, mathematics, and medicine from the National Academies of Sciences, Engineering, and Medicine, defined mentorship as a "professional, working alliance in which individuals work together over time to support the personal and professional growth, development, and success of the relational partners through the provision of career and psychosocial support." Mentoring relationships, therefore, are reciprocal, defined, and agreed upon by all participating individuals.

The National Academies committee that developed that report also made a series of recommendations that we build on in this article. A key point made in the report is that mentorship is as much a science backed by evidence as are other fields of research. Like other parts of the scientific enterprise, mentoring needs institutional support, commitment to best practices and innovation, accountability and oversight, and rewards and recognition. Effective mentorship, in other words, requires deliberate and intentional actions at the individual as well as institutional levels.

Currently, ineffective and even harmful mentorship practices are commonplace in academic science. Regardless of the mentor's intentions, these practices affect the confidence, the mental health, and, ultimately, the retention of early stage researchers in academia. Research on mentorship has shown that negative mentoring experiences are detrimental to the conduct of research, leading to lower job satisfaction, higher likelihood of leaving, and increased stress. Negative mentorship experiences happen more frequently *and with more detrimental impact* to researchers of color, particularly those who are Black or Indigenous, along with researchers who are queer, disabled, and neurodivergent. Those negative experiences then have a downstream effect on the overall diversity of the scientific community as a whole. When the scientific establishment fails to train the next generation of scientists in ways that are intentional and effective, both individuals and the academic research enterprise as a whole are shortchanged—which in turn negatively affects the taxpayers who fund and trust the enterprise and benefit from its findings. Ineffective mentorship ultimately affects everyone.

### Adopting a collaborative model

In labs throughout the country, including those on the cutting edge of research, mentorship practices still take their cue from the earliest European colleges, where a single, experienced, sage-like scholar served as mentor to a group of excited and engaged students. This literally medieval basis for mentorship in science is so entrenched that most research training programs at the graduate and postdoctoral levels take a hands-off approach to mentoring, leading to a wide variety of mentorship experiences for trainees, even within the same departments and programs.

Scholarship from both industrial and academic perspectives indicates that no one person can provide the full spectrum of career guidance and psychosocial support that even a single mentee, let alone an entire team, will need. Rather, mentees should be given the resources to build comprehensive mentoring networks or mentoring constellations, enabling them to meet individual needs with support and guidance from multiple people. Because their needs will vary based on their strengths, social and intellectual capital, and areas for growth, they will require a wide range and differing number of mentors and resources. One useful tool is mentoring maps, which can guide a mentee through the process of building structured networks of mentors. The network approach can also decrease the burden on any one mentor, allowing them to focus on areas of mentorship that they are best suited to provide.

Just as a research project might involve the collaboration of colleagues—incorporating various perspectives and areas of expertise to fully understand and untangle complex systems—effective research mentoring requires multiple perspectives, ideas, and sources of support. Academic institutions, departments, and leadership committed to the effective mentorship of the next generation of scientists should incorporate collaborative mentorship networks into their training of graduate students and postdoctoral scholars.

### Supporting innovation and evidence-based practices

Like any science, the science of mentorship evolves as experts in the field innovate solutions. Currently, mentorship researchers are especially interested in how to provide more effective support to minoritized students and professionals. Although studies of mentorship have provided key insights into what works, for whom, and in which contexts, until recently much of the research has focused on practices shown to be effective in majority white populations, rarely taking into account important factors such as social identity and social capital. The 2019 National Academies report noted the continued persistence of colorblind approaches to mentorship in academia, which involve "focusing exclusively on individual performance measures without consideration of factors that are highly correlated with performance such as social identities, cultural background, and social context, [a focus that] tends to privilege individuals with better preparation, higher social capital, and fewer additional obligations." Such commonplace practices fail to reflect the reality of who stays in and who leaves the system.

Given the long-standing failure of attempts to diversify the scientific research community, designing and implementing inclusive and culturally aware research environments must be a priority. Some evidence-based resources to help advance culturally responsive mentorship practices do exist, but more must be done to fully develop, disseminate, and implement them. For example, the NIH-funded National Research Mentoring Network includes a collective effort focused on "evidence-based mentorship and professional development programming that emphasizes the benefits and challenges of diversity, inclusivity, and culture," according to the network's website. This trove of practices and resources should be leveraged to inform mentoring relationships and built upon to expand understanding of the science of mentorship.

Innovation in mentorship, like innovation in research, though, requires commitments not just from individual PIs, but also from leadership at federal funding agencies, deans and department chairs in academic institutions, and scholars of mentorship. Recent studies on the development and implementation of culturally aware mentorship training have found that, while research mentors reported gaining a deeper understanding of mentee challenges and developing improved communication practices, they also expressed frustration at the lack of institutional support to apply what they learned over the long term. In addition, although both training for PIs and evidence-based metrics to measure PIs' confidence in engaging in culturally aware mentorship behaviors exist, these practices have yet to be widely implemented, sustained, and supported at a systemic level.

Just as innovation in scientific research is supported by offices and executive leadership dedicated to enhancing grant applications, study design, and effective communication of findings, supporting and implementing innovations in mentorship will require investment. Committing financial, human, and structural resources in specific areas—such as requiring mentor training for all faculty taking on trainees—indicates an institution's priorities and commitment. Creating inclusive, equitable, and responsive research environments will require deploying resources, support, and paid personnel to mentorship across an institutional ecosystem.

## Providing incentives and accountability

The academic research system currently relies primarily on the individual commitment of PIs to ensure good mentorship. At the level of funders and institutions, there are few mechanisms such as departmental awards to incentivize effective mentorship, and there are even fewer mechanisms to hold individuals accountable for uninformed, neglectful, or even harmful mentorship practices. While lack of training, ineffective communication, or misalignment of expectations and styles contribute to negative mentorship, it is important to recognize that racism, abuse, sexual harassment, ableism, and queer- and transphobia persist in academic spaces to this day with little to no consequences for individuals who cause harm to trainees and their careers. Full commitment of the scientific enterprise to the professional development and retention of future scientists will only be accomplished when proper oversight and regulation of mentorship are established for grants that fund research done by graduate students and postdocs.

Currently, the majority of graduate students and postdocs supported by NIH are funded on R mechanism grants (the organization uses letters to code different kinds of programs it supports), which do not have any mandates for holding PIs accountable for providing evidence-based training and mentorship practices. NIH does have established mechanisms—such as its individual K or institutional T awards—that include varying levels of accountability for mentorship education or support. However, in the same way that it is accepted practice for scientists to explain the "what" and the "how" of their proposed research project, PIs should be asked to demonstrate the "who" *and* the "how" they will provide career development and support of their research teams. Including this as a requirement on all research funding should be part of the responsible conduct of research. Funding agencies and academic leaders who are committed to improving mentorship need to work to develop rigorous guidelines that incentivize good mentoring behavior and ensure that evaluation of mentoring plans becomes a meaningful and integrated part of all research proposals that fund trainees, not just the small percentage currently specified for training.

Academic institutions can also incentivize and facilitate improved mentoring in numerous ways: through providing resources and training faculty, conducting rigorous evaluation, and recognizing effective mentoring in a manner that rewards faculty and reflects the true value of these activities. Today, when mentoring is recognized, it is often woven into recognition and evaluation of an individual's teaching or service—but it deserves its own stand-alone evaluation. Throughout academia, there are performance expectations, rewards, and metrics broadly recognized as demonstrating excellence; these should be offered for mentorship, with the same stature and career import as research awards. Likewise, research merit reviews should directly acknowledge mentoring—contrary to the current practice of irregularly applying quantitative metrics to the number of students and postdocs trained.

The science of mentorship can help inform the performance expectations, rewards, and metrics for the evaluation and recognition of mentorship by faculty members. The 2019 National Academies report notes that leaders can establish guidelines for evaluating mentorship, include mentorship outcomes in annual reviews and promotion and tenure packages, and provide clear criteria for mentorship awards. Merit and review committees can incorporate anonymized feedback on mentoring, enabling leaders to identify promising practices that deserve amplification and reward, as well as areas of individual or collective focus for improvement. In their annual and promotion reviews, faculty members could be asked to report on their mentoring philosophies, their mentees' contributions to manuscripts and grants, any mentoring awards received, and bilateral assessments measuring outcomes of mentoring. When hiring new faculty members, leaders could ask for mentoring statements or certifications of completing mentorship education, which institutions could provide for their graduate students, postdocs, and faculty. In elevating mentoring preparation and stewardship to institution-wide priorities, campus leaders can take concrete steps to improve the quality of mentoring for early career researchers.

## Mentorship as a science

Leaders set the tone, both culturally and systemically, within their spheres of power. They guide the development of those around them and can align policy, culture, and practices with what we know works to unlock the greatest productivity and creativity among all scientists. Funders and academic leaders have a moral imperative to begin implementing the systemic changes needed.

To transform mentorship and provide the support early-career scientists need, institutions will need to use evidence-based practices and innovations at the system level, while providing leadership support and accountability structures. Doing so will entail structural changes in how trainees are supported, as well as how some established scientists are recognized.

Our goal is a future in which mentorship is deeply and intentionally embedded into the scientific enterprise, starting with funding and extending to academic leadership and individual PIs. We envision mentorship as intentionally involving teams, including people who specifically focus on mentorship. Together, these teams would provide support for the scientific, pedagogic, and career development of future scientists. Universities would fund offices dedicated to providing mentorship education and support to both students and faculty in the same fashion as done in research safety and ethics offices. Faculty responsible for mentoring students or benefiting from their labor would submit training and development plans demonstrating competence and intentionality in the stewardship of their career development. Promotion and tenure would explicitly take mentorship into account, and mentorship education would be a part of all careers.

Mentorship is central to the research ecosystem, and it must be treated as such. Mentorship takes skill, time, effort, resources, and dedicated individuals who should be adequately trained, recognized, and valued. Intentions, however good, will not make up for a lack of intentionality: our future scientists and science are at stake.

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DARSHAN KARWAT

# Creating a New Moral Imagination for Engineering

From lifesaving vaccines to weapons of mass destruction, engineers seem willing to enable any enterprise for the right price. How might engineering become better aligned with sustainability, justice, peace, and human rights?

Engineers are responsible for some of the awesome achievements of our era, such as the electrical grid, vitamin A-enriched “Golden Rice,” getting astronauts to the Moon and back, and innumerable others. They are also complicit in degrading things—unwarranted surveillance, for example, and even monstrous projects like the atom bomb. These contrasts are even more paradoxical when we realize that abundant engineering energy and talent are devoted to efficiency, however destructive, in the exploitation of natural resources; to superiority, however lethal, in the arms race between powerful states; and to dominance, however polarizing, in the market of online attention. Engineers sometimes seem so interested in answering questions of technical feasibility that they may overlook questions of purpose or ulterior motive. This tendency raises the question: Does engineering have a moral compass? I contend it can, but only insofar as the profession commits explicitly and publicly to values widely accepted by a free and open society—like those of sustainability, justice, peace, and human rights.

As things stand, though, it is not fully evident how engineering can live up to such a commitment, since at the heart of the engineering enterprise lies contradiction. Engineers in Texas figure out how to extract ever-harder-to-reach fossil fuels, while engineers in Florida develop urban adaptations to rising sea levels caused by global warming. Engineers for gun manufacturers refine assault weapons, while other engineers devise medical instruments to treat gunshot wounds. Engineers design addictive social media apps, while others design apps to manage that addiction.

One can acknowledge the arguments that fossil fuels create immense value, that social media use is voluntary, and that militaries are necessary for stability. But what these contradictions reveal is that, except for obvious cases, it is not easy to map, one-to-one, engineering endeavors onto moral dichotomies of right and wrong, good and bad. In fact, moral questions often get *more* complicated as new engineering projects, trying to undo the problems of older ones, themselves bring about harm or injustice in their wake—in this way, engineering can create a moral morass. Despite this reality, we can insist on an engineering enterprise that is self-conscious of its process and its outcomes.

Codes of ethics seek to give direction and set constraints for practitioners and have long been adopted by associations such as the National Society of Professional Engineers, the American Society of Mechanical Engineers, and the American Society of Civil Engineers. These codes dispense good advice, but they are far clearer about not breaking the law, falsifying data, or deceiving those who put faith in engineers than they are about the social purpose of engineering or the kind of work that engineers must eschew. The lack of attention given to moral dilemmas in engineering and the values that undergird engineering itself can allow engineers to disclaim responsibility for the uses of their inventions. One degree removed from the polluters, the shooters, and the social media trolls who make use of engineering innovations, engineers can shield themselves behind plausible deniability.

But experience from established programs such as the Community Engineering Corps, which taps into a volunteer network of 200,000 practicing engineers, shows that many engineers want to do work that is socially responsible in new ways—they want to be of direct service in solving pressing needs. What's more, recent research provides a snapshot of the desire of engineers and scientists to engage in work that is personally meaningful to them. These examples show that engineers and scientists across all age groups and employment sectors are willing to use their technical skills to work on causes within their local communities and beyond. More programs designed to build rapport between engineers and underserved communities, address knowledge and cultural gaps, help engineers understand how communities benefit from their skills, and demonstrate the social and professional value of such work can energize a new direction for engineering work.

To turn this interest into an action-based and ongoing commitment that redefines the profession, engineering requires a new moral imagination that goes far beyond codes of ethics. A call for such change, if it is to be anything more than a platitude, must contemplate the incentives, practices, institutions, and narratives that regulate engineering work. In the following sections, I present some sketches of modest but realistic ways to promote an engineering profession ready to interrogate its own assumptions and methods, and ready to act to change itself.

## Looking beyond engineering students

Calls to strengthen investments to secure the future of engineering in the United States have almost exclusively focused on engineering education and the science, technology, engineering, and mathematics (STEM) pipeline. While important, these calls overlook the fact that most engineers are *not* in college; they are in the workforce. While there are approximately 760,000 undergraduate and graduate engineering students in US colleges and universities, there are approximately 2 million engineers and 4.1 million computational professionals in the workforce, making decisions today that will have long-term impacts. Yet little is known about how this diverse group understands its role in society and what social challenges motivate and inspire them. One cannot assume that the priorities, ethics, and politics of engineers stay the same as their lives unfold. The descriptive statistics of employer type and terminal degree from the National Science Board's Science and Engineering Indicators provide the barest of insight into engineers' concerns and attitudes; far more needs to be learned about the ethos of practicing engineers.

To give practicing engineers opportunities to deploy their skills and experience in more direct service of their communities and society at large, professional development and continuing education programs at engineering schools can help their alumni develop new perspectives on engineering and public values, as well as inspiring new approaches for engineers to advance sustainability, justice, peace, and human rights. Such programs could also promote important translational work to take theoretical and conceptual advances in academic research—for example, work on technology for environmental justice—and apply them to real-world engineering contexts.

## Moving beyond pro bono and volunteerism

Engineers' desire to contribute to society in broader ways currently manifests in volunteerism or efforts above and beyond their day jobs. Over the last decade, programs like the American Association for the Advancement of Science's On-call Scientists and American Geophysical Union's Thriving Earth Exchange have engaged engineers and scientists across the country in dozens of projects addressing natural hazards, climate change mitigation, environmental justice, and human rights challenges. Engineers & Scientists Acting Locally helps increase local civic engagement of STEM professionals. Community Engineering Corps provides pro bono services for underserved communities to address water, energy, and structural engineering challenges. These programs have facilitated important projects to deploy new drinking water infrastructure for rural American communities, set up air pollution monitoring networks around industrial facilities, create night-sky-friendly lighting, and detect chemical weapons use in Syria.

While these programs are immensely important, visions of a new moral imagination for engineering that rely *only* on volunteerism, pro bono efforts, and the goodwill of engineers and scientists will likely not engage them at the scale necessary to address the macro-social challenges of our times. These macro-social challenges are more often than not collections of hundreds of almost identical problems deemed "local." It is not, for example, just one US urban community that is concerned about lead in drinking water; hundreds are. It is not just one agricultural community that is looking for ways to build a more climate-resilient future; hundreds are.

Thus, efforts to assess the monetary value of services provided by professionals engaged in the programs mentioned above, to quantitatively and qualitatively evaluate their social impact, and to understand the transferability of knowledge and products created along the way can help articulate new value propositions for such work. The cost of replicating projects will likely go down as more of them are executed, particularly those that focus on design and planning. If that is the case, local governments and communities with fewer resources may be able to both access and afford critically needed engineering and scientific services. The possibility of such a virtuous cycle needs to be explored. It can be seeded by federal and philanthropic support that funds the creation of organizations experimenting with new business models to make such work financially sustainable. Practical insights can be drawn here from the years of successes and failures of social entrepreneurship businesses, revolving funds, and open-source communities and foundations, among other approaches.

## Creating spaces for debate and reflection

Another way to nurture and expand engineers' desire for social engagement is to expand the discourse within the profession that can lead to action. The recent reckoning with race and gender issues in the workplace and the emergence of frameworks like activist engineering—which seeks to have engineers reflect in new ways on the problems they're addressing and their proposed solutions—create new opportunities to institute policies and programs to support and foster debate about engineering and public values.

This sort of debate became visible activism in 2018, when Google employees questioned the company's involvement in an artificial intelligence pilot program for the Department of Defense called Project Maven. The goal of this project was to use drone technology and machine learning to improve the military's ability to track and target objects of interest. More than 4,000 employees—among them many engineers—signed a petition condemning Google's participation in the "business of war" and urged CEO Sundar Pichai to cancel Google's participation in Project Maven and renounce contracts for "warfare technology."

Google employees largely succeeded in that protest. Even as Google left the door open to work with the military, it did abandon the design or deployment of "weapons or other technologies whose principal purpose or implementation is to cause or directly facilitate injury to people," as Pichai wrote in a blog post.

While such stories of activist engineering are rare, self-reflection and debate among engineers organized across small and large companies, government, academia, and nonprofits can bring purpose and impact to the center of engineering debates.

## Extending the gaze of United States-centric engineering

A contemplative turn for engineering can also extend the profession's critical gaze beyond US borders. Almost all engineering projects and products are now integrated in global supply chains. Consider lithium-ion batteries, used in consumer electronics and especially important for expanding the electric vehicle market. The largest known natural reserves of cobalt, an element used in those batteries to increase their energy density, are in the Democratic Republic of the Congo (DRC), where growing demand for the metal has triggered a vicious political battle over control of and rights to this extremely valuable resource. Consequently, consumer demand for batteries—which engineers stoke with ever more ingenious products—has significant repercussions in the DRC, with the exploitation of workers and displacement of communities from their ancestral land.

This is a story that repeats itself with every new natural resource in high demand. Yet engineers seem to not bring this history to bear, remaining largely unconcerned about harm in which they might be complicit. Engineers can help build a new moral imagination for their profession by advocating for technology and knowledge transfer to countries in need, increased data transparency, and prohibitions on the import of unethically or illegally sourced goods and resources.

In his book *Engineers for Change*, historian Matthew Wisnioski observed that questioning the goals and motives of engineering has been suppressed by companies and professional societies. It is therefore not surprising that the very same questions engineers raised in the past—about who engineering is for and to whom it is accountable—remain largely ignored today. But a new moral imagination for engineering can be made real through the innovative leadership of social entrepreneurs, activist engineers, and new fora for critical reflection, action, and organizational development. I believe engineers of all disciplines and ages can confront persistent questions about what engineering is for by committing themselves to the service of public values such as sustainability, justice, peace, and human rights. In doing so, engineers themselves will profoundly reshape science and technology policy for the next 75 years.

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KAYE HUSBANDS FEALING, AUBREY DEVENY INCORVAIA, RICHARD UTZ

# Humanizing Science and Engineering for the Twenty-First Century

Science cannot live by and unto itself alone: forward-thinking science and technology policy depends on better integrating the humanities, arts, and social sciences.

Dr. Nettrice Gaskins is a widely recognized African American digital artist who creates works that combine images of individuals with an artificial intelligence (AI) application that synthesizes patterns. When her larger-than-life portraits were displayed in the Smithsonian Institution's "FUTURES" exhibit in 2021, viewers saw familiar faces rendered with finely grained and sometimes disorienting details, inviting them to consider moral and ethical questions about future uses of AI. By fusing artistic exploration with moral and political reflection on technology, Gaskins's work exemplifies the creative possibilities that lie at the intersection of science, engineering, and art.

We think work such as Gaskins's—which integrates science, technology, engineering, and mathematics (STEM) with the humanities, arts, and social sciences (HASS)—is an important and long-overlooked element that should be included in forward-thinking science policy. More than 75 years ago, Vannevar Bush's report for President Roosevelt, Science, the Endless Frontier, focused on spurring research and training in the physical and biological sciences. Yet "it would be folly," Bush warned, "to set up a program under which research in the natural sciences and medicine was expanded at the cost of the social sciences, humanities, and other studies so essential to national well-being." As another report that Bush references put it: "Science cannot live by and unto itself alone."

That warning was not heeded. STEM fields have long insulated themselves from the arts and humanities in problem discovery, in the design and implementation of solutions, and even in the public policies and communication strategies needed to ensure optimal outcomes. In Bush's vision, scientific progress was essential not just for improving public health, jobs, and living standards, but also for advancing what he termed "cultural progress." All of this requires careful attention to the interrelations among science, technology, and society—interrelations that are not fully illuminated with a STEM lens alone. Indeed, STEM and HASS domains intersect in the challenges and threats people face every day, from poverty and energy production to climate change, food and water safety, and national security.

Solving such complex problems is never a purely technical or scientific matter. When science or technology advances, insights and innovations must be carefully communicated to policymakers and the public. Moreover, scientists, engineers, and technologists must draw on subject matter expertise in other domains to understand the full magnitude of the problems they seek to solve. And interdisciplinary awareness is essential to ensure that taxpayer-funded policy and research are efficient and equitable and are accountable to citizens at large—including members of traditionally marginalized communities.

Bridging the STEM-HASS divide is a crucial task for the coming decades of science and technology policy. Society needs robust institutional frameworks for equipping STEM practitioners with a humanistic lens to elucidate problems, imagine solutions, and craft interventions. As a first step, colleges and universities must better integrate STEM and HASS in their curricula. While this is a daunting challenge, a wide range of efforts over the last two decades helps point the way forward.

## Methods for integrating the humanities

Technological universities offer a particularly fruitful institutional climate for imagining new forms of HASS and STEM integration. At our own institution, the Georgia Institute of Technology, HASS faculty recently published a collection, Humanistic Perspectives in a Technological World (2021), featuring dozens of case studies illustrating how HASS and STEM can be brought together in research, scholarship, teaching, and community projects.

One approach is to focus on the design of individual courses, with HASS faculty members purposefully collaborating with STEM colleagues. A two-semester junior capstone sequence at Georgia Tech is cotaught by a subject matter specialist in computer science and a technical writing faculty member. This arrangement not only sharpens students' communication skills; it also inspires them to situate their scientific work in a larger context—for example, by considering how it will be received in a field rife with gender and racial bias. Another example is project EarSketch, used by one million students worldwide, which integrates coding education with music composition and has helped underrepresented students learn to code. Project Code Crafters merges the creativity of computing and quilting for diverse adult audiences, building knowledge in how to broaden public engagement in computational thinking. And DramaTech, Georgia Tech's student-run theater troupe, regularly infuses theatrical performances with elements of digital media, as when it staged a dramatic adaptation of Haruki Murakami's short story collection after the quake, employing a motion-sensing device to track an actor's gestures to amplify emotions.

Another approach is to restructure entire degree programs. Georgia Tech's undergraduate major in computational media, for example, is collaboratively administered by faculty in computing and the humanities. Similarly, a master of science in the human-computer interaction program draws on faculty in computing, design, humanities, and the natural sciences. Rather than being housed in a single department, both programs have interdisciplinarity built in as a basic feature of institutional design. The result is that students are trained to think across a range of disciplines and to leverage their exposure to diverse methodologies to better understand and tackle complex problems.

These initiatives are a small part of a larger interdisciplinary transformation. Georgia Tech is part of a systematic, nationwide effort described in the 2018 National Academies of Sciences, Engineering, and Medicine consensus report, The Integration of the Humanities and Arts with Sciences, Engineering, and Medicine in Higher Education: Branches from the Same Tree. As the report documents, integrating the humanities and arts in STEM and medical education is linked to numerous positive learning outcomes, including increased skills in communication, critical thinking, and teamwork; improved visuospatial reasoning and overall content mastery; increases in empathy and resilience; and improved motivation, enjoyment of learning, retention, and graduation rates. The report also presents evidence that STEM-HASS integration positively affects the recruitment, learning, and retention of women and individuals from underrepresented minority populations in science and engineering.

The Branches from the Same Tree report notes that deep and intentional integration of disciplines is essential to preparing "for the challenges and opportunities presented by work, life, and citizenship in the twenty-first century." It thus takes aim at a development Bush may well have foreseen as early as 1945: higher education's "increasing specialization" and discipline-based "fragmentation of curricula," which prevent students from seeing all human knowledge as "fundamentally connected."

## Training better doctors

It is in medical education that this paradigm shift has had some of its most enthusiastic early adopters. Over the last 22 years, the number of health humanities programs in the United States has ballooned from 12 to 140, and in 2000 the Journal of the Medical Humanities was founded as a companion publication to the Journal of Medical Ethics. The

Association of American Medical Colleges recently evaluated these efforts in The Fundamental Role of the Arts and Humanities in Medical Education (FRAHME), highlighting four "functions" of humanities and arts integration: mastering skills, perspective-taking, personal insight, and social advocacy or sociocultural critique and change.

A central component of the FRAHME report is what its authors call the "Prism Model," in which

> each function is conceptualized as a lens in a prism that can help educators approach any domain they wish to teach (e.g., communication, empathy) in multiple ways, depending on which function is emphasized. Each function offers a different yet interrelated way of seeing arts and humanities teaching. The four functions are most powerful when used in combination, as a way to more fully recognize all pedagogical possibilities for arts- and humanities-based teaching in medical education.

Recent examples from medical schools of such measurably successful integration range from individual class sessions and learning activities to longitudinal tracks and programs.

At the level of individual learning activities, studies show that even brief reflective pieces of creative writing have helped teach medical practitioners and students to develop humanistic and ethical understanding of patient care and to view themselves as healers, even when they work in highly systematized environments. In addition to reflective writing, the practice of close reading and application of narrative theory to clinical texts (such as medical charts and patient interviews) can significantly enrich conventional medical routines of diagnosing patients' conditions. Now generally recognized as central to developing more trusting and efficacious patient-physician relationships, "narrative medicine" makes use of script writing, performance of medical stories, documentary films, dance, and jazz improvisation.

Intentionally integrating HASS methods and skills over several years of training leads to deeper engagement and sometimes to social advocacy. The Johns Hopkins University School of Medicine, for example, offers a scholarly concentration in the history of medicine as part of its independent mentored research program during the first two years of study, adding a 16-month humanistic learning experience to students' basic science and clinical research requirements. In the concentration, students work with assigned faculty historian mentors to learn literature-based, archive-based, and oral-historical research theories and methods. They apply these to fieldwork and narratives across historical periods, leading to publications geared toward clinical, historical, public health, and popular audiences. Graduates of the program become medical doctors with a deep appreciation of history as an effective mode of humanistic engagement in clinical practice.

For example, students in the program compared anti-Asian sentiments during the COVID-19 pandemic with xenophobia during a bubonic plague outbreak in Cape Town, South Africa, in 1901 to explore the potential dangers of discriminatory health policy responses. By researching the Cape Town plague, they were able to understand how it gave colonial authorities a pretext to forcibly remove most of the city's Black population from neighborhoods, laying the foundation for apartheid. Grounded in this new historical perspective, students in the program publicly advocated against the stigma and racism that have sometimes influenced the pandemic response and policy.

The full Prism Model would require integrating the four basic functions at all levels of training, from individual assignments and courses up through the curricular structure of whole degree programs. Some medical schools are well on their way to such deep integration. Florida International University's Herbert Wertheim College of Medicine, for example, uses art analysis during museum tours as a practice analogous to detailed patient diagnosis.

## Early-stage and wide-ranging integration

One lesson to be drawn from all this work is the importance of incorporating HASS into STEM as early as possible. Unfortunately, apart from notable early upstream inclusion of economics, integrating HASS later is the norm; these disciplines are often considered relevant only at a late stage in conveying scientific results and technological innovations to the public, not in early-stage planning, design, or research and development. To take just one example, social scientists have found that in European energy research and policymaking, HASS concerns are effectively treated as project "add-ons" rather than as equal partners in the production of evidence. But excluding HASS disciplines and methodologies can lead to results that are ahistorical and future-centric and emphasize quantitative methods while treating society as passive. The exclusion is also self-reinforcing, introducing a path dependency that affects future funding decisions and the overall trajectory of the field.

Other studies have demonstrated what stands to be gained from more robust HASS and STEM integration. A recent marine science study in Scotland, for instance, showed how collaboration across HASS and STEM led to resolution of a seemingly intractable dispute between government conservation scientists and an economically fragile community in the Outer Hebrides. Government researchers initially did not recognize the political nature of a dispute over preservation of biological diversity in a proposed marine conservation area. But when collaboration among a researcher, an artist, and community stakeholders facilitated a participatory mapping process, they were able to see the relationship between biological diversity protection and sociocultural heritage and knowledge. The outcome was the creation of the Sea Stories' online, interactive map representing the narratives and values of the community in the marine context. The map came to be used by policymakers and community partners alike as they created a collective co-management process for the area. Initiating partnerships across disparate fields and actors facilitates the meaningful coproduction of scientific knowledge, which can strengthen the relationship between science and society and propel cultural change. It may also result in tangible policy outcomes—in this case, improving the planning and management of a protected marine environment.

Another recent National Academies report, Integrating Social and Behavioral Sciences Within the Weather Enterprise (2018), provides examples of successful HASS-STEM integration while recommending further opportunities for collaboration. Today, weather forecasts are often seen as simply projections of future atmospheric conditions, but to apply them in ways that prevent damage and deaths as a result of severe weather requires a deeper understanding of the social and behavioral factors involved. Beyond meteorology, then, combining interdisciplinary insights can generate systems and products that more holistically and accurately account for people's cognitive processes, behavior, and interpretation while optimizing public safety, which is especially useful during severe weather warnings. Understanding how weather forecasters make decisions, and how laypeople interpret what forecasters say, is less a meteorological concern than one for the social sciences.

Indeed, as scholar Victoria Martin has written, "many of the environmental challenges we face are, fundamentally, human problems" and will therefore benefit from the knowledge, training, and experience embedded in the social sciences. This can be seen across disparate fields. Scholars have explained, for example, that transitions from fossil energy to renewable forms are "fundamentally socio-technical (meaning that society and technology affect each other and co-evolve) in both their underlying processes and outcomes." In other words, solving such challenges requires not only a knowledge of electrons, materials, and transmission rates, but also a sense of how human concerns, social values, and aesthetics may come to bear on the issues. Incorporation of social science expertise ensures that natural science studies build on appropriate prior scholarship and apply robust methods—from research design to data collection, analysis, and reporting of results—to produce sound knowledge that does not waste resources.

## Bringing the two cultures together

Failing to take advantage of the types of knowledge that the humanities and social sciences offer is already yielding an opportunity cost for the STEM disciplines themselves. Consider, for example, the relatively new field of "science of science policy" (SOSP), kindled in the 2000s and championed by the former director of the White House Office of Science and Technology Policy, John Marburger. The purpose of SOSP is to improve decisionmaking on investments in research and development and build talent in science and engineering fields. It is a systematic integration of scientific knowledge, analytical capacity (from the social sciences), and policy processes with the purpose of improving scientific output, economic growth, and social well-being.

Marburger and others called for the social sciences to take on greater responsibility in the process, particularly in developing high-quality frameworks, tools, and data, a corps of trained professionals in the science of science policy, and a network of convenings fostering engagement that improves policy. So far, much of the SOSP work has been quantitative, but early engagement of scholars in the humanities and social sciences could elevate a more robust science policy.

Interdisciplinary approaches could yield benefits including sharper assessments of policy impacts, tailored communication of policy impacts to affected groups, improved policy design, and methodologies grounded in a broader scope of disciplines. The question of whether science policy "works" is not only a question of whether the right number of widgets are produced or whether projections turned out to be correct, but rather whether the policy meets the greater aspirations of the society in which it is embedded. For that sort of analysis, the humanities provide a set of lenses that are essential for charting a shared future.

Crucially, enhanced integration between the humanities and the natural science disciplines could enable a more ambitious vision for achieving Vannevar Bush's goals for scientific and cultural progress. Breakthroughs in science, arts, and humanities will remain dormant unless these fields learn to cultivate a diverse and inclusive talent pool and generate socially relevant research that informs policy. World-renowned cellist Yo-Yo Ma said it best: "Culture turns 'the other' into 'us.'" As he explained:

> From the golden rule to the iconic "Ode to Joy" from Beethoven's Ninth Symphony, a symbol of freedom and unity around the world, to $E=mc^2$, the radical formula that changed how we understand the universe, these words, sounds, and codes help us speak a common language and agree on shared values. They give us a foundation for trust.... It's not enough to outsource culture to the artists and musicians, and receive it as a passive audience. We must engage the full spectrum of human understanding, and every one of us needs to participate in strengthening our cultural resources, all the time—to generate trust and understanding by pursuing basic scientific research, playing music together, or simply looking at the stars. We need to put culture first, because it is the only way to make sure that the decisions we make as a global society are actually good for humanity.

Integrating cultural and socially relevant values and approaches into science and technology policy and research will enhance progress in all these disciplines.

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# Collaboration in a Global Context

VALERIE J. KARPLUS, M. GRANGER MORGAN, AND DAVID G. VICTOR

# Finding Safe Zones for Science

Serious cooperation between US and Chinese scientists is getting more difficult as geopolitical tensions increase. But with a deliberate strategy, the two countries can realize massive potential gains.

For those of us engaged in international scientific collaboration, today's geopolitics are starting to rhyme with history. In the 1960s, US and Soviet scientists sought new ways to collaborate despite deteriorating political relationships. These opportunities required navigating real and imaginary national security concerns. In the 1980s, it was Japan that offered a myriad of opportunities for cooperation with US universities, at a time when that country's growing strength was seen as a competitive economic threat.

Today the rising power is China. While opportunities for the United States to work cooperatively with China are immense, so are the challenges as the two countries are competitors across many dimensions, encompassing both economic and national security. Still, the lessons learned from Soviet and Japanese collaboration can help shape a practical US-Chinese strategy. And what we learn working with China should shape the next frontier of international cooperation decades hence—with a rising Brazil, a resurgent Russia, and other ascendent powers.

The opportunity to collaborate with China is clear enough. Both countries are powerhouses in global high technology manufacturing: the United States produced 31% and China 21% of a global total of $1.6 trillion of high-tech products in 2016. Yet their very success economically puts them into direct competition. Scholars estimate that import competition from China eliminated 2–2.4 million US jobs between 1999 and 2011, mostly among less skilled workers.

Thanks mainly to the rise of China, the two nations also now compete in basic science, a source of future economic growth. China boosted its research and development spending by 18% per year between 2000 and 2015; today, rising from a mere margin, the country accounts for 21% of global R&D. By contrast, the United States has expanded basic research investments by a paltry 4% per year, a rate that matches the world's growth rate but keeps the US share of the global total stuck at 26%. In 2015, Chinese innovators filed almost double the number of patents filed in the United States. And in 2016, China overtook the United States in terms of total scientific publications and now leads the world in top citation counts in some critical fields such as advanced materials.

Technologies such as artificial intelligence and cybersecurity, which might have otherwise opened opportunities for collaboration, now stoke adversity because they can be applied to weapons and cyberespionage—giving their development the flavor of an arms race. In cybersecurity, for instance, it is hard to distinguish between offensive and defensive moves, and in an atmosphere of mistrust, responses and counterresponses make it ever harder to return to a cordial relationship. These tensions do not yet amount to a new Cold War, but their persistence corrodes goodwill between the two countries. Despite all these challenges, the potential gains from collaboration between the United States and China remain massive and, plausibly, will get bigger as each country advances.

It is no longer good enough for the scientific community to merely declare that there are big gains from collaboration. Abstract gains often don't carry much political weight, especially in the context of deep mistrust. We in the scientific communitymust get better at managing collaborations to align with geopolitical realities and risks. We must pick and choose among opportunities that aren't prone to toxic geopolitical spirals. Where cooperation requires bigger geopolitical risks, we must have structures and strategies that lower the risks. These strategies for engagement must be based in reality and built to survive inevitable ups and downs, not just justified by abstract and theoretical gains.

Creating an agenda for collaboration won't be easy, for the political context that has underpinned such efforts in recent decades is quickly eroding. Internal politics in both nations now rewards hostility, making it even harder to mount and sustain efforts aimed at stanching today's wounds. Here in the United States the pressures to avoid cooperation are bipartisan and growing in intensity. In fact, one of the few areas of continuity from the Trump to the Biden administrations has been ever-frostier relations with China.

To help address this situation, we propose a framework for thinking about where US-Chinese research collaboration, in today's tense environment, can most usefully and most practically occur. Our framework helps to identify safe zones: places where traditional cooperation will be greatest. And it puts a spotlight on those places where gains, while potentially large, are steeped in political risk. The hard but most fruitful work of collaboration will come in those places—but only with active political engineering to help manage the risks.

It is one thing to offer an idealized scheme for focus, but quite another to put that system into practice. Thus, we also offer an outline of US science and technology (S&T) policy that can facilitate cooperation, and we invite a comparable effort in China. With such support, deliberation by practical-minded scientists, technologists, and research administrators in both countries can help their governments coordinate joint action.

## A framework for cooperation

The centerpiece of our argument is a framework for identifying areas that have the potential for large gains and where cooperation—intrinsically or with policy design—can be buffered against inevitable geopolitical shocks. In the next 75 years, learning how to achieve and sustain these gains from cooperation will have many advantages. By expanding the domain of ideas and the size of markets for experimentation, cooperative approaches can push the technological frontier faster and allow more rapid and pervasive scaling in the application of novel technologies.

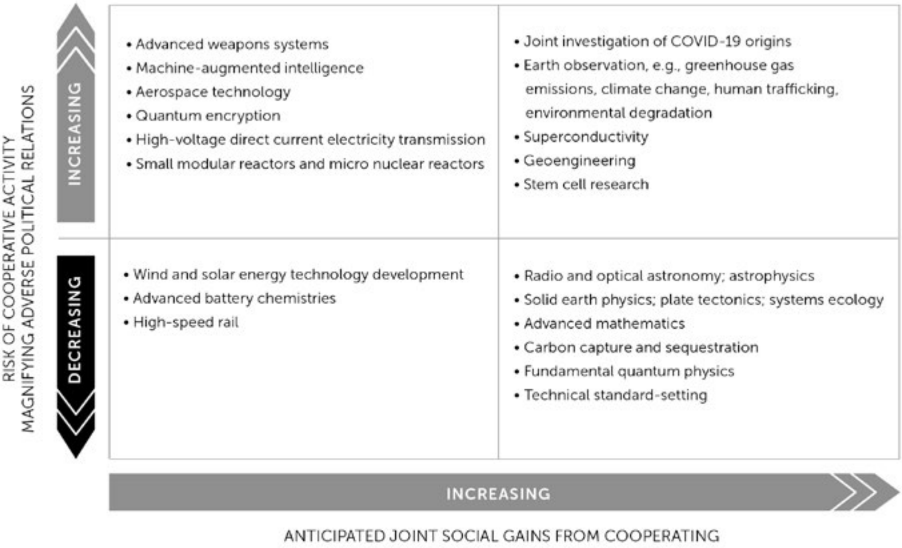
This wave of cooperation could give the United States a stronger hand in shaping standards and norms for technologies that could go awry, such as artificial intelligence and solar geoengineering. And cooperation, where it works, can cultivate goodwill that can help the two countries through periods of geopolitical tensions and form a basis for broader mutual efforts. During and after the Cold War, scientists who had cooperated across the Iron Curtain helped their countries navigate difficult issues, just as scientists with similar histories helped the United States and Iran reach a deal on the latter's nuclear program even as the two remain at loggerheads on many other issues.

Only a decade ago, when the United States and China weren't steeped in suspicion of each other's intentions, it might have been possible to identify areas where there would be gains from collaboration and to get started on building them. At that time, economic or scientific shocks could have been tamped down. Today, much more careful design of cooperative policies will be needed, and we must anticipate storms that could blow plans off course. A realistic S&T cooperation policy, advanced in the context of low levels of trust, requires that the scientific community and its allied diplomats get better at understanding where debilitating shocks may arise and how to manage their fallout.

The framework in Table 1 maps two dimensions of possible outcomes from potential US-Chinese cooperation in particular domains of science and technology.

One outcome, displayed on the horizontal axis, is possible joint social gains from cooperating in contrast to a scenario in which each country works independently. Along the scale of gains, we expect mature technologies and scientific knowledge, along with innovations closer to commercial application such as wind energy or aerospace technology, to yield low gains from cooperation. These fall on the left half of the table. By contrast, activities that fall on the right half, such as fundamental research, offer, in

**Table 1.** Framework for Assessing Trade-Offs in joint social Gains versus political Risks in US-ChinA Cooperation



| | | |
|---|---|---|
| INCREASING | • Advanced weapons systems<br>• Machine-augmented intelligence<br>• Aerospace technology<br>• Quantum encryption<br>• High-voltage direct current electricity transmission<br>• Small modular reactors and micro nuclear reactors | • Joint investigation of COVID-19 origins<br>• Earth observation, e.g., greenhouse gas emissions, climate change, human trafficking, environmental degradation<br>• Superconductivity<br>• Geoengineering<br>• Stem cell research |
| DECREASING | • Wind and solar energy technology development<br>• Advanced battery chemistries<br>• High-speed rail | • Radio and optical astronomy; astrophysics<br>• Solid earth physics; plate tectonics; systems ecology<br>• Advanced mathematics<br>• Carbon capture and sequestration<br>• Fundamental quantum physics<br>• Technical standard-setting |

our estimation, clearer potential for gains. In this domain are areas in which neither country has a clear lead or projects are complex and expensive. Such areas are likely to generate large spillovers that, because they are difficult to appropriate, benefit from recombination of diverse ideas and market pull at scale. These potential shared interests could also make the relationship more resilient to future political shocks that can undermine practical cooperation.

The vertical axis shows the risk that collaboration could spark or intensify political tensions. Bilateral relations are always perturbed by events; what matters is the capacity to contain the political damage and sustain valuable interactions. For instance, the US bombing of the Chinese embassy in Belgrade in 1999 rocked the relationship, at what was otherwise a relatively high point. Protesters stormed the US embassy district in Beijing, but the tensions abated when a compensation agreement was later drawn up. Collateral damage to the long-term relationship was contained, and relations were normalized—including, in 2001, when the United States backed China's entry into the World Trade Organization.

Today, relations are less stable, and collateral damage is harder to contain. A variety of possible shocks—such as a major computer or biological hacking event, a military escalation in the South China Sea, metastasizing anti-Chinese racism in the United States, or dramatic financial losses in world stock markets linked to heavy-handed government interventions—could quickly scuttle fragile support for ongoing or potential cooperation. These sorts of shocks will put any collaboration agreement at risk, but if the agreement itself generates or exacerbates tensions, cooperation is unlikely to take hold and be fruitful.

Fallout is likely to be lower if the collaboration generates powerful stakeholders in both countries who want the effort to continue or if domestic interests in both countries don't much care about the domain of cooperation. Fundamental work in quantum and particle physics, for example, could distribute high fixed costs while generating new knowledge. Potential fallout increases if joint research products have applications in areas that are primed for contestation, real or perceived, such as national defense or economic competitiveness.

As technology development advances, the opportunities and risks from cooperation may shift. More fundamental research domains, long thought to occupy a benign world of apolitical thinkers, may migrate northwest in the framework. For example, some advances in solid earth physics (lower right quadrant) could inform the design of guidance systems for missiles (upper left quadrant). Uneven advances within each country could yield more benign shifts. For example, if carbon capture and sequestration or direct air capture technologies advance—as has happened in wind power—that might limit the potential for joint gains from continued cooperation. Shifts that cause a technology to migrate from the lower right to lower left quadrants require rethinking traditional S&T collaborations but are unlikely to poke the geopolitical bear. In the United States, some will fear that China's innovators may be able to move more swiftly, and with state support, to capture market share; but that risk exists even if innovation proceeds independently. The case of lithium-based batteries offers a current example: because China (along with Korea) dominates the field, cooperative efforts to advance even fundamental research in this area are viewed with skepticism.

## Outlining a policy strategy

When used to inform policymaking, the implicit message of our framework is that successful collaborations must start with a wisely chosen domain. Regardless of the personalities of scientists or institutions involved, the determining factor in long-term scientific cooperation will be the ability to generate mutually beneficial gains while lowering the risks from geopolitical shocks. This context varies with different concerns and technologies.

Cooperation is likely to be most politically viable and durable if focused on the activities that sit in the lower right quadrant of the table. These are activities that create hard-to-appropriate fundamental knowledge or hard-to-realize resource-intensive demonstrations of technologies that have the potential to improve the human condition. In areas of fundamental science ranging from basic biology and genomics to radio astronomy, gravity waves, and the study of neutrinos, Chinese research is strong and growing and ripe for a mutually beneficial collaboration with the United States.

One example of technology demonstration can be found in the US-China Clean Energy Research Center (CERC)—a consortium created during the Obama administration as part of a comprehensive strategy to link the two countries more closely. CERC facilitated productive interactions between academic and industry researchers focused in thematic areas such as cleaner coal and green buildings, generating publications, patents, networks, and goodwill, and helped to manage potential intellectual property conflicts. Had CERC been bigger in scale and more reliable in its commitment, the impact probably would have been much larger, with higher odds of joint discoveries that could cause fundamental shifts and commercial applications of clean energy technology at scale. Such engagement with China around advanced technology and deployment might also have made it much easier to help shape that country's massive energy technology export program linked to the Belt and Road Initiative.

It may be possible to maximize gains from cooperation by navigating around areas of toxic fallout. For example, rather than launching a collaborative study on the origins of COVID-19, China and the United States could establish a joint research program to control future zoonotic diseases that could lead to global pandemics. However painstaking, this process could successfully move this sensitive area from the upper right to lower right quadrants in our scheme.

Collaborations outside the lower right quadrant in the framework will demand utmost tact in their management. The area where strategic thinking is most important is the upper right quadrant, featuring areas with large potential gains from collaboration, despite high risks. Work undertaken in this quadrant requires a degree of "political engineering"—ensuring that collaboration generates domestic benefits for a powerful constituency and thus guaranteeing political supporters that will sustain the enterprise through rough periods in foreign relations.

Such an engineering of political support for a research program has precedent. The US Department of Energy's programs on carbon capture and sequestration (CCS), for example, have shifted from integrated cross-border activities when relations have been good to separate but coordinated activities when relations turn rough—all the while continuing to deliver benefits. The Advanced Coal Technology Track of the CERC created opportunities for top CCS researchers and industry practitioners from both countries to interact regularly and develop joint projects, part of a longer history of US-Chinese collaboration on energy. The cooperation built on and reinforced over 15 years of research funded by DOE and spread across the country, from West Virginia to New Mexico, with local academic and industry partners. The program survived renewed US-Chinese tensions under the Trump administration. Although it has not been renewed post-2020, the groups it funded in both countries will continue research with strong domestic backing—and establish a foundation for restarting practical collaboration. Pressure to deliver on decarbonization will push innovators in both countries in parallel, with the result that any progress is likely to continue and to deliver associated benefits. Governments can't orchestrate that fully, but their actions can raise the odds that innovators will find partners and their joint efforts will thrive.

The most problematic domain for collaboration involves topics that fall in the upper left quadrant of the framework. Here expectations should be lowest, though there remains merit in monitoring opportunities closely. Without access to classified evidence, it is unclear to what extent US concerns about the telecommunication systems being supplied around the world by China's Huawei are motivated by legitimate security concerns (hidden software capabilities) and to what extent they reflect a desire to advance the commercial interests of American competitors. Such potential risks of hidden security vulnerabilities are real for high-voltage circuit breakers, transformers, pumps, valves, and other critical devices in networked systems, all of which are now integrated with digital control and communications systems. "Proving" all the associated code, to make sure there are no hidden traps, is probably not possible, but the computer security and regulatory communities should be working harder on developing strategies that can dramatically reduce our vulnerabilities.

## Beyond specific technologies

In the real world, cooperative action often does not sit neatly in just one of the quadrants. Rather collaboration in one domain is frequently linked to others, and, as noted above, cooperation that begins in one quadrant can migrate to another. What seems like a low-risk venture at one time may become embroiled in controversy as the relationship between nations sours. The task is therefore to figure out how to avoid global bifurcation in areas where the gains from cooperating are highest while taking clear-eyed steps to address potential security threats. Civilian space programs offer an excellent example. Today, in part because of an early congressional ban on all forms of US collaboration with China in this domain, the world is witnessing the development of parallel programs to build space stations and lunar bases. Rather than the ongoing competition, it seems likely that a collaborative international program could be achieving much greater benefit for all.

Supply chains provide a good example of the multiquadrant nature of real commercial and S&T activities. One of the many lessons of the pandemic has been that supply chains built for economic efficiency can quickly break down when circumstances change. The narratives we have generated around such interdependencies need to be re-examined. Supply chains that are critical require careful management and international cooperation. We know, for example, we will continue to need advanced semiconductors, power electronics, high-performance batteries, civilian aircraft, and large high-voltage circuit breakers and power transformers. For these technologies, national security hinges on understanding the geography of supporting supply chains in detail and building redundant pathways for critical components.

In some cases, redundant production in friendly countries plus domestic stockpiles will be sufficient. In other cases, identifying supply chain vulnerabilities and reducing them in a sustainable way may be challenging. Two years ago, public health officials found it hard to persuade policymakers that the United States had a vulnerability in the supply of personal protective equipment (PPE) and ventilators. Shortages and skyrocketing prices in the early months of COVID-19 proved the former vulnerability correct and the latter obdurate. The lesson is that US policy should value resilience in critical supply chains more highly—to incentivize investments in flexible capacity and ensure that stress testing for resilience occurs alongside commercial pressure to optimize efficiency. As system ecologists have told us for years, there is an inherent tension between resilience and efficiency. If an environment is very stable, it is expensive to maintain capabilities that will only become important when the environment changes.

Flexible manufacturing capacity is thus paramount. A nation does not have to be making or stockpiling lots of ventilators if it has supported the ability of its manufacturers and suppliers to rapidly pivot to provide them when the need arises. However, developing this capability is more than a technical problem. It requires coherent and supportive public policy and regulation to make it economically viable for private sector players to invest in production flexibility to support resilience. Stockpiling has a role, but what really matters is a stockpiling strategy that is informed by frontier information about how quickly and flexibly production lines can pivot and scale as needed in extreme circumstances. In the era of global supply chains, no government can make those policy choices independently.

A similar shift in interdependencies can be seen in frameworks for dual-use technologies and export controls, which now seem outdated. Determining when restrictions apply to a specific technology is challenging. For instance, we have placed "fundamental quantum physics" in the lower right quadrant of the framework and "quantum encryption" in the upper left because we can see basic ideas in the former and national security application in the latter. But some forms of progress in quantum physics could quickly upend the implications for encryption and other applications. There will always be those in the security community who will argue that any area that could in theory lead to national security consequences should be controlled.

An expansive interpretation of dual-use technologies will, over time, isolate the United States from ideas and capital in the rest of the world. An example of harmfully expansive definitions is when the Committee on Foreign Investment in the United States, headed by the Treasury secretary, rejected a China-linked company's bid to invest in US wind farms. Similarly, for years the United States banned the export of higher-end encryption technology needed in the financial industry. The result was that European suppliers moved in to fill the need, using knowledge either available in the literature or that they had independently developed, and the United States lost much of that market. Keeping export control systems efficient and up to date will never be easy, but a failure to devise much better and balanced strategies can have serious consequences for the competitive position of US industry.

As with export control, the development of commercial standards is an area that, if handled poorly, could impede cooperation. The standards to which products and processes are designed and certified may strike many as dull or obscure, but they are critical to modern technical society and can underpin national competitive advantage in subtle ways. China's government has figured this out and is working to establish standards that will advantage its manufacturers in both formal and informal ways. The Western democracies must engage more actively in preserving an inclusive, even-handed approach to global standard-setting for emerging technologies. There is considerable evidence that the best standards are those developed through negotiation among relevant experts and firms, *not* simply imposed by national governments.

A full-blown assessment of US export control, supply chain, and dual-use systems is beyond the scope of this article, but a few elements are clear. The United States has a great need for a cross-government strategy with a mandate to do a better job of balancing security with other important goals like economic competitiveness, integration, and access to the world of ideas.

Absent proactive and nimble policies in these vital areas of collaboration, the massive benefits of scale that come from a global perspective will be lost. Consider the challenges of the transition to lower carbon energy. Several profound revolutions have made solar power cheaper. The first began in the West with cooperation on solar research that generated ideas that, as happens with ideas, spread widely. A relentless drive to cut manufacturing costs in China, driven partly by large government subsidies, in order to sell to a global market resulted in a 90% fall in prices over a decade, making solar panels competitive, in some circumstances, with fossil fuels. A huge part of the value in cooperation around innovation comes from scale, and now that the system is fragmenting, solar power prices are rising again. The fracturing of the US-Chinese relationship reminds us that scale doesn't happen automatically and must be nurtured.

## Science meets geopolitics

As we write, China and the United States are in the process of rewriting their national attitudes toward each other. The sense that we are again rhyming with history is getting stronger. A very similar recasting of national policy—and national biases against the people of other countries—occurred as contests heated up with the Soviet Union and Japan (and with other countries even earlier). Hearing rhymes can be instructive, but our policy responses need not echo the past, especially when those echoes prevent us from recognizing what is different or how we can do better.

Scientists love global science because the search is expansive and the benefits are highly diffused. Witness the gains that have accrued globally—albeit unequally and unevenly—from investments, concentrated in the West, in basic research that have made novel vaccines for the coronavirus possible. Such global science cannot thrive without openness—freedom of ideas, people, and capital.

The story of post-World War II science is that such a diffusion of global benefits has not led to paralysis in policy because the benefits have been big enough that the risks have been politically tolerable. That idea was never really tested with the Soviet Union, even though there were some fragile bridges between Western and Soviet science and those bridges proved highly useful. The concept met another test in the 1980s with Japan and survived, in part because Japan's economy stalled.

The test with China will be much harder, although the benefits from successful collaboration may be significantly larger than anything previous efforts have offered. The political constituencies that must be satisfied to hold together scientific cooperation aren't global but national and local, and we must also create enough tangible benefits to keep scientists themselves engaged. The US government is now making it increasingly difficult for Chinese students in STEM to pursue graduate studies in the United States and stay here after they graduate. In some cases, administrators implementing US policy are hassling US investigators, especially those of Chinese origin, who collaborate with colleagues in China. China, meanwhile, is finding ways to keep its top graduates at home. These shifts are transforming what is possible for scientific cooperation. Failure to create a durable strategy for scientific collaboration could deprive both countries—and humanity in general—of the fruits of such joint efforts.

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DIVYANSH KAUSHIK AND CALEB WATNEY

# Attracting (and Keeping) the Best and the Brightest

Foreign students and entrepreneurs helped make the United States an innovation powerhouse. With more countries competing for talent, Congress must create a system that attracts highly skilled immigrants.

For the first time in a decade, the US Congress is actively debating legislative approaches to solidify the country's global leadership in science and technology. While several different bills have been proposed, all approaches attempt to build on the foundational legacy of Vannevar Bush's 1945 agenda, *Science, the Endless Frontier*, by infusing billions of dollars into US science funding institutions.

There is no question that the American science enterprise needs significant investment. US federal research and development investment as a percentage of gross domestic product has been on a downward slope since the 1970s. But funding is only part of the puzzle.

The reason some countries stay at the cutting edge of science and emerging technologies is a complex question, but one crucial factor is the sheer number of smart, talented people they attract from all around the world. Our country's scientific leadership has been strengthened by a massive influx of global talent over the last century. As the United States seeks to fortify its position in the world, policymakers need to do better by the immigrant scientists who helped the country achieve its preeminent status—and the immigrants who are yet to come. Grudgingly accepting the world's best and brightest students, scientists, and entrepreneurs is no longer enough; the United States needs to be actively recruiting them. And legislators need to give them a clear legal path to work here.

It's relatively easy for national governments to build the physical infrastructure for science, including expansive new scientific laboratories and the funding for elaborate experiments. But the world's smart and dedicated scientists are inherently scarce, so their choice of where to live and work is critical. Seventy-six years ago when Bush wrote his report, the United States' main international scientific competitors were in Europe. Winston Churchill's military assistant secretary, Ian Jacob, is said to have remarked that the Allies won World War II "because our German scientists were better than their German scientists." Bush recognized that strength: "The government should take an active role in promoting the international flow of scientific information."

Over the years Bush's proposal was realized via the one-way flow of smart, skilled scientists to the United States. Jacob's snarky remark about German émigrés foreshadowed immigrants becoming a pillar of US innovation policy. Today, while immigrants make up 18% of the US workforce, they have won 39% of the country's Nobel Prizes in science, comprise over 40% of STEM PhD graduates and 28% of the science and engineering faculty in US universities, and produce 28% of the nation's high-quality patents. Immigrants have founded more than 50% of the billion dollar start-up companies in the United States.

The process of recruiting and retaining the immigrants who have powered this innovation engine has been done in a haphazard way. Attracted by US universities for undergraduate or graduate school, many came and stayed through a hodgepodge of student programs.

This informal system benefits not only the universities themselves—which have come to rely on the higher overseas tuition rates as well as foreign graduate students and postdoctoral labor in their labs—but also their local economies. In a 2021 paper, the economists Natee Amornsiripanitch, Paul A. Gompers, George Hu, and Kaushik Vasudevan found that 1 in 5 entrepreneurs who start venture-backed companies in the United States are immigrants—and 79% of them had come for college. This study found that 40% of these immigrant founders started their companies in the same state where they attended school.

We can clearly see the benefits of skilled immigration in cities such as Pittsburgh, which have transformed their declining steel economies to those driven primarily by research and development (R&D) as well as entrepreneurship in the fields of artificial intelligence and the life sciences. International students make up approximately 50% of the Carnegie Mellon University students seeking to launch a start-up company in Pittsburgh.

Despite the labyrinthine and politically charged characteristics of the US immigration system, some international students have been quite successful. "The story of Pittsburgh's revitalization lies not only in bringing young people to learn at our world-class institutions," Pittsburgh Mayor Bill Peduto commented last year, "but in encouraging young minds to invest in Pittsburgh and call it home. The economic benefit of international students on our regional economy is undeniable. In our region, one job is created for every two international students enrolled in our colleges and universities. Supporting international students is critical to the well-being of Pittsburgh."

While the current arrangement has brought obvious benefits to the United States, it was based on an implicit promise to immigrant students and scientists that hard work and the courage to think boldly would be rewarded. The pursuit of excellence and innovation, regardless of a person's country of origin, would be encouraged for the benefit of all. It is a compelling promise, and the country's apparent ability to deliver rewarding careers to generations of scientists created an innovation ecosystem where attracting and retaining global talent is now more crucial to R&D institutions than having the latest supercomputers and semiconductors.

But there are signs that this promise is no longer enough, and that the informal structures that bring international talent to the United States need to be formalized. Just a decade ago, the economist William R. Kerr documented that between 2000 and 2010 more international inventors immigrated to the United States than to the rest of the world combined. But this population of global scientists and technical practitioners now has other, more welcoming places to go. The economists Michael Roach and John Skrentny found that immigration barriers are a significant deterrent against PhD graduates' ability to realize their start-up career interests, compelling them to either leave the country or work at larger US firms where visa pathways are more well-established. While this undoubtedly suppresses the formation of new businesses, these barriers around visas and immigration are also leading early career scientists and entrepreneurs to pursue their careers in countries with a more liberal stance on immigration.

And now other countries are working more formally to welcome them. Global competition to recruit international scientists and entrepreneurs has already begun. In January of 2020, the United Kingdom implemented the Global Talent visa, an uncapped visa program to provide an expedited pathway to residency for international scientists and engineers who are leaders in their fields. Some countries (including Canada, Australia, and the United Kingdom) have adopted versions of a start-up company visa to create a dedicated pathway for international entrepreneurs, while other countries (such as China) have elaborate talent recruitment programs to try and bring back talented students and workers who are living abroad.

In contrast to this global trend, the United States does not have an uncapped visa or a realistic pathway to residency for many international scientists and engineers. In fact, the country's process for awarding visas and green cards is restrictive, unnecessarily convoluted, and highly polarized. It's ironic that at a time when concerns about China's growing technological ambition are so central, the US response has been to shut the door on China's brightest pupils and send them home.

For many foreign graduate students, the most viable path to staying in the United

States legally is often a temporary H-1B visa, which gives workers little leverage over their workplace conditions or their wages because they cannot leave their employer without having to also leave the country. Further, the H-1B is a lottery program, which means talented PhD students with highly paid job offers in hand can easily lose out to applicants with more modest entry-level information technology jobs because the former weren't lucky enough to have their name drawn from the (virtual) hat.

For immigrants, starting a business in the United States after graduating is even more difficult. Because the United States does not have a statutory start-up company visa category, trying to use traditional pathways such as the H-1B visa is effectively impossible as an entrepreneur because of the requirement that the visa holder be an "employee" and thus fireable. Other pathways for highly skilled immigrants, including the O-1, EB-1, and EB-2 visas, rely on a strong record of prior accomplishments and are not a good fit for entrepreneurs whose potential accomplishments lie in the future. Some of these visas also suffer from decades-long backlogs due to arbitrary annual caps established by Congress in 1990.

The US visa system, so necessary for the nation's future success, is hampered by its backward-looking outlook. Entrepreneurs such as Steve Jobs or Paul Allen had little track record of success before founding Apple and Microsoft; if they had been born in another country, it is unlikely that traditional employment-based US immigration pathways would have allowed them to launch their respective firms here. This inability to recognize prospective success is one of the core deficiencies in the US immigration system. The United States wants to attract Nobel Prize-winning scientists as they are actively working on their groundbreaking contributions, not after they've won the prize.

The Biden administration has made an important change by reestablishing the nascent International Entrepreneur Rule for prospective founders who can secure at least $250,000 in investment from a qualified US investor. The program allows a renewable two-and-a-half-year period for entrepreneurs to try building a business in the United States, with the ultimate goal being permanent residence via a transition to a Green Card.

However, as an executive parole program (meaning the duration of entry is determined by the Department of Homeland Security rather than by Congress), the program's impact will inherently be limited. Future administrations can effectively freeze the program—as the Trump administration did. Many pathways to legal status rely on a degree of certainty for their effectiveness. It's difficult for students or entrepreneurs to plan their lives around moving to the United States, or for investors to contemplate large investments in immigrant entrepreneurs, when the enabling program could be wiped from the code of regulations at any time.

As Congress debates funneling more money into science and research, it should consider partner legislation to bolster the nation's ability to attract and retain international scientific and technical talent. The US Citizenship Act of 2021, proposed by President Biden on his first day in office, featured an ambitious and lofty set of immigration reforms, including exempting US-educated STEM—science, technology, engineering, and mathematics—PhD graduates from Green Card caps; increasing the number of available H-1B visas; creating a "Heartland visa" to allow cities and counties to sponsor immigrants to support a region's economic development strategy; and providing stability to recipients of Deferred Action for Childhood Arrivals protections. These reforms would help make a serious dent in this problem. But the bill is also unlikely to pass.

Sections of the bill with bipartisan appeal, however, could be combined with other reforms to create a national competitiveness bill for talent development. From a scientific talent perspective, the most promising starting place would be to expedite the Green Card exemption for STEM PhD students that was featured in the Biden proposal. Under the status quo, promising PhD graduates can be kept waiting for years (or forced to leave the country) as they wait in line for a Green Card along with all other candidates. During this period, it's difficult or impossible for them to launch a new business, switch employers without filing copious paperwork, or work with the federal government in a variety of research or security capacities. The exemption would let them instantly apply for a Green Card upon graduation, without impacting other applicants. Importantly, this would provide a tangible and stable pathway to permanent residency that students could envision and aim for from the outset of their studies.

This approach should be paired with a statutory start-up visa so that talented international entrepreneurs have a pathway to launch technology and science start-ups in the United States. As discussed above, a simple way to do this would be to solidify the International Entrepreneur Rule in legislation so that future presidents cannot simply freeze the program on a whim. This legislation would provide certainty to students who are considering coming to the United States with the goal of eventually launching a business, as well as for investors as they attempt to recruit talented researchers and entrepreneurs from around the world.

The combination of these two reforms, of course, will not fix all that ails the US talent system. There is a great need to nurture US-born talent to enter the technology and sciences workforce as well. Thus any changes to immigration legislation should be bundled with increased funding for domestic STEM training. A large demand-side boost in science funding envisioned by Congress will be most effective when paired with a supply-side increase in the number of scientists available to work on these difficult problems.

Senate Majority Leader Charles Schumer and the Chairwoman of the House Committee on Science, Space, and Technology, Eddie Bernice Johnson, are long-standing champions of immigration reform. Senator Schumer—who led the Border Security, Economic Opportunity, and Immigration Modernization Act of 2013 that provided two statutory pathways for international entrepreneurs—also emphasized the importance of pairing National Science Foundation funding proposals with immigration reform before he introduced the Endless Frontier Act. Chairwoman Johnson championed legislation in the last Congress to provide Green Cards to US-educated STEM PhD graduates.

The success of the US scientific enterprise—and its ability to create jobs—relies heavily on the contribution of scientists who came to the United States from around the world and work alongside the domestic STEM workforce. This can be clearly seen in the examples set by dynamic US immigrants: Katalin Karikó came to the United States from Hungary and performed the foundational research that led to mRNA vaccines for COVID-19; Ibrahim AlHusseini moved to the United States as a student and founded FullCycle, an investment company working to reverse the effects of climate change; and Sethuraman Panchanathan, who helped Arizona State University become a major research university before he was unanimously confirmed by the US Senate to lead the National Science Foundation in 2020.

Despite protectionist rhetoric over the past decade, there has never been any doubt that the success of the US innovation engine rests on its ability to attract global talent. As aerospace expert and former Under Secretary of the Army Norm Augustine said in April 2021 testimony to Congress, "It is vitally important that more of America's youth be motivated and qualified to pursue careers in science and engineering; yet, without continuing to attract talent from around the world there is little chance that America can remain competitive."

To "put America in a position to outgrow, out-innovate, and out-compete" other countries, as Senator Todd Young put it in reintroducing the Endless Frontier Act, the United States must redouble its efforts toward fostering an open and global scientific community. This means formalizing the country's relationship with foreign scholars. The United States needs to attract promising students and highly skilled workers and support their drive and ambition—not only when they're celebrated but also when they're at the beginning of their careers. Policymakers must recognize that the nation's ability to draw talented and ambitious immigrants from around the world enriches US scholarship, US culture, and US industry. This acknowledgment of value needs to be enshrined in legislation that cannot be repealed with every new presidency.

The key to being a global leader in science and technology over the next 75 years is recognizing who helped make the United States powerful in the first place. As legislators seek to dramatically expand the nation's scientific enterprise, US leaders should be sure to put up a "Now Hiring" sign in the window.

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# Democracies Must Coordinate Industrial Policies to Rebuild Economic Security

The United States can control its technological future only by working with other liberal democracies to reduce shared risks and vulnerabilities.

Russia's invasion of Ukraine has created a watershed moment for the world's leading liberal democracies. Perhaps most striking is the degree to which the invasion has renewed cooperation among democracies to address a shared challenge to their military and economic security. Their response demonstrates that these allies can mount a coordinated and rapid response to a shared threat. But will this translate into an ability to work together to address other pressing challenges—in particular, their economic, technological, and geopolitical vulnerability to China?

The rapidly growing concern over "techno-nationalism," "technological sovereignty," and "research security" reflects the fact that geopolitical jockeying and economic competition are increasingly focused on emerging and extant advanced technologies. These concerns are also evidence that liberal democracies with market economies—the United States among them—are struggling to come to grips with how to control their linked technological and economic futures.

Over the past decade, many liberal democracies have become aware of their growing economic links with China, considering that country's role as both a huge market for exports and a global leader in manufacturing capability and related innovation. Further, as China's economy and science and technology capabilities have grown, it has rolled out ambitious industrial policies to develop specific areas of advanced technology. Such moves fuel concerns about dependence on China for critical dual-use technologies (those with both military and commercial applications) such as artificial intelligence (AI), as well as for dual-use advanced technology components including semiconductors, smart communications equipment, and next-generation batteries.

In the wake of Russia's invasion, liberal democracies have quickly and clearly demonstrated their ability to act in concert when they share interests. But what collaborations with other democracies will limit the shared and common risks of technological dependence on geopolitical competitors such as China?

## Two critical policy shifts

First, US policymakers, along with those from other liberal democracies, need to recognize that China's market size and rapidly growing R&D and innovation capability can only be matched if they work together. Democracies with regulated market economies, basic freedoms, and the rule of law need to expand beyond collaboration in basic science to engage in problem-focused, precompetitive R&D and later-stage applications of new scientific and engineering knowledge.

Given the dominant role of private companies in the science and technology (S&T) enterprise of liberal democracies, there is no way to reach adequate scale and scope unless fair and enforceable sovereign-to-sovereign R&D alliances and collaborations encourage and support applied R&D collaboration among private companies headquartered in different democratic nations. This is the case in domains of knowledge and application as diverse as AI, orbital space development, future wireless (6G), and alternative aviation fuels. Without immediate moves to reach global scale and scope in applied research through cross-border collaborations that leverage the private sector, there is a growing risk that the liberal democracies will be outmatched by China in critical sectors and dual use technologies.

Second, since liberal democracies depend heavily on private companies for most R&D, most innovation, and virtually all delivery of tech-intensive goods and services, the governments of these nations need to promote cross-border alignment and cooperation among their mostly private national innovation systems. They also need to develop and implement shared approaches to managing the risks and vulnerabilities of trade, cross-border investment, and advanced technology exchange and collaboration with geopolitical competitors such as China. This will require substantial work, of course, within each nation and in negotiating cross-border agreements and policies with each other.

In the immediate post-Cold War period, there was a belief that global free trade agreements—organized via the World Trade Organization—could knit together the market activities of all nations. That approach has not lived up to its promise. All nations "work the edges" of agreements to serve their own interests; but in China, state influence over companies goes further. In recent years, the Chinese Communist Party (CCP) has increasingly used approaches such as placing party units within firms, adding the pursuit of national geopolitical goals to corporate profit-making missions. International competitors cannot trust that Chinese firms' market motives exist separate from their obligations to CCP political goals, and they cannot be sure that the Chinese government will not put its thumb on the scales of competition by changing the rules to favor Chinese companies. Therefore, the market-based R&D and innovation systems operating within and among the liberal democracies need to be working together and aligned and in dealing with nations that do not maintain regulated free-market economies.

The goal of making these two policy shifts in the United States—still the world's largest investor in S&T—is not just compete economically, but also to encourage other democratic nations to act together to retain adequate technological independence from China and other potential competitors. In most liberal democracies, and in the United States in particular, this requires substantial political will to make domestic changes and some particularly heavy lifting in international S&T policy and in reconfiguring economic relationships with democratic allies.

## Companies and global competence in innovation

Appreciating the need for these shifts requires understanding the unique role private businesses play in the S&T enterprise in liberal democracies. US businesses spend over three times as much as the US federal government on R&D. Even more importantly, the nation relies on private enterprise for innovation. Companies execute virtually all development, design, process engineering, and scale-up necessary to create a commercial product or service ("from lab to fab" or "code to download").

The decline of US dominance in global R&D is not because the United States has fallen behind but because the rest of the world has gained ground. US public and private investment in R&D is now about 30% of the global total, down from 69% in 1960. Similarly, starting around 30 years ago, there has been much greater global dispersion of the engineering and innovation capabilities that translate new knowledge into commercially viable products and services. And over the same period, intracompany and intercompany activities of MNCs—including supply chains, corporate partnerships, and joint ventures—have become almost wholly internationalized. The explosion in cross-border activity applies not only to those large organizations traditionally called multinational corporations, but also to technology-focused start-ups and smaller businesses that can today find suppliers or markets as easily in Europe or Asia as in the United States. This change has been both deep and wide and by now is deeply entrenched; private company cross-border R&D, design, and production activities have created knowledge networks and innovation ecosystems that span the globe.

The result of these long-term trends is that corporations now operate in, and take advantage of, a world of global competence in R&D, design, scale-up, and production, resulting in unparalleled choices as to how to organize their business on an international level. This abundance of choice, coupled with internet access, means that cross-border economic and military capability spillovers from private and public R&D are now the norm. An AI start-up, seeded by basic research funded by the US National Science Foundation and spun out from Stanford University, may look for programming talent in Asia or Europe and set up operations there. The same may be true in reverse for an AI spinout from Cambridge University in the United Kingdom seeking talent in Boston, Palo Alto, or Munich. An academic paper published online by a professor at Berkeley may be read instantaneously in Berlin and Beijing.

## New concerns and a silver lining

These changes are forcing shifts in the long-standing attitudes of government toward the overseas activities of private industry. Thirty years ago, just after the end of the Cold War, the US government was hardly concerned when a US multinational set up a commercial R&D facility in China, the United Kingdom, Germany, or Russia. The same was true when US companies created complex cross-border supply chains, obtained or sold advanced technology components overseas, or set up manufacturing facilities in other nations. As long as US companies complied with international treaties and justified their actions in terms of commercial and shareholder interests, the US government regarded US companies' overseas market activities—even in non-free market countries—as serving US national interests. The main exceptions have been activities that involve products and services related to defense and national security. In those cases, the US government has used export controls and investment controls managed by the interagency Committee on Foreign Investment in the United States (CFIUS), to restrict the actions of private companies. The situation is quite different today, when there is growing awareness that overseas activity by US companies may be inadvertently creating significant technological, economic, and military security risks for the nation.

This set of concerns—along with necessary US government action to address the risks—may be a hard pill for many US big tech companies to swallow. The largest tech companies in the world, including Apple, Microsoft, Alphabet (Google), Meta (Facebook), and Amazon, either did not exist or were in their infancy when the Cold War ended. None of them would have emerged and thrived without one or more forms of public support, from research and education funding at universities to government contracts, grants, loans, and procurement. While the issue of technological vulnerabilities with China has been simmering, these companies are now, with the Russian invasion of Ukraine, getting their first taste of the kinds of constraints the US government can apply to cross-border activity during a period of geopolitical confrontation.

There is a silver lining here for both US S&T policy and US companies. Just as geopolitical concerns may motivate increased scrutiny of the interface of market and nonmarket systems, they also provide a powerful incentive to strengthen regulatory alignment and increase market-based, tech-oriented collaboration among liberal democracies. Of the 20 most R&D-intensive nations, 19 are liberal democracies with market systems broadly similar to that in the United States; China is the one exception. Nine of the world's 10 largest economies by gross domestic product are liberal democracies, again with China as an outlier. The aggregated population of those nine countries (a very rough measure of market size in the largest liberal economies) is, thanks to India, about 2.2 billion as of 2020.

And, of course, a large number of liberal democracies are among the richest countries in the world; the G7 nations, European Union members, and other developed liberal democracies in Asia such as South Korea and Singapore have very high per capita GDP, three to five times higher than that of China or Russia. Companies operating within and among liberal democracies will find scale and scope—in markets, applied R&D capability, and production capacity—almost surely exceeding those of China and its allies.

To secure the US technological future, and that of our political and economic allies, two new policy tracks are urgently needed: first, cross-border, applied R&D and innovation collaborations; and second, economic and security policies that support collaboration with other liberal democracies to limit the risks and vulnerabilities arising from potential technological dependence on geopolitical competitors.

## New applied cross-border R&D collaborations

Cross-border applied R&D joint ventures and collaborations are common in the private sector but rare in US sovereign-to-sovereign relations. This is not surprising, as they require co-investment by companies in the United States and allied nations and the creation of workable cross-border alignments in laws and regulatory approaches.

This type of working relationship is manifest both in the Biden administration's approach to semiconductor supply chain resilience and in the historic activity of SEMATECH in the semiconductor industry decades ago. Public-private collaboration, combined with engagement of allied nations and non-US multinational corporations, is somewhat familiar ground in traditional US defense industries (and NATO, for that matter), but it needs to become the norm across the wide range of modern industries that can be passively or actively "weaponized" by geopolitical competitors in full-scale hot wars or low-grade confrontations. This range includes industries such as social media and cloud-based services, uses of orbital space, health products and services, climate change mitigation and adaptation, intelligent systems, food production and distribution, and advanced manufacturing. In the same way that today's semiconductor or supply chain security problems cannot be solved with purely domestic actions, it is impossible to secure the United States' future in a multitude of commercial but also security-critical industries without cross-border collaboration in applied R&D and innovation.

The US government lacks the organized institutionalized capacity to lead or even to follow in these types of activities. While the United States has well-developed models for cross-border investment agreements, and free trade norms and practices have been worked out in detail and are negotiated by the US trade representative, S&T agreements and cross-border investments are often left to individual agencies or the Department of State and tend to be heavily biased toward collaboration in basic science or relatively pure public goods (such as seismic information or weather data). Periodic episodes of White House-coordinated activity (such as the semiconductor plan or critical supply chain resilience) are not adequate. There is a need for a US government agency with the budget and capacity to lead a sustained intragovernmental coordination and funding mission in cross-border applied R&D.

Meeting this need requires an operation larger than a single program but smaller than a sweeping bureaucracy: something scaled at least initially between ARPA-E's $500 million 2022 budget request and DARPA's $3.5 billion annual budget (managed by 100 program managers). The new agency, like the Office of the United States Trade Representative, will need institutionalized external consultative processes. It is particularly important that this new entity be able to identify, bring forward, and vet cross-border R&D and innovation needs that arise from industry and to tap the large and diverse community of researchers in US universities and nonprofit labs. Its challenge in intragovernmental coordination will be to use its budget to catalyze and target increased cross-border activities by research funding agencies such as the National Science Foundation (NSF) and National Institutes of Health (NIH), as well as mission-oriented research activities in the Departments of Energy and Defense, the National Institute of Standards and Technology, and other agencies.

There is also an important legislative step that would allow agencies such as NSF and NIH to allocate increased funds to cross-border collaborative research. Similarly, the legislative and executive branches will need to review, and may need to revise, antitrust laws and guidelines to avoid chilling important cross-border precompetitive R&D collaboration.

The EU has already moved in the direction of industry-engaged cross-border R&D collaboration through efforts such as Eureka and, more recently, the Important Projects of Common European Interest (IPCEIs). Eighteen countries and the European Commission launched Eureka in 1985. Now expanded to 48 countries in and outside Europe (South Korea, for example, is a member, but not Japan or the United States), Eureka blends public funding from government sources with industry interest in R&D projects designed to "support international industry-led R&D." IPCEIs, for their part, are less about R&D than innovation and the entire supply chain for critical sectors. A microelectronics IPCEI was launched in 2018. A two-part IPCEI focused on batteries was established in 2019 and has received two tranches of funding totaling €6.1 billion for a "research and innovation project along the entire battery value chain." A health IPCEI was announced in March 2022, emphasizing the importance of pharmaceutical manufacturing and innovation to address such issues as antibiotic resistance, future pandemics, and gene and cell therapies.

The motivation for Eureka was arguably to pool European resources to match the scale of R&D investment in the United States and Japan. IPCEIs represent a new form of cross-border industrial strategy—with heavy industry involvement—focused on innovative production processes for products with high research and innovation content. Neither Eureka (which is often said to be bureaucratic and political in its allocations) nor IPCEIs may be models for US engagement with other liberal democracies. And, of course, the European Union has a leg up in this type of cross-border activity as its members have already committed to considerable policy and trade alignment.

US dominance in R&D has waned and many other nations have developed deep production capacity in advanced technology products and components. Simply to keep up in commercial and dual use innovation the United States needs to move quickly to develop and join with other liberal democracies in cross-border applied R&D programs that leverage the wide range of emerging and extant advanced technology capabilities in industry.

## Limiting risks and vulnerabilities

The second major shift needed involves economic and S&T policy changes that can limit US vulnerability to China in a wide range of dual-use advanced technologies. The challenge here is not doing something that has rarely been done before—indeed, nations have long protected their technological competitive edge for both military and commercial purposes. Rather, it is using existing logic and mechanisms, along with some new ones. The economic policy challenge is to maintain competitive markets among political and economic allies, even while working together to reduce the shared risk of dependence on technology and innovation from strategic competitors.

The United States has a long-standing resistance to industrial policy—to government selection of the "technologies of the future" or the promotion of national champions. This resistance has been bolstered by the tremendous success of US companies in S&T generally and tech-based US multinational corporations in particular. But the last decade has seen a slow erosion of such skepticism as politicians and policymakers have become aware that the lack of US industrial policy gives other nations some leverage to shape market outcomes, both globally and in the United States. Supply chain disruptions caused by the COVID-19 pandemic and concerns about a lack of domestic semiconductor production have only heightened the sense that government must—in an era of rising geopolitical tension—play a more active role in shaping the economy for economic and military security. Although national security is not the traditional justification for industrial policy, industrial policy ideas that would have been dismissed in 2010 are now widely seen as necessary to preserve national economic and military security.

Because of the role of private companies in the health and global integration of the US tech enterprise, this second policy track inevitably entails more government scrutiny of companies' cross-border, technology-intensive actions. But what should oversight of those actions look like in practice? The logic of export control—share with allies, not with adversaries—has already taken hold in the US political process. The House of Representatives version of the America COMPETES Act, currently in reconciliation with an alternate version from the Senate, includes a provision to create an interagency Committee on National Critical Capabilities that, among other responsibilities, would selectively review and regulate outbound investment. Its focus would be parallel to CFIUS, which has a brief to review and, as necessary, halt inbound investment for national security purposes.

Though implementation details are still undefined, this new committee's review process would introduce scrutiny of overseas activity. Does, for example, a private company opening an R&D laboratory in an authoritarian country inadvertently create a problematic military or commercial advantage for that country? Or is there a material national security risk if the supply chain for an advanced technology product—a medical device or an advanced material—depends on components from, or processing in, China? Given that complex supply chains are now the norm for technologically sophisticated products and services, this oversight process will be difficult, but this proposal is not a wild idea added to legislation by a small group of radicals; it is lifted directly from recommendations accompanying the 2021 Annual Report to Congress of the US-China Economic and Security Review Commission.

These ideas were given new force when US export controls—foreign direct product rules (FDPRs)—became a centerpiece of US sanctions on Russia for invading Ukraine. FDPRs are aimed at shutting off Russia's ability to purchase both US advanced technology products and products made elsewhere using US advanced technology such as design or control software. This was the same powerful and far-reaching tool used by the United States to temporarily hobble Huawei, the Chinese telecom company, for alleged unfair practices.

Whether the America COMPETES Act—almost certain to be passed in some form—includes a Committee on National Critical Capabilities is uncertain. This is likely only the first salvo in a barrage of proposals aimed at managing cross-border vulnerabilities and risks arising as an inadvertent consequence of the actions of private companies in R&D, innovation, or production. In the United States, a new generation of international economic policy proposals will almost certainly include, in some form, both incentives for onshore activity and regulations preventing the offshoring of certain types of economic activity and new tech applications to countries that do not meet established standards of the rule of law and free markets as well as reciprocity and national treatment in international dealings.

The immediate US policy challenge lies in building a less crisis-driven capacity to work with allies to identify and act on areas of geopolitical vulnerability and risk. The key concern will be how the activities of mostly private companies shape national technological competencies and vulnerabilities. Some necessary policy changes will be amenable to existing export and cross-border investment control approaches, whereas others will require new mechanisms and incentives to shift private R&D as well as production and innovation activities to the US and other market economies. Global supply chains and the global dispersion and network character of both "lab to fab" and R&D capability, mean that any policy effort of this sort will be meaningless if it is not pursued in close collaboration with a substantial majority of the leading technology-intensive liberal democracies.

Finally, it is important to recognize that the US research university community a critical aspect of the US advanced technology enterprise and is enmeshed with both US and foreign tech companies, especially in engineering and applied sciences. The new generation of international economic policies and practices will need to address the differences between curiosity-driven research (openly published in the service of humankind) and research and innovation that—for military or commercial purposes—may require barriers to some knowledge flows between liberal democracies and nonmarket economies.

### Collaborative policy for a shared challenge

The escalating economic, geopolitical, and technological competition between free-market liberal democracies and China is changing the worldview of US policymakers, companies, and citizens. The powerful economic and national security logic of free trade is still a very important guide for US economic and S&T policy. There is, however, a clear need for policies designed to limit risks arising from dependence on geopolitical competitors that do not meet basic standards of free and fair markets or of reciprocity and national treatment in trade, investment, and R&D collaboration.

Fortunately, the world's leading democracies do meet those standards. By working together on cross-border economic and S&T policy, they can materially improve economic and military security in the twenty-first century. Indeed, it is only by working together that they can do so.

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SUSAN COZZENS

# Collaborate for the Future

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The military plays an outsized role in US research and development, but the costs are rarely acknowledged. Shifting from a competitive model of innovation to a collaborative one would bring benefits—and security—to the United States and the world.

National science policy reflects a country's sense of its internal and external challenges and its place in the world. Since the end of World War II, US science policy has embodied the view of generations of American policymakers that the United States is, to use the Cold War idiom, "the leader of the free world." Over time, the military competition implied in that phrase became economic competition, not only between West and East but also among countries constituting the free world. US leaders have enjoyed representing the world's "biggest" and "strongest" economy and use anxiety about other nations "catching up" to push particular policies.

But the post-World War II global order has crumbled, and it isn't clear what a new world order will look like—or whether today's turbulence will persist. To imagine the role the US science and technology enterprise could have in shaping global conditions in the future, it is necessary to reconsider the competitive framing of these policies.

The first aspect to reconsider is treating research and innovation policies as *national* endeavors. National governments strive to provide the conditions that support well-being for their populations and economic success for their enterprises. In this view, investments in research and innovation must be oriented to benefits that will accrue within national boundaries. But in the early twenty-first century, the idea of national boundaries themselves is beginning to look quaint. Problems including COVID-19, mpox, climate change, supply chain disruptions, and even disinformation easily transcend lines on a map.

Today, most of the important systems of human interaction stretch across national boundaries. Humanity is so embedded in densely interwoven systems of production, communication, health, and environment that national policymakers are forced to consider what their constituents give as well as take in networks that extend well beyond their control. In the postwar era, well-being was pursued as a largely national project; that goal now needs to be pursued globally. The question for national policymakers is how they will interact within global systems, rather than how to dominate them. The current reality of systemic interconnection requires not only different frameworks for analysis, but also different ways of evaluating benefits and trade-offs. Clinging to the nation-level framing has a prominent opportunity cost: the benefits that come from global collaboration.

I argue here that, if policymakers are to achieve the goal of sustainable well-being in the United States, US science policy needs to shift its way of thinking away from competition and toward collaboration. Many of the systems in which the United States is embedded globally are science- and technology-intensive. In considering the options for the next 75 years of science policy, it is thus appropriate to ask how the United States depends on those systems and how it can maintain domestic well-being through cooperation within these systems. An assessment of the current system configuration and global circumstances yields insight into trends the United States can influence—and those it cannot—with its domestic science policy.

From the outset, however, policymakers need to acknowledge that science and technology do not determine the characteristics of these systems. Global decision processes are the result of political, military, and financial relationships at different scales, while technological prowess and scientific sophistication influence a nation's capabilities and options but do not determine actions or outcomes. At the moment, many collaborative global efforts to solve problems appear stalled, and authoritarian powers are on the rise, in no small part through their application of technologies. The major obstacles to shared human development over the coming decades are likely to be located in human rather than technological systems.

## Military research as an engine of innovation

One direct outcome of the competitive, nationalized framing of US innovation policy is that military spending on research and development exceeds R&D budgets for all other purposes. Despite this fact, the enormity of the US military R&D effort is one of the quietest topics in national and international research and innovation policy discourse.

The United States spends more on its military than any other country: $801 billion in 2021 or 38% of the world total; for 2023, the US defense budget is more than those of the next 10 countries combined. The drive for technological superiority in weapons and intelligence systems pulls with it enormous amounts of spending. In fiscal year 2021, the Department of Defense budget for research, development, test, and evaluation was $106.6 billion, up more than 79% since 2013. Proposed spending on national defense R&D was $75.6 billion for 2021, over half of all federal research and development spending. This was twice as much as proposed 2021 federal spending on R&D in health ($37.5 billion) and dramatically more than energy ($2.1 billion) or natural resources and environment ($1.8 billion).

In an earlier essay for *Issues*, the science and technology policy scholar William Bonvillian identifies military R&D as an implicit industrial policy, but it remains difficult to quantify the true impact of this policy choice. Indeed, a recent study shows that military investment increases even private activity in the industries where the funds are spent, influencing priorities directly as well as indirectly. Industries that produce weapons and surveillance get a boost; those that increase health for babies do not. Ingenuity goes to better tanks, not better schools. Tax revenues, which could be used, say, to create markets for cleaner energy, instead are consumed protecting fossil fuel supplies.

The use of the military as an engine of innovation has important opportunity costs as well. First, because no other countries spend so much on military R&D, there are fewer opportunities for collaboration and joint learning stemming from the military spending. Among the member countries of the Organisation for Economic Co-operation and Development (OECD), the United States accounts for more than 80% of total government military R&D funding. The United States also spends a larger percentage of its gross domestic product on military R&D—nearly 70% more than the next highest OECD country. The amounts spent on military R&D thus inhibit the United States from fully participating in the international networks of knowledge on which innovation and economic growth increasingly depend.

A second cost of the military model is that it has locked society out of discussing appropriate goals for innovation and their societal benefits. Military innovation is by its nature secretive, and it reinforces a sense that innovation is a "black box": taxpayers pour money in one end, and out the other pop game-changing technologies (GPS, Velcro, etc.). In the fields of health, food, or environment, the mechanisms that connect research with its benefits can be described and evaluated publicly; in military research, the opposite is true.

Finally, the militarization of US technology has had spillover effects in American society that may run counter to the idea of well-being, or even basic safety. The weapons industry is interlocked with law enforcement and the prison industry, with products developed for military use being applied in civilian contexts. For example, Cadre Holdings, which supplies the Department of Defense with smoke grenades, pepper spray, and body armor, also manufactures tear gas weapons for law enforcement, including the US Border Patrol, prison authorities, and police departments across the United States.

Both military-industrial and prison-industrial complexes feed on fear. Over two million people were in jail or prison in the United States in 2019, about 25% of the world's total incarcerated population. Neither complex delivers security: if prisons made us safer, America would be the safest country in the world. US citizens certainly want to live in a peaceful world. But the price they pay domestically for overgrown military systems displaces other investments and makes it difficult to achieve other public goals.

## Collaboration in communications technology

A collaborative, rather than competitive, paradigm for innovation policy is not only possible; it has been wildly successful. There is no more global system than telecommunications—which combines computers, wireless phones, and infrastructure on land and in space—and American firms have been at the forefront of its development. The growth of communications technology thus serves as a model for one way the US economy can interact productively with the world. Businesses have grown. Lives have been transformed. Competition has opened.

Rather than being siloed in military applications, communications companies have taken military innovations such as digital computing and satellites and embedded them in socially driven uses. Computing was born in the military realm and then moved into business, household, and individual use. In the meantime, telephones became wireless and mobile, as well as ever smaller and more powerful, until they too merged into the tablets and smartphones that so many people carry with them today. The infrastructure to support these systems also evolved rapidly, from cable to wireless, with satellite capabilities added to the mix. The result has been an explosion of social interconnection, accompanied by innovation that has widespread benefits.

Households around the world now have instant access to enormous amounts of information. The costs of staying in touch with others have dropped dramatically, and newer modes of interaction such as text messaging and social media are now widespread. Particularly importantly, information technology and telecommunications innovations have reached into the lives of the world's poorest households. Nestled among the fortunes made in the industry—and they are prodigious—are spaces for bringing financial services to the unbanked through mobile banking, inexpensive pathways for remittances from people in rich countries to their relatives in poor ones, and current market information to small farmers in remote rural areas. In short, these technologies have made a plethora of contributions to the reduction in world poverty in recent decades. These benefits only came about through an international ecosystem of small and large enterprises engaging at multiple scales and with a variety of objectives and levels of openness—in contrast to the secrecy of military efforts.

The telecommunications example illustrates that intellectual property provisions are a key element of future innovation policy. Ownership and control have been important objectives for some US industries in intellectual property policy. These need to be shifted into a stronger concept of investing in know-how in global business. New enterprises in Africa or Latin America, for example, would buy and use new production technologies more effectively if local researchers shared in their development. Both the global North and South would be better off.

## Contradictions in health innovation

The way that such interconnected systems succeed and fail can be seen in the second largest area of federal R&D spending in the United States: health, which had a proposed R&D budget of $37 billion for 2021. America has built the world's premier biomedical research institution in the National Institutes of Health, which supports a knowledge base that forms the environment not only for domestic medical care but also for pharmaceutical and medical equipment industries that operate globally. The Centers for Disease Control and Prevention and the US Food and Drug Administration, leading institutions of public health and pharmaceutical and medical device regulation, operate very much in a globally networked research space where they gain as well as contribute knowledge.

However, the American experience with COVID-19 vividly illustrated both the strengths and weaknesses of that knowledge configuration. There was never really a possibility that the virus would remain confined to its origins; contemporary life is just too mobile for that. As the disease became a pandemic, a global knowledge network quickly sprang into action. A vaccine approach that had already been under development was brought into play in record time, boosted by massive public spending and competition among companies across the rich world.

At that point, contradictions in the larger networks and systems of public health began to appear. Older adults in wealthy nations were fully vaccinated and getting boosters while other countries were still waiting for vaccines. Even within wealthy nations, notably the United States, vaccine access and uptake varied. As of January 11, 2023, only 69.1% of the US population of all ages has completed the primary series of COVID-19 vaccines, with the lowest percentage by racial/ethnic group for Black Americans. Domestic and international organizations attempted to expand vaccine availability and distribution, but have seen limited success in their efforts. While over 200 countries have at least some vaccine access, vaccination rates are in the single digits in some places, even as new COVID-19 variants emerge and move quickly around the globe.

The pandemic experience thus reflects the contradictions that public policy scholar Shobita Parthasarathy describes in assessing today's health innovation system. Health outcomes in the United States do not measure up to biomedical research spending because the system fails to define health appropriately and to deliver the right services. And since biomedical research in the United States is oriented to the health challenges of relatively affluent people, America's huge research investment skews the reward system for health researchers in other countries, even where the challenges are very different. Furthermore, aggressive protection of the interests of pharmaceutical firms in international trade agreements can create barriers to diffusion of essential medicines.

Contradictions and tensions are prominent in this area. On the one hand, US biomedical research assertively shares knowledge globally. On the other, US industry equally assertively privatizes the innovation that grows from that knowledge. The nationalist values expressed in US science, technology, and innovation policy applaud the privatization ("capturing the benefits"), while the human health commitments of the biomedical research community strain in the opposite direction. This tension must be resolved. Markets for drugs and medical devices will grow if the economies of poor countries improve. For that to happen, people there need to be nourished and healthy. A virtuous circle is possible.

### A need for global approaches to environmental innovation

The vexing difficulty of addressing global systems when innovation is pursued through a competitive national lens can be seen clearly in global climate policy. Climate-warming carbon dioxide emissions continue to grow despite the scientific evidence of their longer-term harms.

The Intergovernmental Panel on Climate Change process, which brings together a global community of scientists to compile and analyze the growing knowledge base for decisionmaking, started in 1988 and has produced five reports that assess and report the status of climate research, modeling, and monitoring. The scientific community was capable of acting globally in response to a planet-wide problem, but decisionmakers have mostly acted at the local level, blinkered by competitive concerns. Each nation's work to constrain carbon emissions appears to be a limited one, a zero-sum choice about maintaining current economic advantages and continue to compete with other economies.

Although they have acted individually, 23 wealthy countries are responsible for producing half of the planet's historical greenhouse gas emissions, leaving poorer countries vulnerable to their increasing effects. This system of unequal contributions and unequal costs cannot be undone by traditional nationalistic or competitive actions. Creating an innovation system that can generate and transfer knowledge and technology between the rich and the poor, the producers and the vulnerable, requires a far broader commitment of economic, political, and social resources than we currently see.

Inspiration for a more globalized, collaborative approach to innovation can be found in the story of solar photovoltaic (PV) technologies, which are now able to produce electricity more cheaply than even the cheapest fossil fuel plants. After the private Bell Labs invented the first PV cell in 1954, the US military funded development of the technology for the purpose of powering satellites. Over the next 40 years, a global mixture of public and private investment increased the efficiency of the cells, eventually deploying them at a scale that enabled learning. By 2019, India was producing the world's cheapest solar electricity by installing PV panels made in China, addressing the country's energy poverty.

## Innovation as a tool for global prosperity and security

The connections between innovation and global inequality should by now be clear. When a country's leaders view the world economy as a race to be won, they are rarely concerned that laggards in the global distribution of income hold everyone back. Hunger, disease, and lack of education anywhere mean less peace and prosperity everywhere. Even as surging middle classes in China and India have begun to reduce global inequality, the bottom of the global distribution remains stubbornly stuck. What's more, middle classes in the global North have lost ground, contributing to political challenges in these countries. Over the next 75 years, I do not believe it is in the best interests of US taxpayers to continue to expand the gap between poor and rich countries. US science, technology, and innovation policy could be a powerful tool to promote prosperity for Americans by promoting it for everyone.

Today, rich countries set the rules of the game, aided by the multinational corporations based in them, and the values of both need to change to create a more secure world. In technology-based industries as well as international negotiations, the United States must learn to collaborate. Sharing the science knowledge base is an important part of that transition. Greater investments in open science, more platforms to work on global solutions, and expanded business models that enable corporations to co-evolve a broader view of economic prosperity: these are shifts in research priorities that will keep American children and grandchildren safe.

Another important shift would be reorienting technological investment away from defense and toward collaborative efforts. Investing in technologies in which American skills complement those of the global South, such as nano-technologies for water systems, could eventually yield the sort of step-change innovation that previous investments in military technology such as GPS have wrought. Similarly, corporations working to create increasing economic interdependence, much the way Microsoft intends to create a global platform for small business growth, could create a world that is more secure and less militarized.

Seventy-five years from now, Americans could enjoy their current benefits and more, but in a world that will be more secure because so many others have those benefits as well.

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LEONARD LYNN AND HAL SALZMAN

# Collaborative Advantage: Creating Global Commons for Science, Technology, and Innovation

Collectively solving problems shared by many nations requires a new global science and technology commons, which could be modeled on successful past experiences.

What was once described as the "American Century" of political and technological dominance is giving way to a polycentric world. In this new order, the fate of nations will depend on international collaboration for innovation and prosperity, particularly as global challenges including disease, poverty, energy deficits, and climate change threaten all. The innovations needed can no longer be produced by only a few nations, nor can the benefits be confined to those few. Developing such innovations, however, will require collaborative efforts at a global scale that go beyond anything previously attempted.

In the postwar decades, the United States pursued a techno-nationalistic path in research and development that became a global norm. The US government was capable of funding research projects at far higher levels than other governments; US firms also directed substantial portions of revenue to R&D, extending federal efforts. The world's most advanced R&D laboratories included the largely independent Bell Labs and Xerox PARC, while companies like IBM, General Electric, RCA, DuPont, and Polaroid were engaged in significant basic and exploratory research. To varying degrees, these labs followed in the footsteps of the "Big Science" organizations of the federal labs such as Lawrence Livermore, Oak Ridge, the National Institutes of Health, and others. And, of course, significant federal funding also flowed to industry as part of the military's embrace of the R&D enterprise. Government and private labs pioneered innovations that gave the United States leadership in the introduction of new technologies, increased productivity, and created new consumer demands. The nation's universities trained large numbers of science, technology, and innovation (STI) workers, while attracting top talent from around the world.

In the twenty-first century, America remains the global leader in science and technology, but other nations are beginning to stand alongside it. Repeated calls for increased R&D funding, stronger patent protections, more surveillance against technological espionage, and greater support of American industry betray a palpable anxiety about America's standing in the world in terms of economic and military power. Although not all the policies proposed to reinvigorate American innovation are inherently techno-nationalistic, often the ways in which they are justified and framed are based on notions of outcompeting other nations—formerly the Soviet Union and Japan, now increasingly China. Policies are deliberated on the assumption that the United States needs to spend more on R&D than other countries, graduate more scientists and engineers, restrict outflows of STI, and sequester global science and engineering students and workers to deny access to them by other countries. Implicit in such proposals is the idea that the international creation and application of STI is a zero-sum game in which one country wins only at the expense of others.

We argue that abandoning this techno-nationalistic approach and instead investing in systems of global innovation commons, modeled on successful past experiences, and developing new principles and policies for collaborative STI could bring substantially greater benefits—not only for the world, but specifically for the United States. Key to this effort will be creating systems of governance that enable nations to contribute to the commons and to benefit from its innovations, while also allowing each country substantial freedom of action.

## Building a commons for science and innovation

The competitive and insular tone of contemporary discourse about STI stands in contrast to our era's most urgent challenges, which are global in scale: the COVID-19 pandemic, climate change, and governance of complex emerging technologies such as gene editing and artificial intelligence. These global challenges, we believe, require resources, scientific understanding, and know-how that can best be developed through common resource pools to enable both global scale and rapid dissemination. Moreover, aside from moral or ethical considerations about sharing such innovations, the reality of current globalization means that solutions—such as pandemic vaccines—must spread beyond national borders to fully benefit the world. Consequently, each separate national interest will be better served by collaboratively building up the global stocks of STI as public goods. Global scientific commons could be vital in addressing these challenges, but will require new frameworks for governance that are fair and attractive to many nations while also enabling them to act individually.

A valuable perspective on the governance of common pool resources (CPR) can be found in the work that Nobel laureate Elinor Ostrom did with her colleagues beginning in the 1950s. Ostrom, a political scientist, studied how communities that must share common resources—water, fisheries, or grazing land—use trust, cooperation, and collective deliberation to manage those resources over the long term. Before Ostrom's work, many economists believed that shared resource systems were inherently unsustainable because individuals acting in their own self-interest would ultimately undermine the good of the group, often described as "the tragedy of the commons." Instead, Ostrom demonstrated that communities can create durable "practical algorithms" for sharing pooled resources, whether that be irrigation in Nepal or lobster fishing in Maine.

Over the years, Ostrom and her colleagues' work yielded a set of design principles for CPR. These grew out of case studies of CPR governance systems to foster and protect resources and allocate them fairly among members. These design principles address, first, who is part of the community and what the boundaries of the resource are. Second, all members participate in setting and modifying rules, which include what they should contribute to the common pool and what they can withdraw. Finally, there are sanctions for rule violators and low-cost ways to resolve disputes between members. Ostrom studied small CPR governance institutions, but she noted they could be part of larger systems organized in multiple layers of nested organizations.

Ostrom and her colleagues derived and verified these design principles across hundreds of case studies of durable community holdings of CPR around the world. We believe the principles might be used to build global STI commons governance systems equal to the task of addressing important threats common to the international community, while allowing each country substantial freedom of action. And we propose that these design principles be adapted to address characteristics particular to STI development as well as moral and ethical issues, including equity in access and use of new knowledge and technology for the purpose of addressing global problems at the local level.

A viable institutional framework to govern a global STI commons would need buy-in from a highly diverse group of national governments and interested organizations. The institutional governance structure would have to ensure representation of the various economic and cultural interests of governments as well as regions. It would have to ensure that smaller and poorer countries were treated fairly. It would have to be structured to reduce temptations of governments to "free ride"—taking resources from the common pool without contributing to the whole. And it would need to fairly apportion access to innovations developed using commons resources. As in Ostrom's successful commons governance systems, there would need to be trusted monitors who could ensure that every country both contributed and withdrew their fair share. And in addition to all of these formidable challenges, the STI commons would need to remain independent from nationalist interests that might undermine the principles of the commons or constrain its governance.

This sounds like a nearly impossible set of tasks, particularly in a world now facing significant environmental and governance issues. But we suggest that the European Organization for Nuclear Research, commonly known by the acronym for the organization's original French name, CERN, appears to have successfully developed precisely such an STI common pool management institution. Founded to support multinational research in subatomic physics, CERN has broadened its research scope and endured over decades, providing not only important technological innovations, but a certain level of stability as the world around it changed. Following Ostrom's approach, we begin with an overview of CERN's governance system and then suggest next steps that might enrich our portfolio of design principles.

## Theoretical physics as a common pool resource

CERN officially came into being in 1954 and has thrived in an often chaotic global environment. Driving forces in its establishment included physicists Niels Bohr and Werner Heisenberg, who were concerned that progress in subatomic physics increasingly required Big Science experimental facilities. Those were only available in the United States and the Soviet Union, where the work was associated with the development of weapons. European scientists had to go to one of these countries, particularly the United States, to do such research, and many of them wanted to avoid contributing to knowledge that would increase the threat of nuclear weapons.

In 1949, a proposal for the laboratory was made at the European Cultural Conference, and it was further promoted by American physicist Isidor Rabi at a United Nations conference in 1950. Under the proposal and initial founding document of the organization, the group of 12 member nations would finance and build one or more international laboratories for research on high-energy particles, creating an important international common pool resource. To avoid exploitation of the facilities for development of nuclear weapons, the convention stated: "The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available." These have remained guiding criteria in establishing the open use of CERN's work and delimiting what research can be done there.

The 12 founding states—Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom, and Yugoslavia—were diverse. Some had been foes in World War II while others remained neutral; some were relatively rich and technologically advanced while others were not. By 2020, the organization had a budget of $1.25 billion with 23 member states, and 11,399 researchers affiliated with 78 countries, including the United States, had used CERN's facilities.

CERN has surmounted a number of challenges that generally face common pool resource organizations and international organizations in general. These have included developing a governance structure that gives voice to members that vary greatly in size, wealth, and cultural values; designing a funding contribution system seen as fair to all; and providing rewards that make participation highly valued by members with diverse needs. And finally, the organization has established boundaries that give advantages to members but allow, and even encourage, spillovers of the common pool resources.

These spillovers have been considerable. In addition to technological achievements, including supporting pathbreaking research in subatomic physics, CERN has nurtured technology that is now used around the world—most notably, the World Wide Web and the first web server. These innovations, which are credited to the Englishman Tim Berners-Lee and the Belgian Robert Cailliau, grew out of CERN's uniquely collaborative culture. In addition, the organization pioneered the touchscreen, medical technologies such as imaging used in cancer detection, and modeling tools, among many other innovations.

Today, CERN members include low-income nations with few technological resources as well as high-income, technologically advanced nations. In the early 1990s, Bulgaria, the Czech Republic, Hungary, Poland, Romania, Serbia, and Slovakia became members. Russia was an observer for many years. In 2020, Azerbaijan, Estonia, Georgia, Latvia, and Montenegro all sent participants, and China sent 334 observers. Funding of the organization is shared according to the size of each country's economy (readjusted periodically so as to account for different rates of growth). Germany, for example, now provides about 21% of the budget, while Serbia provides less than a quarter of a percent. Countries like Germany, France, and the United Kingdom benefit by being able to share the cost of very expensive advanced facilities. Small countries also benefit from having a voice in setting research and policy agendas, developing connections, and having early access to research findings and the opportunity for their own scientists and innovators to collaborate in world-class research.

CERN's organizational operations reveal important principles for developing STI global commons. The organization's governance system provides some shelter from national political constraints: low-income countries have full rights of membership but with lower financial contributions. In addition, there are options for participation by nonmembers through associate and observer status. Importantly, individual scientists are able to participate in global-standard science and have access to resources while maintaining their permanent residency in their home countries. And, conversely, CERN as a global science organization can draw on global resources without requiring individuals to migrate. Although CERN is undoubtedly Eurocentric in culture and practice, reflecting its origins and initial political purposes, its operating principles are not intrinsically constrained to a geographic region or geopolitical regime.

In this way, CERN demonstrates that an STI global commons is not inherently restrictive and can be expanded to incorporate other scientific values and approaches, including non-Western science and knowledge, as its membership grows. Thus, the development of operating principles is a dynamic process that will follow a broadly inclusive membership rather than prescribed rules. That said, the guarantee of free inquiry, discussion, and debate is essential to STI governance and may conflict with some national governance restrictions.

CERN is governed by a council made up of representatives of each of the 23 member states. Each state has two delegates: one representing his or her government's official interests, the other representing its national scientific interests. Each member state has a single vote on policy matters such as which programs to support. Most decisions are made by a simple majority, but the council aims for a consensus. The council appoints the Scientific Policy Committee, which evaluates the scientific merit of activities proposed by physicists and makes recommendations. Scientific Policy Committee members are elected by current members based on scientific eminence without regard to nationality and can include scientists who are not from member states.

CERN has developed a capacious approach to membership, which could be a model for future STI collaborations. In addition to its 23 member states, it has eight associate member states, including India, Pakistan, Türkiye, and Ukraine, as well as observers, including Japan and the United States (Russia was an observer from 1993 until its status was suspended after its invasion of Ukraine in 2022). Observers attend meetings and make financial contributions to projects. The United States was given observer status in 1997 upon making a contribution of $531 million to the large Hadron Collider, after Congress withdrew support for the well-over-budget and politically contentious Superconducting Super Collider project.

This move on the part of the United States was a significant validation of the vision of CERN as a scientific global commons. As a collaborative resource, CERN appeared to be a more efficient investment in Big Science for US resources than the go-it-alone model of the Super Collider. And CERN also has a governance regime that could better navigate small internal and larger geopolitical disputes. Finally, to the extent that the innovations from CERN were intended to be shared with the world, investments in the common pool have also benefitted the rest of the planet. CERN's endurance shows that it found a way both to accommodate countries with widely different needs and to provide a means for ensuring that decisions did not discriminate against smaller or less affluent countries, while providing benefits for all.

## Developing the global STI commons

As Ostrom noted in 1990, "'getting the institutions right' is a difficult, time-consuming, conflict-invoking process" when structuring successful common resource governance systems. When Ostrom sought to identify governance principles for CPR, she and her collaborators looked at examples that had endured for decades or sometimes centuries. Similarly, CERN's principles have stood the test of time, serving the interests of its highly diverse members while continuing to attract new ones. But there is a crucial difference: Ostrom's CPR organizations governed the use of limited natural resources, while CERN is concerned with the constant creation of new resources—scientific and technical knowledge. Building on Ostrom's work and CERN's example, we believe there are important lessons for the governance of STI efforts to solve emerging global problems.

Although some attributes of CERN's governance system were the result of specific national, institutional, disciplinary, and geopolitical circumstances, the system demonstrates flexibility that may be important for future efforts. For example, CERN's utility was increased beyond its primary focus of subatomic physics because it attracted a broader range of innovators, who worked on a number of far-reaching innovations. Key to its success is that it is governed by respected experts in STI fields from many countries, which has helped CERN avoid "capture" by military-industrial or parochial economic industries.

To advance the concept of creating global STI commons organizations, we propose following Ostrom's example by building a body of knowledge and practice. Just as Ostrom studied working systems, we propose finding further instances of successful (and unsuccessful) systems for the development and governance of global STI commons. Examples might include the Scientific Committee on Antarctic Research, which established a global geography for science, as well as recent initiatives to address the COVID-19 pandemic. Efforts to collect and study examples would examine failures in addition to successes, such as the perceived unfairness of international regimes to govern intellectual property rights. Identifying best practices through experimentation, iterative development, and evaluation will be crucial in establishing ground rules for new collaborations.

CERN provides a model that offers an intriguing glimpse of the expansive possibilities of well-designed global STI collaborations. Among its key achievements have been constructing an alternative institution for innovation at a moment when techno-nationalism was laid bare by the devastation of World War II and entrenched interests had slackened, and then surviving the emergence of the Cold War and growing tensions. Similarly, the challenges of the current moment could provide an impetus and opening for an alternative to today's nationalized innovation systems.

Near the end of her life, Ostrom suggested that rather than simply waiting for global solutions to climate change, public and private actors and researchers should encourage the emergence of a polycentric system to start the process of reducing greenhouse gas emissions. This vision suggested that rather than delaying action until development of a global regime to control carbon emissions, small, complementary local efforts could begin to make changes at multiple levels. The purpose was twofold: the polycentric system not only starts the process of reducing greenhouse gas emissions, but it also acts as a spur to international regimes to do their part. We suggest that the current environment provides incentives and opportunities to begin developing a variety of new STI common resource pool governance systems that could be put to work solving our looming problems while encouraging the development of new global initiatives.

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# Science Philanthropy's Evolving Role

ROBERT W. CONN

# Why Philanthropy Is America's Unique Research Advantage

Centuries of philanthropic endowments, and a culture of giving back, support many of today's research institutions—and could be powerful in shaping the future of American science.

The United States' particular approach to supporting and carrying out science and higher education confers upon our nation a unique advantage. Our system of public and private higher education as well as private nonprofit research institutions is unequalled anywhere in the world. This system is reinforced and amplified by an array of support mechanisms for science and technology involving government, industry, and—unique in its scale, scope, and longevity—philanthropy. Developed in part organically and in part by the deliberate actions of government and individuals, this system gives the United States an opportunity to maintain leadership in science, engineering, technology, and medicine while driving innovation across all sectors. It is crucial that we understand and capitalize on philanthropy's distinctive history, perspectives, and synergies within the overall system.

To understand this unique advantage, consider what the United States has in common with other major countries and economies and what is solely American. Support for science in the United States comes from four major sources. The first two are government and industry, sources that we have in common with other economically advanced nations. According to 2019 data from the Organization for Economic Co-Operation and Development, Israel, South Korea, Taiwan, Sweden, Japan, Austria, and Germany all spend a greater percentage of gross domestic product on R&D than the United States' 3%.

It is the other two sources of support that are distinctly and uniquely American: current philanthropy and the vast scale of past, or legacy, philanthropy. The Science Philanthropy Alliance notes that philanthropists currently contribute support for 44% of basic science research conducted at domestic universities and nonprofit research institutes. This impressive number is joined by the legacy philanthropy that is held by universities in their endowments. The sum of the respective endowments of the more than 60 US institutions of the Association of American Universities (AAU) totaled nearly $400 billion in 2018. And this value continues to accrue. The combination of legacy and contemporary funding gives America's research institutions an unmatched scale and diversity of resources that support an extraordinary array of scientific projects, particularly early-stage science where the ideas are not quite ready for government support. The scale at which this entire ecosystem of science and higher education works is America's unique advantage.

Perhaps more generally, philanthropy is a long-standing and distinctly American cultural characteristic. Over more than two centuries, it has assumed a variety of roles in supporting science, technology, and medicine. In this article, I describe four historical epochs that have shaped the emergence of the American scientific enterprise. Identified in sequence, the epochs are dominated first by agriculture, second by industrialization, third by manufacturing, and today by digital information. This historical perspective illuminates how the philanthropy of the nineteenth century changed the landscape of science and higher education in the country, and how the exceptional collection of public and private research universities created in that era continues to shape the future today.

Over time, another feature emerged—the American cultural characteristic of "giving back" as a societal good. For the very wealthy, philanthropy came to be seen as a moral imperative. Over generations, this characteristic shaped the landscape of US science as well as the psyche of philanthropists and innovators themselves. The realization of these ideals has led to the creation of a remarkable set of institutions of higher education and research, and a large and diverse set of funding sources that have turbocharged America's leadership and underpinned much of our economy, defense, and health.

The United States can extend its leadership into the future by explicitly recognizing its distinctive advantages and operating as a more wholly organized scientific ecosystem that intentionally incorporates philanthropy. This proposal is less a specific strategy than a recommendation that the synergy of our system of government, philanthropy, industry, and universities, all supporting science, technology, medicine, and innovation, should be consciously and actively considered when formulating national agendas and policies. Today, for the most part, philanthropy is left out of the discussion despite its long-proven role in leading science and technology into the future and improving the lives of people everywhere.

## Four epochs of American economic history and wealth creation

Four epochs of innovation and wealth creation in the United States have had significant effects on our economy and society. These epochs provide a framework for discussing the future of science, higher education, research at universities and private nonprofits, and innovation, as well as the optimal roles of government, industry, academia, and philanthropy.

### *Epoch 1: The Age of Agriculture*

From the earliest days of the British colonies until about 1840, the US economy and society were largely shaped by agriculture. Science was an avocation, perhaps symbolized best by Benjamin Franklin and Thomas Jefferson. Higher education was almost all private and mostly associated with religious denominations. None of these early universities had the character of a "research university," an approach to higher education that emerged in Europe, mainly in Germany, in the early 1800s. Harvard, Yale, Penn, Delaware, Princeton, and Columbia were all founded by 1754, with Michigan, Virginia, and Duke following in the early nineteenth century. During this time, which I characterize as Epoch 1, philanthropy was episodic and associated mostly with the support of religion.

The start of any new epoch is never exact, and there is often a 20- to 30-year period before each comes into full recognition. Nevertheless, by about the 1840s, change was clearly underway as the Industrial Revolution, pioneered in Britain, took hold in the United States.

### *Epoch 2: The Age of Industry*

The second epoch, which extended from roughly 1840 to about 1930, saw dramatic, disruptive changes in industry, work and labor, the economy, and society. It was a remarkable age of technology and innovation as well as a time of financial innovation, the latter leading to the emergence of large company trusts that transformed the economy. For the first time in US history, individuals began to generate enormous fortunes.

The rapid accumulation of wealth gave rise to a new "culture of philanthropy" among the rich, driven by a sense that those who had accumulated great fortunes had an obligation to return those fortunes to society. This idea was articulated most famously by Andrew Carnegie in his 1889 essays that have come to be known as *The Gospel of Wealth*: "The man who dies thus rich dies disgraced." In a remarkable 1963 history of this era, Merle Curti, Judith Green, and Roderick Nash noted that philanthropic giving in Western Europe amounted to less than one-half of 1% of annual national income, whereas in the United States, such giving amounted to about 2% of national income. The authors concluded then that there was nothing comparable anywhere in the world to the scale of philanthropy in America. This conclusion holds true today, as philanthropy remains a distinguishing aspect of the American national character and culture.

One particular focus of philanthropy in Epoch 2 involved founding new private, secular research universities based on the German model of universities developed in the early nineteenth century. Johns Hopkins University, founded in 1871, was the first of these "new model" universities in the United States, with professors serving as both instructors and researchers, and graduate students doing research and earning doctoral degrees. Over the next 50 years, philanthropic donations led to the founding of many more privately endowed and secular institutions that are today our leading private universities. A sampling includes Vanderbilt University, Stanford University, the University of Chicago, the Carnegie Institute of Technology, Rice University, Rockefeller University (founded as a research institute in 1901), and the Mellon Institute (later to combine with Carnegie Tech to form Carnegie Mellon University). Individual philanthropists may have been motivated to fund universities to leave a legacy and ultimately to foster innovative institutions that far outlive them. This aim was the case with Stanford University, founded in 1885 by railroad magnate and US Senator Leland Stanford and his wife, Jane, as a memorial to their deceased son and with the intent "to promote the public welfare by exercising an influence in behalf of humanity and civilization."

While philanthropists were establishing new private institutions, federal policies were providing support to mostly public institutions of higher education. The Morrill Act of 1862 led to a system of new or repurposed land-grant universities stretching from Cornell in the East through Michigan and Iowa in the Midwest to California, Oregon, and Washington in the West. The Morrill Act of 1890 extended the system to other colleges and universities, including historically Black colleges and universities.

These institutions of higher learning were complemented by many extraordinary private, nonprofit research institutions founded in the middle and late nineteenth century, including the Smithsonian Institution (1846), Cold Spring Harbor Laboratory (1890), the Carnegie Institutions (1902), and the Institute for Advanced Study at Princeton University (1930).

Nonetheless, America would not lead in science and basic research until after World War II, when federal government funding began to grow rapidly. Thus, Epoch 2 is an era based more on invention, technology, and innovation than on scientific discovery. But Epoch 2 did mark the beginning of the philanthropic investments that continue to underpin our research enterprise today.

### *Epoch 3: The Age of the Corporation and Government Support of Science and Technology*

Epoch 3 begins roughly in 1920 and ends in 1980, encompassing the rise of the modern corporation and the emergence of federally funded science as a force for transformational societal change. This postwar period of Epoch 3 is a reference point for many of today's science policymakers and decisionmakers, yet one can argue that this period, roughly 1945 to 1975, is an anomaly. The extraordinary expansion of government funding of science, technology, and medicine during this period was unprecedented and remains so. That sharp increase leveled off after 1975, after which it grew more slowly—at more typical rates.

Given this framework, one can argue that we misunderstand the history and strength of the US research enterprise by underestimating or even ignoring the long-standing outsize role of philanthropy. Today, philanthropy has re-emerged as a strong force, and here I seek to recontextualize this period of Epoch 3.

During Epoch 3 overall, corporations emerged as a force for use-inspired basic research, some of which created major breakthroughs in science and technology. AT&T and its famed Bell Laboratories produced many innovations and discoveries. Two of the most famous are the discoveries of the transistor in 1947 and the cosmic microwave background in 1964. IBM Research discovered high-temperature superconductivity and pioneered the field of nanotechnology with the invention of the scanning tunneling microscope, among other discoveries. The invention of the microprocessor by Texas Instruments and Intel underpins all of microelectronics today. Discoveries by scientists and engineers at Bell Labs, IBM, Texas Instruments, and Intel were all later awarded Nobel Prizes. Hughes Research Laboratories invented the ruby laser in 1960, while the Xerox Palo Alto Research Center (Xerox PARC) became legendary in the 1960s and 1970s as the source of innovation and invention that helped enable the computer and digital information age we live in today.

Epoch 3 was also one of innovation in management as symbolized by Alfred P. Sloan's approach at General Motors. Sloan created both the organizational model for the large corporation and the marketing idea of creating products that would be affordable for people at different levels of income and at different stages of their lives. From 1923 into the late 1930s, he led GM as it surpassed Ford to become the most successful US automobile and large truck company. Yet despite his enormous influence, Sloan's personal fortune was large but nothing like that of the fortunes in Epoch 2, nor like the fortunes being made today in Epoch 4 by company founders such as Bill Gates, Jeff Bezos, Larry Page and Sergey Brin, Elon Musk, and Mark Zuckerberg. These individuals have driven their companies to enormous size, and they have maintained a large percentage of ownership in their companies.

During and after World War II, in the second half of Epoch 3, science emerged as a new and powerful force for change, particularly after a transforming vision for a "science-oriented America" described by Vannevar Bush in his now-famous 1945 report, *Science, the Endless Frontier.* The report's thesis was that the federal government should take responsibility for and sharply increase its funding of science and technology and, critically, that it should conduct this research largely at the nation's colleges and universities. I've already remarked that, as a result of adopting this strategy, the federal government's support for science writ large exploded, growing to great heights through the 1960s.

This new approach to supporting scientific and technological research solidified America's system of research universities, represented today by the 64 US member institutions of the AAU. It also ensured that America has had a well-educated science and technology workforce, even if the scale is insufficient. We continue to rely on foreign undergraduates coming to the United States for graduate research in science, engineering, and medicine and staying to augment American graduates.

One unanticipated consequence of this postwar policy was the retreat of philanthropy from the support of science. Consider the history of such funding at the Rockefeller Foundation. After occupying a central role in US science funding through the first half of the twentieth century, the foundation decided in the early 1960s that support for basic science was now the responsibility of the federal government. The foundation turned its attention to other areas of need such as overpopulation and agriculture, leading to its role in creating the Green Revolution. Philanthropies that were established during this period tended to have science as a small part of their portfolios.

### *Epoch 4: The Digital Gilded Age*

Epoch 4, the epoch we are living in today, began around 1980. It was initiated by a set of changes in law and regulation in the late 1970s that led to the creation of new and extraordinarily large individual fortunes. By the year 2000, after these new businesses and fortunes had grown, there was substantial annual growth in philanthropic giving. Somewhat coincidentally, federal investment in scientific research began to level off during this period, while corporate reorganizations led to lower investment in companies' industrial laboratories.

Key policy changes in the late 1970s took place in areas as diverse as taxes on capital gains, the regulations governing large pension fund investing, and the deregulation of many industries, beginning with the airline industry. Finally, the Bayh-Dole Act of 1980 permitted universities and private nonprofit research institutions to own the intellectual property and patents developed by their faculty and students, even if their work was supported by a federal research grant. Together, these regulatory changes created a constellation of new opportunities for finance and wealth accumulation that coincided with the growth of information technology.

The inventors and creators of new companies, often backed by venture capital, were now able to retain a large percentage of ownership in their start-ups. This phenomenon was especially true of software companies that showed success quickly, expanded rapidly using retained earnings, and, as such, did not need large additional capital infusions. Meanwhile, partners in venture capital and private equity firms often made fortunes comparable to those of technology company founders.

From a philanthropic point of view, this remarkable period has a clear and undeniable parallel with Epoch 2, often called "the Gilded Age." In 1990, the United States had 66 billionaires. Today it has 613. About half of these individuals made their fortunes in finance and investing or in the technology and information sectors of the economy. The total wealth of US billionaires rose from about $240 billion in 1990 to $4.18 trillion in March 2021. Adjusted for inflation, these values still show a tenfold increase over 30 years. Rather clearly, Epoch 4 is a second Gilded Age.

Today we also are witnessing a continuation of the American cultural imperative to give back to society, echoing Andrew Carnegie's exhortation to avoid dying a billionaire. The Giving Pledge campaign, begun in 2010 by Bill and Melinda Gates and Warren Buffett, asks wealthy individuals to pledge to give the majority of their wealth to philanthropy or charitable causes. This giving will mostly persist long after the founders are gone. Carnegie's famous admonition in 1889 and the Gates-Buffett Pledge of 2010 are thus bookends, 120 years apart, reflecting the distinctive cultural role of American philanthropy.

The rise of today's new philanthropists somewhat coincided with changes in funding for US science. The end of the Cold War in 1990 removed the strongest rationale—that of defense—for funding basic research in the physical sciences. At the same time, more and more research is carried out by large teams using expensive equipment in areas that are at the intersection of disciplines, such as the Human Genome Project or CERN's Large Hadron Collider. This practice is far removed from the single investigator model characteristic of science in earlier times. The research ecosystem finds itself greatly transformed, and with issues ranging from health disparities to climate change to far-reaching discoveries, there is once again a need for leadership.

Recognizing all of this, in 2013 six foundations—the Alfred P. Sloan Foundation, the Howard Hughes Medical Institute, the Gordon and Betty Moore Foundation, The Kavli Foundation, the Research Corporation for Science Advancement, and the Simons Foundation—came together to establish the Science Philanthropy Alliance with the objective of encouraging and accelerating philanthropic support for basic science. The alliance has grown to 30 members whose combined endowments are estimated at $110 billion—a measure of the potential benefit to science from this newly energized philanthropic sector.

Since its formation, the Science Philanthropy Alliance has advised philanthropists and foundations about the importance of science philanthropy and how to increase the effectiveness and scope of their giving. Our opportunity is to recognize more clearly—and take more consciously into account—the unprecedented scale and scope of America's growing philanthropic enterprise and to maximize its returns for society, leaving a legacy at least as durable as that left by the philanthropists in the first Gilded Age.

## Imagining the way forward

The strategy for optimizing the return on America's assets in science, technology, and medicine will be different from the one articulated 75 years ago in *Science, the Endless Frontier.* Today we must take account of the still large-scale funding of the federal government, recognize the applied nature of research carried out by industry, and include in planning and strategy-making the significant and growing pipeline of private wealth and philanthropy. Echoing the Gilded Age, when philanthropists founded new private, secular universities, today's philanthropists are directing large donations to the creation of new colleges or schools within existing universities. For example, John A. Paulson, the hedge fund manager, donated $400 million to Harvard to endow the John A. Paulson School of Engineering and Applied Sciences. Stephen A. Schwarzman, co-founder and leader of The Blackstone Group, donated $350 million to MIT as the foundational gift to create the Stephen A. Schwarzman College of Computing.

Going forward, making good use of philanthropy is the key to sustaining America's unique advantage. Any new strategy must be formulated with an eye on global R&D spending, but for America, science policy and strategy developed both inside and outside of government should integrate philanthropy into the enterprise. With the scale of science philanthropy growing, philanthropy will bring a different and distinctive voice to the table. Philanthropy can bring new perspectives to discussions about policy and strategy precisely because the sector uses a different model of support for science, has different ways by which its programs are evaluated and implemented, and, crucially, has a higher level of risk tolerance, often supporting proposed scientific ideas well before those ideas are sufficiently developed to earn government support.

The conscious integration of philanthropy into the national science and technology enterprise will require at least two changes—one in how philanthropy is viewed by government, and the other in how philanthropy is included in the national enterprise of science policymaking. The first change recommended is to ensure that the possibilities of philanthropic-public partnerships are considered by all sides as a way of making scientific progress more rapidly and more coherently. While this change may seem simply one of coordination and awareness, there can be enormous synergy and benefit from an awareness and cooperation that lead to partnering for the benefit of all.

A prime example is the US BRAIN Initiative (Brain Research Through Advancing Innovative Neurotechnologies), launched in 2013. The BRAIN Initiative was the first government-supported science grand challenge problem of the twenty-first century, and it grew out of a unique example of philanthropy partnering with government by catalyzing the effort at its earliest stage. Early on, three foundations supported a meeting of about 40 scientists gathered to consider the opportunities at the intersection of nanoscience and neuroscience. The idea of mapping the functioning human brain emerged, based on the well-founded expectation that tools expected to become available because of advances in nanoscience would make the feat possible.

Subsequent meetings sponsored by The Kavli Foundation led the government, mainly the National Institutes of Health and the National Science Foundation, to join in developing the grand challenge plan for this work. Within 18 months, and with leadership from the White House Office of Science and Technology Policy, the NIH, and the NSF, President Obama announced the initiative in April 2013. Today, the BRAIN Initiative is a $5 billion neuroscience initiative extending over ten years and is a prime example of philanthropy front-ending major government support and partnering thereafter. This initiative compellingly illustrates how science can be advanced when there is synergy among government, philanthropy, and social need. A coherent and cooperative partnership among government, universities, private nonprofit research institutions, philanthropies, and industry is one way forward for America.

The second change would be to recognize that philanthropy brings a distinctive voice to the national conversation about science, technology, medicine, and innovation, a voice that could be useful if given a greater presence on public and private committees and advisory boards. At the federal level, all cabinet departments and independent agencies have advisory boards, but many do not currently incorporate representatives from the science philanthropy community. Adding a philanthropic voice to these advisory committees—some of which currently include voices from industry—could help extend and diversify the overall US science ecosystem, convene novel partnerships, and catalyze cooperation between diverse groups to fill gaps in funding with the goal of maximizing benefits for society. Of course, philanthropies will need to be mindful of their participation, taking steps to be transparent regarding their intentions and to address and avoid perceived and actual conflicts of interest as necessary.

Philanthropy and the nation's remarkable group of public and private research universities are America's unique advantage. If we enable the synergistic interplay of government, philanthropy, universities, and industry in support of our needs in science, technology, health, defense, innovation, and higher education, the United States can continue to reap the benefits of scientific leadership well into the future.

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### FRANCE A. CÓRDOVA

# Envisioning Science for an Unknown Future

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Philanthropy looks to nurture and sustain a scientific infrastructure that is both resilient and flexible.

> *Every great advance in science has issued from a new audacity of imagination.*
>
> *—John Dewey*

It's hard to imagine what science will look like 75 years from now. For that matter, no one knows what *we* will look like in 75 years, given current breakthroughs in gene editing and tissue engineering. Will we be launching new space missions to faraway celestial bodies, crewed by creatures that have the brains of humans and fabricated "body" parts that will not wear out over the long journey? And how will space itself be managed once many countries demonstrate their capability to build space stations and land on various other planets, moons, and asteroids in the solar system?

What will be the relative position of the United States compared to global competitors in technology such as China? Indeed, will there be new global competitors as we approach the year 2100? Will we have solved current big mysteries, like the nature of dark matter and dark energy, which we think together comprise 95% of the mass-energy content of the universe? Recall that 75 years ago no one had verified the existence of dark matter, dark energy, planets orbiting other stars, or the supermassive black hole at the center of our Milky Way galaxy. What other surprises await us as we investigate the origin, shape, and evolution of the cosmos and its often-peculiar denizens? Will we find clear evidence for life beyond Earth?

While we can hardly envision what awaits humankind in 2100, we can prepare today for a better planet, a thriving planet, one in which humanity benefits from the discoveries of science.

We can do that by shoring up today's science infrastructure, making investments in new areas of research and new institutions for research, and embracing a new generation of potential discoverers. We can adopt carefully considered policies to preserve the integrity of science and foster trust in it. We can acknowledge and engage with a progressive international community that has like-minded goals. We can make science inclusive, recognizing how much we have to lose when it is not. We can view new ideas with respect and interest and take some risks to invest in them.

All of this depends on nurturing and sustaining a scientific infrastructure that is both resilient and flexible. Indeed, the most resilient infrastructures are the ones that are most responsive and adaptive to changing times and have a strong vision of the future.

Private philanthropists were among the earliest investors in the arts and sciences, endowing universities, museums, and libraries in the 1800s and continuing into the 1900s with investments in telescopes, agricultural science, and health care. As a young astrophysicist in the 1970s, using powerful telescopes paid for in the first decades of the twentieth century by private donors, I was immensely grateful for the foresight of these earlier philanthropists.

Public funding has, of course, played a much greater role in the intervening decades. Since the 1990s, however, private money has once again begun to have a greater impact—thanks to a number of new philanthropies, founded on new wealth derived from the finance, data, and information technology sectors. Some of today's philanthropic investments complement research funded by other sectors like government or universities, and some are uniquely oriented towards specific goals identified by the funder. A growing number of private funders are also making significant investments in basic research that are critical to a resilient scientific infrastructure.

In many ways private funders can be more nimble than public institutions, can stick with a promising idea far longer, and can often even lead the way on important initiatives. For example, Frances Arnold, who won the 2018 Nobel Prize in Chemistry, recently testified before Congress that "all three US women who have won Nobel Prizes in the sciences since 2018 were supported in their early years by the Packard Foundation. This is remarkable, and it is not a coincidence."

At the same time that Arnold was advocating for increased funding for research, I was taking on a new role working with the Science Philanthropy Alliance—a network of funders who are committed to increasing philanthropic support for basic research in the sciences. Among other goals and activities, the Alliance shares innovative practices for funding science among private philanthropies—particularly with respect to hiring a talented and diverse staff, consulting expert science advisors to guide the effort, designing optimal funding strategies, and, when appropriate, staying involved with the aspirations and discoveries of new initiatives.

Since its formation by six private funders in 2013, the Alliance has focused on advising foundations new and old, sharing successful models, organizing and staffing shared interest groups, vetting promising partnerships, and always working toward increased philanthropic funding for basic science.

Private philanthropists have a large menu of questions to consider. How do they match funders with grantees and in doing so include all talented people with great ideas? How do they identify—or even generate—new big science ideas worthy of funding? How can they best accelerate discovery? How can they tie basic scientific research to inclusive, equitable societal outcomes? How can they analyze outcomes to determine which practices are best to nurture and repeat? What should be the role of science philanthropy—not only on the national stage but in the world?

I am happy to say that the Science Philanthropy Alliance now counts more than 30 foundations—some prominent, some emerging—among its membership.

## Private philanthropy's advantages

There can be no doubt that future scientific endeavors will require public funding—just as today's research initiatives do. There simply is no other source of funds that provides the necessary scale that government budgets can provide. Yet, importantly, private philanthropy offers particular advantages that complement the overall scientific landscape. Some examples illustrate how philanthropy is uniquely positioned to support the scientific research enterprise.

Private funders can serve as incubators for new challenges that need scientific research. When Priscilla Chan and Mark Zuckerberg were looking to create a philanthropic initiative, Nobel Prize winners Harold Varmus and David Baltimore pointed the nascent organization to the Science Philanthropy Alliance. Marc Kastner, founding president of the Alliance, and Valerie Conn, its vice president, met frequently with staff from the Chan Zuckerberg Initiative (CZI) for about a year before the public announcement of the initiative's commitment of $3 billion over a decade. The Alliance provided advice on the formation and management of a science advisory board. It also connected CZI to funders and scientists to inform the leadership on topics from science to immigration to grants management. The Alliance helped CZI prepare the scientific and philanthropic communities for the rollout of the initiative's unprecedented commitment to basic science. In the years since, it has aided CZI's staff recruitment and partnerships with other philanthropic organizations. Today CZI is a member of the Alliance.

To get a good sense of the hard work involved in starting a new foundation intent on funding basic scientific research, consider the story of Ross Brown, an engineer and entrepreneur who was able to start a fellowship program to identify and fund "the restless minds" (his words) that want to take scientific risks.

Private funders can stick with a good project longer than many public institutions. Case in point: the Sloan Digital Sky Survey project, whose history has been well documented by Evan Michelson. This project began over 25 years ago, and one of the ingredients of its scientific success has been the staying power of its philanthropic funder, the Alfred P. Sloan Foundation. The project was initiated to statistically analyze massive data sets produced by telescope observations of the sky. It has encouraged from its inception a culture of open data to accelerate discovery. Foundation program officer Michelson has said that it required a willingness to take risks and much patience on the part of the Sloan Foundation to invest in the project over decades, but it was well worth it in terms of discoveries made—including the largest three-dimensional map of the universe, insights into the origin and evolution of galaxies, and one of the most precise measurements of the cosmic expansion rate over the last 4 billion years.

Private funders can support new discoveries in basic science by leveraging the investments that government, industry, and university groups have already made. The Galactic Center Group at the University of California, Los Angeles provides a timely example of this kind of synergy. Led by Andrea Ghez, who won the Nobel Prize in Physics in 2020, the group has been conducting research on the center of the Milky Way galaxy for more than 25 years, supported by government and private sources. Among its many accomplishments is proving the existence of a supermassive black hole at the center of our galaxy. Ghez's team was also able to make the first direct test of Einstein's equivalence principle (measuring the gravitational redshift) in the vicinity of this black hole.

Whereas support from the National Science Foundation and NASA has been vital to the group's research efforts, those agencies do not fund astronomy centers (in the way they fund, for example, artificial intelligence or quantum science centers) because their limited funds for astronomy generally go instead to build large telescopes and instruments. (The NASA-funded Hubble Space Telescope center is an exception.) This gap is where individuals and philanthropic foundations have stepped in with private funding, giving researchers the flexibility to try new approaches in a focused environment. In fact, while federal support was important to individual researchers during the earlier years of Ghez's Galactic Center Group, foundations have been its dominant source of support every year since 2013.

Philanthropic support was also important in the earliest days of the Vera Rubin Observatory because it invested in demonstrating proof of difficult technical concepts, thus paving the way for later substantial government investment.

## Looking ahead

Today's pressing issues call for increased investment in science. Such challenges as coping with a virulent worldwide pandemic and preparing for future pandemics, global environmental changes, addressing the quality and quantity of the world food supply, and ensuring an ethical framework for new technologies such as artificial intelligence and gene editing have spawned a new generation of philanthropists open to novel approaches. These include beneficial collaborations with other philanthropies and other sectors, such as government, university, and industry.

Because many challenges are global in nature, the future of philanthropy must look to new approaches to engage partners beyond our nation's borders. For example, the US Brain Research Through Advancing Innovative Neurotechnologies (BRAIN) Initiative, a program spearheaded by the National Institutes of Health but with many partners in the public and private sectors, is also part of an international collaboration of researchers and organizations that seek to catalyze and advance neuroscience research as well as grapple with the ethical issues stemming from such research.

The future of philanthropy must also prioritize support for areas with gaps in research and funding. As another example, the Science Philanthropy Alliance surveyed its network in 2020 to assess COVID-19 priorities. We hosted funder-led discussions of the first vaccines and testing. Shirley Tilghman, senior science advisor to the Alliance, convened a group of more than 20 experts in infectious diseases to identify priority research areas that were underfunded. The Alliance then held an event for interested funders focused on zoonotic infections prevention, epidemiological and surveillance studies, and novel infrastructure, tools, and technologies, as well as basic research to inform therapeutic drug development. We are now following up with scientific workshops and events to explore possible funding collaborations. With funding from The Kavli Foundation, the Alliance has assembled and published several COVID-19 prequel stories to persuade new funders of the importance of investment in research on infectious diseases.

When I talk with foundation heads, the word most frequently used is "impact"—they want their investments to make a difference. For some, the driver of the future is inspiration: how can their investments support discoveries that inspire youth to become scientists and engineers? For others, it is social imperatives that drive their giving: how can scientists make discoveries that will contribute significantly to resolving societal challenges? The philanthropist of the future cares about science communication, data science, analytics, science education, diversity, equity, and inclusion. Many philanthropic foundations have developed analytical tools to measure impact, and the Science Philanthropy Alliance is serving as a vehicle for sharing these tools. The Alliance serves as a convener on other shared interests too, such as how to broaden the talent pool of grantees, which includes expanding solicitations to diverse communities and organizations, recognizing the value of diverse leadership in building staff, and examining philanthropy's policies and practices for implicit biases.

With a host of new computational and communication tools at its disposal, an alliance of philanthropic foundations can create a new, virtual kind of research park, rivaling the Tuxedo Parks, Bell Labs, and Xerox PARCs of their day. It can guide investment in the "restless minds" to address fundamental questions and surface new big ideas, including innovative solutions to the challenges we face. It can encourage imaginative partnerships that leverage the strengths of each partner and scale small ideas into big ones. And it can reach across continents and oceans to address problems that know no borders.

Every philanthropist, I think, is an architect, with a plan in her mind's eye. Her plan is characterized by several features: awareness of change around her, including technological, social, cultural, and even political change; a keen ear open to the young scientist or engineer with a bold idea; a desire to expand the envelope of opportunity to all talent, no matter what its background; a desire to shape the future by embracing—not fearing—the human-technology interface; a desire to impact the future and its people for the better; a willingness to form deep partnerships to share best practices and realize common goals; and an appreciation of the unity of nature, from Earth to the cosmos. It is inspiring to this architect that today's science philanthropists aim to build a better future through collaboration.

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EVAN S. MICHELSON AND ADAM F. FALK

# A Vision for the Future of Science Philanthropy

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Philanthropy will play a critical role in shaping the conduct of science over the coming decades. Getting it right will require adopting practices that further the scientific enterprise while simultaneously helping to move society toward greater collective well-being.

Although we can envision many ways that the scientific enterprise might evolve in the future, an often-overlooked component will surely play an essential role: science philanthropy. By this we mean the provision of charitable giving for science or technology research by individual donors or foundations. As Robert Conn, past president and chief executive officer of The Kavli Foundation, details in his overview of the emergence of philanthropic giving for research, science philanthropy has always played a critical and leading role in America's approach to research and development, with a history that predates much of the federal funding apparatus.

Today, the landscape of science philanthropy is rapidly changing. It consists of both established and newer foundations, a constellation of institutions including organizations with an illustrious history of giving for research as well as entities created more recently. Collectively, science philanthropy accounts for at least $2 billion in annual support for research. If we include spending from university endowments that supports research at those institutions, the total impact of philanthropy on science is estimated to be as much as $20 billion per year. There are now over 30 members of the Science Philanthropy Alliance, a group of foundations interested in helping increase giving for basic research—up fivefold from the alliance's six founding members in 2013.

Of course, the entire research ecosystem has evolved considerably from the vision Vannevar Bush famously espoused more than 75 years ago in *Science, the Endless Frontier.* Humanity faces problems more severe, perhaps, than at any other time in our history. While Bush barely discussed the role of charitable giving, we are now at a moment when philanthropy must be considered an integral element of the scientific enterprise. Science philanthropy has arrived at an important stage in its evolution. As Conn notes in his article, there are now numerous established science philanthropies that have a long and distinguished history of shaping the direction of scientific research, with many of these institutions marking their centennial anniversaries over the coming decades. Similarly, as indicated by the rapid membership growth of the Science Philanthropy Alliance, many new donors are emerging with an interest in supporting cutting-edge science.

For these reasons, in both scale and scope science philanthropy is positioned to play a crucial complementary role to the much larger, but sometimes unwieldly and bureaucratic, federal funding agencies. Having grown substantially in magnitude since the publication of *Science, the Endless Frontier*, science philanthropy is now both significant enough in terms of dollars spent and prominent enough in many scientific fields to influence what research is pursued. At the same time, philanthropy remains sufficiently bounded and manageable—in terms of the number and size of institutions involved—to allow adjustments to be made flexibly and deftly.

If science is to accomplish all that society hopes it will in the years ahead, philanthropy will need to be an important contributor to those developments. It is therefore critical that philanthropic funders understand how to maximize science philanthropy's contribution to the research enterprise. Given these stakes, what will science philanthropy need to get right in the coming years in order to have a positive impact on the scientific enterprise and to help move society toward greater collective well-being?

The answer, we argue, is that science philanthropies will increasingly need to serve a broader purpose. They certainly must continue to provide funding to promote new discoveries throughout the physical and social sciences. But they will also have to provide this support in a manner that takes account of the implications for society, shaping both the content of the research and the way it is pursued. To achieve this dual goal of positive scientific and societal impact, we identify four particular dimensions of the research enterprise that philanthropies will need to advance: seeding new fields of research, broadening participation in science, fostering new institutional practices, and deepening links between science and society. If funders attend assiduously to all these dimensions, we hope that when people look back 75 years from now, science philanthropy will have fully realized its extraordinary potential.

## New areas of research

Naturally, the most important factor determining science philanthropy's impact on society over the coming years relates to the very research questions, topics, methodologies, and domains that foundations choose to support. Given the high degree of freedom that science philanthropies enjoy in selecting which research areas to address, it is not surprising that *what* research science philanthropy decides to support will shape the trajectory of discovery.

In particular, science philanthropies will need to balance the desire to see near-term impact from research they support with the need to advance speculative basic research laying the groundwork for discovery that might only come to fruition years or even decades in the future. Since many philanthropies are designed to exist in perpetuity, they can choose to be highly tolerant of risk, and thus they can support investigations that would likely be difficult to fund with federal dollars. A recent and very salient example of the simultaneous importance of near-term and long-term goals relates to COVID-19: philanthropic giving laid the conceptual groundwork for the rapid development of the COVID-19 vaccine by supporting basic biomedical research in the preceding decades, while also being instrumental in assisting with the vaccine's distribution and rollout. This capacity to act quickly while keeping an eye on the horizon needs to remain a quintessential feature of science philanthropy.

So what kind of research should science philanthropy fund going forward? One of the most important roles that foundations can play is to support research that draws on more than one discipline, both because the most creative scholarship is often pursued near and across disciplinary boundaries and because work that spans disciplines in new ways is notoriously difficult to slot into existing categories supported by federal funding agencies. In particular, science philanthropies can focus their resources to help transfer tools, techniques, and insights from one domain to another, unlocking previously unrealized lines of inquiry.

Examples of this kind of intervention abound and can be built upon in the years ahead. For instance, The Kavli Foundation supports a set of research institutes around the world where scientists apply advanced computational, imaging, and visualization techniques in disciplines as varied as astrophysics, theoretical physics, neuroscience, and nanoscience. Similarly, the Sloan Digital Sky Survey (SDSS) is an excellent example of how combining data science and basic research can spur incredible discovery. In operation for over 25 years and now one of the most productive and highly cited surveys in the history of astronomy, the key aspect of SDSS's success was the pioneering application of sophisticated data science analysis and storage techniques to astronomy and cosmology. As one of the first "big data" projects in basic science, SDSS helped set the stage for adoption of these approaches in other disciplines.

Moreover, with the encouragement of the Alfred P. Sloan Foundation from the outset, SDSS developed the routine practice of publicly releasing all of its available data at regular intervals. Doing so facilitated the widespread use of the survey's findings and has informed the design of subsequent research projects in astronomy and other fields. The Sloan Foundation's technology program has supported expansion of such data-sharing approaches and platforms to other research areas. For example, it has funded an extension of the SDSS data science platform, now known as SciServer, to be applicable to numerous research domains beyond astronomy. These kinds of philanthropically supported programs are transforming what research gets done, addressing the need for cross-disciplinary collaboration, and facilitating the sharing of tools and techniques across research areas.

Of equal importance, we believe that more attention needs to be paid to advancing interdisciplinary research that links the social and natural sciences. For instance, the Sloan Foundation's energy and environment program has a focus on facilitating multidisciplinary collaborations that can make progress on decarbonizing energy systems. This strategic approach was set in recognition that energy system decarbonization requires the integration of research from fields as diverse as economics, politics, energy systems analysis, atmospheric science, chemistry, geology, and oceanography. Whether it is examining the role new carbon dioxide removal technologies might play in future energy systems or exploring new ways of decarbonizing various sectors of the economy, grants provided in this program regularly support interdisciplinary scholarship using both qualitative and quantitative research, making both empirical and theoretical contributions.

The hardest problems the planet faces, such as climate change, cannot be solved without combining the methods and discoveries of natural science, technology, and social science in deeply integrated ways. Science philanthropy is especially well positioned to address such broadly interdisciplinary questions because foundation programs can be deliberately structured around solving specific problems and supporting interdisciplinary research, unlike government funding programs largely organized along disciplinary lines. This is one of the benefits of the flexibility that characterizes philanthropic grantmaking. Resources can be provided for any number of strategic purposes—to start a new project, to address unfunded research gaps, to extend existing work in new directions, to encourage collaborative use of instruments and tools, and so on—that, if approached with considered intention, can help advance interdisciplinary research.

### New participants in science

Science cannot flourish without vibrant, inclusive, and diverse communities of excellent researchers, communities that are continually renewed with emerging talent. Achieving this vision will require attracting and retaining scientists from every corner of society, changing *who* participates in the scientific enterprise.

A number of science philanthropies focus particularly on supporting early-career researchers looking to move their fields of inquiry forward. The numerous programs of this kind include the Howard Hughes Medical Institute Investigator Program, the Schmidt Science Fellows program, and the Sloan Research Fellowships, just to name a few. These programs ensure that scholars at the beginning of their careers have the resources to push the boundaries of knowledge in their fields. Such investments in young investigators, even if modest in scale, have long been understood to be especially vital contributions that foster robust research communities.

This work of building new communities of researchers cannot be fully achieved if diversity, equity, and inclusion are not made explicit, core considerations of philanthropic grantmaking. Many science philanthropies recognize the essential need to diversify the research enterprise by drawing on the widest possible talent pool. Even more so than government funders, private philanthropy has the freedom and flexibility to target research funding strategically by more intentionally involving scholars from underrepresented groups and better accounting for the impact of research on underserved communities.

Freeman Hrabowski and Peter Henderson of the University of Maryland, Baltimore County (UMBC), write that perhaps the best example of a case in which philanthropic giving has successfully helped diversify the scientific enterprise is the Meyerhoff Scholars Program. Initially implemented at UMBC, the program involves a comprehensive and inclusive model of training and support for students from underrepresented communities in science and engineering. It includes not just financial support for individual students, but a series of "wraparound" components that promote more collaborative learning environments, such as summer training sessions, small study groups, and extensive faculty mentoring and administration involvement. With support from science philanthropies like the Howard Hughes Medical Institute and the Chan Zuckerberg Initiative, this model is being replicated at other universities across the country.

Beyond supporting individuals, many science philanthropy efforts are designed to bring about deeper systemic change and address the institutional and community-level barriers faced by scientists from underrepresented groups. For instance, the Sloan Foundation supports two programs, the University Centers for Exemplary Mentoring and the Sloan Indigenous Graduate Partnership, with the goal of achieving systemic change in how students are recruited and trained across a range of scientific and technological disciplines, including chemistry, mathematics, computer science, physics, agricultural sciences, and civil and environmental engineering.

Science philanthropies can also thread considerations of diversity, equity, and inclusion throughout their strategic planning, operational, and grantee selection processes. Doing so, and doing so visibly, sends an important message to the research community. The Wellcome Trust in the United Kingdom has been a leader on this front, examining the culture of doctoral education and shining light on many of the invisible barriers to success, such as mental health challenges, that students—especially those from underrepresented groups—face. Many other foundations have reviewed and updated their grantmaking processes to account for diversity factors. For instance, the Sloan Foundation requires every prospective grantee to directly address how their project will contribute to broadening participation in the research enterprise. The firm, consistent pressure to make diversity and inclusion part of the core conversation about the design of research projects has the potential to profoundly change the character of research environments.

## New institutional practices

Science philanthropy also has the capability to advance new institutional practices that will be crucial to facilitating the increasingly complex and interdisciplinary science of the decades ahead. These emerging approaches can reshape *how* the research enterprise operates by addressing some of the rigid institutional structures that can hinder the advance of science.

Given the wide variety of approaches that science philanthropies pursue, one such bottleneck that often arises is the challenge of coordinating collaborative funding across foundations. Former National Science Foundation director and current president of the Science Philanthropy Alliance France Córdova describes how this desire to foster collaboration among philanthropies was one of the motivations for forming the Science Philanthropy Alliance: to introduce new donors to the underlying practices associated with funding basic research and to better link existing foundations working in this space.

Some science funders have addressed this challenge head-on in their operational strategy–in particular, the innovative approach to collaborative funding developed by the Research Corporation for Science Advancement (RCSA). RCSA has taken the lead on organizing a series of science-oriented dialogues, known as Scialogs, that encourage small groups of early career scholars to work together and quickly propose speculative ideas that explore new research frontiers. A subset of these proposals is then selected for support by RCSA and its philanthropic partners, which have included foundations such as the Heising-Simons Foundation, the Paul G. Allen Frontiers Group, the Chan Zuckerberg Initiative, the Frederick Gardner Cottrell Foundation, and the Sloan Foundation, among others. This flexible partnership approach to funding science has led to creative study of questions such as searching for signatures of life in the universe, examining the chemical machinery of the cell, developing negative emissions interventions to reduce carbon dioxide in the atmosphere, and studying linkages among the microbiome, neurobiology, and disease.

Still other novel modes of philanthropic support for science are increasingly doing away with the traditional structures of philanthropy altogether. One such practice is for philanthropies to establish research entities themselves, giving them the ability to directly shape the direction of research and ensure that these new organizational structures reflect their own interests and values. For example, creating an entirely integrated research infrastructure can better allow for the advancement of collaborative team science. A prominent case of this alternative institutional practice is the Flatiron Institute at the Simons Foundation. The Flatiron Institute has helped to integrate computational research capacities with leading scholars in fields such as astrophysics, biology, mathematics, and quantum physics, providing a link with sophisticated data science resources that might be hard to access at many universities. Another example is the Allen Institute, a philanthropic institution composed of a number of research teams in the fields of neuroscience, cell science, and immunology.

A related approach is to build and maintain instruments and research infrastructure for the scientific community in order to change and direct research practices. While there is a long history of science philanthropy providing external support for large-scale instrumentation and infrastructure such as telescopes and observatories, the phenomenon of foundations' managing instrumentation in-house is rather new. For instance, the Schmidt Ocean Institute does not give grants to researchers in a traditional sense, but instead is outfitting a state-of-the-art oceangoing research vessel and allowing researchers to utilize this resource by providing instrumentation testing, technical assistance, data management, and standardization of reporting results. The Dalio Philanthropies is pursuing a similar strategy, developing a high-tech oceangoing research enterprise, called OceanX, that not only features a suite of customized research equipment to conduct ocean science, but includes an advanced multimedia studio capable of sharing research findings and scientific results with the general public.

## New links between science and society

Over the past 75 years, discussions surrounding the social contract for science have been significantly guided by the basic premise of Bush's report: government funding allows scientists to pursue curiosity-driven research, which results in new products, applications, and technologies that benefit society. Yet this hands-off approach to realizing public benefit misses a lot, and there are elements of the science-society relationship that are neglected in Bush's formulation. Science philanthropy can help by deepening public understanding of *why* science does what it does and how discoveries can best be directed to improve people's lives.

One way to bridge this gap is by supporting the infusion of science throughout the broader culture. The Sloan Foundation has a long-standing program aimed at improving the public understanding of science, technology, and economics by funding creative projects across many types of media. This effort includes the production of books, films, television, radio, and theater programming, and other forms of artistic expression to engage the public about the role science plays in the arts, humanities, and everyday life—from research itself to stories of discovery to the lives of practitioners. Many of the most compelling stories have a significance that extends beyond research findings and technical discovery. For instance, the Sloan-supported book *Hidden Figures*, by Margot Lee Shetterly, which was later made into a movie, is both about telling the story of how mathematics got humans to the Moon and about honoring the underappreciated Black women who were indispensable to that breakthrough effort. Other science philanthropies have developed similar programmatic and grantmaking ventures related to science, communication, and public engagement, creating a growing collection of outputs that explore the myriad intersections between science and society.

A particularly impactful strategy that philanthropies can pursue to bolster the science-society relationship is to bring scientists into policy-relevant roles, placing scholars and those with technical expertise in federal, state, local, and nonprofit institutions. For instance, the Rita Allen Foundation and The Kavli Foundation have supported cohorts of Civic Science Fellows that embed researchers in such public-oriented positions. Additionally, a number of science philanthropies have supported scientists participating in the Science & Technology Policy Fellowships program at the American Association for the Advancement of Science, with the Moore Foundation and Simons Foundation supporting the development of state-level versions of these programs around the country. Many science foundations, led by Schmidt Futures, have supported establishment of the Day One Project, which engages scientists to introduce novel, actionable science policy ideas into public discourse.

Finally, there are growing developments to further engage the public by expanding both who gives to science and who conducts science. The rising prominence of crowdfunding platforms for scientific research, on sites such as Experiment and Kickstarter, has increased opportunities for scientists to go directly to the general public to secure funding for research. Although the amount of money received by a project is often relatively small, especially compared with amounts raised from philanthropic or government sources, these platforms also democratize the funding of science.

The rise of crowdfunding is, in many ways, a counterpart to the rise of citizen science, which has begun to influence how research is conducted in a variety of fields. Science philanthropy has helped to accelerate interest in citizen science, funding the development of easy-to-use instrumentation and access to shared platforms that allow members of the public to participate in large-scale science projects by collecting and analyzing data. In the past, the Sloan Foundation has helped to bolster citizen science platforms such as Zooniverse and SciStarter, and philanthropies such as the Simons Foundation, Schmidt Futures, and Burroughs Wellcome Fund have supported citizen science efforts as well. As they continue to gain traction, citizen science activities can help connect the research enterprise with broader society by engaging a wider range of stakeholders in the research process.

## Potential perils and pitfalls in science philanthropy

The substantial discretion that science philanthropies enjoy—in terms of the *what, how, who,* and *why* dimensions elucidated above—must be managed wisely and responsibly if their societal impact is to be a positive one. The flexibility of philanthropy, in contrast to that of other funders, carries pitfalls to be avoided so as not to compromise the effectiveness of philanthropic giving for science.

One such potential danger arises if scientific projects that capture the imagination of a funder are not thoughtfully designed to move a field forward in productive ways. Such missteps can reflect mistakes not only of *what* to fund, but also of *how* and *whom* to fund. Shortcomings could include not addressing diversity considerations sufficiently early enough in the life of a research project or not paying attention to important matters such as data sharing or availability.

A second and related danger is that a funder may develop idiosyncratic enthusiasm for particular projects, thereby not consulting sufficiently with a broad range of knowledgeable experts to inform grantmaking decisions or attending to only a small number of viewpoints about which programmatic areas to pursue. The concern here is that a handful of voices, potentially drawn from the fringes of a field or from those with particular agendas to advance, may wield an outsize influence on what research questions science philanthropies pursue.

A third potential pitfall is giving in to impatience or inconsistency in setting strategy or selecting priority areas. As with any funder, foundations can succumb to a temptation to favor short-term "wins" over the long view. All too often, when they shift focus and funding strategy, foundations do so without fully realizing the impact it has on grantee communities. Science philanthropies need to provide a stream of consistent resources over a long enough period of time to have a hope of making research progress or having a significant impact on decisions related to complex societal questions. Especially when funding does come to an end, science philanthropies can help prepare their grantees for success by helping them think about sustainability and long-term planning, whether that means looking for opportunities to be incorporated into government funding programs, designing and experimenting with alternative funding models, or simply winding down research projects responsibly. Even beyond dollars, foundation staff can draw on their systemic view of a field to provide this kind of perspective and guidance.

Fourth, science philanthropies need to appreciate the dangers associated with spreading resources too thinly—or, conversely, with putting so much money into a single area that it cannot be productively deployed. We recognize that determining a suitable balance to this breadth versus depth question can be difficult, and we acknowledge that how such decisions are made depends on each institution's resources and priorities. However, this is a set of trade-offs that science philanthropies need to contemplate regularly to avoid the risk of becoming too myopic or too diffuse.

Fifth, and perhaps most consequentially, science philanthropies face the overarching challenge of needing to take a systemic approach to every aspect of their work. Without that, funders can fall too easily into the trap of operating under a narrow, instrumental view of science funding, one that fails to account for the entire ecosystem in which science takes place—from the individual situations facing researchers to the need to ensure the health of institutions where science occurs and the challenges of linking scientific research to societal impact.

## Societal responsibility and strategic philanthropy

With relatively few external constraints, it is absolutely critical that science philanthropies develop a strong and consistent internal rudder, a compass by which they deliberately devise strategies to avoid these perils and pitfalls. They must establish boundaries wisely to provide sufficient guidance for the work they do without being so restrictive that new and creative ideas get filtered out.

Science philanthropies should draw explicitly on their mission, culture, history, and values to establish practices and procedures to guide their grantmaking. We recognize that, for new funders, building such structures from scratch is difficult. One solution is for them to learn from institutions with a long history of honing operational, structural, and review practices that have allowed them to navigate these thorny issues. Additionally, the approaches sketched in this article can help serve as such guideposts, linked together by the broad imperative of societal responsibility.

Science philanthropies can and should explicitly find practical ways of linking support for basic science with achieving beneficial societal outcomes. In *Philanthropy and the Future of Science and Technology*, one of us (Michelson) suggests that foundations draw on the notion of responsible research and innovation (RRI) to regularly review, assess, and adjust their roles in the research ecosystem. The RRI framework, more widely used in Europe, can lead science philanthropies to think more purposefully about how to anticipate new research directions, center deliberation and inclusion at the heart of their endeavors, and regularly reflect about how societal responsibility can be achieved.

Putting all these elements together, we think a vision for societally responsible science philanthropy is both achievable and sustainable. Many of the procedures and practices critical to realizing this goal are already in place, and we are confident that many more examples of science philanthropy's powerful potential to improve our world will emerge over time. As with every sector of society, those of us in science philanthropy face many unknowns as we move into the years ahead. In the face of uncertainty, operating with the intent of achieving responsible societal impact with the *what,* the *how,* the *who,* and the *why* of our grantmaking is the surest way for science philanthropies to make the world the better place that we aspire for it to be.

***Evan S. Michelson** is a program director at the Alfred P. Sloan Foundation.* ***Adam F. Falk** is the president of the Sloan Foundation. Some material from this article draws from Michelson's book,* Philanthropy and the Future of Science and Technology *(Routledge, 2020).*

HARVEY V. FINEBERG

# Stark, High, and Urgent

The COVID-19 pandemic reveals the stakes of the relationship between science and society—and shows how science can rise to meet new challenges. How can this experience shape science policy in the future?

In 1964, the physicist Harvey Brooks famously differentiated between science for policy and policy for science. In an analogous way we can see pandemics as accelerant for scientific innovation and science as solution to pandemics. Without the pandemic, certain advances in science would occur more slowly or not at all. Without science, our ability to track and suppress a pandemic, reduce its impact, and preserve lives and health would be drastically curtailed. A pandemic reveals both lessons *from* science and lessons *for* science.

The COVID-19 pandemic is a global conflagration, as was the world war that preceded Vannevar Bush's 1945 report, *Science, the Endless Frontier.* Bush begins his report's letter of transmittal with reference to the role of the war in advancing science: "What can be done," he was asked in preparing his report, "to make known to the world as soon as possible the contributions which have been made during our war effort to scientific knowledge." Bush concludes the letter with reference to the manifold benefits of science to society: "Scientific progress is one essential key to our security as a nation, to our better health, to more jobs, to a higher standard of living, and to our cultural progress." Without diminishing the horrors of war or the devastation of a pandemic, we can nevertheless recognize ways they may spur scientific advances and provide insight into the key role that science can play in policymaking.

## Outcome-oriented science

Pandemics summon a wide array of sciences, from artificial intelligence to zoonotic disease. The fabric of science that covers a pandemic weaves together basic biological sciences, translational biosciences, clinical sciences, epidemiological and other public health sciences, policy and regulatory sciences, behavioral and social sciences, and ecological sciences. Spanning molecules and populations, pandemic science extends from the laboratory to the natural habitat of wild animals; it also courses through clinics, hospitals, communities, nursing homes, schools, and factories.

We can learn much from pandemic-induced science and from science as applied to the pandemic. Science in a pandemic thrives on individual creativity, attracts many participants, and can benefit from focused, sometimes elaborate collaboration. The urgency and stress of a pandemic highlight the value of pre-established research protocols and clinic- and community-based networks to rapidly produce needed scientific knowledge. And the advances in science in obtaining new knowledge, in organizational innovation for the conduct of science, and in modes of providing scientifically informed advice have salience for finding solutions to other pressing problems and meeting social needs, the "one essential key" that Vannevar Bush described.

In the context of a pandemic, the traditional division between basic and applied science is not as helpful as thinking of science as a spectrum spanning curiosity-driven science, problem-solving science, and product-targeted science—in short, what we might call outcome-oriented science. This span extends across the lines demarcated by the political scientist Donald Stokes in *Pasteur's Quadrant*, differentiating pure basic research (exemplified by Niels Bohr), pure applied research (exemplified by Thomas Edison), and use-inspired research (exemplified by Louis Pasteur). Science in a pandemic illustrates the continuities and interdependencies that reveal truths of nature. Science can clarify a murky reality, while also illuminating gaps in knowledge and skills, creating solutions, and delivering improvements in people's lives.

## Prequels and sequels

Science relevant to a pandemic begins long before the pandemic appears. Indeed, none of the critical breakthroughs in COVID-19 prevention, diagnosis, or treatment would have been possible without the foundation and accumulation of critical scientific knowledge and experimentation. The Science Philanthropy Alliance has compiled a series of summaries called "Prequels" that illustrate the role of prior science in enabling detection, assessment, and response to the COVID-19 pandemic. These include genetic and genomic sequencing, viral imaging and modeling, epidemiology of disease transmission, vaccinology, and more. While the endless frontier ahead of science remains to be explored, it is possible to trace back the many pathways that led to where science has progressed thus far.

The science that bears on a pandemic is linked to numerous matters of metascience, including public attention and political support, priority setting, funding, organization, public-private and intercorporate cooperation, international relations, and equity. While these issues always hover around science, pandemics expose and intensify them. The stakes in a pandemic for science—as for society—are stark, high, and urgent.

Pandemics therefore compel attention. The eighteenth-century writer Samuel Johnson observed that when a man knows he is soon to be hanged, "it concentrates his mind wonderfully." A pandemic exerts a similar effect simultaneously on many people, as it affects every sector and segment of society, mobilizing massive public and private resources. In a pandemic, everyone who can help, and that includes many scientists, stands ready to help.

A pandemic interrupts many experiments and delays progress in laboratories abruptly rendered off-limits as indoor work-spaces. The disruption caused by a pandemic also creates space for innovation. Scientists engage in creative new ways to conduct their work, adopt safer protocols to prevent spread of infection, redirect their laboratories, generate new collaborations, and pursue novel experiments to solve specific problems. All this and more came in response to the COVID-19 pandemic.

The creation of multiple vaccines to protect against SARS-CoV-2 infection is a dramatic illustration of scientific innovation, capitalizing on previous research, ample public investment, private-public partnership, and cooperation across industry. For reference, most of the influenza vaccine produced in the United States relies on egg-based viral cultures, a technology that has been in use for more than 70 years. Although messenger RNA vaccines, such as those developed by Moderna and Pfizer-BioNTech, had been recently contemplated for use against several viruses, no mRNA vaccine prior to COVID-19 had been tested in large-scale, phase 3 clinical trials. Before COVID-19, the fastest any new vaccine had gone from viral samples to approval by the US Food and Drug Administration (FDA) was four years, for a mumps vaccine in 1967.

A revealing article by the microbiologist and immunologist Arturo Casadevall in the *Journal of Clinical Investigation* elegantly portrays the multiple lines of research that contributed to mRNA vaccines against SARS-CoV-2. These include decades of study in molecular biology, microbiology and virology, immunology, lipid chemistry, and pharmacology. Prominent along the way was the discovery by Katalin Karikó and Drew Weissman that a modified mRNA nucleoside prevented a premature inflammatory response to mRNA. This finding, one that was essential to the development of mRNA vaccines, garnered these scientists the 2021 Lasker-DeBakey Clinical Medicine Research Award.

## Speed and focus

The full-bore commitment to develop, produce, and distribute an effective and safe vaccine as part of "Operation Warp Speed" will stand as one of the US government's outstanding achievements in the early phase of the COVID-19 pandemic. In this effort, a pharmaceutical giant such as Pfizer could partner with the German biotechnology firm, BioNTech, and deploy its own resources to develop a vaccine, benefiting from government support of previous research and relying mainly on a governmental guarantee of purchase should the vaccine prove successful. Meanwhile, a smaller contender, Moderna, could receive federal funding in the development phase. There was no guarantee of the operation's success—as the experience of Merck and other companies demonstrates. And there was certainly no assurance of the rapidity and favorable benefit-to-risk ratio that the mRNA vaccines provided. Other useful COVID-19 vaccines rely on a variety of technologies, including viral vectors (such as Johnson & Johnson-Janssen and Oxford-AstraZeneca), subunit protein (Novavax), and inactivated whole virus (Sinopharm and Sinovac).

Producing such an array of vaccine types against a single organism, available about a year after the organism was isolated, is a remarkable scientific achievement. And yet, vaccines themselves do not save lives. Immunization saves lives. The last stage of vaccine acceptance and use is therefore as critical as any previous step of discovery, design, development, testing, regulatory authorization, manufacture, or logistics of distribution. The science bearing on vaccines and immunization extends from basic biology to behavioral science. We expect and require extensive randomized controlled trials testing the efficacy and safety of vaccines. We should similarly design, fund, conduct, and learn from studies comparing different communication, messaging, and social marketing strategies on the acceptance of COVID-19 vaccines among groups defined in various ways, including by race, ethnicity, age, region, political affiliation, social group, or religion. Downplaying, and underfunding, the social sciences is self-defeating in a pandemic that is fundamentally a social and public health—as well as biological and medical—challenge. These soft sciences can pierce our hardest problems. Underfunding the social sciences, as with chronic underfunding of the public health infrastructure, undermines society's capacity to respond to a pandemic as surely as shortchanging any biological or biomedical sciences.

## New collaboration and organization

In a matter of months, the COVID-19 pandemic transformed the way science is done, sparking innumerable innovations, novel partnerships, new funding, and new forms of organization. Scientists previously working independently began to collaborate. Companies working on other organisms or diseases turned their attention to coronaviruses and COVID-19. Universities and publications began to compile, use, and release data and to model projections on the course of the pandemic. Laboratories with extensive capacity for genomic testing, normally utilized for research, redirected their instruments to detect and diagnose infection.

One notable example of innovation in the strategy for sponsoring and conducting science is the Rapid Acceleration of Diagnostics (RADx) initiative at the US National Institutes of Health (NIH).

After an early, flawed diagnostic test for SARS-CoV-2 was withdrawn by the Centers for Disease Control and Prevention, the United States did not have enough diagnostic tests to produce accurate, timely, and useful results. US Senators Lamar Alexander of Tennessee (now retired) and Roy Blunt of Missouri recognized that fast, reliable, and affordable testing would be critical to managing the pandemic and reopening schools and businesses. They turned to leaders in NIH to gain a better understanding of what needed to be done to secure the number and variety of tests America required.

As a result of what they learned, the senators directed $1.5 billion to NIH as part of the Paycheck Protection Program and Health Care Enhancement Act (2020) to speed up development, commercialization, and implementation of testing for SARS-CoV-2 through what became the RADx program.

Rather than establishing a traditional, investigator-initiated, peer-reviewed grants program, RADx adopted a venture capital model—soliciting ideas from every corner of relevant science; relying on a "shark tank" approach to place early bets; organizing and committing to ongoing support and nurturing of the candidate technologies; and assisting with overcoming regulatory hurdles, supply limitations, and other constraints. Hundreds of experts in fields ranging from clinical chemistry to business development were brought into the mix. Like the basic science antecedents of vaccine development, this organizational design benefited from approaches pioneered years earlier by the Consortia for Improving Medicine with Innovation and Technology (CIMIT) and further enhanced by CIMIT as the coordinating center for the Point-of-Care Technologies Research Network, which NIH enlisted to provide day-to-day management of the RADx program.

In its first 18 months, RADx supported more than 100 companies and successfully launched 32 FDA-authorized tests, including the first over-the-counter test for use at home and tests that yield results in minutes rather than days. The program has resulted in more than 800 million tests for COVID-19 on the market. The array of new technologies supported by RADx includes handheld polymerase chain reaction (more commonly known as PCR) devices, loop-mediated amplification tests, paper-based diagnostics, rapid lateral flow assay antigen tests, smartphone readers, next-generation sequencing, and artificial intelligence-assisted diagnostics. The federal government recently intensified its commitment to produce more high-quality, home-based tests, and NIH and FDA pledged close working relations to facilitate review and authorization of new, more accurate, and convenient tests.

The lessons of this success are far-reaching, specifically for COVID-19 diagnostics and broadly for the way that NIH conducts its work. RADx exemplifies outcomes-oriented science, reaching as it does from basic research through product development, licensure, market availability, and use. RADx shows how NIH can live up to its name as the National Institutes of *Health*, rather than the National Institutes of Biomedical Research. By spanning insight to innovation, engaging the public and private sectors, and working with universities, research institutes, and companies, the selection funnel process fostered by RADx accelerates the transition from discovery to product. RADx holds lessons for the proposed $6.5 billion Advanced Research Projects Agency for Health and offers a model for future science aimed at any definable and desired health outcome.

## Separating fact from fiction

Science has played a key role in differentiating what *might* work in treating patients or managing COVID-19 from what actually works. Hydroxychloroquine might have worked; but it failed to show effectiveness in a randomized controlled trial. Though steroids might not have been helpful in advanced stages of the disease, they proved to reduce mortality among patients hospitalized with COVID-19 in a well-designed trial. A promising antiviral pill reportedly cuts the incidence of hospitalization and death by 89%, and monoclonal antibodies are recommended for treatment in the early stage of COVID-19 infection. A clear lesson for clinical and public health sciences in a pandemic is the value of having established study templates, ready protocols, and existing networks prepared to rapidly evaluate posited advances in prevention and care.

Just as the need to provide credible information in real time challenged scientists as individuals, it also prompted innovations in mechanisms to advise policymakers. At the request of the White House Office of Science and Technology Policy and the Department of Health and Human Services, the National Academies of Sciences, Engineering, and Medicine established a standing committee to advise these federal agencies on matters of science that arose during the pandemic. Since the Civil War era, the National Academies have provided independent, science-based guidance to federal agencies and the public. However, this advice is not always quickly forthcoming, focused, and relevant to immediate decisions. The Standing Committee on Emerging Infectious Diseases and 21st Century Health Threats created a new, highly responsive form of written assessment called rapid expert consultations. In the first five weeks of its existence, in March and April 2020, the standing committee provided federal agencies with 11 rapid expert consultations on such topics as bio-aerosol spread of the virus, the effectiveness of cloth masks, and conditions calling for adoption of crisis standards of care. These are a tiny fraction of the total body of reports and other scientific guidance emanating from the National Academies in response to the pandemic.

A pandemic, as with any urgent and threatening situation, exposes differences as well as convergence in scientific understanding and guidance. The airwaves, news columns, podcasts, blogs, social media, and academic journals are filled with opinion as well as evidence on matters of science and the pandemic. It is challenging for experts, much less the lay public, to distinguish responsible and well-grounded information from the irresponsible and misleading. Certainly, we have learned that strength of conviction is not a reliable guide to scientifically sound opinion or scientifically informed advice. The intense vitriol directed at Anthony Fauci—an exemplary scientist, physician, health leader, public servant, and policy advisor—demonstrates the deeply politicized anger of some segments of American society. Just as pandemics cannot be separated from their larger social context, neither can the processes and communication of science. In the end, support for science and its place in society depends on public understanding of science, its workings, and its role.

## The scientific process

At the Accademia Gallery in Florence stands Michelangelo's magnificent sculpture of David, naked, gazing steadily to his left, in ready repose with sling and stone. In the same museum, one can find four unfinished sculptures, intended for the tomb of Pope Julius II, that reveal much of Michelangelo's artistic genius and concept. He did not sculpt in the round. Rather, he proceeded from front to back, revealing the figure along the way. The partially finished figures appear to be emerging from a pool, yet permanently immersed in the stone that holds them. As sculptor, Michelangelo conceived his craft as chipping away the negative space of stone and thus revealing the figure that was always embedded within.

Truths of nature are like Michelangelo's figures embedded in stone. Although these truths may be hard to discern, a fundamental tenet of science is that the truths of nature are constant and not capricious. As Albert Einstein reportedly observed, "God may be subtle, but He is not devious." The role of science, like the sculptor's chisel, is to continually chip away at the covering, so that what remains is an ever-closer approximation to the complete figure of nature's truths, an ever-deeper exploration of Vannevar Bush's endless frontier.

The brilliance and durability of science rest on its inherent capacity to change in the face of new evidence, to attain a more accurate and complete understanding of the world. This is the essence of the process of science, as practiced during a pandemic or in any context. It is the hallmark of science dating from long before Bush penned his prescient report, and it will remain so for the indefinite future.

## Science—a global enterprise

A pandemic, like climate change or any similarly global, disruptive, and daunting threat, teaches that enlightened science policy would incorporate both global cooperation and national competitiveness, and would recognize when the balance favors cooperation. Because a pandemic, by definition, is widespread, scientific insights and advances to contain and conquer it can come from anywhere. In some instances, as with the Pfizer-BioNTech vaccine, international collaboration manifestly pays off. Overcoming technical obstacles to equitable access to preventives and treatments is a matter for global science and engineering as well as financing, organization, legal arrangements, and political will. Some critical and contentious questions, such as investigating the origin of the pandemic, can only be carried out with global cooperation. And in the future, agreement on the terms for such inquiry should be established before a pandemic occurs.

But if overcoming a pandemic and understanding emerging infections require international cooperation, it is not always easy to achieve or to sustain in a fractious world. In every country, science is promoted as the key to national competitiveness and future prosperity, a meritorious argument that is persuasive to national leaders and legislators.

Those who favor international cooperation in science need to confront such genuine concerns as national security, the protection of intellectual property, and scientific integrity. While difficult to accomplish, the effort is worthwhile.

The revelations of this worldwide pandemic—that all must be protected before anyone is truly safe—are lessons that scientists and policymakers can apply to other global catastrophes. Science, in a pandemic and beyond, can build durable bridges between nations as an expression of our common humanity, in recognition of our vulnerability to pathogens and other threats to life, and as a reflection of our shared aspirations for a healthy planet.

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FRED H. GAGE AND ERIC D. ISAACS

# Independent Science for a Daunting Future

Nonprofit research institutions must find new ways to wield their historic strengths as they seek to expand their impact in a rapidly evolving scientific ecosystem.

When President Franklin D. Roosevelt called on Vannevar Bush to conceive a new future for American scientific research in the waning days of World War II, Bush responded with a breathtakingly bold proposal. He called for massive, sustained federal investments in science—driven and overseen by researchers, not politicians. Bush saw this centralized model as the only means possible to assure the scientific progress that he considered essential to this nation's future. For Bush, the "endless frontier" of science began directly at the steps of Congress. "There are areas of science in which the public interest is acute but which are likely to be cultivated inadequately if left without more support than will come from private sources," he stated. "These areas—such as research on military problems, agriculture, housing, public health, certain medical research, and research involving expensive capital facilities beyond the capacity of private institutions—should be advanced by active Government support."

The brilliance of Bush's vision has been validated across 75 years of scientific discovery and innovation. Yet, when looking back at his groundbreaking report, it is both perplexing and significant that Bush—then president of the legendary Carnegie Institution for Science—barely gives a mention to the role of independent, private research institutions in supporting and advancing American science. Now, looking forward, it seems clear that independent scientific research institutions are once again at an inflection point. It is time to take a thoughtful look at these institutions' past successes (and shortcomings) and develop a strategy that will enable them to exert a new level of leadership and help negotiate the complexities of an increasingly challenging future.

For the first decades of the twentieth century, independently funded private organizations held the reins of discovery science. The Carnegie Institution, endowed by its founder with a then eye-popping $22 million, set the international standard for astronomy, biology, and Earth science. Bell Laboratories, initially founded to develop commercial telecommunications technologies, grew into a research powerhouse, making groundbreaking discoveries that included radio astronomy, sonar, and first-generation computing. The Rockefeller Foundation's largesse launched the study of molecular biology, while the Guggenheim Foundation's investment in wind tunnels and other aircraft-testing equipment at universities across the country essentially created the academic discipline of aeronautical engineering.

Yet even the greatest scientific achievements enabled by the private sector were dwarfed by the massive scientific advances driven by the war effort in the 1940s. As director of the Office of Scientific Research and Development during World War II, Bush knew firsthand that no private sector endeavor could ever hope to match the scale of a Manhattan Project. So, in his response to Roosevelt's request, Bush focused his advocacy on the urgent need for federal funding on an unprecedented scale. His fervent demands were heeded, leading to more than seven decades of public funding that has yielded immeasurable dividends in US prosperity, health, and national security.

The rise of the federal government as the primary funder of American scientific research gave private research institutions a new freedom and a new responsibility. Relinquishing leadership of the scientific enterprise to the federal government made it possible for independent research institutions to fund unconventional, even eccentric lines of inquiry, ranging from basic science to medicine, energy, and environmental science. Again and again, their independent approach led to significant discoveries—as when Carnegie's astronomer Vera Rubin ignored conventional wisdom and persisted in studying the rotation of spiral galaxies, making observations that eventually confirmed the existence of dark matter and revolutionized humans' understanding of the universe. Or with virologist Renato Dulbecco's study of oncogenes, which earned him and his colleagues the Nobel Prize and paved the way for the Salk Institute to carve out a leadership role in cancer research, producing decades of discoveries that have transformed scientists' basic understanding of disease and saved lives.

But looking toward a future shadowed by the existential challenges of galloping climate change and global pandemics, it is clear that all independent research institutions must find new ways to adjust their historic strengths to the needs of a changing world if these institutions are to retain their position and expand their influence in the research ecosystem.

The challenge is increased by the need to make necessary changes while staying true to the priorities of the founders and funders who have made this work possible. It is a difficult needle to thread. Many large, well-established, independent, privately endowed research institutions and foundations that have the financial capacity to make a meaningful contribution to climate science must contend with the legacy of founders whose massive fortunes were accumulated through carbon exploitation and emission. These institutions must learn to honor their founders while acknowledging the environmental and social devastation that may have been left in their wake, and they must be forthright in addressing troubling aspects of their own organizational histories. These institutions also must find ways to reassure loyal longtime supporters that candor about the founders' flaws enables these organizations to maintain and even expand their legacies in an evolving social context.

These institutions also face the sometimes daunting task of expressing the urgency and revolutionary potential of their research to the public. Basic science research and exploration may seem dry in comparison to the contributions of philanthropic organizations whose annual reports showcase examples of their emotionally compelling work, illustrated by gripping images of people in desperate circumstances. Independent research institutions can feel reticent to celebrate intellectual discoveries when confronted with pressing, immediate human needs, and they often stumble in trying to explain the relevance and potential impact of their work without taking refuge in scientific jargon and baffling acronyms. As a result, these organizations struggle to attract popular attention and build an enthusiastic base of support as they seek funders and partners for their most ambitious projects.

At the same time, these institutions are fortified by distinctive and powerful capabilities. Unlike the federal government, whose funding cycles are influenced by the two-year and four-year power shifts of Congress and the White House, financially independent research organizations have the flexibility to support work that may require a time horizon of a decade or more. By providing scientists with the time necessary to pursue promising ideas, these organizations make sure that important new lines of research are not interrupted or even abandoned because of politically motivated funding shifts.

These institutions' smaller size and restrained bureaucracy give them the agility to initiate or terminate research programs swiftly in response to new discoveries or more urgent questions. Scientists in these institutions also have the great luxury of devoting themselves to research without the responsibilities and time commitments of a formal teaching requirement. Although the independent research sector plays an important role in preparing the next generation of scientists, its educational mission is primarily devoted to hands-on training of graduate students and postdocs. Researchers are thus released from the duties of classroom lectures and grading, which, although often rewarding, require countless hours away from the laboratory bench.

More fundamentally, independent research institutions such as Salk and Carnegie have developed interdisciplinary and collaborative models that provide a research blueprint for investigating the complexity of an increasingly interconnected and interdependent world. After achieving worldwide fame with his development of the first safe and effective polio vaccine, Jonas Salk in 1957 launched a new institute to create a collaborative, interdisciplinary environment where top researchers could follow their curiosity in exploring the basic principles of life. As his namesake institute's first director, Salk underscored the importance and potential impacts of its open-ended research philosophy: "We cannot be certain what will happen here, but we can be certain it will contribute to the welfare and understanding of man."

Similarly, the Carnegie Earth and Planets Laboratory combines astronomy, astrophysics, chemistry, planetary physics and dynamics, atmospheric science, experimental and theoretical petrology, and mineral physics to answer fundamental questions about the nature of exoplanetary solar systems and the characteristics necessary for rocky planets to develop and sustain life. By bringing together a wide range of experts, equipping them with highly specialized instrumentation, and giving them the freedom to follow their curiosity across disciplinary boundaries, the project hopes to answer bold questions about the potential for life on other planets.

These institutions' independent status allows them to remain true to their founders' insistence on the central importance of fundamental research, driven by curiosity and undertaken without immediate need to establish its practical use or relevance. In an increasingly impatient and utilitarian world, independent research organizations bear a deep historical responsibility to keep on interrogating the fundamental mysteries of life and the universe.

In part, the independent research organizations' ability to pursue basic research across disciplinary boundaries reflects narrower missions; unlike universities, they can focus financial and intellectual resources on targeted areas of inquiry, with the goal of delving into fundamental questions and potentially making profound, high-impact discoveries. When their researchers have satisfied their curiosity, or when a line of inquiry expands beyond their capabilities, they can then hand their discoveries off to colleagues in academia and the national laboratories for continuing study, collaboration, and innovation.

These institutions' flexibility and independence also enable them to pursue research on topics that may be politically controversial. Consider the Salk Institute's Harnessing Plants Initiative, launched in 2017 as President Donald Trump was announcing the United States' withdrawal from the Paris Agreement on climate change. Undeterred by political headwinds, this initiative's geneticists, plant biologists, chemists, and computer scientists began working together to design carbon-capturing plants—literally from the ground up. Through selective breeding and genetic programming, the Salk Institute hopes to develop plants that can more efficiently sequester large amounts of excess carbon from the atmosphere and store it in their roots, with the goal of scaling use of these plants to sequester up to 20% of humanity's current annual emissions by 2035. Without the institute's financial independence, this crucial work might have been delayed for years by partisan political considerations—and frankly, it might have begun too late to have much impact on the quickening pace of global warming.

These institutions' financial and political independence also enables them to serve as trusted conveners, building collaborations that combine the strengths of government and academia to tackle enormous tasks. In 2009, for example, the Alfred P. Sloan Foundation seeded $50 million over 10 years to create the Deep Carbon Observatory, a diverse global community of more than 1,000 scientists who spent a decade investigating the quantities, movements, forms, and origins of carbon on Earth. This interdisciplinary effort brought together geologists, mineralogists, geophysicists, chemists, biochemists, microbiologists, and technologists from hundreds of institutions and nations, and ultimately drew hundreds of millions of dollars in international investment. Beyond the scientific impact of this unprecedented effort, the Deep Carbon Observatory demonstrated another unique strength of the nonprofit research sector by setting the explicit goal of strengthening the geophysical research community through the training of the next generation of scientists. Thanks to the Sloan Foundation's ability to think in terms of decades rather than years, the ideas, techniques, and collaborations created by this project will continue to yield novel results and exciting insights from this talented, diverse group of young researchers for decades to come.

The independence, agility, and interdisciplinary approach of nonprofit scientific research institutions are likely to become even more crucial in the race to halt and mitigate the impacts of climate change. Perhaps just as importantly, these independent science institutions also bring a unique sense of optimism to their work that is inherent in their histories. Their founders endowed and established these institutions because they believed in a brighter future, and they further believed that scientific research was the surest path toward achieving that future. As Jonas Salk said in a 1985 television interview, "I already see enough evidence for this optimism.… In recent years, I find that perhaps what I'm seeking is a scientific basis for hope, and I think I've found it."

That optimism in the face of massive challenges, pragmatically combined with thoughtful recruiting and robust fundraising, will position these exceptional institutions to continue making unexpected discoveries, building powerful, mission-driven teams, and bringing together far-reaching collaborations that exceed even the reach of the federal government. Despite the daunting scale of the problems the United States and the world face, private research institutions will endeavor to continue serving as scientific pioneers and trusted partners, guided by Jonas Salk's personal motto: "The reward for work well done is the opportunity to do more."

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ANGELA BEDNAREK AND VIVIAN TSENG

# A Global Movement for Engaged Research

Philanthropic organizations have a special role to play in setting bold new expectations for a research enterprise that works in direct dialogue with the rest of society.

The US research enterprise is famously well developed, but there is a mismatch between the research knowledge that is produced and the socially robust knowledge that is needed to address the challenges facing coming generations. We are two research funders whose efforts began separately—one in conservation and the other in education—but as our paths crossed and eventually merged, we came to share a new vision of how to produce what we call "engaged research," the production and use of knowledge through active collaboration with policymakers, practitioners, or communities. From our shared experience, we are now working to build a new global network of donors, public funders, and foundations that share the aim of expanding an approach to scientific research that is inclusive of and relevant to the rest of society.

This is the story of how we came to see such engaged research as a method to bring together government, civil society, and communities to shape research agendas for *their* needs and grounded in *their* expertise, as well as to foster *their* uses of research to drive policy and practice to benefit society. We feel that our experiences in this realm offer important insights that can be applied more broadly in future science policy initiatives.

Philanthropic organizations have a special role to play in setting bold new expectations for the research process, workforce, and institutions. By tearing down systemic barriers to engaged research, funders can spur a new vision of science that is in direct collaboration with the rest of society. The organizations in our new network support research that leads with societal needs across many sectors, including environment, education, public health, medical research, international development, and foreign policy. Each has pushed hard against deeply entrenched conventions about how research is conceived, conducted, and utilized, and we now hope to accelerate progress by working collectively.

## Separate paths, similar goals

The story begins with finding common purpose in separate paths. One of us (Bednarek) worked for more than a decade with colleagues at The Pew Charitable Trusts developing a grantmaking program, The Lenfest Ocean Program, aimed at supporting policy-relevant research about ocean conservation. The program started as a classic dissemination model of funding academic research and then communicating it to relevant audiences. Over time, program leaders shifted to engaging decisionmakers and other stakeholders directly in the development of research questions to ensure support was going to projects that policymakers needed and wanted. They also built trusting relationships between researchers and policymakers by supporting intensive engagement.

The further program leaders developed this approach, the more they realized the complexity of the problem. Teasing out Lenfest's contribution as a funder was difficult in the swirl of advocates and other actors working on a specific policy issue. In addition, what did it mean to inform policy? Did it mean that decisionmakers talked about the research in their deliberations? What if they decided on a course of action that wasn't grounded in the program's research findings? None of the usual measures—citation counts, impact factors, media hits—helped Pew understand how decisionmakers were using the research it was funding.

The program's leaders also realized that spending time talking to policymakers, researchers, and other stakeholders led them to formulate more useful research questions. But this required not only an intensive amount of staff time, but also the expertise to facilitate researcher-policymaker engagement and knowledge translation. Research grantees didn't necessarily have the time, skillset, or institutional incentives for these tasks. And it was often difficult to find additional staff with these skills because this kind of boundary-spanning work wasn't a well-recognized role.

At the same time, the other of us (Tseng) was working with the William T. Grant Foundation (WTG) to support research in education, as well as other child and youth policy areas. She was also frustrated that research was not sufficiently useful to and used in policy and practice. For Pew, the journey toward engaged research originated in on-the-ground observations about what worked to facilitate evidence use. In contrast, WTG's interest in engaged research in the form of research-practice partnerships grew out of the foundation's support of scholarship on the use of research evidence in policy and practice. Research on research use across diverse sectors and policy settings indicated that relationships between researchers and users were critical for fostering the use of findings in practice and policy. The "use problem" was not one of information deficits that could be solved simply by new dissemination or communication strategies.

When researchers and practitioners collaborated to develop research agendas, the resulting work was more useful to practitioners and more likely to be trusted and used in decisionmaking.

Embedded within these findings were a host of new puzzles. Research-practice partnerships are promising strategies, but what does it take for them to be successful? How can the success of partnership work be measured? Researchers, practitioners, and funders were all asking these questions. Researchers and practitioners wanted answers that would help them improve their work. Funders wanted to improve their funding support process and understand whether that funding was successful.

In addition to these questions, WTG observed a lack of funding models to sustain such partnerships over the long term. And although an increasing number of education funders began supporting partnerships, questions remained about how to scale them to meet the needs of school districts and states across the country.

## Kindred spirits among research funders

A mutual colleague, recognizing that we had each been asking similar questions about what it means to meaningfully improve the use and usefulness of research, connected the two of us. We had set out separately in our respective sectors to change the conversation about what it means to support research that is useful as well as used, and we recognized each other as kindred spirits.

In comparing our grantmaking approaches, we discovered that we shared a keen interest in democratizing the research process by including more perspectives when defining what research gets done and how it is used. We both sought to identify the conditions that led to use of research findings for the purpose of fine-tuning our investment strategies as funders. Even more critically, we witnessed the same systemic barriers to engaged research across our policy sectors. In particular, we struggled with a misalignment between academic incentives and the objectives of engaged research. Academic tenure and reward systems tended to prioritize scientific publications and grants, rather than sustained engagement with policymakers and communities. And we both observed a lack of funding and trained workforce to support engaged research.

Recognizing similarities in our goals and in the systemic barriers we had identified, we began co-convening colleagues and grantees across sectors (environment, education, and social services) to bridge our efforts. We also looked for funders in other policy sectors who were similarly investing in engaged research. In early 2019, Pew and WTG commissioned a survey of more than 20 foundations that support improvements in the production and use of research as a core strategy in their grant portfolios. The results revealed funders around the world, working in many diverse sectors, who were eager to promote researcher-user engagement.

The two of us then took a next step toward building our network and gathered some of these same public and private funders at the offices of the Wellcome Trust in London in December 2019 to identify concrete ways to work together. As this diverse group of nearly two dozen funders talked, a clearer articulation of our vision emerged. It became apparent that engaged research is a viable way to democratize the research process by including current and potential stakeholders who could have a say about what research gets done and how it's used. This inclusiveness yields what science and technology scholar Helga Nowotny calls "socially robust knowledge." Such knowledge includes and values the expertise of stakeholders beyond researchers in its production, and it is tested and validated in settings outside the laboratory.

However, to push the changes necessary to realize the promise of such engaged research, we recognized that like-minded funders would need to join forces.

## Leveraging expertise and demand across sectors and around the world

With this shared vision in mind, in 2020, Pew and WTG established the Transforming Evidence Funders Network (TEFN). Through TEFN, more than 30 public and private funding programs spanning a wide range of issue areas, geographies, and sectors work together with the ambitious vision of expanding engaged research and evidence use around the world. The network serves as an ecosystem of funders that can collectively build on effective practices, link pockets of momentum, and coordinate action.

TEFN started with what its members knew best: grantmaking practices to support engaged research. By drawing on their experiences as funders, TEFN participants began identifying characteristics of strong proposals for engaged research. Funders across sectors have found that successful engaged research requires non-research partners to meaningfully participate in the process. This goes well beyond an initial consultation to encompass relationship-building between partners. Strong proposals for engaged research also provide a credible assessment of the policy or practice relevance of the proposals, not just their scientific value. Further, the experiences of many funders point to the need for expert intermediaries to facilitate engaged research.

TEFN is compiling grantmaking practices that support these needs. These include sufficient time for partners to engage before a research question is defined; support and funding for non-research partners' engagement in the work; a schedule of regular engagement between partners; inclusion of practitioners in review panels; and when possible, an expert intermediary to facilitate projects, translate knowledge, and manage power dynamics.

TEFN members also strategized about how they can collectively move the needle on broader challenges in expanding engaged research. Specifically, the group saw opportunities to create wider change in three ways. First, by supporting scholarship on how policymakers and practitioners use evidence to more effectively guide future efforts. Second, by investing in the infrastructure and workforce needed to coproduce research for use in policy or practice. And finally, by finding ways to reshape academic reward systems to support engaged research.

***Building the evidence base for evidence use.*** TEFN participants want to support the development and growth of a rigorous and coordinated scholarship base that can guide understanding of how to improve research use, including through research-practice partnerships. To accomplish this, partners in the network need to increase understanding of what it takes for research and other forms of evidence to be routinely used by government, communities, and other practitioners. Because too many initiatives lack scholarship about when and how practitioners use evidence, those efforts are rooted in hunches about what it takes to "make a difference" and tend to focus on one-way communication or dissemination models.

To create a coherent evidence base, TEFN is developing a shared research agenda to help align its partners' knowledge-building efforts. The network is also exploring the creation of a global network of hubs devoted to research on research use that can connect what is learned across policy sectors, countries, and disciplines. TEFN partners have already provided seed funding for a sister learning and action network, the Transforming Evidence Network (TEN). While TEFN brings together funders, TEN encompasses a broader community of evidence stakeholders across countries and policy sectors. This network enables learning across academic disciplines and practice areas. It also serves as a much-needed professional home for scholars of research use, boundary spanners, and other intermediaries engaged in the practice of research use.

***Building the infrastructure for engaged research.*** To enable engaged research, TEFN participants have identified advantages in supporting research-practice partnerships (known by a variety of terms, e.g., coproduction in sustainability) and the infrastructure necessary to sustain them. This support includes identifying the institutional and funding configurations needed to build and sustain partnerships, increasing funding to support effective partnerships, and strengthening the capacity of organizations—research institutions, governments, and others—to foster and manage partnerships.

A key component of expanding research-practice partnerships is building capacity for expert intermediaries, or boundary spanners, including boundary organizations. Bringing partners together around a common goal requires integrating knowledge across research disciplines, policy issues, and practice needs. It also requires a dedication to building relationships while negotiating competing interests and power dynamics. But the experts and organizations that do this work often lack neat job descriptions or clearly identified roles. Even more challenging is that they lack sustainable funding and clear career pathways.

As a start, TEFN participants are considering how to include dedicated support for boundary spanning in their grantmaking. Lenfest and WTG have both developed resources about boundary spanning that are guiding those efforts. TEFN participants have also prioritized solidifying boundary spanner professional identities and networks though the Transforming Evidence Network.

***Developing incentives for engaged research.*** Reshaping academic incentives and norms to reward societally relevant research is one of the biggest challenges. Academic promotion and tenure still rely heavily on peer-reviewed publications and other metrics that don't readily accommodate the outputs of engaged research. Moreover, even with a long-standing cooperative extension system within US public universities, engaged research is often considered less desirable or rigorous than "curiosity-driven" science. Such challenges can disincentivize academic participation in engaged research. An unsupportive academic reward system can also perpetuate inequities. Many engaged research efforts are conducted by women or scholars of color, who already experience bias in their disciplines. Younger scholars find it difficult to participate in engaged research for fear of not receiving tenure. Researchers driven to conduct engaged research anyway often do so in addition to other work more prized by the academy.

Reshaping research incentives has emerged as a strong shared priority within TEFN. Several participants were investing in incentive grants that encourage universities to support engaged research even before TEFN was created. For example, the Institutional Challenge Grant Program—supported by the William T. Grant Foundation, the Doris Duke Charitable Foundation, the Spencer Foundation, and the American Institutes for Research—has led institutions such as the University of California, Berkeley to issue guidance about how to credit non-peer-reviewed products of engaged scholarship as scholarly contributions rather than community service. The Carnegie Corporation of New York funds a "Bridging the Gap" grant competition for schools of international affairs, initially launched as part of its "Rigor and Relevance Initiative." This program encourages interaction among policymakers, faculty, and students and is working to reshape incentives in tenure and promotion to support faculty engagement in policy work.

Academia is a globally connected enterprise, and without coordinated action to transform academic norms and incentives across disciplines and geographies, change will be limited. Thus, TEFN is also exploring ways to coordinate efforts to create widespread change across colleges, universities, and other parts of the research ecosystem, such as academic publishing, around the world.

## A call to action

The opportunity has now arrived to position science to be of service to the rest of society: engaging researchers in true partnerships with governments, civil society, citizen movements, and other community organizations. To achieve this requires funders, scientists, and institutions to engage with unfamiliar sectors, disciplines, and geographies. We believe that funders should be instigating the deep and sustained institutional changes required to meet this ambitious charge.

The Transforming Evidence Funders Network provides a way for funders to link arms in marching toward a common vision, that of a future where science and the rest of society are in regular and meaningful dialogue to meet the challenges of our times. As the world navigates its way through climate change, pandemics, and the many other wicked problems of the twenty-first century, engaged research is a promising new way to do science.

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Vannevar Bush's landmark report *Science, the Endless Frontier* has profoundly shaped US science policy over the past 75 years. In the spirit of envisioning the next 75 years, *Issues in Science and Technology* commissioned this special collection of ambitious, challenging, and innovative proposals on how to structure the resources of science to enable the best possible future for everyone.

Global scientific leaders, philanthropists, policymakers, and early-career researchers alike shared their insights and expertise—creating a broad forum for the exchange of ideas about reinvigorating the scientific enterprise. This book aggregates these contributions in one place to serve as a guide for reimagining and rebuilding the systems of science for success in the decades ahead.

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