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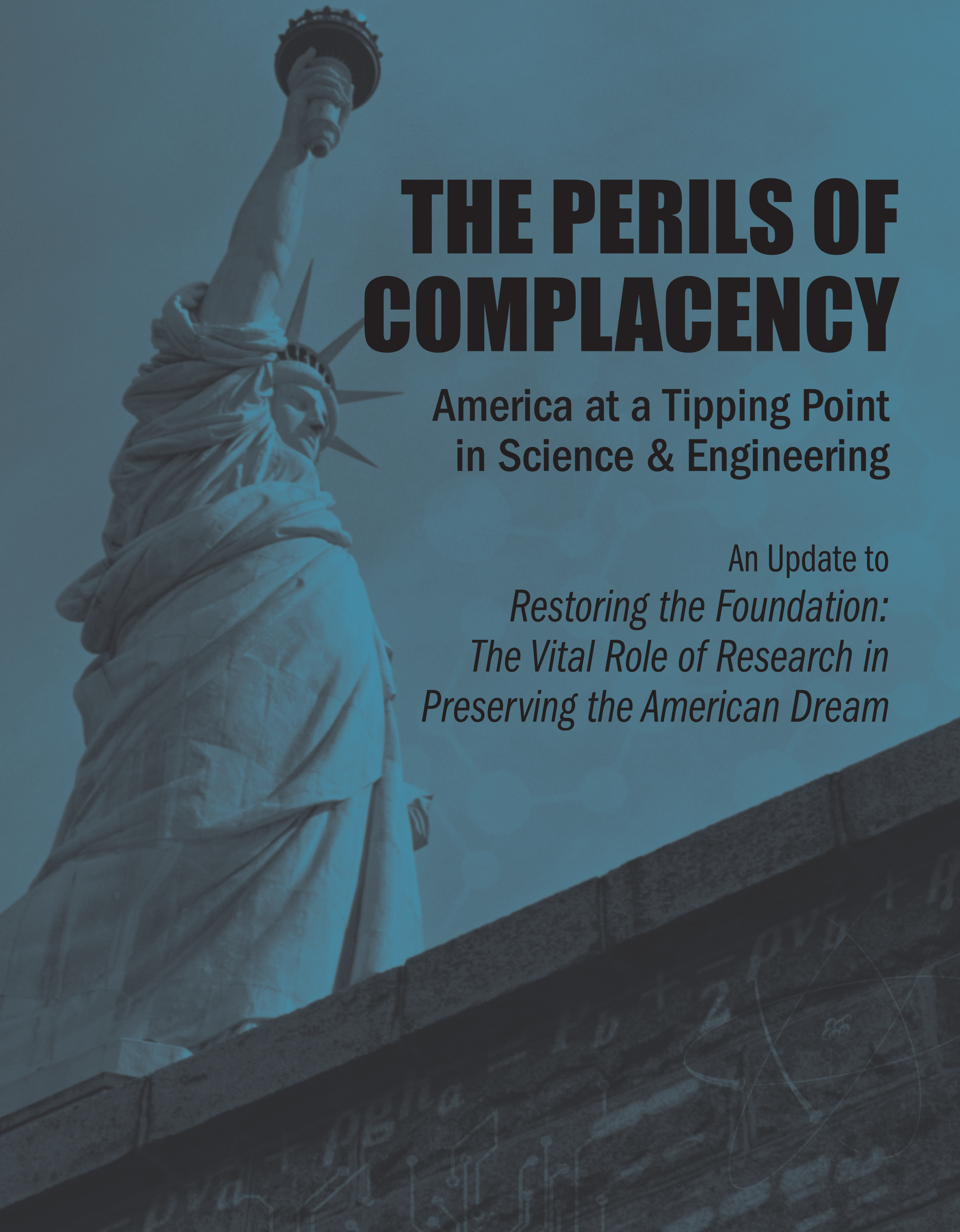

THE PERILS OF COMPLACENCY

America at a Tipping Point in Science & Engineering

An Update to
*Restoring the Foundation:
The Vital Role of Research in
Preserving the American Dream*

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AMERICAN ACADEMY OF ARTS & SCIENCES
Cambridge, Massachusetts

This report and its supporting data were finalized in April 2020. While some new data have been released since then, the report's findings and recommendations remain valid. Please note that Figure 1 was based on NSF analysis, which used existing OECD purchasing power parity (PPP) to convert U.S. and Chinese financial data. OECD adjusted its PPP factors in May 2020. The new factors for China affect the curves in the figure, pushing the China-U.S. crossing point toward the end of the decade. This development is addressed in Appendix D.

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Acknowledgments

The American Academy's 2014 report *Restoring the Foundation: The Vital Role of Research in Preserving the American Dream* was produced by an expert committee chaired by Norman R. Augustine (Lockheed Martin Corporation, retired) and Neal Lane (Rice University). The committee and the project staff, working with a large range of partner organizations, devoted countless hours over the ensuing years to ensuring that the report's recommendations were discussed thoroughly with U.S. policy-makers and science and engineering leaders. While those efforts were productive, much remains to be done, and the world has changed markedly in ways that have profound implications for U.S. leadership in science, technology, and innovation.

The Academy is pleased to offer this five-year update to *Restoring the Foundation* that highlights significant developments, many of which were foreshadowed in the original report, and emphasizes actions that remain in urgent need of attention from U.S. policy leaders. I am grateful to the *Restoring the Foundation* committee, especially to Norm Augustine and Neal Lane, for their dedication to producing an informative and forceful document, as well as to the Academy staff members who worked on the report: John Randell, the John E. Bryson Director of Science, Engineering, and Technology Programs, and Amanda Vernon, Program Officer and Hellman Fellow in Science and Technology Policy.

This report has also benefited from substantial data collection and analysis by scholars from the Science and Technology Program at Rice University's Baker Institute for Public Policy, particularly Kirstin Matthews and Kenneth Evans. The American Academy and the *Restoring the Foundation* committee are grateful for the many hours that they devoted to compiling the data that underpin the arguments in the following pages. We offer our deep appreciation to the Kavli Foundation for helping to fund this report. Finally, we would like to thank Louise and John E. Bryson for their generous support of our Science, Engineering, and Technology programs; John also served on the Committee on New Models for U.S. Science & Technology Policy that gave rise to the *Restoring the Foundation* report.

The COVID-19 pandemic, which began to unfold as this report neared its publication, has only underscored our vital need for a robust and innovative American scientific enterprise. I join with all the contributors to this report in urging that those arguments be given full consideration by America's leaders.

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President, American Academy of Arts and Sciences

American Academy of Arts and Sciences

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Preface

In 2014, the American Academy of Arts and Sciences published the report *Restoring the Foundation: The Vital Role of Research in Preserving the American Dream*. The present report, an update, focuses on significant changes that have occurred in the past five years, especially the rapid rise of Asia, particularly China, as a major competitor in science, engineering, and innovation. In a remarkably short period of time, China has dramatically strengthened its commitment to achieving world leadership in science and engineering by increasing its R&D funding, number of researchers, research publications in top international journals, size of its science and engineering (S&E) workforce, number of universities and research facilities, patent filings, and rankings in international innovation indices. We write this update because the crucial message in our previous report about the vital importance of research has been reflected in China's priorities but has not stimulated the much-needed action by the United States.

Although the current era is often referred to as "The Age of Technology," the United States has no coherent strategy for maintaining the high standing it has built through past efforts as a world leader in science, technology, and innovation. In recent decades the United States has failed to grow its investment in research and development (R&D), make the necessary policy changes that could boost scientific discovery and innovation, or improve its altogether inadequate system of public primary and secondary education, which, in part, discourages or precludes America's youth from pursuing careers in science, mathematics, and engineering. Today, the United States and China are on markedly different trajectories that will lead to very different consequences.

Fifty years after the momentous achievement of the *Apollo 11* moon landing, largely motivated by the Soviet Union's launch of *Sputnik 1* a decade earlier, America is once again at a "tipping point," this time driven by China's overtaking the United States in many indicators of prowess in R&D and innovation. In this update report, the prescriptions and recommended actions in the original *Restoring the Foundation* report are reaffirmed, several actions are highlighted to reflect recent developments, and several additional policy actions are offered.

As this report was going to press, the COVID-19 pandemic was raging across the United States and most parts of the world, resulting in millions of infections, hundreds of thousands of deaths, millions of job losses, personal hardships to families and communities, and unprecedented economic damage at all levels, including disproportionately severe effects on Black, Native, and Latinx people. At the same time, demonstrations calling attention to discrimination in our system of justice were occurring across America, an issue not addressed in this report. While these events were precipitated by the killings of George Floyd and other Black Americans, they also highlight the fact that all Americans do not have access to a quality education and the well-paying jobs created by advances in science and technology.

The non-partisan Congressional Budget Office (CBO) projects that the U.S. Gross Domestic Product will contract by 11 percent in the second quarter of 2020 and the jobless rate in this country will reach 15 percent. The CBO projects recovery to be gradual, with unemployment over

8 percent at the end of 2021, but it emphasizes the large uncertainties in making any projections. China, where the coronavirus originated, has also been impacted; and its economy, which was already cooling prior to the COVID-19 outbreak, will be further slowed. Notwithstanding all the uncertainties, the fundamental issues addressed in this report will be as relevant following the COVID-19 pandemic as they were before, perhaps more so. As the United States and other nations deal with this crisis, the vital importance of science has become apparent to policymakers and the general public. The future health, safety, and prosperity of the American people will increasingly depend on the nation developing and deploying robust scientific and technical capabilities to benefit all its citizens.

Key Messages in this Report

1. China and other countries have revamped their national R&D policy to respond to the twenty-first-century innovation landscape, wherein the countries that succeed will be those that not only make the greatest discoveries but innovate the fastest.

2. The U.S. approach to federal R&D investments appears to assume that we can rest on our past successes, defend our intellectual property, sustain economic growth, and assure national security on the basis of largely incremental innovations to past accomplishments in science and engineering.

3. The United States is in severe danger of no longer being the premier destination for S&E talent. An increasingly unwelcome environment for foreign talent, together with a failure to cultivate an adequate domestic S&E workforce, threatens a decline in American health, prosperity, and national security.

4. America's ability to respond to other countries' rise in science and engineering, particularly that of China, is likely to be impeded by increasingly severe fiscal constraints on nonmilitary discretionary spending.

How to Lose Global Competitiveness in 10 Easy Steps

☑ 1. Underfund R&D: fail to increase basic research funding to 0.3 percent of GDP and fail to grow the national R&D investment to 3.3 percent of GDP

☑ 2. Deter immigration of talented STEM students and workers

☑ 3. Have no integrated, coherent federal funding strategy

☑ 4. Provide minimal capital resources to federally funded R&D facilities

☑ 5. Fund long-term scientific projects through single-year, volatile funding cycles

☑ 6. Saddle researchers with onerous regulations that offer no clear benefit

☑ 7. Maintain a second-rate primary and secondary education system in STEM

☑ 8. Continue to cut state investments in higher education

☑ 9. Avoid high-risk/high-potential research and federal support of innovation

☑ 10. Maintain a federal budget that produces vanishing discretionary funds in the future

Executive Summary

At the very moment this report was being written, China[1] was passing the United States in research and development (R&D) investment (at purchasing power parity, PPP) (Figure 1).[2] Yet this is an era in which a vast majority of the growth in America's economy (gross domestic product, GDP) and all that it supports is attributable to advancements in science and technology. Indeed, we live in what is not infrequently referred to as the Age of Technology. But, astonishingly, headlines in the media make no note of this watershed event, nor has the topic been raised in presidential debates. The nation seems oblivious to the consequences of what is occurring – and what will follow.

Other recent developments are placing additional stress on the U.S. research system even as they underscore its indispensability in providing the fuel for American innovation and competitiveness as well as the know-how required to address the nation's many societal challenges. As this report was being prepared, a major coronavirus outbreak was impacting thousands of lives in China, America, and other parts of the world. Meanwhile, security concerns have led some policy-makers to propose draconian restrictions on the very same foreign researchers on whom we have come to rely to fill the persistent domestic talent gap in science and engineering. One result of recent and proposed immigration restrictions is that other countries have become more competitive at attracting workers – and U.S. corporations are more inclined to move R&D laboratories to other countries. Compounding this problem is a continued weakness in U.S. support for basic and applied research; the FY2021 Presidential Budget Request would cut federal support for these categories by $7.9 billion, or just over 9 percent.[3]

The global pace of scientific and technological (S&T) discovery is accelerating. Today, global leadership in science and technology is measured in months or years, not decades or centuries. For example, the time between doubling the computing capacity on that critical element of virtually all modern electronic devices – the semiconductor integrated circuit – is just a small number of years.[4] The half-life of articles published in scientific journals, as measured by the frequency at which they are referenced, is five years or less in many fields.[5] To fall behind even

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1. All references to "China" in this report are to the People's Republic of China, rather than the Republic of China, aka Taiwan.

2. For additional analysis, see Task Force on American Innovation, "Benchmarks 2019: Second Place America? Increasing Challenges to US Scientific Leadership" (Washington, D.C.: Task Force on American Innovation, 2019), http://www.innovationtaskforce.org/benchmarks2019/.

3. Matt Hourihan, "Latest White House Budget Features A Few Big Research Priorities Amid Ranging Reductions," February 10, 2020, https://www.aaas.org/news/latest-white-house-budget-features-few-big-research-priorities-amid-ranging-reductions.

4. "Moore's Law and Intel Innovation," Intel, https://www.intel.com/content/www/us/en/history/museum-gordon-moore-law.html.

5. John Bohannon, "The Secret Half-Lives of Scientific Papers," *Science*, December 19, 2013, https://www.sciencemag.org/news/2013/12/secret-half-lives-scientific-papers.

a few years in S&T R&D can have grave consequences for a country's economy, job creation, standard of living, and national security.

The United States became a world power – economically, militarily, and culturally – in significant part by placing a high priority on innovation, fueled by advances in science and technology. This priority, in turn, required investing in R&D, especially fundamental research conducted in universities and national laboratories across the fields of science, technology, engineering, medicine, and mathematics.

China is projected to become the world's largest economy when measured by GDP by 2030.[6] By 2026, the 250th anniversary of the United States, China's strategic plan calls for it to be well on its way to becoming the unchallenged world leader in science, technology, and innovation. These developments are perilous for America, which today, 50 years after the *Apollo 11* moon landing, is at a tipping point in R&D.

The well-being of America and its individual citizens depends heavily on the strength of America's economy, which, in turn, depends heavily on research and development. Without a strong economy, jobs disappear – along with the tax receipts needed to provide healthcare, social security, education, infrastructure, and homeland and national security. Numerous studies, including two that won Robert Solow and Paul Romer the Nobel Prize in Economics in 1987 and 2018, respectively, have concluded that as much as 85 percent of the long-term growth in America's economy (measured by GDP) is attributable to advancements in just two closely related fields: science and technology.[7]

Five years ago, a study committee of the American Academy of Arts and Sciences prepared the report *Restoring the Foundation: The Vital Role of Research in Preserving the American Dream* (referred to herein as RtF1).[8] The report examined the state of American innovation policy and informed the bipartisan American Innovation and Competitiveness Act, which Congress passed by unanimous consent in December 2016 and President Barack Obama signed into law in January 2017. The Academy and other organizations worked with corporate leaders to issue a call to action,

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[6] Callum Paton, "World's Largest Economy in 2030 Will Be China, Followed by India, with U.S. Dropping to Third, Forecasts Say," *Newsweek*, January 10, 2019, https://www.newsweek.com/worlds-largest-economy-2030-will-be-china-followed-india-us-pushed-third-1286525.

[7] "The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 1987," The Nobel Prize, https://www.nobelprize.org/prizes/economic-sciences/1987/summary/; "Paul M. Romer: Facts," The Nobel Prize, https://www.nobelprize.org/prizes/economic-sciences/2018/romer/facts/; C.I. Jones, "The Facts of Economic Growth," in *Handbook of Macroeconomics* (Amsterdam: Elsevier, 2016), 2:3 – 69, https://doi.org/10.1016/bs.hesmac.2016.03.002; and Robert Solow, "Technical Change and the Aggregate Production Function," *The Review of Economics and Statistics* 39 (3) (1957): 312 – 320, https://doi.org/10.2307/1926047.

[8] *Restoring the Foundation: The Vital Role of Research in Preserving the American Dream* (Cambridge, MA: American Academy of Arts and Sciences, 2014), http://www.amacad.org/restoringthefoundation.

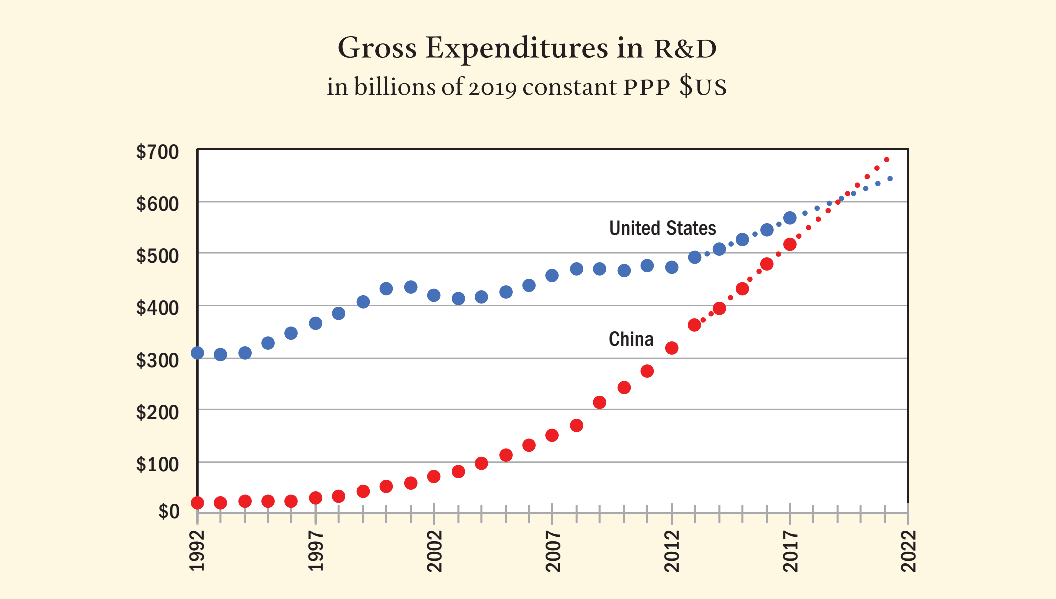

Figure 1

Gross Expenditures in R&D in billions of 2019 constant PPP $US

Adapted from National Science Board, "National Science Board Statement on Global R&D Investments NSB-2018-9," February 17, 2018.

Source: OECD. 2019. "Main Science and Technology Indicators," OECD Science, Technology and R&D Statistics (database), https://doi.org/10.1787/data-00182-en.

Constant dollars are calculated using total nondefense composite outlay deflators found in Table 10-1: Office of Management and Budget. 2019. "Fiscal Year 2020 GDP and Deflators," https://www.whitehouse.gov/omb/historical-tables/.

Note: FY2017 and FY2018 include a new definition for R&D, which excludes DOD's late-stage development, testing, and evaluation "development" category, formerly included. Trend lines are linear fit of last five points extended four years.

"Innovation: An American Imperative," that was signed by more than 500 major businesses, universities, scientific societies, and other organizations.[9]

The present committee is guardedly encouraged by this strengthening of our national understanding of the importance of R&D and by recent increases in federal research funding in some areas, the FY2021 budget request notwithstanding. Yet the challenges within the United States, along with rising government investment by China and other countries, remain basically unchanged. This report presents a comprehensive update on America's situation and provides

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[9] *Innovation: An American Imperative,* http://www.innovationimperative.org/.

policy recommendations that, if enacted, would help ensure that the United States does not lose the preeminent position in discovery and innovation that it has built through investments and efforts since the end of World War II.

AMERICA AT A TIPPING POINT

America's total national investment in research and development as a fraction of GDP has remained stagnant at 2.4–2.7 percent for nearly half a century (Figure 2).[10] Meanwhile, other nations, especially China, have accelerated such investments. Because of America's tepid response to rising competition from abroad, the United States has fallen to tenth place among Organisation for Economic Co-operation and Development (OECD) nations in investment in R&D (public and private) as a fraction of GDP.[11]

While national R&D spending as a fraction of GDP is but one metric of developed economies that are largely driven by advances in science and technology, the ratio is a strong indicator of the intensity of a nation's investment in its future. The rapid drop in global ranking of the United States in R&D as a fraction of GDP reflects government policy-makers, corporate boards, and CEOs focusing on near-term issues at the expense of longer-term, potentially existential issues. That is perhaps to be expected, given the short-term incentives that drive politics and business today, but it does not bode well for the future of a country in a world where others, particularly China, are committed to, and investing in, long-term strategies for success – if not outright dominance.

THE INGREDIENTS OF INNOVATION: CHINA AND THE UNITED STATES

The United States cannot compete with China through the size of its workforce, where China possesses a major advantage, but rather must compete through creativity and innovation. Yet China is gaining the upper hand in the latter as well, closing in or surpassing the United States in measures including gross R&D spending, funding for basic research, patents granted, S&E articles published, S&E bachelor's and doctorates awarded, and researchers employed (Figure 3).

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[10] "Historical Trends in Federal R&D," American Association for the Advancement of Science, https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd.

[11] Because of past variations in its definition of R&D, Switzerland has not been included in the figure. Were it to be included, the United States would be in 11th place.

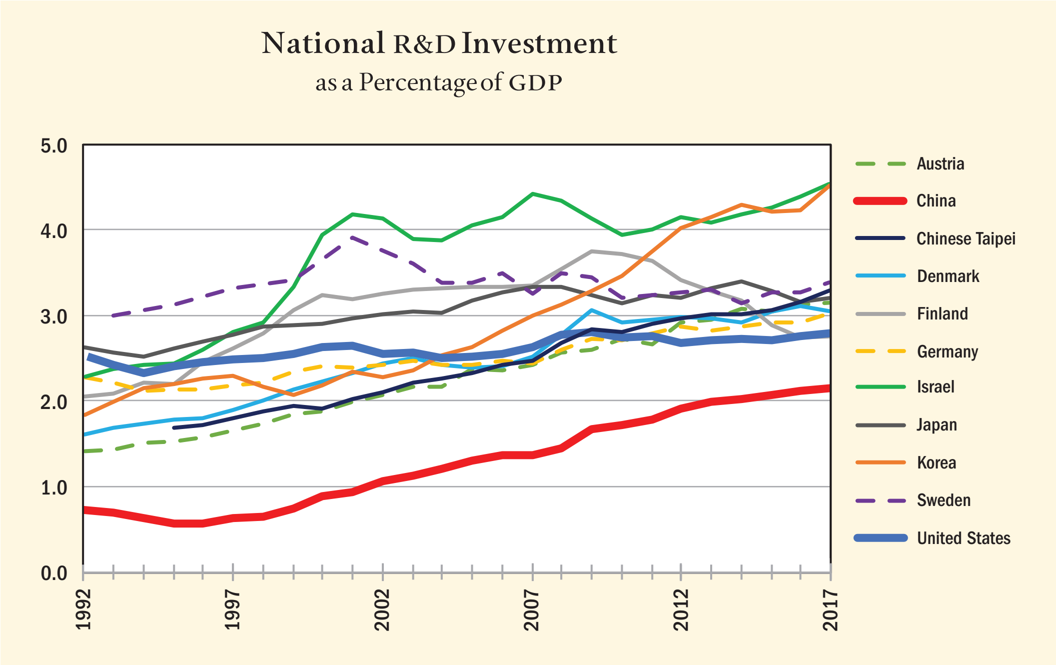

Figure 2

National R&D Investment as a Percentage of GDP

Source: OECD, "Main Science and Technology Indicators," 2019, OECD Science, Technology and R&D Statistics (database), https://doi.org/10.1787/data-00182-en.

Innovation through science and technology has four fundamental and closely interrelated components: 1) human capital; 2) knowledge capital; 3) an ecosystem conducive to innovation; and 4) financial capital. The following paragraphs examine innovation in China and the United States using these four metrics.

Human Capital

Today, China awards more bachelor's degrees in science and engineering than the United States, the European Union (EU), and Japan combined, having bypassed the United States in 2003.[12] To keep pace with demand, China is projected to continue to increase the numbers of S&E graduates substantially. The number of corresponding degrees awarded by U.S. institutions continues to be relatively flat (Figure 4a).[13] A substantial share of those degrees goes to international, frequently Chinese, citizens. China remains behind the United States in the production of S&E graduates with doctorates from its own universities (Figure 4b) but is rapidly increasing these numbers, and Chinese university rankings are increasing as well.[14]

Lesser interest in science, technology, engineering, and mathematics (STEM) careers among America's youth is exacerbated by the inadequacy of the nation's precollege educational system.[15] The Program for International Student Assessment (PISA), which tests 15-year-olds in reading, mathematics, and science, finds U.S. students are ranked 25th among OECD nations (Figure 5).

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[12] "S&E" includes engineering, physical sciences, environmental sciences, mathematical sciences, computer sciences, life sciences, psychological sciences, and social sciences. See "S&E Field Classification," National Science Foundation, https://www.nsf.gov/statistics/rdexpenditures/glossary/s_efield.htm.

[13] National Science Board, *Science and Engineering Indicators 2018*, NSB-2018-1 (Alexandria, VA: National Science Foundation, 2018), 2-47 – 2-60, https://nsf.gov/statistics/2018/nsb20181/report.

[14] "China, Japan Raise Pressure on US, UK in Global Ranking," *University World News*, September 12, 2019, https://www.universityworldnews.com/post.php?story=20190912131138561.

[15] Brian Kennedy, Meg Hefferon, and Cary Funk, "Half of Americans Think Young People Don't Pursue STEM Because It Is Too Hard," *Fact Tank*, January 17, 2018, Pew Research Center, https://www.pewresearch.org/fact-tank/2018/01/17/half-of-americans-think-young-people-dont-pursue-stem-because-it-is-too-hard/; and Olga Khazan, "Lack of Interest and Aptitude Keeps Students Out of STEM Majors," *Washington Post*, January 6, 2010, https://www.washingtonpost.com/blogs/on-small-business/post/lack-of-interest-and-aptitude-keeps-students-out-of-stem-majors/2012/01/06/gIQAoDzRfP_blog.html.

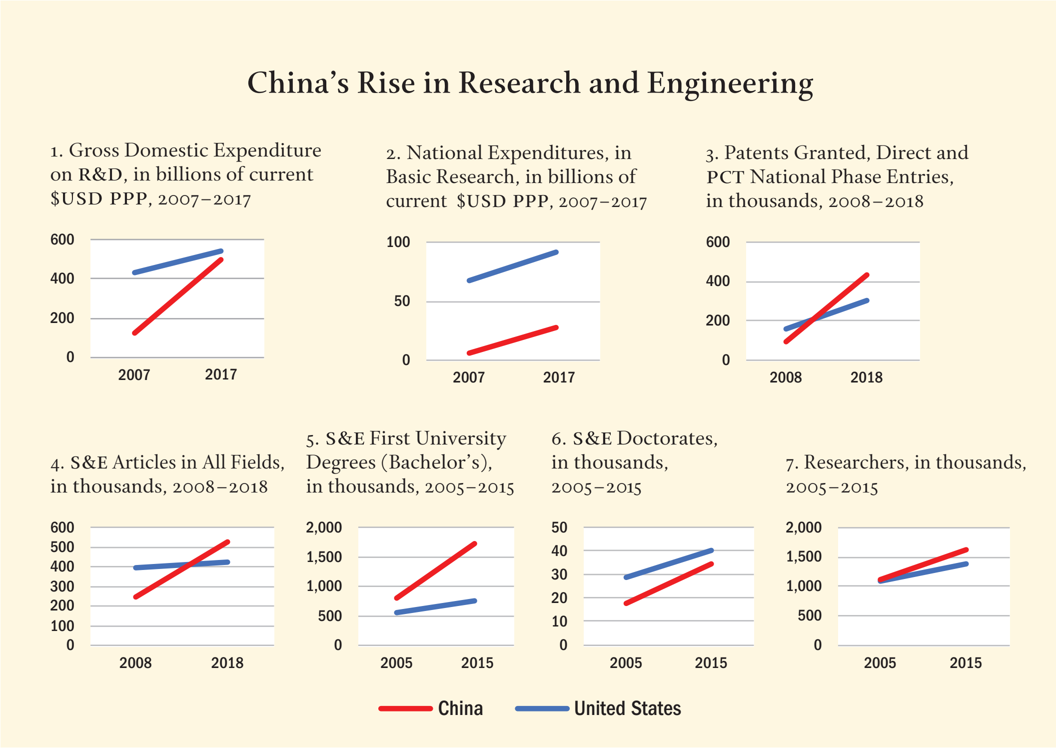

Figure 3

China's Rise in Research and Engineering

Source: 1. OECD, "Main Science and Technology Indicators," 2019, OECD Science, Technology and R&D Statistics (database), https://doi.org/10.1787/data-00182-en.

2. Ibid.

3. World Intellectual Property Organization. 2019. "WIPO Statistics Database," https://www3.wipo.int/ipstats/index.htm?tab=patent.

4. National Science Board, *Science & Engineering Indicators 2020* (Alexandria, VA: National Science Foundation, 2020), https://ncses.nsf.gov/indicators.

5. Ibid.

6. Ibid.

7. National Science Board, *Science & Engineering Indicators 2018* (Alexandria, VA: National Science Foundation, 2018), https://www.nsf.gov/statistics/2018/nsb20181/.

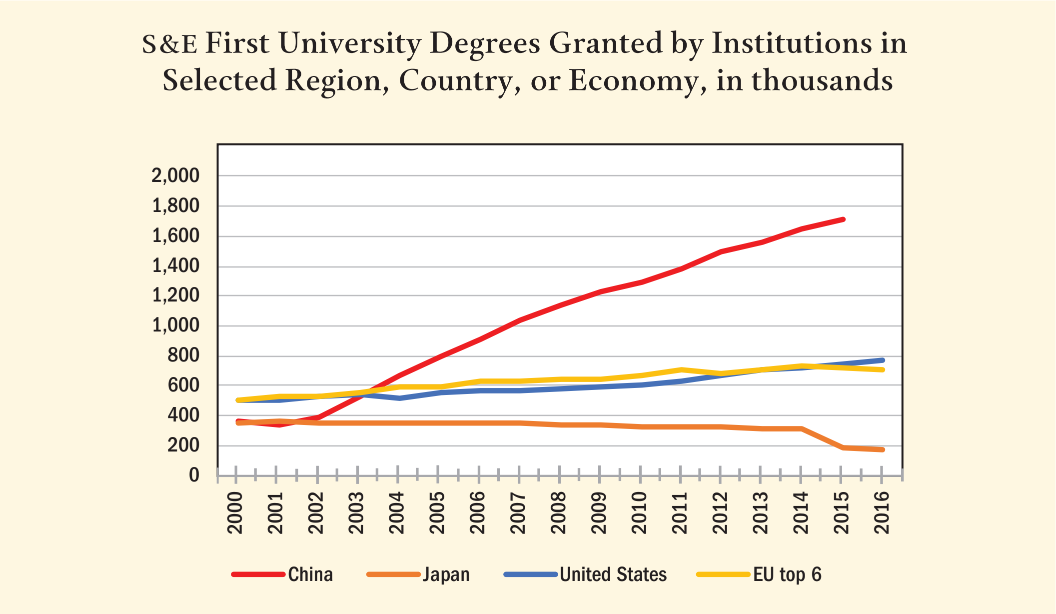

Figure 4a

S&E First University Degrees Granted by Institutions in Selected Region, Country, or Economy, in thousands

Source: Reproduced from Figure 2-19 in National Science Board, *Science & Engineering Indicators* 2020 (Alexandria, VA: National Science Foundation, 2020).

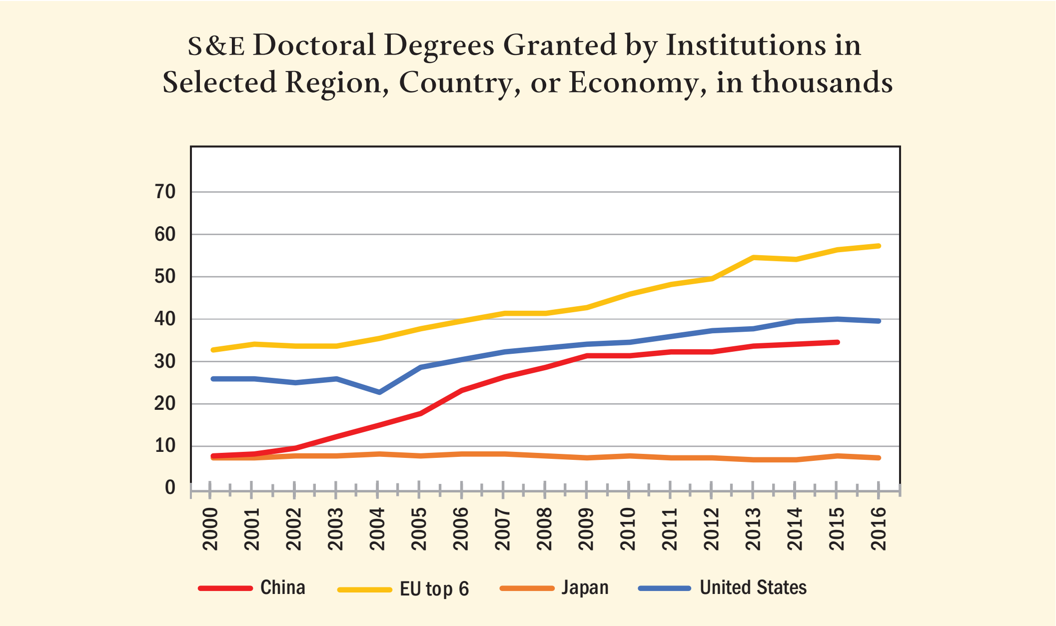

Figure 4b

S&E Doctoral Degrees Granted by Institutions in Selected Region, Country, or Economy, in thousands

Source: Reproduced from Figure 2-21 in National Science Board, *Science & Engineering Indicators* 2020 (Alexandria, VA: National Science Foundation, 2020).

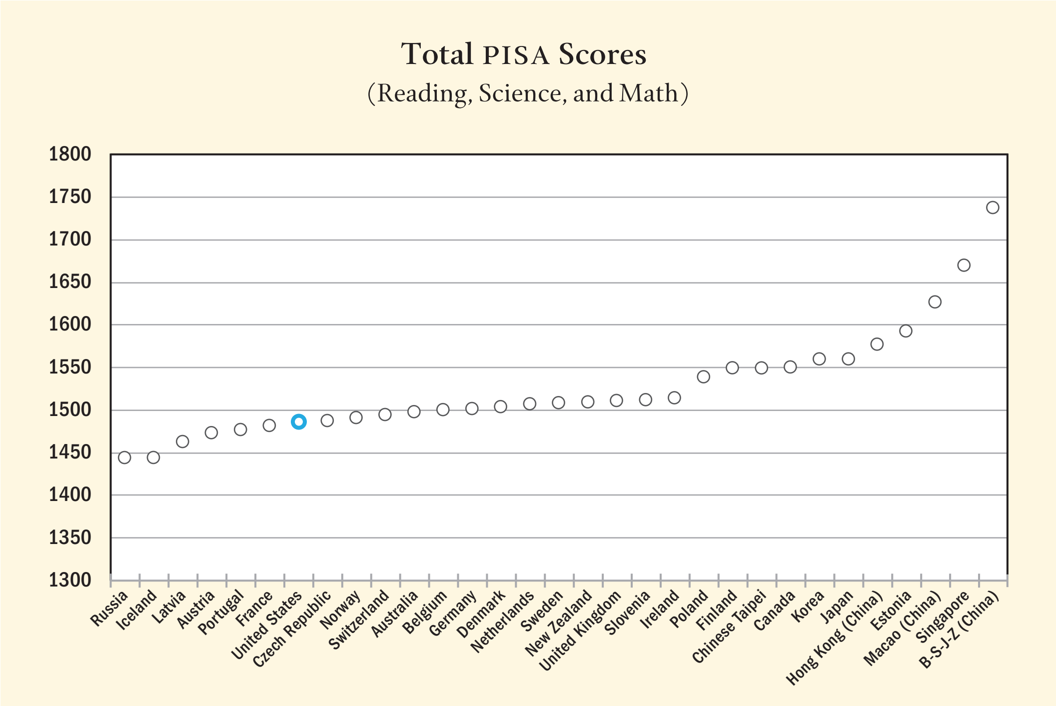

Figure 5

Total PISA Scores (Reading, Science, and Math)

Source: OECD, "Main Science and Technology Indicators," 2019; PISA 2018 Results (Volume I): *What Students Know and Can Do*, https://doi.org/10.1787/19963777.

Note: B-S-J-Z refers to four PISA participating China provinces: Beijing, Shanghai, Jiangsu, and Guangdong.

Compounding the issue of overall poor domestic K-12 STEM education, the United States is systematically failing to attract Americans of diverse backgrounds into STEM careers, whether measured by gender, race, socioeconomic status, sexual orientation, disability, religion, or geographic location within the United States.[16] If not addressed, this underrepresentation will continue to hamper U.S. efforts to develop a strong domestic STEM workforce, especially as historically underrepresented groups become an increasing proportion of the overall U.S. population.

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16. National Science and Technology Council Committee on STEM Education, *Charting a Course for Success: America's Strategy for STEM Education* (Washington, D.C.: National Science and Technology Council, December 2018), https://www.whitehouse.gov/wp-content/uploads/2018/12/STEM-Education-Strategic-Plan-2018.pdf.

U.S. academic research in STEM fields relies heavily on foreign-born individuals from China, India, and other parts of the world. In recent years, about one-third of U.S. Ph.D. STEM graduates have not been U.S. citizens or permanent residents, and 28 percent of U.S. S&E faculty were born overseas, as were over half of U.S.-trained S&E postdoctoral workers.[17] Nearly half of U.S. Fortune 500 companies were founded by immigrants or children of immigrants.[18] Similarly, 26 percent of the members of the U.S. National Academy of Sciences and 31 percent of the members of the U.S. National Academy of Engineering are foreign-born.

Demand for workers in the STEM fields continues to be very high, and the United States continues to be extremely dependent upon immigration of talented men and women to meet this demand. While there is no standard definition of the STEM workforce, the American Immigration Council (AIC) uses both a narrow definition – physical and life sciences, engineering, mathematics, and computer science – and a broader definition that adds physicians, nurses, and social scientists. According to the AIC, in 2015 STEM workers (narrow definition) made up about 5 percent (approximately 8 million) of the total U.S. workforce, and 24 percent (approximately 2 million) of STEM workers (narrow definition) were foreign-born (Figure 6a).[19] These data do not include academic positions, many of which are held by foreign-born faculty.[20]

In the academic year 2017 – 2018, about 280,000 men and women from China were enrolled in U.S. colleges and universities as undergraduate or graduate students, amounting to about one-third of all international students studying in the United States.[21] Second to China in terms of total U.S. undergraduate and graduate enrollment is India (120,000), followed by South Korea (44,000) and Saudi Arabia (39,000).[22] Strikingly, the percentage of Chinese students who return

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[17] National Science Board, *Science and Engineering Indicators 2018*, 2-61 – 2-85, https://nsf.gov/statistics/2018/nsb20181/report/sections/higher-education-in-science-and-engineering/graduate-education-enrollment-and-degrees-in-the-united-states.

[18] Ian Hathaway, "Almost Half of Fortune 500 Companies Were Founded by American Immigrants or Their Children," *The Avenue*, December 4, 2017, Brookings Institution, https://www.brookings.edu/blog/the-avenue/2017/12/04/almost-half-of-fortune-500-companies-were-founded-by-american-immigrants-or-their-children/.

[19] American Immigration Council, *Foreign-Born STEM Workers in the United States* (Washington, D.C.: American Immigration Council, June 14, 2017), Table 2, https://www.americanimmigrationcouncil.org/research/foreign-born-stem-workers-united-states.

[20] National Science Board, *Science and Engineering Indicators 2018*, NSB-2018-1 (Alexandria, VA: National Science Foundation, 2018), 2-47 – 2-60, https://nsf.gov/statistics/2018/nsb20181/report. See Appendix Table 5-17.

[21] "International Student Data," IIE, https://opendoorsdata.org/data/international-students/academic-level-and-places-of-origin/.

[22] "Places of Origin," IIE, https://opendoorsdata.org/data/international-students/academic-level-and-places-of-origin/.

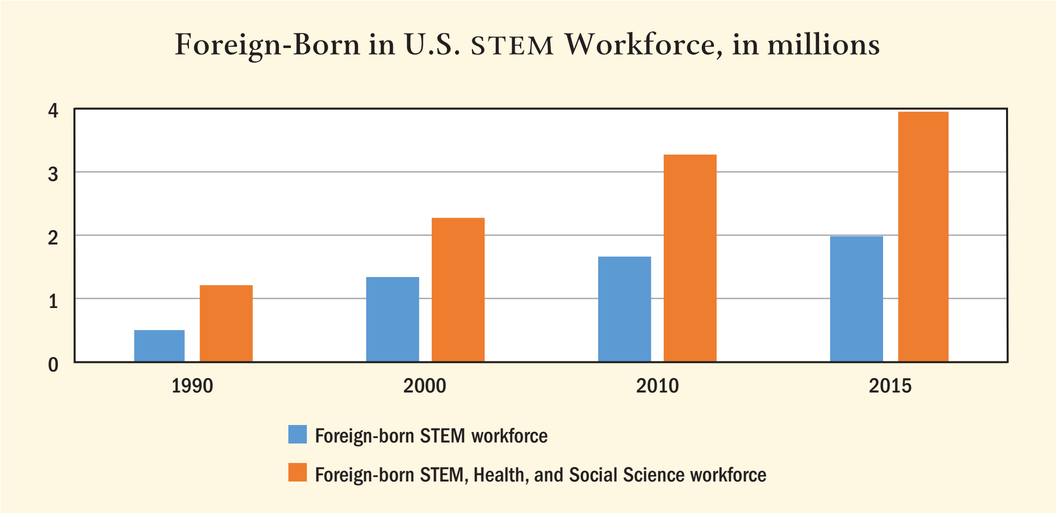

Figure 6a

Foreign-Born in U.S. STEM Workforce, in millions

Source: American Immigration Council, "Foreign-Born STEM Workers in the United States," 2018, https://www.americanimmigrationcouncil.org/research/foreign-born-stem-workers-united-states.

to China following their studies has increased markedly over the past decade (Figure 6b),[23] representing a loss of talent for the countries who train them, including the United States.

Members of Congress, U.S. intelligence officials, and others have raised concerns that China's government – through its consulates – is directing some Chinese students and visiting researchers to steal intellectual property and spread pro-China political propaganda on America's campuses. There is clear evidence that both are happening, at least to some degree. The U.S. Federal Bureau of Investigation (FBI) has issued warnings about China's talent programs and espionage.[24] According to a senior U.S. Department of Justice official, over 90 percent of U.S. economic espionage prosecutions include individuals or firms from mainland China.[25]

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[23] Brief Report on Chinese Overseas Students and International Students in China, March 31, 2018, http://en.moe.gov.cn/documents/reports/201901/t20190115_367019.html.

[24] "FBI Counterintelligence Note: Chinese Talent Programs," Public Intelligence, August 11, 2016, https://publicintelligence.net/fbi-chinese-talent-programs/.

[25] Adam S. Hickey, remarks at the Fifth National Conference on CFIUS and Team Telecom, Washington, D.C., Wednesday, April 24, 2019. Text available at https://www.justice.gov/opa/speech/deputy-assistant-attorney-general-adam-s-hickey-national-security-division-delivers-0, accessed February 24, 2020.

FBI officials have visited various universities to provide briefings on the attendant risks, and research has documented isolated incidents of Chinese students attempting to pressure fellow Chinese students, faculty, and administrators viewed as critical of China.[26] University leaders are working with federal officials to ensure that any new policies do not undercut the openness that has always been a fundamental strength of American higher education.[27]

Altogether, the benefits of foreign-born individuals contributing to U.S. science and technology far outweigh the risks.[28] Recognizing this, the committee concludes that an appropriate solution is not blanket prohibitions within basic research, as some have proposed, but rather enhanced alertness and action in cases where evidence indicates violation of U.S. law. This, of course, applies to domestic as well as foreign-born individuals.

Knowledge Capital

There is no agreed-upon single measure of knowledge capital; however, commonly used metrics include the numbers and quality of publications and patents.

The publication of scientific discoveries in peer-reviewed journals is a principal mechanism for the dissemination of research.[29] Historically, the United States has ranked first in the number of research publications, as well as the number of publications in the most highly cited journals. However, in 2016, China passed the United States in the number of research articles published, and it is rapidly rising in the number of articles published in the most recognized journals (Figure 7a and Figure 7b).

One measure of the effectiveness of the transition from research discovery to practical application is the number of patents granted, a category in which China has taken the lead in recent

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[26] Emily Feng, "FBI Urges Universities to Monitor Some Chinese Students and Scholars in the U.S.," NPR, June 28, 2019, https://www.npr.org/2019/06/28/728659124/fbi-urges-universities-to-monitor-some-chinese-students-and-scholars-in-the-u-s; Bethany Allen-Ebrahimian, "China's Long Arm Reaches into American Campuses," *Foreign Policy*, March 7, 2018, https://foreignpolicy.com/2018/03/07/chinas-long-arm-reaches-into-american-campuses-chinese-students-scholars-association-university-communist-party/; and Anastasya Lloyd-Damnjanovic, *A Preliminary Study of PRC Political Influence and Interference Activities in American Higher Education* (Washington, D.C.: Wilson Center, September 6, 2018), https://www.wilsoncenter.org/publication/preliminary-study-prc-political-influence-and-interference-activities-american-higher.

[27] Lee C. Bollinger, "No, I Won't Start Spying on My Foreign-Born Students," *Washington Post*, August 30, 2019, https://www.washingtonpost.com/opinions/no-i-wont-start-spying-on-my-foreign-born-students/2019/08/29/01c80e84-c9b2-11e9-a1fe-ca46e8d573c0_story.html.

[28] JASON, "Fundamental Research Security," JSR-19-2I, December 2019, https://www.nsf.gov/news/special_reports/jasonsecurity/JSR-19-2IFundamentalResearchSecurity_12062019FINAL.pdf.

[29] Ewen Callaway, "Beat It, Impact Factor! Publishing Elite Turns against Controversial Metric," *Nature* 535 (2016): 210–211, https://doi.org/10.1038/nature.2016.20224.

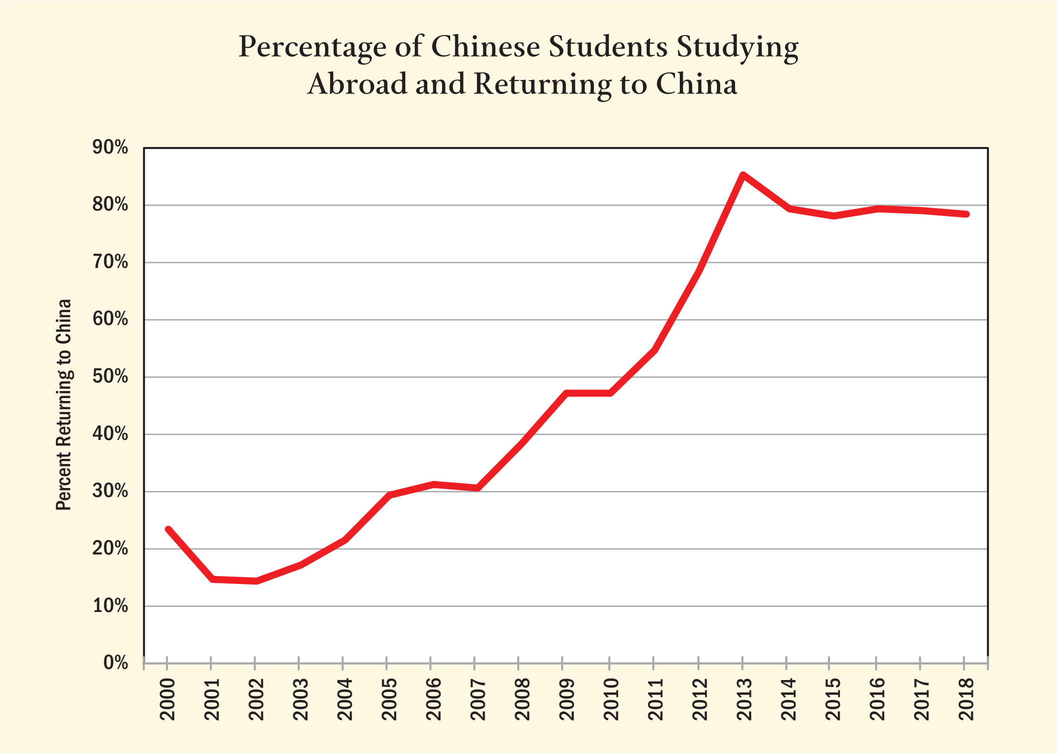

Figure 6b

Percentage of Chinese Students Studying Abroad and Returning to China

Source: National Bureau of Statistics of China, China Statistic Yearbook 2019.

years (Figure 8). However, the large fraction of Chinese patents that go unrenewed after five years calls into question the value of many of those patents in the first place.

Innovation Ecosystem

Today is a time of unprecedented opportunity for scientific discovery and rapid advances in technology and its applications. Research discoveries lead to new technologies, and new technologies provide tools that in turn accelerate research discovery. And this is happening at an accelerating pace. Examples include big data, artificial intelligence (AI), machine learning, quantum technology, CRISPR, genomic medicine, medical imaging, robotics, high-performance materials, nanotechnology, and much, much more. The sciences have been described as undergoing a "revolution" that, to achieve meaningful progress, requires a significant and purposeful convergence of methods and approaches from scientists and engineers across fields and industries.[30]

One measure of how the United States compares to the rest of the world in innovation is its ranking on the Bloomberg Innovation Index. In Bloomberg's 2019 assessment, the United States ranks eighth overall, tenth in R&D intensity (national R&D spending as a percentage of GDP), 28th in researcher concentration (professionals engaged in R&D per capita), 25th in manufacturing value added, 43rd in tertiary efficiency[31] (principally the fraction of individuals receiving tertiary – university or college – education),[32] and 76th in the fraction of initial degrees awarded in engineering.

The World Intellectual Property Organization (WIPO), an agency of the United Nations, publishes a Global Innovation Index (GII) based on its assessment of 80 indicators of innovation performance in 126 countries, including such metrics as political environment, education, infrastructure, and business sophistication. In the 2018 report, which focuses on energy innovation, China advanced to 17th place because of "an economy witnessing rapid transformation guided by

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[30] *Convergence: The Future of Health* (Washington, D.C.: MIT Washington Office, June 2016), http://www.convergencerevolution.net/s/Convergence-The-Future-of-Health-2016-Report-55pf.pdf.

[31] Michelle Jamrisko and Wei Lu, "The U.S. Drops Out of the Top 10 in Innovation Ranking," *Bloomberg*, January 22, 2018, https://www.bloomberg.com/news/articles/2018-01-22/south-korea-tops-global-innovation-ranking-again-as-u-s-falls; and Michelle Jamrisko, Lee J. Miller, and Wei Lu, "These Are the World's Most Innovative Countries," *Bloomberg*, January 22, 2019, https://www.bloomberg.com/news/articles/2019-01-22/germany-nearly-catches-korea-as-innovation-champ-u-s-rebounds.

[32] The index bases its ranking on the following criterion: "Postsecondary education: Number of secondary graduates enrolled in postsecondary institutions as a percentage of cohort; percentage of labor force with tertiary degrees; annual science and engineering graduates as a percentage of the labor force and as a percentage of total tertiary graduates." See Jamrisko et al., "These Are the World's Most Innovative Countries." The United States is penalized by the six-year graduation rate at public universities of only 60 percent.

S&E Articles, by Global Share of
Selected Region, Country, or Economy

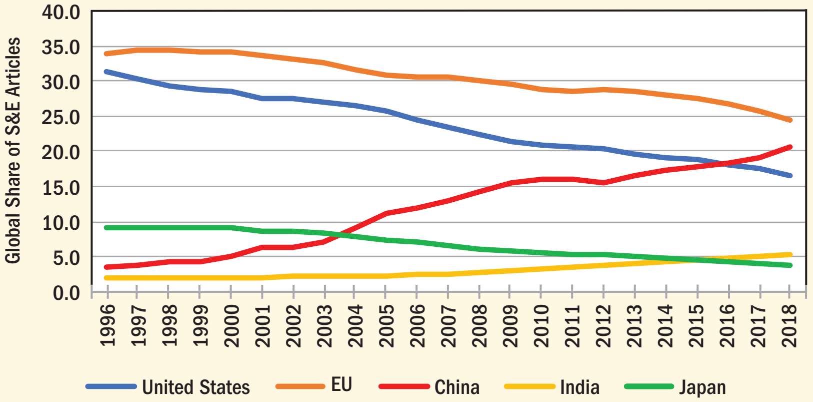

Figure 7a

S&E Articles, by Global Share of Selected Region, Country, or Economy

Source: Reproduced from Figure 5a-3 in National Science Board, *Science & Engineering Indicators* 2020 (Alexandria, VA: National Science Foundation, 2020).

S&E Publication Output in the Top 1 Percent of
Cited Publications, by Selected Country or Economy

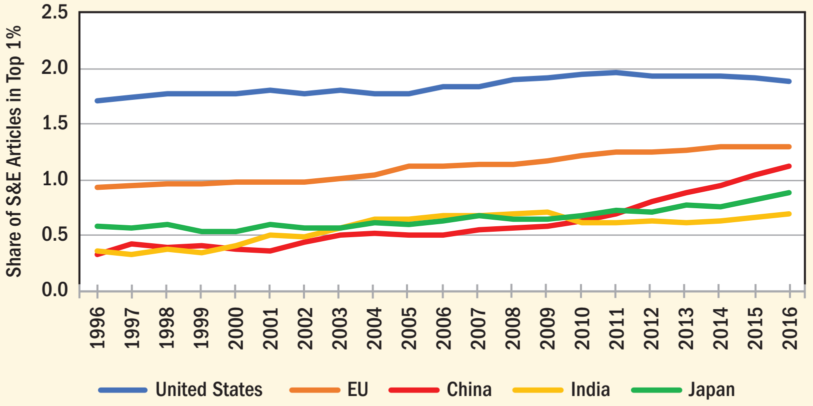

Figure 7b

S&E Publication Output in the Top 1 Percent of Cited Publications,
by Selected Country or Economy

Source: Reproduced from Figure 5a-9 in National Science Board, *Science & Engineering Indicators* 2020 (Alexandria, VA: National Science Foundation, 2020).

government policy prioritizing R&D–intensive ingenuity." In contrast, the United States slipped from fourth to sixth place in one year. The United States was in first place as recently as 2008.[33]

Even in cases where the United States performed significant early research, markets and jobs have been lost to others because of barriers (regulations, laws, taxes, etc.) to the rapid transition of new knowledge into products and services. Examples of this occurrence include solar cells, batteries, television, and 5G communications. As the pace of transition from the laboratory to the market accelerates, the U.S. position becomes increasingly endangered (Figure 9).

Financial Capital

The United States, with a GDP in 2018 of approximately $20 trillion, has the largest economy in the world based on current exchange rates.[34] China is the world's second largest economy by this particular measure, and analyses project that China will close the gap with the United States by 2030.[35] China passed the United States in GDP adjusted for purchasing power parity in 2014.[36] China became a member of the World Trade Organization in 2001 and in a single decade, from 2008 to 2018, the number of Chinese Global Fortune 500 companies rose from 29 to 120, while the number of U.S. companies fell from 153 to 126 (Figure 10). China is on a path to pass the United States by this latter measure in the very near future, if it has not already done so.

In the United States, pressures from stockholders tend to encourage publicly held companies to favor investments that promote near-term increases in stock price as opposed to long-term returns, thereby discouraging investments in such areas as infrastructure and research.[37]

The task of laying the groundwork needed to ensure that the United States continues to be a country of scientific discovery and innovation has thus increasingly fallen to the U.S. federal

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[33] Cornell University, INSEAD, and WIPO, *Global Innovation Index 2018: Energizing the World with Innovation* (Geneva: WIPO, 2018), http://www.wipo.int/publications/en/details.jsp?id=4330; http://www.wipo.int/pressroom/en/articles/2018/article_0005.html; https://www.globalinnovationindex.org/userfiles/file/GII-2008-2009-Report.pdf.

[34] Noah Smith, "Who Has the World's No. 1 Economy? Not the U.S.," *Bloomberg*, October 18, 2017, https://www.bloomberg.com/opinion/articles/2017-10-18/who-has-the-world-s-no-1-economy-not-the-u-s.

[35] Callum Paton, "World's Largest Economy in 2030 Will Be China, Followed by India, with U.S. Dropping to Third, Forecasts Say," *Newsweek*, January 10, 2019, https://www.newsweek.com/worlds-largest-economy-2030-will-be-china-followed-india-us-pushed-third-1286525.

[36] https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.CD?locations=US-CN-1W, accessed on February 13, 2020.

[37] Beatriz Pessoa de Araujo and Adam Robbins, "The Modern Dilemma: Balancing Short- and Long-Term Business Pressures," Harvard Law School Forum on Corporate Governance, June 20, 2019, https://corpgov.law.harvard.edu/2019/06/20/the-modern-dilemma-balancing-short-and-long-term-business-pressures/.

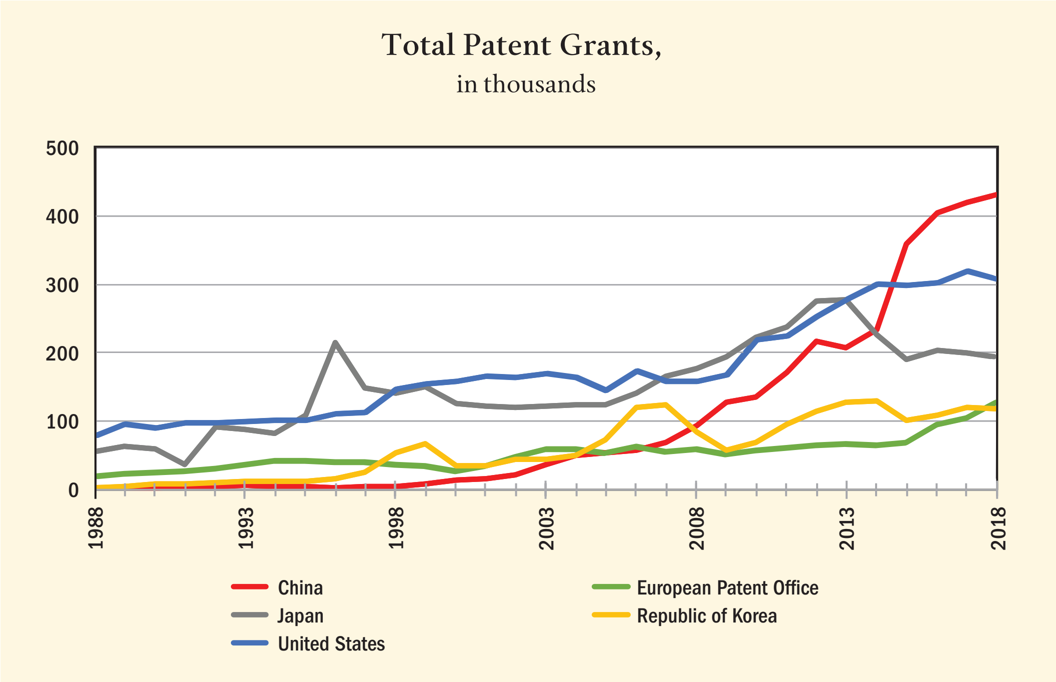

Figure 8

Total Patent Grants, in thousands

Source: World Intellectual Property Organization, "WIPO Statistics Database," 2019, https://www3.wipo.int/ipstats/index.htm?tab=patent.

Note: Includes both total patent grants and Patent Cooperation Treaty national phase entries.

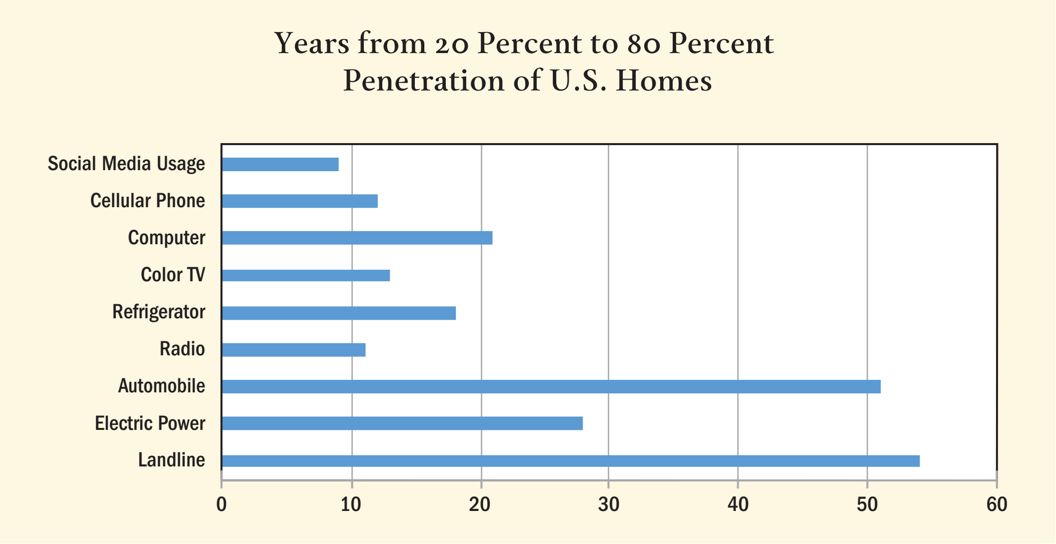

Figure 9

Years from 20 Percent to 80 Percent Penetration of U.S. Homes

Source: Hannah Ritchie and Max Roser, "Technology Adoption," 2019, https://ourworldindata.org/technology-adoption, accessed February 13, 2020.

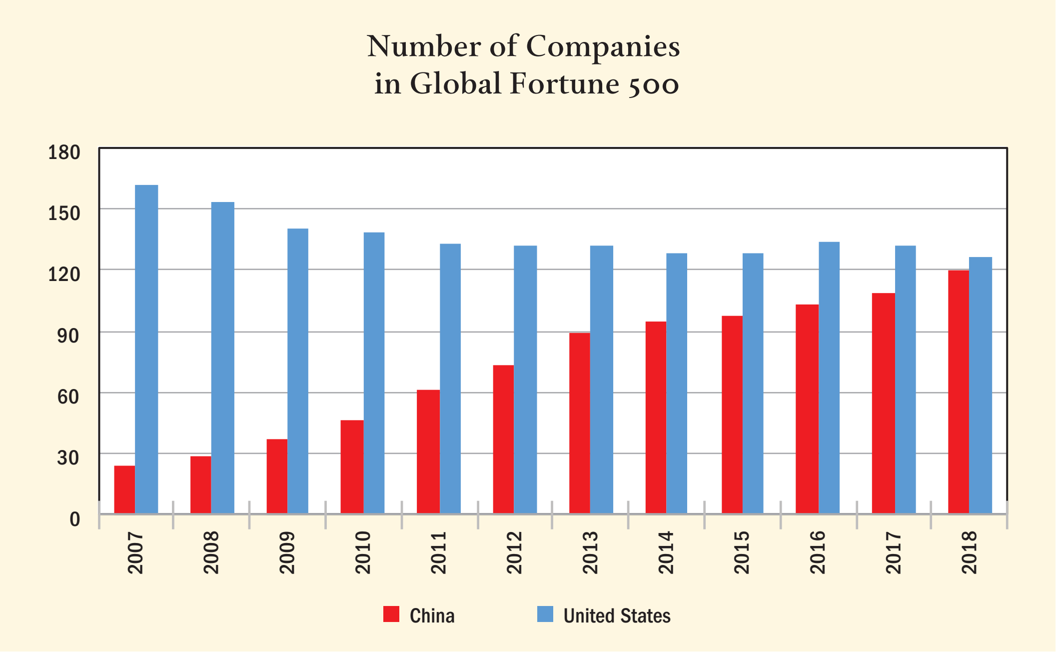

Figure 10

Number of Companies in Global Fortune 500

Source: "Global 500," *Fortune*, https://fortune.com/global500/.

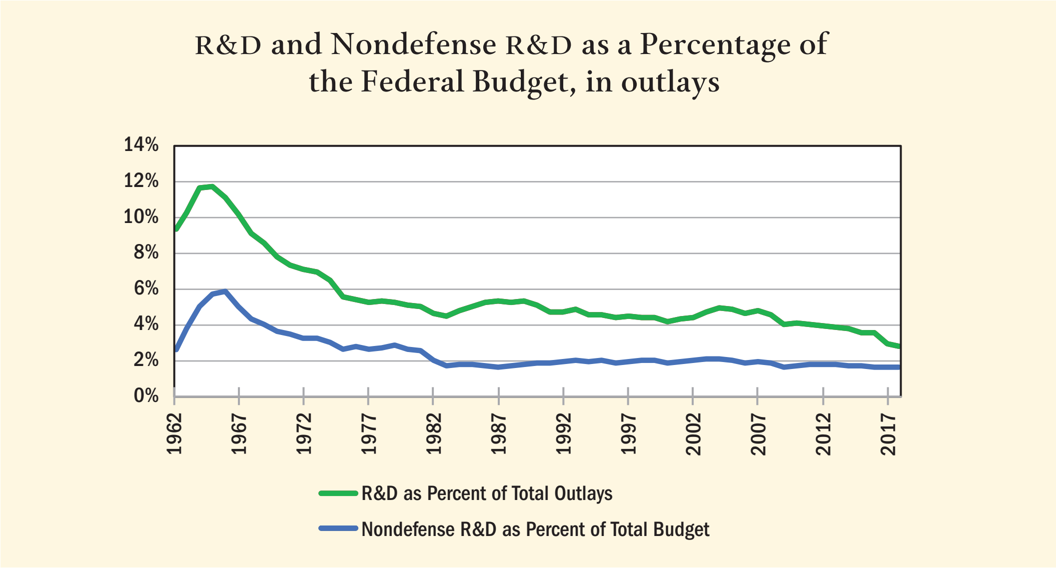

Figure 11

R&D and Nondefense R&D as a Percentage of the Federal Budget, in outlays

Source: American Association for the Advancement of Science, "Historical Trends in Federal R&D," 2019, https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd.

government.[38] However, federal spending (annual outlays) for R&D have remained generally flat at about 4 percent of total federal spending and about 10 percent of discretionary spending for more than 30 years (Figure 11).[39] With the federal government's redefinition of *development* in fiscal year 2018 to exclude "pre-production development" and other nonexperimental work, these percentages have moved even lower.[40]

In contrast to the United States, overall R&D spending in China has increased significantly over the past two decades. From 2000 to 2012, R&D spending as a percentage of GDP increased by

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[38] Ben S. Bernanke, "Promoting Research and Development: The Government's Role" (speech at the New Building Blocks for Jobs and Economic Growth conference, Washington, D.C., May 16, 2011), https://www.federalreserve.gov/newsevents/speech/bernanke20110516a.htm.

[39] "Historical Trends in Federal R&D."

[40] Matt Hourihan, "The Federal Government Is Tweaking What Counts as R&D: Q&A," American Association for the Advancement of Science, June 13, 2018, https://www.aaas.org/news/federal-government-tweaking-what-counts-rd-qa.

18 percent per year in China (Figure 2). China surpassed the European Union in 2015 in overall R&D investment, having allocated about $400 billion (with PPP correction) in 2015.[41] As shown in Figure 1, the U.S. National Science Board has estimated that China's spending on R&D at PPP equaled that of the United States sometime in 2018 or soon thereafter.

A LOOMING THREAT

Approaching in the not-too-distant future is a fiscal circumstance that could greatly complicate any plans for increased R&D funding in the United States. This near-existential issue has received little attention from those addressing the nation's future investments in R&D.

The issue has been noted by the Congressional Budget Office (CBO) for several years, but with seemingly little impact. As illustrated in Figure 12, expenditures already committed under current law for only two general budgetary categories – entitlements and debt interest – are projected to equal the totality of federal revenues by 2042. At that time any R&D funding will have to compete directly with such priorities as national defense, homeland security, and infrastructure. Major elements of entitlement (nondiscretionary) outlays are Social Security, Medicare, Medicaid, and pension obligations – each exceedingly difficult to reduce, at least from a political standpoint. If the tax reductions enacted by the Tax Cuts and Jobs Act of 2017 are extended beyond their scheduled expiration in 2025, revenues will be further reduced. Similarly, if interest rates rise above currently projected levels (about 1.5 percent over the next ten years), outlays will further increase. The most recent CBO projection, assuming rapid economic recovery from COVID-19, is that federal spending in 2030 will reach 23 percent of GDP, while revenues equal 17.8 percent of GDP.

The U.S. national debt is now over $23 trillion, while its GDP is nearly $22 trillion. The federal debt held by the public (as opposed to debt held by government accounts or intragovernmental debt) equals 73 percent of that total. Prospects for reducing debt, given recent history, must be considered tenuous at best. During fiscal year 2019 alone the national debt increased by nearly 6 percent, driven by a deficit increase of 26 percent. Should the economic decline due to the pandemic linger for an extended time, this dilemma will be intensified.

Even under the most favorable conditions, R&D will be increasingly squeezed as it competes for a portion of the vanishing discretionary element of the federal budget – absent large increases in taxes or borrowing or major reductions in entitlements. These observations highlight the

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[41] "R&D Expenditure," Eurostat: Statistics Explained, last modified September 2019, https://ec.europa.eu/eurostat/statistics-explained/index.php/R_%26_D_expenditure.

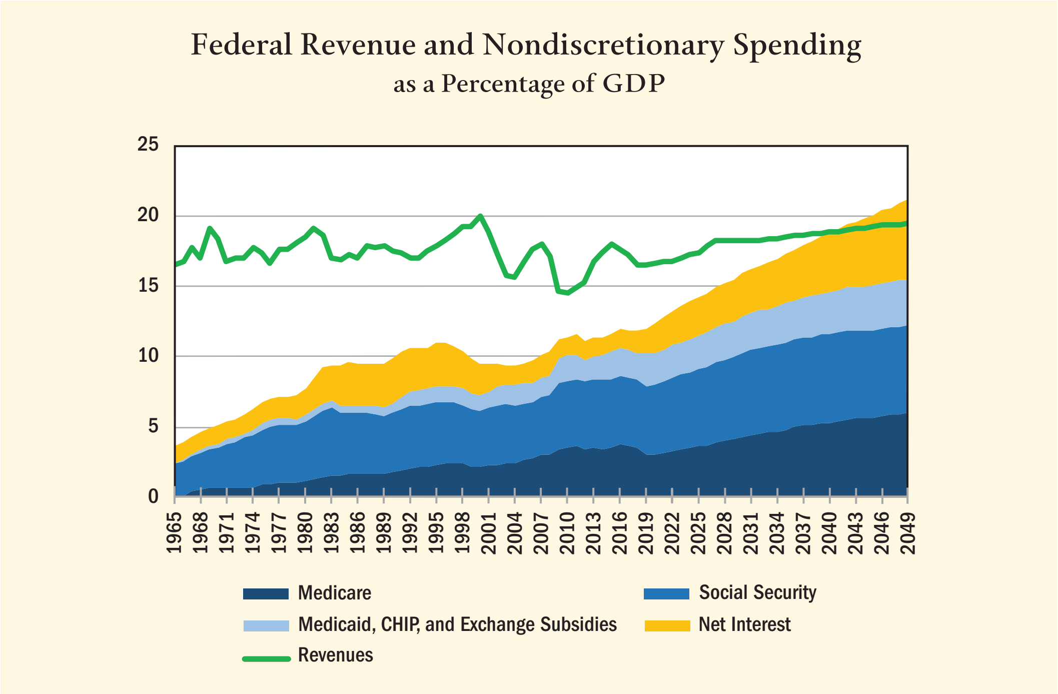

Figure 12

Federal Revenue and Nondiscretionary Spending as a Percentage of GDP

Source: Congressional Budget Office, https://www.cbo.gov/about/products/budget-economic-data, accessed January 23, 2020.

need to establish a national understanding of the importance of research and the impact it has on the standard of living of Americans.

THE PERILS OF COMPLACENCY

Some observers, not unreasonably, ask why the government should fund R&D, particularly when industrial firms (and their stockholders, customers, and employees) are significant beneficiaries. In fact, industry now funds about two-thirds of the nation's R&D and the government funds nearly one-fourth – a complete reversal of shares since the mid-1960s. Accompanying this shift, however, has been a transition in industry investment practice, wherein the highest priority is placed on D (development) rather than R (research). As a result, most of America's great corporate research institutions have declined or been shuttered. The canonical example, Bell Laboratories, the home of nine Nobel Prizes and 15 Nobel laureates, along with the laser and transistor, is now owned by the Finnish company Nokia.[42] Overall support for basic research, which has the potential to be the most transformative research in the long term, has suffered in the United States and is now much more dependent on government or other (nonbusiness) sources of funding such as private philanthropy.

With regard to the translation of research results into marketable products and services, the United States has benefited from a robust private equity market that has made very substantial amounts of capital available to start-up firms. Venture capital investment in U.S. companies was estimated to be over $100 billion in 2018 alone.[43] However, the financial markets upon which innovators depend for resources are also increasingly seeking near-term returns. In the case of corporate equity, shareholders now hold their shares for only about four months rather than the eight years of a few decades ago.[44] In the case of day traders and arbitrageurs, the holding period can frequently be measured in nanoseconds.[45] In such an environment, the government becomes the funder of only resort, the default funder for long-term, high-risk/high-payoff endeavors – such as basic research – that serve the citizenry as a whole but do not necessarily immediately reward the investor or researcher.

China has addressed this issue by establishing sizable government funds to support innovation and making substantial investments in promising American firms that have been unable to obtain domestic funding. In the first half of 2018, China, for the first time, raised more money for venture capital than America.[46] China is investing tens of billions of dollars in arguably the

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[42] "Global Recognition for Groundbreaking Discovery," Nokia Bell Labs, https://www.bell-labs.com/about/recognition/.

[43] Kate Clark, "Venture capital investment in US companies to hit $100B in 2018," *TechCrunch*, October 9, 2018, https://techcrunch.com/2018/10/09/venture-capital-investment-in-us-companies-to-hit-100b-in-2018/.

[44] "Stocks For Rent: Holding Periods At 60-Year Lows," First Fiduciary, https://www.firstfiduciary.com/newsletter/2017/12/19/stocks-for-rent-holding-periods-at-60-year-lows.

[45] John Markoff, "Time Split to the Nanosecond Is Precisely What Wall Street Wants," *New York Times*, June 29, 2018, https://www.nytimes.com/2018/06/29/technology/computer-networks-speed-nasdaq.html.

[46] https://www.scmp.com/tech/article/2153798/china-surpasses-north-america-attracting-venture-capital-funding-first-time.

most important enabling element of the ongoing technological revolution, the semiconductor integrated circuit, through the recent establishment of its Integrated Circuit Investment Fund.[47]

China is, of course, not without its internal challenges. These include large groups of restive citizens in several areas of the country, including dissent in Hong Kong, backlash over constraints on everyday life, gender imbalance, COVID-19, an aging population, an environmental crisis, and slowing economic growth. But the nation's performance over recent decades in innovation through science and technology cannot be denied, and the Chinese government has given no indication that it plans to alter its growth strategy for R&D. In fact, it continues to publicly state its intentions of dominance – and is providing the funds to achieve it. For the United States to embrace an R&D investment strategy that depends on China imploding seems fanciful at best.

The competitive position of the United States in the world is thus poised to shift rapidly in the next several years. Given the enormous scale and rate of progress of Asia, particularly China, the United States will find that reversing its own downward slide will be very difficult. In the world of R&D and innovation, change occurs rapidly. As but one example, Apple's omnipresent iPhone (the quintessential smartphone) has been on the market for only 13 years.

Developments at home and abroad have placed the United States at a precarious "tipping point" regarding its future global competitiveness. America's creation of jobs, its healthcare, national security, and overall quality of life may well hang in the balance. And, with the increased attention being paid to science and technology and rapid growth in R&D funding in other countries, especially China, the urgency is increasing for the United States to respond . . . and respond decisively. The future of the nation depends on taking action to assure a vibrant and productive R&D enterprise. If we ignore this issue, declines in the economic well-being of our citizenry and our ability to influence world affairs will be inevitable.

A FINAL OBSERVATION

If the United States is to continue to be a leader in the increasingly competitive global markets that now characterize the 21st century, the pace of American innovation – translation of discoveries and inventions from laboratory research to products – will have to accelerate. That industry will focus its R&D investments on meeting relatively immediate challenges is understandable and makes it all the more important that the federal government accelerate its own investment in research, especially basic research in all fields of science, engineering,

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[47] Li Tao, "How China's 'Big Fund' Is Helping the Country Catch Up in the Global Semiconductor Race," *South China Morning Post*, May 10, 2018, https://www.scmp.com/tech/enterprises/article/2145422/how-chinas-big-fund-helping-country-catch-global-semiconductor-race.

medicine, and mathematics, encouraging truly bold ideas and funding projects that have a low probability of obvious success at the time of funding but have the potential to be transformative in the long term. Lowering the barriers to industry-university collaboration will then make it much easier for those pathbreaking discoveries to move quickly into applications, including commercial products, markets, economic growth, and high-paying jobs.

To predict, with high confidence, what new capabilities science and technology will bring in the decades ahead is impossible. But to see how different our lives would be today without the contribution of science and technology in past decades is not difficult: no smartphones, high-definition TV, laptops, electric and hybrid cars, magnetic resonance imaging, laser eye surgery, artificial joints, stents, or vaccines for diseases such as polio. Nor would the world have e-commerce, global positioning systems in its cars, or cures for hepatitis C. Without advances in science and technology and without private-sector innovation, the world will not be able to have cleaner power generation, adapt to climate change, or conquer future diseases.

Not every scientific discovery or technological innovation will have its origin in the United States, which makes international scientific cooperation vital to American interests. Protecting America's science and innovation from foreign competitors by closing America's door to cooperation is not the answer. Rather, the answer is for America to accelerate its investment in science and innovation and remain a strong competitor itself. Unless the United States remains a leading contributor to the discovery of new knowledge and has the capacity and the will to translate that knowledge into applications, Americans and America will be left behind, isolated, and increasingly impoverished in a 21st-century world powered by science and technology. A great opportunity will have been lost.

For recommendations to secure America's leadership in science and engineering research, see page 117 of this report.

Chapter 1

Introduction

> *"Many Americans have long been concerned that we [are] mortgaging our children's future with ever-increasing federal budget deficits. Rightly so. We must not, however, foreclose on their future by failing to invest in their education and in the research that will be the basis of their progress."*
>
> – Charles M. Vest, President of MIT, July 18, 1995,
> in a speech to the National Press Club

The bookshelves of policy-makers, scholars, business leaders, and other relevant parties are lined with reports – many excellent ones – on the state of American science, technology, engineering, mathematics, and medicine. These reports are relied upon to find solutions to many of the challenges the nation and world confront, including health, energy, the environment, space exploration, food safety, manufacturing, national and domestic security, the creation of jobs, and the maintenance of a high standard of living. It is appropriate to ask why yet another report – or, in the present case, an update to an earlier report – is needed. The answer lies in the hope that a report such as this one will help stimulate actions desperately needed to invigorate science and technology (S&T) research and innovation in America – before it becomes too late. A leading position in science and technology, once lost, can be exceedingly difficult and costly to regain – if it can be regained at all.

In 2014, the American Academy of Arts and Sciences published *Restoring the Foundation: The Vital Role of Research in Preserving the American Dream*, which argues that scientific research and innovation, which are fundamental to the nation's economy and the creation of quality jobs, as well as to the health, safety, security, and overall prosperity of the American people, are in jeopardy. These are matters that relate to the iconic American Dream, which itself seems endangered. The report cautions that various indicators of the state of America's S&T enterprise and future progress in research and development (R&D) are deeply troubling, and it provides recommended actions to reverse this trend.[48] However, since the release of RtF1, America's relative position in science, technology, and innovation has further eroded, now reaching what can be called, without exaggeration, a "tipping point."

One indicator emphasized in RtF1 as a sign of impending trouble is the rapid decline in the position of the United States relative to other economically developed nations in R&D intensity – national investment (both public and private) in R&D as a fraction of their economies, the latter measured by gross domestic product (GDP). Although this figure is but one important metric for economies that rely on advances in science and technology, it is nevertheless a strong indi-

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[48] "New Models for U.S. Science and Technology Policy," American Academy of Arts and Sciences, https://www.amacad.org/content/Research/researchproject.aspx?d=1276.

cator of national investment and a measurement of the relative amount of economic activity that each dollar invested in R&D must support. Overall, U.S. spending on R&D as a fraction of its economy has stagnated over the past three decades while other countries have increased their investments. As a result, by this measure the United States has dropped from first to tenth among Organisation for Economic Co-operation and Development (OECD) nations, closely matching Finland (Figure 1-1). Meanwhile, China, although beginning from a lower base, has more than quadrupled its investment in R&D over the past two decades. The cumulative impact of these and other trends is examined in detail in this report and provides reason for deep concern regarding America's future well-being.

The rapid drop in global ranking of the United States in R&D as a fraction of GDP reflects government policy-makers, corporate boards, and CEOs focusing on near-term issues at the expense of longer-term, potentially existential issues. This may not be surprising given that politics and business are increasingly driven by short-term incentives. However, given that other countries, particularly China and South Korea, are making strategic, long-term investments in R&D, this trend does not bode well for the future of the United States. China, in particular, is investing to achieve success – if not outright dominance.

Since RtF1 was issued five years ago, much has changed, politically and economically, in the United States and throughout the world, with implications for the future of the United States, its S&T enterprise, and its competitive position in the world. As this report is being published, the COVID-19 pandemic is compounding changes with dramatic implications for America's scientific global leadership.

The United States enjoyed a period of extraordinary accomplishment in science and technology, private-sector innovation, and economic growth following World War II (WWII), moving well ahead as Europe, Japan, and other nations sought to recover from the devastation of that conflict. In his iconic 1945 report *Science – the Endless Frontier*, Vannevar Bush, wartime advisor to Presidents Franklin D. Roosevelt and Harry S. Truman, argued that the kinds of scientific discoveries and innovations that helped win the war would also be important to the country in peacetime.[49]

The decisions of post–WWII presidents, backed by Congress, continued to direct substantial funding to R&D activities in universities and national laboratories, in part due to Cold War policies, thus enabling U.S. industry to deliver the world's strongest economy. But in recent decades, as policy-makers grappled with other serious challenges, often hindered by political distractions, America's focus on science and technology waned. While that should trigger deep concerns regarding America's future, there is little indication that this has been the case. In political debates, science and technology are rarely even mentioned.

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[49] Vannevar Bush, *Science – The Endless Frontier* (Washington, D.C.: GPO, 1945), https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm.

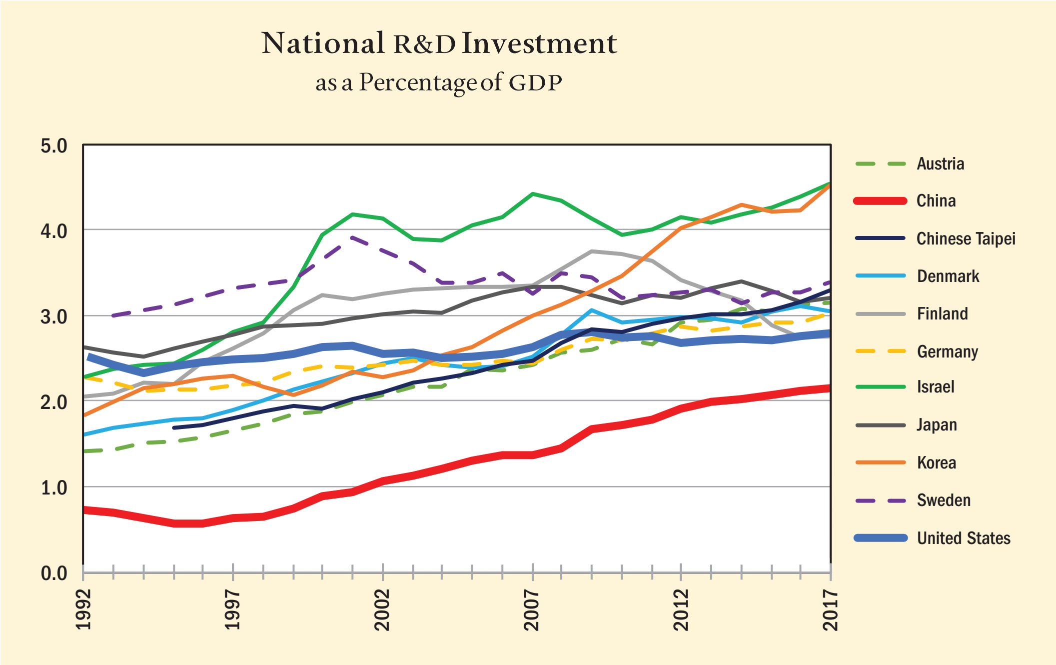

Figure 1-1

National R&D Investment as a Percentage of GDP

Source: OECD. 2019. "Main Science and Technology Indicators," OECD Science, Technology and R&D Statistics (database), https://doi.org/10.1787/data-00182-en.

The purpose of the current report is to remind our nation's leaders of the importance of R&D, particularly the federally funded fundamental research that underpins the nation's overall S&T enterprise and economy; to underscore the risks of failing to address America's deteriorating position in R&D and related policies that impede progress and global competitiveness; and, hopefully, to stimulate action by the nation's leadership that will ensure that all Americans enjoy the benefits of science and technology in the future, just as they today enjoy the benefits of past investments.

If we are to harvest, we must plant seeds. Today, America's seed corn is being consumed.

1.1 WHY NOW?

"As the United States encounters new global realities, policy-makers face a choice: we can compete in the international arena or we can retreat. . . . America can only grow jobs and improve its competitiveness by choosing to compete globally, and that will require renewed focus on innovation, education and investment."

– Craig Barrett, retired CEO of Intel,
January 7, 2004, in reference to the Computer Systems Policy Project

We live in a time of seismic change in America and the world, and much of that change is deeply troubling. It includes the growing challenge of providing citizens with long-term quality jobs that support a high standard of living, ensuring national security, and providing future generations with a sustainable and livable planet. In today's world, scientific progress and technological change will continue to happen with or without the participation of America. But for America to benefit fully, it must remain competitive as a leader in scientific discovery and innovation. The time for action is at hand.

The 21st-Century Innovation Environment

Now is a time of unprecedented opportunity for scientific discovery and rapid progress in technology and its applications. Research discoveries lead to new technologies at an accelerating pace, and these new technologies not only improve quality of life but provide tools that accelerate research discovery. The sciences have been described as undergoing a "revolution" as methods and approaches from scientists and engineers across fields and industries converge to achieve great leaps in scientific achievement.[50] We can see the output of this revolution in advancements in big data, artificial intelligence (AI), machine learning, quantum technology, CRISPR and genomic medicine, medical imaging, robotics, high-performance materials, nanotechnology, and much, much more.

But the United States is now on track to lose its standing as the world leader in science and technology and innovation, and thereby its competitive advantage in global markets and its ability to provide the American people with the benefits of advanced technologies: high-paying jobs, better healthcare, a higher standard of living, and national security. For much of the past 75 years, America relied on its ability to apply its technological advantages to meet its economic and security needs while simultaneously preventing adversaries from illegally accessing the fruits

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[50] *Convergence: The Future of Health* (Washington, D.C.: MIT Washington Office, June 2016), http://www.convergencerevolution.net/s/Convergence-The-Future-of-Health-2016-Report-55pf.pdf.

Advancing Research in Science and Engineering

In 2008, the American Academy of Arts and Sciences published *ARISE (Advancing Research in Science and Engineering)*, a publication focusing on the importance of U.S. investment in early career scientists and transformative research of a high-risk, high-reward nature. That report contains several recommendations that continue to be relevant today. For example, federal agencies should:

- Create or strengthen large, multiyear awards for early career faculty.
- Continue to consider targeted programs, grant mechanisms, and policies – and adapt existing grant programs – to foster transformative research.
- Establish new research programs only if they have enough critical mass to avoid fruitless grant-writing efforts. Grant programs that fund only a tiny percentage of applications are inefficient uses of money, time, and effort.

Advancing Research in Science and Engineering II

In 2013, the American Academy of Arts and Sciences published *ARISE II (Unleashing America's Research and Innovation Enterprise)*, which concludes that moving from intradisciplinary to more integrative, transdisciplinary research and promoting cooperative, synergistic interactions among the academic, government, and private sectors throughout the discovery and development process would bolster U.S. R&D and its impact. Its recommendations include:

- Expand education paradigms to model transdisciplinary approaches. Develop new and support existing graduate and postdoctoral training programs that integrate concepts and technologies across the physical sciences and engineering and the life sciences and medicine.
- Establish one or more "grand challenges" that will motivate alignment, cooperation, and integration of efforts and approaches across academia, industry, and government. The magnitude and potential impact of these challenges should engage the scientific and engineering communities; inspire the next generation of science, technology, engineering, and mathematics students; and capture the public imagination.
- Enhance permeability between industry and academia at all career stages.

of its efforts. In the global innovation and communications environment of the 21st century, fully protecting one's technological advances from breaches of information security is no longer possible. Instead, tomorrow's leading R&D nations will be those that capitalize on new innovations within the short window available to do so, while simultaneously working to anticipate and lead the next new field that emerges. The 21st-century environment will require thinking strategically, focusing on the long term as well as the short term. No nation can be preeminent in every field – strategic thinking and planning is the coin of the realm when limited resources are allocated.

Furthermore, as highlighted in the American Academy report *ARISE II: Unleashing America's Research and Innovation Enterprise* (see sidebar), the very nature of research itself has changed, with a strong convergence of science and engineering (S&E) disciplines and greater emphasis on solving grand societal challenges, such as climate change and the provision of clean energy, safe water, adequate nutrition, and healthcare to an expanding world population.

While many countries in Europe, Asia, and other regions of the globe continue to be strongly engaged in scientific discovery and innovation, China, because of its enormous scale, extraordinary pace of development, work ethic, and commitment to scientific progress, warrants particular attention. China, in its "Made in China 2025" ten-year plan, has openly and candidly stated its intention to dominate in global high-tech manufacturing, including such critical fields as AI, telecommunications, robotics, and computers.[51] China's goal of advancing the quality of life of its people is to be applauded – but for the United States to abandon the very kind of investments that have contributed to its greatness and prosperity is to be lamented and rejected.

America's Future in Question

At the present time, the United States stands number one in the world in overall scientific discovery and innovation and, not coincidentally, has the world's strongest economy and enjoys one of the highest standards of living. Americans benefit from a GDP per capita that is nearly *six times* that of the average person living outside the United States.[52] This is the consequence of investments that have been made over decades past. But today's standing is not a guarantee for the future.

By 2030, China is projected to be the world's largest economy when measured by GDP exchange rates.[53] It is already the largest when measured by purchasing power parity (PPP).[54] By 2026, the 250th anniversary of the United States, China's strategic plan calls for it to be well on its way to becoming the unchallenged world leader in science, technology, and innovation. Today, 50 years after the *Apollo 11* moon landing, America is once again at a tipping point. Even as the present report was being written, China was surpassing the United States in absolute investment in R&D, using PPP (this important converter takes differences in price levels between countries into account to generate a currency conversion).[55]

Previously, the United States was the leading financial investor (public and private) in R&D, with China having rapidly advanced into second place. But the highly regarded National Science

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[51] Wayne M. Morrison, "The Made in China 2025 Initiative: Economic Implications for the United States," Congressional Research Service In Focus, IF10964, last updated April 12, 2019, https://fas.org/sgp/crs/row/IF10964.pdf.

[52] World Bank, 2018, in current US$.

[53] Callum Paton, "World's Largest Economy in 2030 Will Be China, Followed by India, with U.S. Dropping to Third, Forecasts Say," *Newsweek*, January 10, 2019, https://www.newsweek.com/worlds-largest-economy-2030-will-be-china-followed-india-us-pushed-third-1286525.

[54] "GDP, PPP (Current International $)," The World Bank, https://data.worldbank.org/indicator/ny.gdp.mktp.pp.cd?most_recent_value_desc=true.

[55] "Purchasing Power Parities (PPP)," OECD data, https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm.

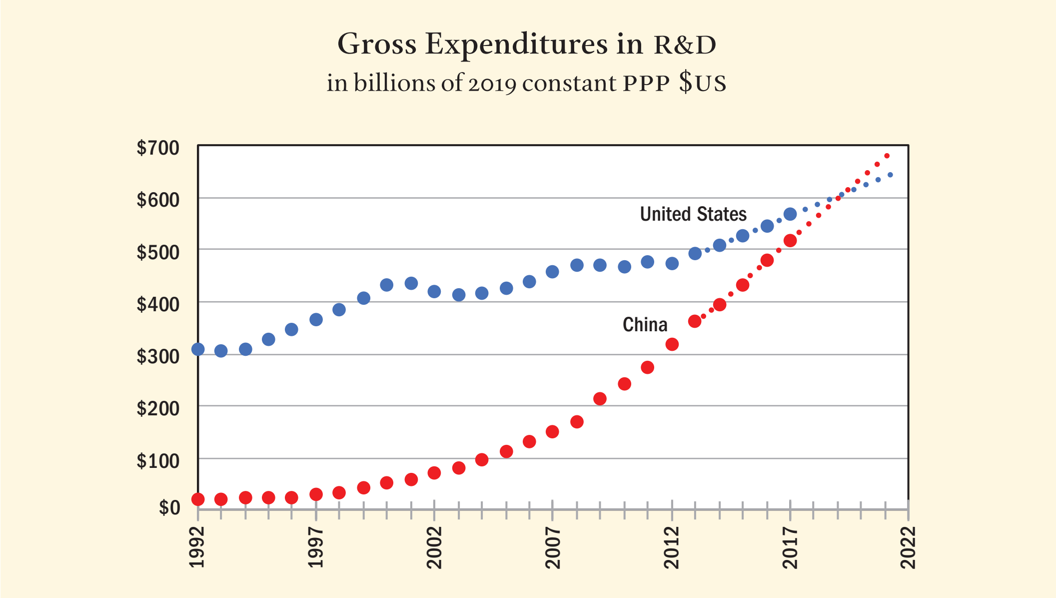

Figure 1-2

Gross Expenditures in R&D in billions of 2019 constant PPP $US

Source: OECD. 2019. "Main Science and Technology Indicators," OECD Science, Technology and R&D Statistics (database), https://doi.org/10.1787/data-00182-en.

Constant dollars are calculated using total nondefense composite outlay deflators found in Table 10-1: Office of Management and Budget. 2019. "Fiscal Year 2020 GDP and Deflators," https://www.whitehouse.gov/omb/historical-tables/.

Note: Dashed lines represent appropriations from the American Recovery and Reinvestment Act of 2009. FY2017 and FY2018 include new definition for R&D, which excludes DOD's late-stage development, testing, and evaluation "development" category, formerly included. Trend lines are linear fit of last five points extended four years.

Board's (NSB) *2018 Science and Engineering Indicators* projected that China would pass the United States in total R&D spending (based on PPP conversion) in or about 2018 (Figure 1-2).[56]

Some critics oppose federally funded research in the United States, arguing that it is neither a public good nor needed.[57] This philosophy usually argues for letting China underwrite research so that the United States can concentrate its investments in downstream development and inno-

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[56] National Science Board, *Science and Engineering Indicators* 2018, NSB-2018-1 (Alexandria, VA: National Science Foundation, 2018), https://nsf.gov/statistics/2018/nsb20181/report. For additional analysis, see Task Force on American Innovation, *Benchmarks 2019: Second Place America? Increasing Challenges to U.S. Scientific Leadership* (Washington, D.C.: Task Force on American Innovation, May 2019), http://www.innovationtaskforce.org/benchmarks2019/.

[57] Terence Kealey, "The Case against Public Science," *CATO Unbound*, August 5, 2013, https://www.cato-unbound.org/2013/08/05/terence-kealey/case-against-public-science; Robinson Meyer, "How Should the U.S. Fund Research and Development?" *The Atlantic*, April 8, 2016, https://www.theatlantic.com/technology/archive/2016/04/us-research-and-development/477435/.

vation. Japan tried that model and found it to be unsustainable.[58] The critics' argument fails for two key reasons. First, in many fields the time between discovery and product introduction is extremely short – and growing shorter – giving the edge to those countries that actually perform the research, form start-up companies to translate discoveries into products, and hire new S&E graduates who are current in the latest technologies. Second, the graduates needed by companies, while students, derive their hands-on skills from working in university laboratories that are largely supported by federal research grants. If federal grant funding diminishes, so do the laboratories along with the scientific and technical education pipeline that is needed to produce a workforce to turn fundamental discoveries into new products and new opportunities.

Additional Constraints

Compounding the threat of the tipping point at which the United States finds itself are the expanding overall budgetary pressures confronting the United States. According to recent Congressional Budget Office (CBO) projections, federal mandatory spending (entitlements and interest on the debt) will soon exceed total federal revenues.[59] Little money will be left for "discretionary" items, such as education, infrastructure, national security, or R&D – other than through substantial tax increases or increases in borrowing – the latter of which concomitantly leads to increased interest to be paid on the debt. In just the five years since RtF1 was published, America's national debt increased from $17.8 trillion to $22.0 trillion – a 24 percent increase.[60]

A number of the challenges facing the U.S. R&D enterprise can be traced to an antiquated system of primary and secondary public education that fails to prepare many, arguably most, young Americans for jobs that increasingly require knowledge and skills in STEM as well as in the arts and humanities. If all Americans had access to quality education and training and could find jobs that were rewarding, the deep, economically based rifts that threaten American society today could also be alleviated.

The United States must intensify efforts to promote diversity, equity, and inclusion in STEM education at all levels to broaden STEM workforce participation among historically underrepresented groups. A majority of Americans belong to such groups due to their gender, race, ethnicity,

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[58] Ichiko Fuyuno, "What Price Will Science Pay for Austerity?" *Nature* 543 (2017): S10 – S15, https://doi.org/10.1038/543S10a.

[59] CBO, *An Update to the Budget and Economic Outlook: 2019 to 2029* (Washington, D.C.: CBO, 2019), https://www.cbo.gov/system/files/2019-08/55551-CBO-outlook-update_0.pdf.

[60] "Historical Debt Outstanding – Annual 2000 – 2019," TreasuryDirect, last updated January 29, 2020, https://www.treasurydirect.gov/govt/reports/pd/histdebt/histdebt_histo5.htm.

sexual orientation, disability, or religion.[61] Presently underrepresented ethnic and racial groups are projected to make up 57 percent of the U.S. population by 2060.[62] If it wants to develop a thriving domestic STEM workforce and compete in the world market for jobs, the United States cannot afford to ignore most of its populace. Improving pre-K–12 public education, including in STEM, should be among the nation's highest priorities.

At the same time, the United States must also prioritize recruiting and retaining foreign talent, including men and women from Asian countries, particularly China, a key source of individuals qualified in STEM fields. Within American universities, approximately 30 percent of graduate students are citizens of other countries, while over half of postdoctoral fellows and approximately 30 percent of S&E faculty are foreign-born.[63] Within the overall U.S. S&T workforce, nearly one-third of workers were born outside of the United States. Immigration is key for industrial innovation – immigrants or their children founded nearly half of U.S. Fortune 500 companies.[64]

> *"If an unfriendly foreign power had attempted to impose on America the mediocre educational performance that exists today, we might well have viewed it as an act of war."*
>
> – President Reagan's 1983 National Commission on
> Excellence in Education, *A Nation at Risk*

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[61] National Science and Technology Council Committee on STEM Education, *Charting a Course for Success: America's Strategy for STEM Education* (Washington, D.C.: National Science and Technology Council, December 2018), https://www.whitehouse.gov/wp-content/uploads/2018/12/STEM-Education-Strategic-Plan-2018.pdf.

[62] Interagency Policy Group on Increasing Diversity in the STEM Workforce by Reducing the Impact of Bias, *Reducing the Impact of Bias in the STEM Workforce: Strengthening Excellence and Innovation* (Washington, D.C.: OSTP and OPM, November 2016), https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/ostp-opm_bias_mitigation_report__20161129.pdf.

[63] National Science Board, *Science and Engineering Indicators 2018*, 2-61 – 2-85, https://www.nsf.gov/statistics/2018/nsb20181/report/sections/higher-education-in-science-and-engineering/graduate-education-enrollment-and-degrees-in-the-united-states; National Science Board, *Foreign-Born Students and Workers in the U.S. Science and Engineering Enterprise* (Washington, D.C.: National Science Foundation, 2018), https://nsf.gov/nsb/publications/2018/foreign-born-one-pager.pdf.

[64] Ian Hathaway, "Almost Half of Fortune 500 Companies Were Founded by American Immigrants or Their Children," *The Avenue*, December 4, 2017, Brookings Institution, https://www.brookings.edu/blog/the-avenue/2017/12/04/almost-half-of-fortune-500-companies-were-founded-by-american-immigrants-or-their-children/.

Meanwhile, America's state-funded institutions of higher education have served as models for the world and educate over 70 percent of American students receiving bachelor's degrees. But in recent decades, especially following the 2008 recession, such institutions have received staggering budget reductions while student loan burdens have increased.[65] From 2008 to 2013, state spending on higher education fell by approximately $20 billion, or 22 percent, and, although spending has increased since 2013, in 2017 it remained 16 percent lower than 2008 spending levels.[66]

Arguably, America's greatest competitive asset, following its traditions of democracy and free enterprise, is its system of great research universities, public and private. That U.S. public colleges and universities no longer be undermined by states disinvesting in higher education is vitally important.[67] Reversing the course of public higher education will require a reordering of priorities at the state level, along with significant growth in federal support for academic research.[68] And while states have been disinvesting in public higher education, the federal government has begun to handicap the nation's leading private universities through such means as taxing the gains on endowments, thereby reducing the funds available for scholarships and research.[69] A "perfect storm" is being created from pre-K through graduate education.

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[65] "State Funding for Higher Education," Humanities Indicators, last updated November 2016, https://www.humanitiesindicators.org/content/indicatordoc.aspx?i=80; Anthony Cilluffo, "5 Facts about Student Loans," *Fact Tank*, August 13, 2019, Pew Research Center, https://www.pewresearch.org/fact-tank/2019/08/13/facts-about-student-loans/.

[66] Michael Mitchell, Michael Leachman, and Kathleen Masterson, "A Lost Decade in Higher Education Funding State Cuts Have Driven Up Tuition and Reduced Quality," Center on Budget Policy Priorities, August 23, 2017, https://www.cbpp.org/research/state-budget-and-tax/a-lost-decade-in-higher-education-funding.

[67] For examples of productive steps that could be taken toward this goal, see *Public Research Universities: Recommitting to Lincoln's Vision – An Educational Compact for the 21st Century* (Cambridge, MA: American Academy of Arts and Sciences, 2016), https://www.amacad.org/publication/public-research-universities-recommitting-lincolns-vision-educational-compact-21st.

[68] National Research Council, *Research Universities and the Future of America: Ten Breakthrough Actions Vital to our Nation's Prosperity and Security* (Washington, D.C.: National Academies Press, 2012), https://doi.org/10.17226/13396.

[69] "What Is the Tax Treatment of College and University Endowments?" Tax Policy Center Briefing Book, https://www.taxpolicycenter.org/briefing-book/what-tax-treatment-college-and-university-endowments.

FOCUS SECTION

Restoring the Foundation Five Years Later

The American Academy of Arts and Sciences report, *Restoring the Foundation: The Vital Role of Research in Preserving the American Dream*, was written by a broadly experienced committee of 25 individuals collectively possessing backgrounds in the domains of academia, industry, and government.

The stated purpose of the RtF1 report was to:

- Remind policy-makers, business and community leaders, and the larger public of the critical role of science, engineering, technology, and innovation in ensuring the nation's security and economy and the health, prosperity, and overall well-being of all Americans – foundational elements of the American Dream.
- Underscore the fact that the discoveries emanating from scientific and engineering research, especially federally funded research carried out in the nation's public and private universities and national laboratories, coupled with industry's strategic R&D investments, fuel the innovation process that delivers goods, services, health, national security, wealth, and jobs to Americans.
- Draw attention to the stark reality that while the United States remains a leader in many aspects of science and technology, most indicators point to future decline and ceding of leadership to other parts of the world, particularly China.

While RtF1 focused on research, emphasizing the unique value of fundamental research, it also spoke to the importance of the total national R&D effort – both public and private. In addition, the report warned that with total U.S. R&D funding – public and private – as a percentage of GDP growing at less than 3 percent per year and China's continuing to grow at 8 percent per year or more, China would surpass the United States in absolute research investment in the immediate future. That day has now arrived.

The RtF1 report was widely promulgated. Members of the committee visited with members of Congress, spoke at congressional hearings, took part in roundtables, made public presentations, and gave media interviews.[70] The American Academy of Arts and Sciences organized events around the country to raise awareness of the report's recommendations, including a panel discussion cosponsored by Rice University's Baker Institute for Public Policy that included Nobel Laureate Steven Chu (a member of the study committee and former secretary of energy under President Barack Obama), and Norman Augustine (cochair of the study committee, former

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[70] For more details, see *Restoring the Foundation: The Vital Role of Research in Preserving the American Dream* (Cambridge, MA: American Academy of Arts and Sciences, September 2014), https://www.amacad.org/publication/restoring-foundation-vital-role-research-preserving-american-dream.

INNOVATION: AN AMERICAN IMPERATIVE

A call to action by American industry, higher education, science, and engineering leaders urging Congress to enact policies and make investments that ensure the United States remains the global innovation leader.

Our nation knows what it takes to innovate: a sustained commitment to scientific research, a world-class workforce, and an economic climate that rewards entrepreneurship and innovation. As the most dynamic and prosperous nation in the world, the United States has long benefitted from policies and investments that have promoted innovation and in turn driven productivity and economic growth, bolstered American trade, ensured our health and national security, and safeguarded the American dream. Our leadership is now at risk because of years of under-prioritizing federal scientific research investments and policies that promote innovation.

Now is not the time to rest on past success. As noted by the American Academy of Arts and Sciences in its 2014 Report *Restoring the Foundation: The Vital Role of Research in Preserving the American Dream*, "There is a deficit between what America is investing and what it should be investing to remain competitive, not only in research but in innovation and job creation." Competitor nations are challenging our leadership by copying our playbook for success. At the same time our nation's support for scientific research and innovation is stagnating. If these trends continue, other countries will soon surpass the United States as the global innovation leader.

We must heed the warnings in the *Restoring the Foundation* report and other salient reports of the past decade and act decisively. In particular, Congress must:

Renew the federal commitment to scientific discovery

by ending sequestration's deep cuts to discretionary spending caps and providing steady and sustained real growth in funding of at least four percent for basic scientific research at: the National Science Foundation, the National Institutes of Health, the Department of Energy's Office of Science, the Department of Defense, NASA, the National Institute of Standards and Technology, USDA, and NOAA;

Make permanent a strengthened federal R&D tax credit

as a part of comprehensive tax reform to encourage more private-sector innovation investment here in America instead of in competitor countries;

Improve student achievement in science, technology, engineering, mathematics (STEM)

through increased funding of proven programs and incentives for science and math teacher recruitment and professional development;

Reform U.S. visa policy

to welcome and keep highly educated international professionals, particularly those holding STEM degrees from U.S. universities;

Take steps to streamline or eliminate costly and inefficient regulations

and practices governing federally funded research to help unburden researchers to focus more time on conducting research and training the next generation of scientists, engineers, health care professionals, and business leaders;

Reaffirm merit-based peer review

as the primary mechanism major federal agencies should employ in making competitive scientific research grants to ensure the most effective use of taxpayer dollars; and

Stimulate further improvements in advanced manufacturing

through support for programs aimed at accelerating manufacturing innovation and new federal-industry-academic partnerships.

We, the signatories, urge support for these actions to keep the United States the global innovation leader. We stand ready to do our part.

Figure 1-3

Innovation: An American Imperative

under secretary of the Army under President Gerald Ford, and retired CEO and chairman of Lockheed Martin Corporation).[71] In addition, RtF1 was cited in a call to action, signed by ten corporate leaders, titled "Innovation: An American Imperative," which called for the enactment of seven key policies or investments – five of which were included in RtF1 – to ensure that

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[71] "Civic Scientist Lecture Series – Restoring the Foundation: Reviving the U.S. Science, Engineering and Technology Enterprise," Baker Institute for Public Policy, https://www.bakerinstitute.org/events/1700/.

the United States remains the global innovation leader (Figure 1-3).[72] Following its release in 2015, the call to action was signed by over 500 leading entities across all sectors of the science, engineering, and technology communities. For the past four years the organizers of this effort have issued an annual progress report outlining actions that have been taken on the imperative's recommendations, as well as areas that remained to be addressed.

Perhaps most notable, members of the RtF1 committee were invited to testify at a hearing of the U.S. Senate Committee on Commerce, Science, and Transportation as that body was considering the 2016 American Innovation and Competitiveness Act (AICA), which would eventually be passed by Congress in late 2016 by unanimous consent and signed into law by President Obama in January 2017. AICA included several recommendations that were espoused by RtF1, the "Innovation: An American Imperative" call to action, and related policy reports from the National Academies of Sciences, Engineering, and Medicine (NASEM) and other organizations. These recommendations included congressional reaffirmation of the value of peer review, reducing regulatory burdens on principal investigators at American universities, and streamlining the grant application process.

RtF1 summarized the challenge facing the nation as follows:

> The American Dream is a national ethos whose foundation is rooted in opportunity: the opportunity for a quality job, a quality life, and a quality education; the opportunity for our children to achieve more than we could and enjoy a better life than we experienced. It imbues the nation with a spirit of hard work and determination. Without opportunity, the Dream fades, and with it goes a key part of our identity as a nation.
>
> These core opportunities are also interconnected: if one fails, the others will follow. Quality of life and well-being rely to a large extent on having a quality job, and both are bound to the health of the nation's economy. Studies have shown that the predominant driver of economic growth over the past half-century has been scientific and technological advancement, the foundation of which is basic, discovery-based research. The federal government is the primary funder of basic research in this country and is the largest reliable source of support for basic research.
>
> Basic research replenishes a pool of knowledge and ideas that grows new products and processes that benefit the American people and strengthen the economy. This process of innovation is not linear, but rather forms a highly interconnected web that engages not only the federal government and universities, but also business, industry, state governments, and philanthropy. If the United States is to take full advantage of this unparalleled period of rapid scientific and technological advancement, then this complex system of research and invention must thrive.

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72. The original call to action and subsequent progress reports are available at *Innovation: An American Imperative,* https://innovation-imperative.herokuapp.com/index.html. The "Innovation Imperative" organizers include the American Association for the Advancement of Science, the Association of American Universities, the Association of Public and Land-grant Universities, Battelle, the Coalition for National Science Funding, the Coalition for National Security Research, the Council on Competitiveness, the Energy Sciences Coalition, the Task Force on American Innovation, The Science Coalition, and United for Medical Research, in addition to the American Academy of Arts and Sciences.

Chapter 2

Science and Technology Matters

> *"As long as they [publicly and privately supported colleges, universities, and research institutes] are vigorous and healthy and their scientists are free to pursue the truth wherever it may lead, there will be a flow of new scientific knowledge to those who can apply it to practical problems in Government, in industry, or elsewhere."*
>
> – Vannevar Bush in "Science, the Endless Frontier,"
> report to President Truman, July 1945

Today, the products that result from the application of research performed by scientists and engineers are ubiquitous in Americans' daily lives – so much so as to often go unnoticed, even by the very people who are the beneficiaries of such effort. Pressing a button makes homes warmer or colder; another button turns darkness into light; yet another provides mobility; and still others permit speaking with friends throughout the world, accessing the world's libraries, navigating travels, and shopping from living rooms. Taking a pill or injection can prevent malaria, polio, smallpox, flu, diphtheria, measles, and hepatitis A and B – other treatments can cure hepatitis C, pneumonia, and even some cancers.

None of these advancements simply "happened." Behind each were scientists seeking to better understand the universe and engineers seeking to invent the future. Both are dependent upon the field of mathematics: the language of scientists and engineers. And none would exist today had government policy-makers, private entities, and individual citizens in earlier decades not invested in research.

Today, the pace of S&T discovery is accelerating. Most of today's everyday comforts first appeared within the past century – even though human beings have walked the face of planet Earth for some 200,000 years. The case has been made that there has been more scientific discovery in the past 75 years than in all prior history. Each passing generation now seems to generate more knowledge than the one that preceded it. Today, leadership in science and technology is measured in months or years, not decades or centuries. For example, the time between doubling the computing power on that critical element of virtually all modern electronic devices – the semiconductor integrated circuit – is just a small number of years.[73] The half-life of articles published in scientific journals, as measured by the frequency at which they are referenced, is

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[73] "Moore's Law and Intel Innovation," Intel, https://www.intel.com/content/www/us/en/history/museum-gordon-moore-law.html.

five years or less in many fields.[74] The iPhone entered the market just thirteen years ago.[75] To fall behind even a few years in S&T R&D can have grave consequences. And if one's educational system simultaneously fails, catching up becomes exceedingly difficult, if possible at all.

X-ray machines were not made feasible by physicians seeking to peer inside the human body. They were made possible by Wilhelm Röntgen testing cathode ray properties and noticing an unpredicted glow.[76] Penicillin was not discovered by companies seeking a way to fight disease; it was made possible by Alexander Fleming performing fundamental research unrelated to antibiotics.[77] Studies of the chemistry of butterfly wings led to a treatment for cancer.[78] Investigations of seals diving below the Antarctic ice shelf led to a discovery that made lung surgery safer.[79] Studies of jellyfish have led to the development of new pharmaceuticals.[80] Such is the character of the creation of knowledge.

But while fundamental research can, and frequently does, lead to important new inventions, the path is often indirect and can be time-consuming. The uncertainty that surrounds the outcome of research, particularly fundamental research, coupled with the sometimes long-term nature of its payoff, makes it difficult for such an endeavor to compete for funds that could otherwise be devoted to fulfilling short-term needs. But polio was not conquered by finding ways to more efficiently produce iron lungs; it was conquered by researchers such as Jonas Salk and Albert Sabin diligently working in their laboratories to discover a means of preventing polio.[81]

Four ingredients are essential for innovation to flourish: knowledge, capable people, an ecosystem conducive to research and innovation, and the provision of adequate funding to support all of the above. Because of their longer-term payoffs, investments in research and education,

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[74] John Bohannon, "The Secret Half-Lives of Scientific Papers," *Science*, December 19, 2013, https://www.sciencemag.org/news/2013/12/secret-half-lives-scientific-papers.

[75] Ben Gilbert, "It's Been over 12 Years since the iPhone Debuted," *Business Insider*, July 22, 2019, https://www.businessinsider.com/first-phone-anniversary-2016-12.

[76] "Medical Milestones: Invention of the X-Ray," *UMHS Endeavour*, November 5, 2014, https://www.umhs-sk.org/blog/medical-milestones-invention-x-ray/.

[77] "Discovery and Development of Penicillin," ACS, https://www.acs.org/content/acs/en/education/whatischemistry/landmarks/flemingpenicillin.html.

[78] Edward C. Taylor, "From the Wings of Butterflies: The Discovery and Synthesis of Alimta," *Chemistry International* 33 (5) (September – October 2011), http://publications.iupac.org/ci/2011/3305/1_taylor.html.

[79] Amanda Schaffer, "Dr. Adventure," *MIT Technology Review*, June 17, 2014, https://www.technologyreview.com/s/527986/dr-adventure/.

[80] Press release, Royal Swedish Academy of Sciences, October 8, 2008, https://www.nobelprize.org/prizes/chemistry/2008/press-release/.

[81] Gilbert King, "Salk, Sabin and the Race against Polio," *Smithsonian Magazine*, April 3, 2012, https://www.smithsonianmag.com/history/salk-sabin-and-the-race-against-polio-169813703/.

despite their enormous importance, can appear unattractive in the competition for funds under the two-year political cycle of government, the one-year federal budgeting process, and the next-quarter fixation of many of today's businesses.

2.1 S&T IMPACTS: WHERE SCIENCE AND ENGINEERING HAVE MADE A DIFFERENCE

> *"You can draw a line from today's technologies – everything from barcodes to cellphones to MRI machines to life-saving drugs, to the Internet and Google – all the way back to a moment when someone simply wondered why and decided to figure it out."*
>
> – France A. Córdova, Director of the National Science Foundation

> *"We have to feed seven to ten billion people. We have to get them water that's potable and clean. We have to be able to move them around in some kind of reasonably efficient way. . . . There is not one thing . . . that I just mentioned, not one, that you can solve without a good STEM team around it."*
>
> – Ursula Burns, former CEO of Xerox[82]

Examples of science and technology affecting American lives today are omnipresent. A healthy economy is the necessary underpinning of virtually everything the United States undertakes, from providing national and homeland security to building infrastructure, from assuring healthcare to promoting human happiness.[83] Economic studies have found that much of the growth in U.S. GDP is attributable to progress in just two closely related fields –

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[82] Taylor Dunn, "Former Xerox CEO Ursula Burns on Importance of STEM and Joining Uber's Board," ABC News, October 25, 2017, https://abcnews.go.com/Business/xerox-ceo-ursula-burns-importance-stem-joining-ubers/story?id=50694553.

[83] The Global Values Survey asked, "How important is 'work' in your life?" In country after country, 88 percent responded that it is either important or very important. "WVS Wave 6 (2010–2014)," World Values Survey, http://www.worldvaluessurvey.org/WVSDocumentationWV6.jsp.

science and technology.[84] Job growth, closely correlated with GDP growth, in a modern society depends heavily on investments in research and technology. In many cases, R&D and manufacturing are closely linked and even colocalized, directly connecting R&D activities with jobs and wealth creation in a region.[85]

One of the 2018 Nobel Prizes in Economics went to the American economist Paul Romer "for his life's work, which is centered on how new ideas – born through technology, encouraged by patents, and spurred on by healthy competition – can drive sustainable, long-term economic growth."[86]

Romer's "endogenous growth theory" builds on the earlier work of Robert Solow (1987 Nobel Prize in Economics), explicitly recognizing the vital role advancing technology has in fueling sustained economic growth and rejecting the traditional notion of production as the major economic driver. In a 2007 interview, Romer invoked a physics analogy to explain the role of scientific discovery and R&D activity in shaping technology: "We don't really produce anything. Everything was already here, so all we can ever do is rearrange things. Think of conservation of mass. We've got the same amount of stuff we've always had, but the world is a nicer place to live in because we've rearranged it."[87] Other current studies of the direct impact of R&D also demonstrate large economic returns on R&D investments.[88]

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[84] C.I. Jones, "The Facts of Economic Growth," in *Handbook of Macroeconomics*, vol. 2 (Amsterdam: Elsevier, 2016), https://doi.org/10.1016/bs.hesmac.2016.03.002; Robert Solow, "Technical Change and the Aggregate Production Function," *Review of Economics and Statistics* 39 (3) (1957): 312 – 320, https://doi.org/10.2307/1926047.

[85] Mikko Ketokivi and Jyrki Ali-Yrkkö, "Unbundling R&D and Manufacturing: Postindustrial Myth or Economic Reality?" *Review of Policy Research* 26 (1 – 2) (2009): 35 – 54, https://doi.org/10.1111/j.1541-1338.2008.00368.x; Inge Ivarsson, Claes Alvstam, and Jan-Erik Vahlne, "Global Technology Development by Colocating R&D and Manufacturing: The Case of Swedish Manufacturing MNEs," *Industrial and Corporate Change* 26 (1) (February 2017): 149 – 168, https://doi.org/10.1093/icc/dtw018.

[86] Hilary Brueck, "Economist Paul Romer Just Won the Nobel Prize in Economics," *Business Insider*, October 8, 2018, https://www.businessinsider.com/paul-romer-nobel-prize-in-economics-endogenous-growth-theory-2018-10; "Yale's Nordhaus and NYU's Romer Win Nobel Economics Prize for Work on Climate and Tech Innovation," CNBC, October 8, 2018, https://www.cnbc.com/2018/10/08/nobel-prize-for-economics-goes-towilliam-nordhaus-and-paul-romer.html.

[87] Russell Roberts, "An Interview with Paul Romer on Economic Growth," The Library of Economics and Liberty, November 5, 2007, https://www.econlib.org/library/Columns/y2007/Romergrowth.html.

[88] Luisa Blanco, James Prieger, and Ji Gu, "The Impact of Research and Development on Economic Growth and Productivity in the U.S. States," Pepperdine University School of Public Policy Working Papers, no. 48, 2013, https://digitalcommons.pepperdine.edu/cgi/viewcontent.cgi?article=1047&context=sppworkingpapers.

In addition to producing a vibrant economy, science and technology has affected American lives through improved health and medicine, stronger national defense and security, lower-cost energy with renewable sources, improved availability of food and clean water, instant communication and access to information through the Internet and Web, and better understanding of the natural world and *Homo sapiens* both as individuals and collectively.

Health and Medicine. At the beginning of the 20th century, life expectancy at birth in the United States was 47 years.[89] By 2010, it had increased to 79 years.[90] Not all the gain was due to biomedical research, although much of it was attributable to such medical breakthroughs as antibiotics, stents, artificial joints, statins, computerized tomography (CT) scans, magnetic resonance imaging (MRI), targeted cancer therapies, and vaccines.[91] Other important advancements that have affected the quality and duration of human life are improved public health services and disease eradication programs, including enhanced sanitation, access to clean water, and control of disease-bearing organisms such as mosquitoes.[92] Furthermore, water treatment and sanitation practices have virtually eliminated the majority of water-borne diseases in the United States that were once among the scourges of humanity. None of these benefits could have been realized were it not for early investments in fundamental research. The same can be said of the control and prevention of COVID-19.

Defense and Security. The United States maintains only the third-largest military force in the world, behind China and India. If paramilitary units are included, the United States drops to seventh place.[93] Secretary after Secretary of Defense has stated that the margin of victory in combat for U.S. forces depends substantially upon technological superiority. Technological breakthroughs have impacted the outcome of battles from the time of the stirrup and the longbow to today's era of stealth, night vision, digital computers, ballistic missiles, and nuclear submarines. Perhaps the most dramatic example in recent decades of the effect of technological superiority in combat is Desert Storm, conducted in 1991 to eject Iraqi military forces from Kuwait.[94] In that conflict, the United States and its allies defeated the world's fourth-largest

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[89] "Health, United States, 2017 – Data Finder," Centers for Disease Control and Prevention, last updated August 9, 2018, https://www.cdc.gov/nchs/hus/contents2017.htm?search=Life_expectancy.

[90] Ibid.

[91] Eileen M. Crimmins, "Lifespan and Healthspan: Past, Present, and Promise," *The Gerontologist* 55 (6) (2015): 901 – 911, https://doi.org/10.1093/geront/gnv130.

[92] "Report on the Environment: Health Status," EPA, last updated September 4, 2018, https://www.epa.gov/report-environment/health-status#importance.

[93] International Institute for Strategic Studies, *The Military Balance 2018* (London: Routledge, 2018).

[94] Kris Osborn, "Stealth, GPS, 'Smart Bombs' and More: How Desert Storm Changed Warfare Forever," *The National Interest*, November 21, 2016, https://nationalinterest.org/blog/the-buzz/stealth-gps-smart-bombs-more-how-desert-storm-changed-war-18477.

army in a ground war that lasted 100 hours. The outcome was heavily dictated by U.S. forces possessing the ability to see in the dark, fly aircraft invisible to enemy radars, monitor enemy forces from space, and place guided precision weapons within inches of their intended targets – all products of American R&D.

To ensure its homeland security and protect against future attacks, such as that which occurred on 9/11, the United States requires massive data-processing capabilities, advanced sensors, and near-instantaneous communications. Rapid progress in computing and information technology is critical to effective cybersecurity of digital networks and communications entities.[95]

Energy and the Environment. Advancements in photovoltaics and aerodynamics have enabled the cost-effective application of solar energy and wind energy to the clean generation of electricity. Even more impactful has been the development of hydraulic fracking, a technology that has allowed the United States to increase its domestic production of energy, reducing its import of oil from the Middle East and the economic and geopolitical constraints associated therewith. The increased use of natural gas over the past decade (from 12 percent of power in 2007 to over 21 percent of power in 2017) has reduced the emission of carbon dioxide per unit of energy produced, as compared with oil and coal, by 30 percent and 44 percent, respectively.[96] Hydraulic fracturing, which produces shale-derived natural gas, was made feasible by research conducted in both industry and federal laboratories on three-dimensional seismology and horizontal drilling.[97] While hydraulic fracturing is not without its detractions – the natural gas it produces, while much cleaner than coal or oil, is still polluting and finite, and concerns persist over groundwater contamination – it has purchased the world time to develop critically needed sources of truly clean, sustainable, affordable energy, all of which will require advanced technology. Achieving a low-carbon future is an urgent and enormous challenge. Without R&D and innovation, any response to this challenge will fall short.

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[95] Arbia Riahi Sfar et al., "A Roadmap for Security Challenges in the Internet of Things," *Digital Communications and Networks* 4 (2) (2018): 118 – 137, https://www.sciencedirect.com/science/article/pii/S2352864817300214.

[96] "Electricity and a Changing Climate: Kenneth B. Medlock III: Testimony," Baker Institute for Public Policy, https://www.bakerinstitute.org/research/testimony-electricity-sector-changing-climate/.

[97] "Shale Research and Development," U.S. Department of Energy, Office of Fossil Energy, https://www.energy.gov/fe/science-innovation/oil-gas-research/shale-gas-rd.

Food and Agriculture. In the year 1900, 38 percent of America's workforce was committed to agriculture.[98] In 2018, that share of the workforce was only 1.6 percent.[99] Satellite imaging; weather sensing, modeling, and prediction; and high-resolution seed, fertilizer, and water allocation have enabled the development of data-driven agriculture, and advancements in machinery, seed, and weed and pest control have increased the per acre yield of many crops – with excess production available to help feed parts of the rest of the world.[100] As but one example of increased harvests, corn yield in the United States increased almost seven-fold from 1920 to 2018, jumping from 26 to 176 bushels per acre.[101] Over half of the planted arable land in the United States produces crops that have been engineered to give high yields with much lower herbicide use.[102]

Information Technology. In its 2000 assessment of the 20th century's most important engineering developments, the National Academy of Engineering (NAE) ranked electrification of the country in first place.[103] The NAE cited the magnitude of the social changes fostered by electrification, including freeing a large segment of the population from the daily chores that once were required to sustain family life.

Today, few Americans can imagine life without television, the Internet, the Global Positioning System (GPS), smartphones, laptop computers, online shopping, search engines, and the engineered materials enabling many of these systems – each of which is the product of R&D underpinned by decades of government-funded basic research.

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[98] Bureau of the Census, *Historical Statistics of the United States 1789 – 1945: A Supplement to the Statistical Abstract of the United States* (Washington, D.C.: GPO, 1949), https://www2.census.gov/prod2/statcomp/documents/HistoricalStatisticsoftheUnitedStates1789-1945.pdf.

[99] "Employment in Agriculture (% of Total Employment) (Modeled ILO Estimate) – United States," The World Bank, https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS?end=2018&locations=US&start=1991&view=chart&year=1991.

[100] David Hest, "Satellite Imagery Boom for Farming," *Farm Progress*, May 12, 2014, https://www.farmprogress.com/precision-farming/satellite-imagery-boom-farming; Sjaak Wolfert et al., "Big Data in Smart Farming – A Review," *Agricultural Systems* 153 (May 2017): 69 – 80, https://doi.org/10.1016/j.agsy.2017.01.023; Guy Sela, "Fertigation as a Precision Agriculture Tool," *PrecisionAg*, August 14, 2018, https://www.precisionag.com/in-field-technologies/irrigation/fertigation-as-a-precision-agriculture-tool/.

[101] USDA, *Crop Production: 2018 Summary* (Washington, D.C.: USDA, February 2019), https://www.nass.usda.gov/Publications/Todays_Reports/reports/cropan19.pdf; "Average Crop Yields, U.S. and Missouri, 1950 – 2011," http://agebb.missouri.edu/mgt/cropyldsmous.pdf.

[102] ISAAA, *Global Status of Commercialized Biotech/GM Crops in 2017: Biotech Crop Adoption Surges as Economic Benefits Accumulate in 22 Years*, ISAAA Brief no. 53 (Ithaca, NY: ISAAA, 2017), http://www.isaaa.org/resources/publications/briefs/53/download/isaaa-brief-53-2017.pdf.

[103] George Constable et al., *A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives* (Washington, D.C.: Joseph Henry Press, 2003), https://doi.org/10.17226/10726.

Understanding Our World. Historically, fundamental understandings of the world have been enhanced by curiosity-driven science. Researchers sequenced the DNA of the human genome, detected new elementary particles (e.g., the Higgs boson), and verified the existence of gravitational waves.[104] The space program, in addition to being a source of national pride and inspiration, increased human understanding of the history and potential future of Earth, along with that of its neighbors and indeed the universe. Research has provided vital information on the depletion of the ozone layer and the impact of greenhouse gases, thereby enabling actions to ameliorate the adverse consequences of these phenomena.[105]

In recent years, America's contribution to bringing about such remarkable advancements has been accomplished with an investment in R&D (including both public and private sources) of about 2.7 percent of the nation's GDP.[106] America's total investment in fundamental research today (0.2 percent of GDP) is roughly equal to national spending on cigarettes, about three-fourths of public spending on the purchase of illegal drugs, and about one-third of spending on alcoholic beverages.[107]

2.2 THE GOOD, THE BAD, AND THE UGLY

> *"Most of the threats we face come from the progress we've made in science and technology. We are not going to stop making progress, or reverse it, so we must recognize the dangers and control them. I'm an optimist, and I believe we can."*
>
> – Stephen Hawking, *Radio Times*, January 2016

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[104] "What Is the Human Genome Project?" National Human Genome Research Institute, https://www.genome.gov/12011238/an-overview-of-the-human-genome-project/; "The Higgs Boson," CERN, https://home.cern/science/physics/higgs-boson; "What are Gravitational Waves?" LIGO, https://www.ligo.caltech.edu/page/what-are-gw.

[105] "Research – Ozone Depletion," NOAA Earth System Research Laboratory, Global Monitoring Division, https://www.esrl.noaa.gov/gmd/about/research.html.

[106] "Historical Trends in Federal R&D," American Association for the Advancement of Science, https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd.

[107] "Economic Trends in Tobacco," Centers for Disease Control and Prevention, last updated July 23, 2019, https://www.cdc.gov/tobacco/data_statistics/fact_sheets/economics/econ_facts/index.htm; Gregory Midgette et al., *What America's Users Spend on Illegal Drugs*, 2006 – 2016 (Santa Monica, CA: RAND Corporation, 2019), https://www.rand.org/pubs/research_reports/RR3140.html; "Research Takes Cents," Research America, https://www.researchamerica.org/advocacy-action/research/research-takes-cents.

> *"If knowledge can create problems, it is not through ignorance that we can solve them."*
>
> – Isaac Asimov, *Asimov's Guide to Science*, 1972

No discussion of the contributions of science and technology would be complete without acknowledging the adverse consequences that can sometimes result from the application of scientific discoveries. Virtually every new innovation since human beings first made use of fire could, if misused, have significant adverse consequences for humanity. Genetic engineering can lead to the prevention and cure of illnesses, but in the hands of terrorists it can be used for biological warfare.[108] Nuclear fission can provide a massive source of low-carbon electric power, but it can also contribute to nuclear proliferation and destruction on a massive scale.[109] Machine learning can permit medical researchers to process enormous amounts of data to identify cures for diseases, but it can also threaten individual privacy.[110] Robotics can remove the drudgery of many jobs, but it can also eliminate many jobs.[111]

Scientific discovery and technological innovation will continue with or without the United States. The critical question is whether human beings will take the steps that are needed to enjoy the benefits of S&T advancements while controlling their potentially harmful consequences. Those nations at the leading edge of scientific progress are likely to be best placed to ensure the control and application of scientific discovery for the benefit of humanity.

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108. National Research Council, *Biotechnology Research in an Age of Terrorism* (Washington, D.C.: National Academies Press, 2004), https://doi.org/10.17226/10827.

109. Charles D. Ferguson, "Proliferation Risks of Nuclear Power Programs," NTI, December 1, 2007, https://www.nti.org/analysis/articles/risks-nuclear-power-programs/.

110. Stephen J. Mooney and Vikas Pejaver, "Big Data in Public Health: Terminology, Machine Learning, and Privacy," *Annual Review of Public Health* 39 (April 2018): 94–112, https://doi.org/10.1146/annurev-publhealth-040617-014208.

111. Mark Muro, Robert Maxim, and Jacob Whiton, "Automation and Artificial Intelligence: How Machines Are Affecting People and Places," Brookings Institution, January 24, 2019, https://www.brookings.edu/research/automation-and-artificial-intelligence-how-machines-affect-people-and-places/.

2.3 THE PAST IS PROLOGUE: FUTURE CHALLENGES FOR SCIENCE AND TECHNOLOGY

> *"The genomic revolution, the computational revolution, the acceleration of discovery in so many fields make this an age that rivals the 17th century's Scientific Revolution in its promise for new understanding and human betterment. It would be worse than a tragedy to waste this moment full of promise, to leave answerable questions unanswered. It is all of our responsibility to ensure that this does not happen."*
>
> – Drew Gilpin Faust, former President of Harvard University,
> to the American Association for the Advancement of Science, 2013

Past S&T innovations have contributed much to alleviate human suffering and improve the overall quality of life. That the formidable problems that beset America and the world today can be resolved without major contributions from R&D and its applications is difficult to imagine. Some of the daunting challenges include:

Improving the Nation's Health. Advancements in such fields as genomics, vaccines, AI, and regenerative medicine offer the potential to greatly reduce the impact of existing and potential diseases. U.S. citizens now devote 17.9 percent of the nation's GDP to healthcare.[112] Per capita healthcare spending in the United States in 2016 was $9,892, which was 25 percent higher than second-place Switzerland and 145 percent higher than the OECD median.[113]

Research now underway on the prevention and cure of diseases offers the possibility that costs can be reduced while further alleviating human suffering, but challenges remain to making new technologies accessible (physically and financially). Genomic medicine is allowing doctors to understand the genetic basis of disease and predict susceptibility but, by its very nature, is also giving rise to questions about how to ensure that genetic and overall health information remains private.[114] Regenerative medicine – using stem cells to replace diseased or injured cells, tissue,

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[112] "National Health Expenditure Data: Historical," Centers for Medicare and Medicaid Services, last updated December 17, 2019, https://www.cms.gov/Research-Statistics-Data-and-Systems/Statistics-Trends-and-Reports/NationalHealthExpendData/NationalHealthAccountsHistorical.html.

[113] Gerard F. Anderson, Peter Hussey, and Varduhi Petrosyan, "It's Still the Prices, Stupid: Why the U.S. Spends So Much on Health Care, and a Tribute to Uwe Reinhardt," *Health Affairs* 38 (1) (2019): 87, https://www.healthaffairs.org/doi/pdf/10.1377/hlthaff.22.3.89.

[114] Karen Norrgard, "Protecting Your Genetic Identity: GINA and HIPAA," *Nature Education* 1 (1) (2008): 21, https://www.nature.com/scitable/topicpage/protecting-your-genetic-identity-gina-and-hipaa-678/.

or organs – will give patients with chronic diseases or debilitating injuries new hope, but this technology requires monitoring patients for decades to make certain that the new cells do not themselves become defective in new ways.[115]

Further, growth in worldwide travel has increased the danger of global pandemics. In 2014, two people – a Liberian national and an American doctor – were diagnosed with Ebola after traveling to the United States, and several more Ebola patients were medically evacuated to the United States.[116] Meanwhile, the United States had more than 1,000 cases of measles in the first six months of 2019 alone – already the highest single-year total since the disease was declared eradicated in the United States in 2000.[117] While the leading factor in measles outbreaks was the refusal of some parents to vaccinate their children, most cases were linked to infectious individuals traveling from one of more than 75 countries.[118] As this report goes to print, COVID-19 is upending daily life across the planet. The ability to respond quickly to such threats will have its foundation in biomedical and public health research – past, present, and future.

Energy Security and Protecting the Earth's Environment. Climate change is projected to produce increased inland flooding, wildfires, extreme weather, drought, heat waves, and sea-level rise, along with mass human migration and concomitant conflict.[119] The past ten years have witnessed multiple $100 billion hurricanes and $15 billion flooding events within the United States.[120] R&D will be vital in mitigating and adapting to climate change and severe weather events. R&D will be required to develop advanced techniques for controlling carbon emissions; removing existing carbon from the atmosphere; providing clean, affordable, sustainable energy through efficient solar and wind systems and, ultimately, nuclear fusion; production of plastics

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[115] "Regenerative Medicine," NIH Research Portfolio Online Reporting Tools, https://archives.nih.gov/asites/report/09-09-2019/report.nih.gov/nihfactsheets/ViewFactSheetcodo.html?csid=62&key=R#R.

[116] Sydney Lupkin, "Ebola in America: Timeline of the Deadly Virus," ABC News, November 17, 2014, https://abcnews.go.com/Health/ebola-america-timeline/story?id=26159719.

[117] "Measles Cases and Outbreaks," Centers for Disease Control and Prevention, last updated January 6, 2020, https://www.cdc.gov/measles/cases-outbreaks.html.

[118] Ibid.; "Fever Pitch: Measles Outbreaks in America Are Getting Harder to Contain," *The Economist*, March 9, 2019, https://www.economist.com/graphic-detail/2019/03/09/measles-outbreaks-in-america-are-getting-harder-to-contain.

[119] *Climate Change, Natural Disasters, and Wildlife* (Reston, VA: National Wildlife Federation, November 2019), https://www.nwf.org/-/media/Documents/PDFs/Environmental-Threats/Climate-Change-Natural-Disasters-fact-sheet.ashx.

[120] "Billion-Dollar Weather and Climate Disasters: Table of Events," NOAA National Centers for Environmental Information, https://www.ncdc.noaa.gov/billions/events/US/2009-2018; "Weather Disasters and Costs," NOAA Office for Coastal Management, https://coast.noaa.gov/states/fast-facts/weather-disasters.html.

from non-oil, biodegradable sources; and production of fuel from sunlight.[121] Similarly, R&D can provide more-efficient means of energy storage, with applications ranging from handheld devices to vehicles to grid-scale systems. All-electric vehicles, powered by electricity generated from clean sources, will greatly reduce atmospheric pollution now attributable to internal combustion engines.

Feeding the Earth's Population and Providing Fresh Water. Today, 821 million people are undernourished, and changing climate and COVID-19 are likely to magnify that number significantly.[122] R&D on engineered crops and other means of further enhancing yields could help alleviate this situation. Additional R&D could improve safety from pests, pathogens, and spoilage of foods during transport.[123] In general, R&D will be essential for generating a circular economy for food and reuse of water in a context where 30 – 40 percent of food worldwide is wasted and aquifers are depleted.[124]

Increasing demand for water as well as increasing desertification due to rising global temperatures will further strain supplies of fresh water for significant segments of humanity. Aging dams provide a similar challenge. More-efficient means of desalination will depend on the development of advanced sources of safe, clean, affordable, and sustainable energy.[125] The efficient movement of fresh water from source to user will represent yet another engineering challenge.[126]

Fixing Transportation and Infrastructure. Each year, 1.25 million people, including more than 30,000 Americans, die in automobile accidents – over 90 percent due to driver error.[127] Road fatalities in the United States could be significantly reduced by transitioning to automated

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[121] For more examples, see "NAE Grand Challenges for Engineering," National Academy of Engineering, http://www.engineeringchallenges.org/.

[122] FAO et al., *The State of Food Security and Nutrition in the World 2018: Building Climate Resilience for Food Security and Nutrition* (Rome: FAO, 2018), http://www.fao.org/3/I9553EN/i9553en.pdf.

[123] FAO, *Global Food Losses and Food Waste – Extent, Causes and Prevention* (Rome: FAO, 2011), http://www.fao.org/3/a-i2697e.pdf.

[124] "Save Food: Global Initiative on Food Loss and Waste Reduction," FAO, http://www.fao.org/save-food/resources/keyfindings/en/; Cheryl Katz, "As Groundwater Dwindles, a Global Food Shock Looms," *National Geographic*, December 22, 2016, https://www.nationalgeographic.com/news/2016/12/groundwater-depletion-global-food-supply/.

[125] Menachem Elimelech and William A. Phillip, "The Future of Seawater Desalination: Energy, Technology, and the Environment," *Science* 333 (6043) (2011): 712 – 717, https://doi.org/10.1126/science.1200488.

[126] Rosie Spinks, "Could These Five Innovations Help Solve the Global Water Crisis?" *The Guardian*, February 13, 2017, https://www.theguardian.com/global-development-professionals-network/2017/feb/13/global-water-crisis-innovation-solution.

[127] "Global Health Observatory Data: Road Traffic Deaths," World Health Organization, https://www.who.int/gho/road_safety/mortality/en/; National Highway Traffic Safety Administration, https://cdan.nhtsa.gov/stsi.htm.

(driverless) vehicles – including heavy-duty trucks – given adequate investment in R&D.[128] In addition, of the more than 600,000 bridges in the United States, 54,000 need substantial repairs that will often involve advanced materials and newly developed construction techniques.[129]

Providing Quality Education. A critical area in which the United States lags the rest of the developed world is public pre-K–12 education, particularly in STEM. Breakthrough uses of AI, personalized computer-aided learning, and improved voice recognition show promise in helping to reverse this situation.[130] Education is significantly linked with health and wealth, and by improving the public pre-K–12 system, the income and quality of life of many Americans can be substantially enhanced.[131]

Assuring a High-Quality Standard of Living. Further advancements in materials science, nanotechnology, quantum computing and communication, AI and machine learning, smart materials, and even items manufactured in real time by additive manufacturing within one's home all offer the promise of new products and services. While new technologies have tended to replace workers in manufacturing and some other fields, new highly rewarding jobs can be created across the education spectrum through advancements in computers, robotics, and machine learning, thereby improving the lives of all segments of the wealth spectrum.

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[128] Michele Bertoncello and Dominik Wee, "Ten Ways Autonomous Driving Could Redefine the Automotive World," McKinsey and Company, June 2015, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/ten-ways-autonomous-driving-could-redefine-the-automotive-world.

[129] Mercedes Leguizamon and Saeed Ahmed, "There Are More Than 54,000 Bridges in the U.S. in Need of Repair, Says This Study," CNN, February 2, 2018, https://www.cnn.com/2018/02/02/us/2018-structurally-deficient-bridges-trnd/index.html; "Bridge Report," ARTBA, https://www.artbabridgereport.org/.

[130] Robert F. Murphy, *Artificial Intelligence Applications to Support K – 12 Teachers and Teaching: A Review of Promising Applications, Challenges, and Risks* (Santa Monica, CA: RAND Corporation, 2019), https://www.rand.org/content/dam/rand/pubs/perspectives/PE300/PE315/RAND_PE315.pdf.

[131] "Unemployment Rates and Earnings by Educational Attainment," U.S. Bureau of Labor Statistics, last updated September 4, 2019, https://www.bls.gov/emp/chart-unemployment-earnings-education.htm; Steven H. Woolf et al., *How Are Income and Wealth Linked to Health and Longevity, Income and Health Initiative: Brief One* (Washington, D.C.: Urban Institute; Richmond, VA: VCU Center on Society and Health, April 2015), https://www.urban.org/sites/default/files/publication/49116/2000178-How-are-Income-and-Wealth-Linked-to-Health-and-Longevity.pdf.

2.4 A GLIMPSE INTO THE FUTURE

> *"[T]he prediction I can make with the highest confidence is that the most amazing discoveries will be ones we are not today wise enough to foresee."*
>
> – Carl Sagan, *Billions and Billions: Thoughts on Life and Death at the Brink of the Millennium*

The preceding section makes the case that many, even most, of the critical problems threatening individuals, the nation, and the world today will depend in substantial part for their solution upon the results of R&D. What particular disciplines will produce the needed breakthroughs – AI, nanotechnology, personalized and regenerative medicine, robotics, materials science and engineering, quantum science and engineering, or some altogether new field that is yet to be established – remains to be seen. But what can be foreseen is that, if the U.S. government and American industry fail to invest sufficiently in R&D, the United States will fall well behind, because it takes longer and costs more to apply solutions developed by other nations.

In seeking to extrapolate the future impact of R&D, it is informative to contemplate how difficult it would have been to foresee, as recently as the year 2000, a salesperson promoting a device that could be carried in one's pocket yet could make telephone calls around the world, provide a personal library greater in size than the Library of Congress, enable one instantly to communicate in writing with friends, navigate one's car, shop for almost any items found in stores, take and store thousands of photographs, stream movies and music of one's choice, record dictation, translate one's conversations into foreign languages, play chess, monitor the location of one's teenagers, wake one up in the morning, and, in its spare time, order a pizza.

That would, of course, be the iPhone, which is now barely 13 years old. And Apple, the maker of the iPhone, is estimated to have created 2 million jobs in the United States alone and many times that number in other parts of the world.[132] All of this was made possible, in part, by government-funded researchers working decades ago in such fields as quantum physics, materials science and engineering, optics, electrical engineering, and microcircuitry.[133] Early R&D performed at industrial labs on multitouch screen displays, high speed electronics, novel transistors, organic light-emitting diodes, and software was also key.

If the United States is to continue to lead in the increasingly competitive global markets that now characterize the 21st century, the pace of American innovation – translation of discoveries and inventions from laboratory R&D to products – will have to accelerate. Industry, understandably,

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[132] "Job Creation," Apple, https://www.apple.com/job-creation/.

[133] Mariana Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*, rev. ed. (New York: PublicAffairs, 2015).

will focus its R&D investments on meeting this immediate challenge. But little of this industrial research is likely to be the longer-term, basic research that has led to so many of the new inventions and products that benefit humanity today.[134] That makes it all the more important that the federal government accelerate its investment in research, especially basic research in all fields of science, engineering, and mathematics, and encourage truly bold ideas and funding projects that have a low probability of succeeding but have the potential to be transformative. By lowering the barriers to industry-university collaboration, some of those pathbreaking discoveries will more easily and quickly move into applications, including commercial products, markets, economic growth, and high-paying jobs.

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[134] "Beyond Discovery: The Path from Research to Human Benefit," National Academy of Sciences, 1996 – 2003, http://www.nasonline.org/publications/beyond-discovery.

Chapter 3

The State of the Union: U.S. and China S&T Futures

> *"Such [scientific and engineering] research is what canals and roads once were – a prerequisite for long-term economic vitality."*
>
> – George Will, Pulitzer Prize – Winning Columnist, January 3, 2011,
> *New York Post*

> *"At the rate we are going . . . we will be buying most of our wind generators and photovoltaic panels from China."*
>
> – Arden Bement, former Director of the National Science Foundation,
> March 24, 2010, to the U.S. Subcommittee on
> Commerce, Justice, Science, and Related Agencies

The United States and some other countries, particularly China, are on very different paths with regard to the priority each places on R&D. The United States takes the (de facto if not publicly stated) position that growth in R&D, especially fundamental research, does not require government nurturing to be competitive with other economies. China, on the other hand, has identified R&D as a top national priority – and has demonstrated that commitment by aggressively funding it and by emphasizing basic research.

3.1 UNITED STATES: DECLINING SUPPORT FOR SCIENCE AND TECHNOLOGY?

> *"If we stop doing fundamental research now, the 'well' that supplies the applications will eventually run dry. In other words, without continuing fundamental research, the opportunities for new technology are eventually going to shrink."*
>
> – Ernest L. Eliel, President of the American Chemical Society,
> *Science and Serendipity: The Importance of Basic Research*, 1992

The United States became a world power – economically, militarily, and culturally – in significant part by placing a high priority on innovation, fueled by advances in science and technology. Investment in R&D was essential for this innovation, especially the fundamental research in all STEM disciplines that was conducted in national laboratories and universities across the country.

With a population of 330 million people and a workforce of 155 million people, the United States, prior to COVID-19, was maintaining an unemployment rate well below 4 percent, accompanied by relatively low inflation.[135] America has had the strongest economy in the world and an ecosystem for S&T discovery and innovation built over decades that is still the envy of the world. Americans also enjoy basic freedoms to live and work with relatively limited oversight from government – a key component of the iconic American Dream.

However, these benefits did not evolve on their own, and the United States is not without serious challenges today. These include recovery from COVID-19; the widening gaps between the rich, the middle class, and the poor; an expensive and inequitable system of healthcare; large disparities in access to quality education at all levels; and, especially in recent years, the use of the Internet to spread misinformation that fuels polarization, including around such critical topics as climate change and vaccinations, and even has the potential to thwart fair elections. Furthermore, in sharp contrast to most of the nation's history, current immigration policies are making it more difficult for talented people from other parts of the world to study in the United States and remain here following completion of their studies. This denies them the opportunity to work and contribute to America's economy and overall well-being, and deprives America of what has been, without question, an essential part of the skilled workforce it has depended upon for over a century.

3.2 CHINA: SCIENCE AND TECHNOLOGY AS A FORCE FOR ECONOMIC AND MILITARY DEVELOPMENT

> *"China, with its large emerging middle class, is among the big beneficiaries of globalization."*
>
> – Joseph Stiglitz, corecipient of the 2001 Nobel Memorial Prize in Economics

China is the world's second-largest economy, as calculated by GDP in current US$ (based on exchange rates).[136] By some projections, China will pass the United States in absolute terms by 2030 (Figure 3-1).[137]

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[135] BLS, "The Employment Situation – December 2019," press release USDL-20-0010, January 10, 2020, https://www.bls.gov/news.release/pdf/empsit.pdf.

[136] "GDP (Current US$), The World Bank, https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?most_recent_value_desc=true.

[137] "OECD Science, Technology and R&D Statistics," OECD iLibrary, https://doi.org/10.1787/data-00182-en.

With a population of 1.4 billion people and a workforce of 800 million, even small increases in productivity will have a major impact on China's economy and related standing in the world. Over the past decade, China has made major investments in science and technology and is now likely the world's largest investor in R&D, having passed Europe (EU28) in 2013 and the United States as early as 2018, when comparisons are based on PPP.[138]

China is rapidly improving its educational system, especially its universities. From 2000 to 2014, the number of Chinese universities increased from approximately 1,000 to 2,500, and Chinese university rankings are increasing too.[139] China is on an upward trend in academic research, steadily increasing funding for university research across S&E disciplines. Major new world-class experimental research facilities, including cutting-edge telescopes and supercomputers, are being planned and built,[140] improvements are being made to the peer review system, and efforts are underway to reduce corruption.[141] These factors alone indicate that China will improve the quality of its science in the years ahead.

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[138] OECD, "China Headed to Overtake EU, U.S. in Science & Technology Spending, OECD Says," press release, December 11, 2014, http://www.oecd.org/newsroom/china-headed-to-overtake-eu-us-in-science-technology-spending.htm; "List of Countries by Projected GDP," Statistics Times, http://statisticstimes.com/economy/countries-by-projected-gdp.php. "Purchasing Power Parity (PPP) compares different countries' currencies through a market 'basket of goods' approach. Two currencies are in PPP when a market basket of goods (taking into account the exchange rate) is priced the same in both countries." "What Is Purchasing Power Parity (PPP)?" Investopedia, https://www.investopedia.com/updates/purchasing-power-parity-ppp/. The use of PPP correction is controversial, and the correction is particularly large for China. For 2015, if currency conversion is used, China's spending on R&D would be $206 billion rather than $409 billion based on PPP. "China's Spending on R&D Rises to 2.07 Percent of GDP," Reuters, November 21, 2016, https://www.reuters.com/article/us-china-r-d/chinas-spending-on-rd-rises-to-2-07-percent-of-gdp-idUSKBN13G1NG. A National Science Board report notes that PPPs are the preferred international standard for calculating R&D comparisons between countries but warns that "PPPs for large developing countries such as China and India are often rough approximations and have shortcomings." Mark Boroush, "Technical Appendix" to National Science Board, *Research and Development: U.S. Trends and International Comparisons* (Arlington, VA: National Science Foundation, 2020), https://ncses.nsf.gov/pubs/nsb20203/technical-appendix.

[139] Te-Ping Chen and Miriam Jordan, "Why So Many Chinese Students Come to the U.S.," *Wall Street Journal*, May 1, 2016, https://www.wsj.com/articles/why-so-many-chinese-students-come-to-the-u-s-1462123552; "China, Japan Raise Pressure on U.S., UK in Global Ranking," *University World News*, September 12, 2019, https://www.universityworldnews.com/post.php?story=20190912131138561.

[140] Stephen Chen, "China Building World's Biggest Quantum Research Facility," *South China Morning Post*, September 11, 2017, https://www.scmp.com/news/china/society/article/2110563/china-building-worlds-biggest-quantum-research-facility.

[141] Dennis Normile, "China Cracks Down after Investigation Finds Massive Peer-Review Fraud," *Science*, July 31, 2017, https://www.sciencemag.org/news/2017/07/china-cracks-down-after-investigation-finds-massive-peer-review-fraud.

Left: China's Five-hundred-meter Aperture Spherical radio Telescope (FAST). Source: Getty Images.
Right: Chinese Supercomputer Sunway TaihuLight. Source: Getty Images.

China is also aggressively acquiring intellectual property, both by demanding that U.S. companies seeking to do business in China share the intellectual property of their business and by conducting surreptitious activities, up to and including espionage.[142]

However, China is not without internal problems of its own, including social unrest in the west, in Hong Kong, and in pockets elsewhere; unpopular restrictions on access to information; environmental challenges and natural disasters; constraints on freedom of movement, expression, and religion; relocation of millions of people from rural to urban areas; gender imbalance and an aging population;[143] an economic growth rate that has declined by half; unsustainable rates of construction; debt exceeding 300 percent of GDP as the government subsidizes an estimated 22 percent of business R&D;[144] and a recent slowing of its economy that is resulting in layoffs in

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[142] U.S. Congress, Senate Committee on Small Business and Entrepreneurship, *Made in China 2025 and the Future of American Industry: Hearing Before the Committee on Small Business and Entrepreneurship*, 116th Cong. 1st sess., 2019 (testimony of Robert D. Atkinson, President of the Information Technology and Innovation Foundation), https://www.sbc.senate.gov/public/?a=Files.Serve&File_id=79588189-A504-4ED6-B957-B352DC4E667D.

[143] Charlie Campbell, "China's Aging Population Is a Major Threat to Its Future," *Time*, February 7, 2019, https://time.com/5523805/china-aging-population-working-age/.

[144] Michael Beckley, "The United States Should Fear a Faltering China," *Foreign Affairs*, October 28, 2019, https://www.foreignaffairs.com/articles/china/2019-10-28/united-states-should-fear-faltering-china; Robert D. Atkinson and Caleb Foote, "To Understand Chinese Innovation Success, Look No Further Than Government R&D Subsidies," Innovation Files, October 23, 2019, ITIF, https://www.itif.org/publications/2019/10/23/understand-chinese-innovation-success-look-no-further-government-rd?mc_cid=831cf461a7&mc_eid=7a24947a11.

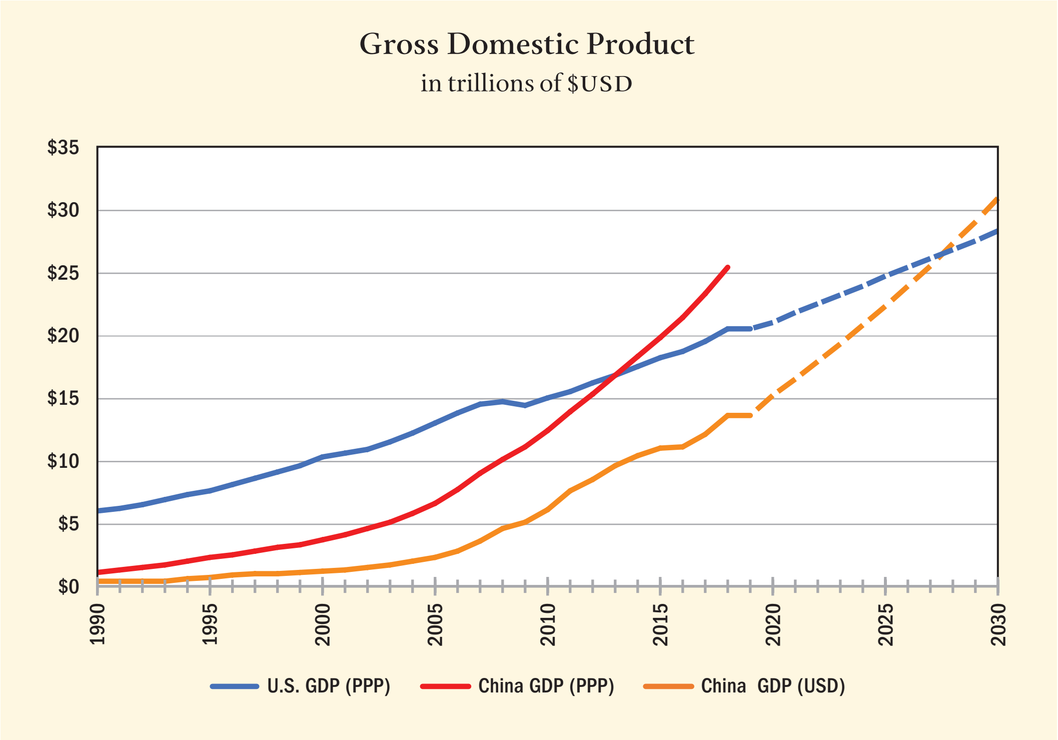

Figure 3-1

Gross Domestic Product in trillions of $USD

Source: World Bank, 2019, "World Bank Open Data," https://data.worldbank.org/.

Note: Years 2019 – 2030 (dashed lines) are based on linear fit.

factories.[145] Can a nation that suppresses the freedom of its citizens in exchange for economic growth ultimately be successful – particularly as economic advancement slows? Despite these issues, China has continued to surprise the experts with its steady gains in science and engineering prominence, the expansion of its economy, and the rise of its middle class since 1980.

The answer to whether China can ultimately be successful if it continues on its current path is critically important not only to the future of China but to the rest of the world. But all nations

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[145] Chas W. Freeman, Jr., "China's Current Problems and Prospects" (remarks to a panel at the Brown China Summit, Brown University, Providence, RI, April 23, 2016), https://www.mepc.org/speeches/chinas-current-problems-and-prospects.

and their histories and cultures are different. Since 1978 China has been running an experiment with its own fusion of strong central control and capitalism.[146] Whatever the ultimate outcome, China can be expected to be a formidable global competitor for decades into the future, and any government that ignores that likelihood will be placing its own economy, and thus the well-being of its citizens, in peril.

Many other nations and regions of the world – Europe, the United Kingdom, Japan, Taiwan, Russia, South Korea, Brazil, India, Israel, Australia, and others – are major contributors to scientific discovery and innovation. Russia, in the past, was a particularly significant contributor to global science, especially in such fields as physics and mathematics. But as the Soviet Union collapsed, leading to disinvestment in scientific research and the emigration of many scientists and engineers in the 1990s, Russian science has suffered.[147]

Europe is the location of many of the world's foremost research laboratories and experimental facilities, such as the European Organization for Nuclear Research (Conseil Européen pour la Recherche Nucléaire, or CERN), which manages research facilities for international studies of elementary particle physics, including the Large Hadron Collider that produced the discovery of the Higgs boson.[148] Through the European Space Agency, Europe supports facilities for research in astronomy and space science.[149] Japan has one of the leading neutrino research programs in the world.[150] What sets China apart is its enormous scale, its rapid pace of progress, the broad dimensions of its scientific work, and its government's commitment to scientific growth. For these and other reasons, the focus of this report is largely on the United States and China.

The Chinese workforce will remain significantly larger than the U.S. workforce, so the United States will have to compete through creativity and innovation. Yet China is not relying solely on scale; it is proving a strong competitor in creativity and innovation as well, especially by taking advantage of its outcomes-focused leadership (Figure 3-2). Although the most recent Politburo Standing Committee does not contain engineers or researchers in the natural sciences (except for President Xi Jinping, who studied chemical engineering as an undergraduate), many Chinese leaders in recent history did possess advanced degrees in engineering and the natural sciences

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[146] "TIMELINE: China Milestones since 1978," Reuters, December 8, 2008, https://www.reuters.com/article/us-china-reforms-chronology-sb/timeline-china-milestones-since-1978-idUKTRE4B711V20081208.

[147] National Research Council, *An Assessment of the International Science and Technology Center: Redirecting Expertise in Weapons of Mass Destruction in the Former Soviet Union* (Washington, D.C.: National Academies Press, 1996), chap. 4, https://doi.org/10.17226/5466.

[148] "The Higgs Boson," CERN.

[149] European Space Agency, http://m.esa.int/ESA.

[149] Davide Castelvecchi, "Gigantic Japanese Detector Prepares to Catch Neutrinos from Supernovae," *Nature* 566 (2019): 438 – 439, https://doi.org/10.1038/d41586-019-00598-9.

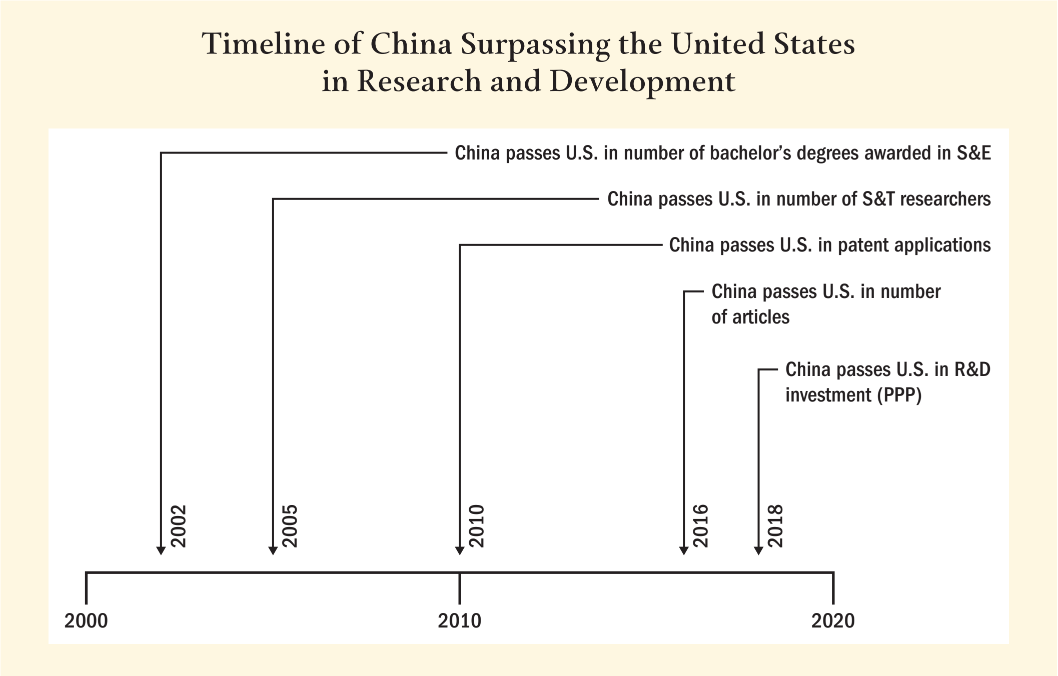

Figure 3-2

Timeline of China Surpassing the United States in Research and Development

from leading academic institutions.[151] Furthermore, the actions of China's leaders indicate that they clearly understand the foundational role of R&D in national prosperity and the need to have a long-term strategy to sustain investments in R&D. The United States will need to reestablish such a vision if it is to retain its position of global competitiveness.

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[151] Viola Zhou, "Out with the Technocrats, in with China's New Breed of Politicians," *South China Morning Post*, October 26, 2017, https://www.scmp.com/news/china/policies-politics/article/2117169/out-technocrats-chinas-new-breed-politicians.

3.3 THE INGREDIENTS OF INNOVATION: CHINA AND THE UNITED STATES

Innovation is driven by creative thinking, often based on new scientific, engineering, and technological opportunities. While challenging to develop, the essential, admittedly overlapping, elements of innovation – at a national level – are (1) human capital, (2) knowledge capital, (3) an ecosystem that inspires innovation, and (4) financial capital. The following paragraphs examine innovation in China and the United States using these four metrics.

3.3.1 *Human Capital*

> *"Given the often long lag time from research to applications, we may not realize the impacts of being behind until we are far behind, watching other nations reap the economic rewards and strategic advantages of early S&T investment. . . . Economic prosperity, national security, and advances in public health in the U.S. have for generations depended on a strong and diverse STEM talent pipeline."*
>
> – Marcia McNutt, President of the National Academy of Sciences,
> to the U.S. House of Representatives' Committee on Science, Space, and Technology

> *"Raising China's innovative capacity requires a multi-pronged approach. We will foster an innovation-friendly environment in which basic research and applied basic research are supported, more corporate R&D spending is encouraged, and innovation outcomes are commercialized at a faster pace."*
>
> – Li Keqiang, Chinese Premier, September 2018, to the World Economic Forum's
> Annual Meeting of New Champions in Tianjin, China

In 2014, China awarded over 1.5 million bachelor's degrees in science and engineering (not including social sciences degrees) compared with about 740,000 (including degrees in the social sciences) by the United States.[152] Today, China awards more bachelor's degrees in science and engineering than the United States, the European Union (EU), and Japan combined (Figure 3-3a). This differential can in part be attributed to the massive size of China's population. How-

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[152] National Science Board, *Science and Engineering Indicators 2018*, figure O-1, https://www.nsf.gov/statistics/2018/nsb20181/report/sections/overview/workers-with-s-e-skills.

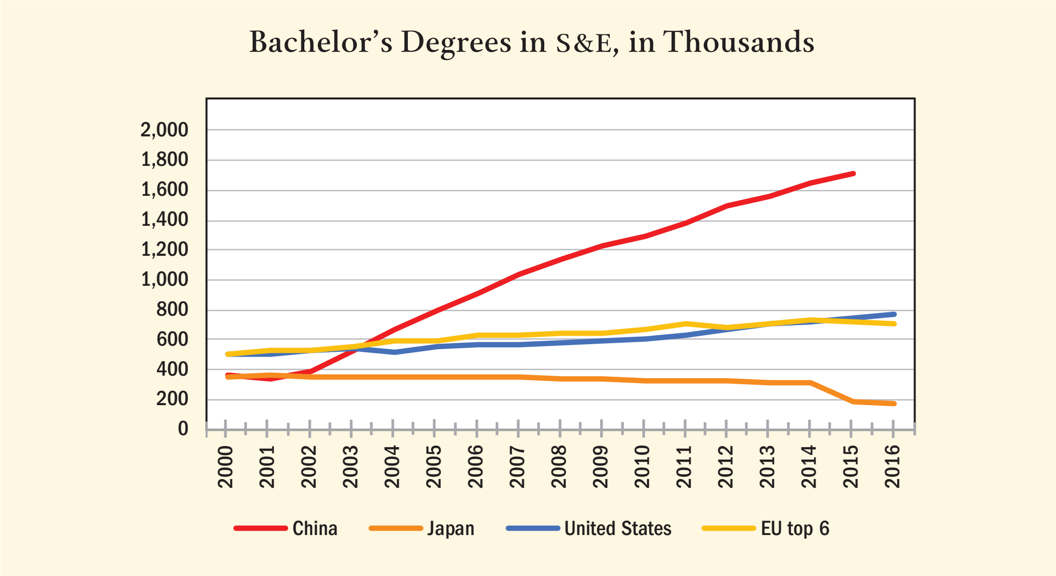

Figure 3-3a:

Bachelor's Degrees in S&E, in Thousands

Source: Reproduced from Figure 2-19 in NSB Indicators 2020, https://ncses.nsf.gov/pubs/nsb20197/international-s-e-higher-education#international-students-in-u-s-higher-education-degrees-earned.

ever, the trend – showing that China's numbers of S&E graduates are increasing substantially to keep pace with demand, while the corresponding numbers of graduates from U.S. institutions continue to be relatively flat – is disconcerting. Thus, the STEM workforce size gap between the United States and China continues to widen.[153] China remains behind the United States in the production of S&E graduates with doctorates from its own universities (Figure 3-3b); however, China is investing in new universities and advanced degree programs, while increasingly pursuing non-Chinese-born students and the Chinese diaspora educated abroad who wish to continue their education in China and accept jobs with Chinese companies. China has stated its aim to become Asia's top destination for international students by 2020, working to enroll 500,000 foreign students per year by that time.[154]

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[153] Ibid., 2-47 – 2-60.

[154] Rahul Choudaha, "How China Plans to Become a Global Force in Higher Education," *The Guardian*, October 12, 2015, https://www.theguardian.com/higher-education-network/2015/oct/12/how-china-plans-to-become-a-global-force-in-higher-education.

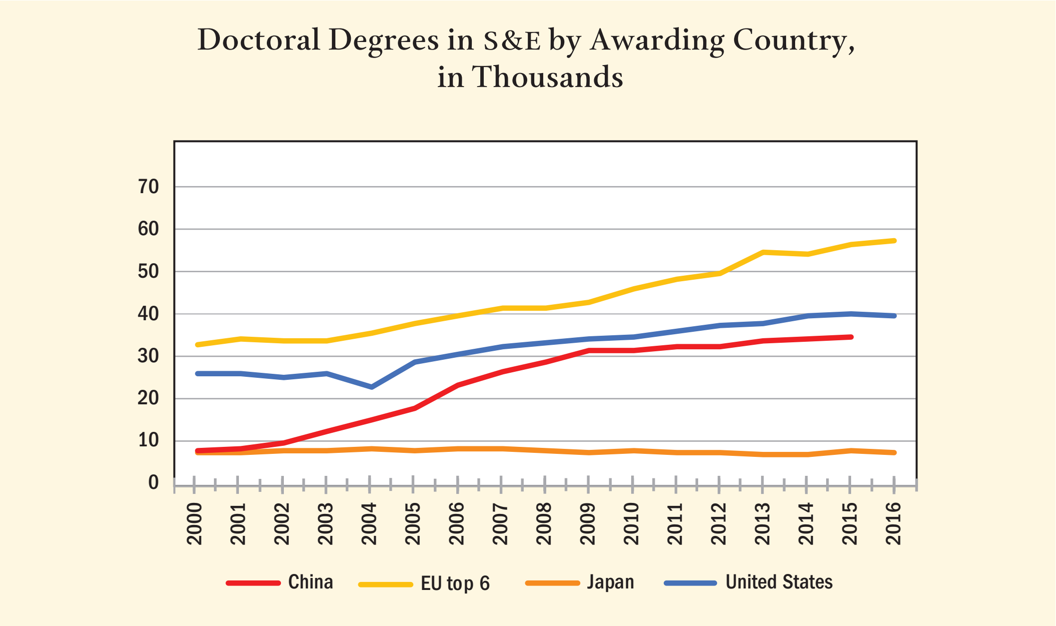

Figure 3-3b

Doctoral Degrees in S&E by Awarding Country, in Thousands

Source: Reproduced from Figure 2-21 in NSB Indicators 2020, https://ncses.nsf.gov/pubs/nsb20197/international-s-e-higher-education#international-students-in-u-s-higher-education-degrees-earned.

The weakness of the U.S. pre-university public education system may well prove to be the major barrier to future progress in American science and engineering and to the overall prosperity of the country. The comparative weakness of the U.S. system is linked to lower interest in STEM careers among America's youth.[155] The Program for International Student Assessment (PISA), which tests fifteeen-year-olds in reading, mathematics, and science, finds U.S. students in approximately 13th place in science and in approximately 31st place in math among 36 OECD nations

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[155] Brian Kennedy, Meg Hefferon, and Cary Funk, "Half of Americans Think Young People Don't Pursue STEM Because It Is Too Hard," *Fact Tank*, January 17, 2018, Pew Research Center, https://www.pewresearch.org/fact-tank/2018/01/17/half-of-americans-think-young-people-dont-pursue-stem-because-it-is-too-hard/; Olga Khazan, "Lack of Interest and Aptitude Keeps Students Out of STEM Majors," *Washington Post*, January 6, 2010, https://www.washingtonpost.com/blogs/on-small-business/post/lack-of-interest-and-aptitude-keeps-students-out-of-stem-majors/2012/01/06/gIQAoDzRfP_blog.html.

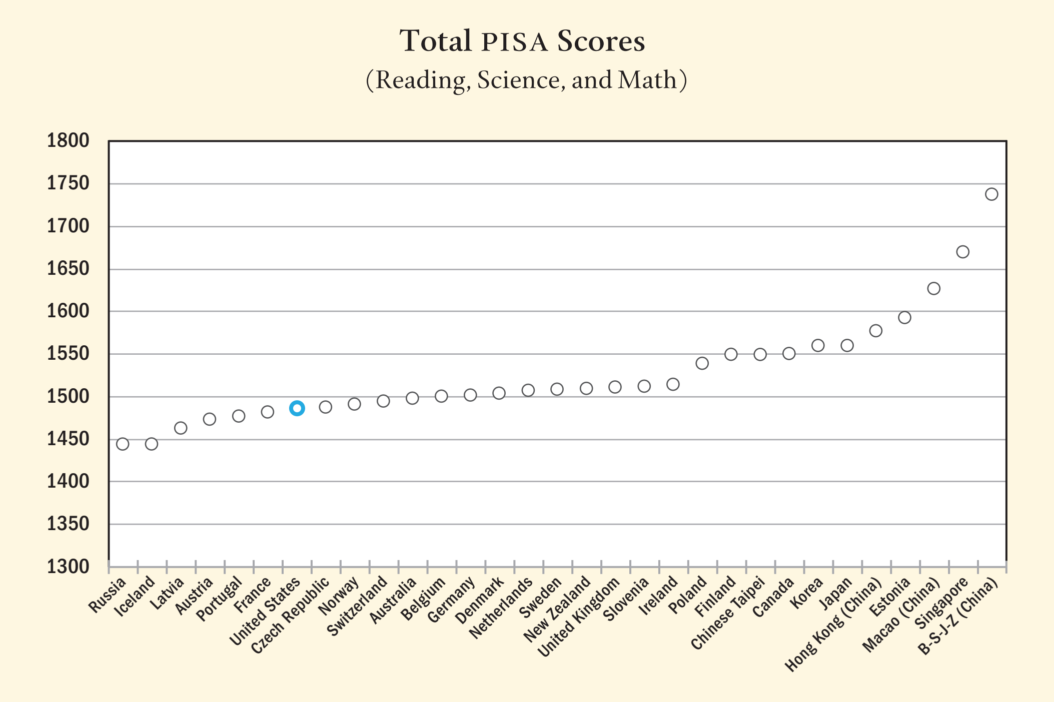

Figure 3-4

Total PISA Scores (Reading, Science, and Math)

Source: OECD. 2019. PISA 2018 Results (Volume I): *What Students Know and Can Do,* https://doi.org/10.1787/19963777.

Note: B-S-J-Z refers to four PISA participating China provinces: Beijing, Shanghai, Jiangsu, and Guangdong.

(Figure 3-4).[156] The existing gap between the quality of U.S. pre-K–12 education, particularly in STEM, and the demand for a highly skilled workforce severely threatens the nation's future competitiveness.

Examining U.S. students' performance through America's own standardized test, the National Assessment of Educational Progress (NAEP), yields an equally stark picture. As the National Science Foundation's National Science Board notes: "Less than half of fourth, eighth, and twelfth

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[156] OECD, "How Did Countries Perform in PISA 2018," in PISA 2018 Results, vol. 1, *What Students Know and Can Do* (Washington, D.C.: OECD, 2019), chap. 4, https://doi.org/10.1787/5f07c754-en. Accounting for statistical error, the United States ranges from 25th to 31st in math and 7th to 18th in science among the 36 OECD countries.

grade students achieved a level of 'proficient' (defined as 'solid academic performance') or higher on NAEP mathematics and science assessments in 2015." The report goes on to state that in the international arena "the Trends in International Mathematics and Science Study (TIMSS) and the Program for International Student Assessment (PISA) 2015 data show that the U.S. average mathematics assessment scores were well below the average scores of the top-performing education systems."[157]

In addition to poor overall K–12 STEM education, the United States generally struggles to attract historically underrepresented groups into STEM careers. These Americans, including people underrepresented because of their gender, race, socioeconomic status, sexual orientation, disability, religion, or geographic location within the United States, make up an increasingly large proportion of the U.S. population.[158] If not addressed, this failure to attract historically underrepresented groups will continue to further hamper U.S. efforts to strengthen America's STEM workforce. Underrepresented ethnic and racial groups were estimated to be 37 percent of the U.S. population in 2016 and are projected to be 57 percent by 2060.[159] Systematically failing to promote a diverse workforce decreases U.S. scientific research gains. Studies have also noted that increased ethnic and gender diversity promotes higher-quality science.[160]

Alongside encouraging a diverse number of Americans to pursue STEM degrees and careers, the United States must seek to retain the workers it does produce. Numerous studies have demonstrated bias against women and underrepresented racial minorities in laboratory and physician hiring processes as well as in grant reviews and paper acceptances.[161] A recent report from the National Academy of Sciences, Engineering, and Medicine identifies sexual harassment as a key obstacle to reducing the "gender gap" in STEM careers, as bias and harassment in STEM careers lead to higher rates of dropout and decreased productivity. The report points to perceived academic tolerance of sexual harassment, male-dominated workplaces, hierarchical power structures, symbolic rather than effective Title IX compliance programs, and poor campus leader-

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[157] National Science Board, *Science and Engineering Indicators 2018*, 1-4 – 1-8, https://www.nsf.gov/statistics/2018/nsb20181/report/sections/elementary-and-secondary-mathematics-and-science-education/highlights.

[158] National Science and Technology Council Committee on STEM Education, *Charting a Course for Success*.

[159] Interagency Policy Group on Increasing Diversity in the STEM Workforce by Reducing the Impact of Bias, *Reducing the Impact of Bias in the STEM Workforce*.

[160] Kendall Powell, "These Labs Are Remarkably Diverse – Here's Why They're Winning at Science," *Nature* 558 (2018): 19 – 22, https://doi.org/10.1038/d41586-018-05316-5.

[161] Maria Asplund and Cristin G. Welle, "Advancing Science: How Bias Holds Us Back," *Neuroview* 99 (4) (2018): P635 – P639, https://doi.org/10.1016/j.neuron.2018.07.045.

ship as five contributing factors to the high rates of gender harassment, and it makes several recommendations to combat gender harassment in STEM education and training settings.[162]

3.3.1.1 Foreign Students in the United States

The success of the Great American Experiment is often ascribed to this nation's spirit of adventure, its willingness to reward risk-taking and entrepreneurship and innovation, resulting in change that can invent whole new industries, create enormous wealth, and generate jobs for workers having the needed education and skills. These attributes, among others, have brought to America motivated, talented men and women from across the globe to study and work. Such individuals have become a vital part of the nation's STEM workforce. Approximately 40 percent of all U.S. Nobel Prize winners since 2000 were, or are, immigrants.[163] Almost half of American Fortune 500 companies were founded by immigrants or their children.[164] Similarly, 26 percent of the members of the U.S. National Academy of Sciences and 31 percent of the members of the U.S. National Academy of Engineering are naturalized citizens who were foreign-born.

U.S. doctoral education and academic research in STEM fields relies heavily on foreign-born individuals from China, India, and other parts of the world, both for students and for faculty (Figure 3-5). In recent years, nearly 40 percent of U.S. Ph.D. graduates in engineering and the natural sciences (which excludes psychology and the social sciences) were not U.S. citizens or permanent residents (Figure 3-6). From 1995 to 2015, U.S. institutions awarded nearly 60,000 Chinese students and 28,000 Indian students Ph.D.'s in these fields.[165] By comparison, from 2000 to 2015, U.S. institutions awarded nearly 280,000 Ph.D.'s to U.S. citizens or permanent residents in these fields.[166] Over half of U.S.-trained S&E postdoctoral workers were born overseas, as were 28 percent of all U.S. S&E faculty.[167] About 50 percent of the latter are of Asian descent.[168]

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[162] National Academies of Sciences, Engineering, and Medicine, *Sexual Harassment of Women: Climate, Culture, and Consequences in Academic Sciences, Engineering, and Medicine* (Washington, D.C.: National Academies Press, 2018), https://doi.org/10.17226/24994.

[163] Stuart Anderson, "Immigrants Keep Winning Nobel Prizes," *Forbes*, October 8, 2017, https://www.forbes.com/sites/stuartanderson/2017/10/08/immigrants-keep-winning-nobel-prizes/#7286de6117bb.

[164] Hathaway, "Almost Half of Fortune 500 Companies Were Founded by American Immigrants or Their Children."

[165] National Science Board, *Science and Engineering Indicators 2018*, table 2-15 and appendix table 2-2s.

[166] Ibid., appendix table 2-32.

[167] National Science Board, *Foreign-Born Students and Workers in the U.S. Science and Engineering Enterprise.*

[168] National Science Board, *Science and Engineering Indicators 2018.*

Men and women from China make up the greatest number of international students enrolled in U.S. colleges and universities as undergraduate or graduate students.[169] In the 2017 – 2018 academic year, 280,000 Chinese students were enrolled, along with 120,000 from India, 44,000 from South Korea, and 39,000 from Saudi Arabia.[170]

Some members of Congress and U.S. intelligence officials have recently raised concerns that China's government is using its consulates to direct some Chinese students and visiting researchers within American universities to spread pro-China political propaganda and steal intellectual property. In particular, the Federal Bureau of Investigation has issued warnings about Chinese talent programs and possible associated espionage and has briefed government and academic officials on attendant risks.[171] Isolated incidents of Chinese students attempting to pressure fellow Chinese colleagues over issues perceived as critical of China have been documented.[172] However, altogether, the evidence does not suggest a widespread campaign of such influence.[173]

Nonetheless, ample evidence supports the view that China has been making aggressive efforts to import intellectual property from the United States and other countries through various means, up to and including espionage.[174] For the most part, indictments have involved spying on companies and on the U.S. government. Huawei, a major Chinese telecommunications company, has been partially banned from selling its products in the United States due to American fears that the company could build "back doors" into equipment for spying, and several other

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[169] "International Student Data," IIE, https://www.iie.org/Research-and-Insights/Open-Doors/Fact-Sheets-and-Infographics/Infographics/International-Student-Data.

[170] "Places of Origin," IIE, https://www.iie.org/Research-and-Insights/Open-Doors/Data/International-Students/Places-of-Origin.

[171] "FBI Counterintelligence Note: Chinese Talent Programs," Public Intelligence, August 11, 2016, https://publicintelligence.net/fbi-chinese-talent-programs/; Emily Feng, "FBI Urges Universities to Monitor Some Chinese Students and Scholars in the U.S.," NPR, June 28, 2019, https://www.npr.org/2019/06/28/728659124/fbi-urges-universities-to-monitor-some-chinese-students-and-scholars-in-the-u-s.

[172] Bethany Allen-Ebrahimian, "China's Long Arm Reaches into American Campuses," *Foreign Policy*, March 7, 2018, https://foreignpolicy.com/2018/03/07/chinas-long-arm-reaches-into-american-campuses-chinese-students-scholars-association-university-communist-party/.

[173] Anastasya Lloyd-Damnjanovic, *A Preliminary Study of PRC Political Influence and Interference Activities in American Higher Education* (Washington, D.C.: Wilson Center, September 6, 2018), https://www.wilsoncenter.org/publication/preliminary-study-prc-political-influence-and-interference-activities-american-higher.

[174] Tribune News Service, "China 'Has Taken the Gloves Off' in Its Theft of U.S. Technology Secrets," *South China Morning Post*, November 19, 2018, https://www.scmp.com/news/world/united-states-canada/article/2173843/china-has-taken-gloves-its-thefts-us-technology.

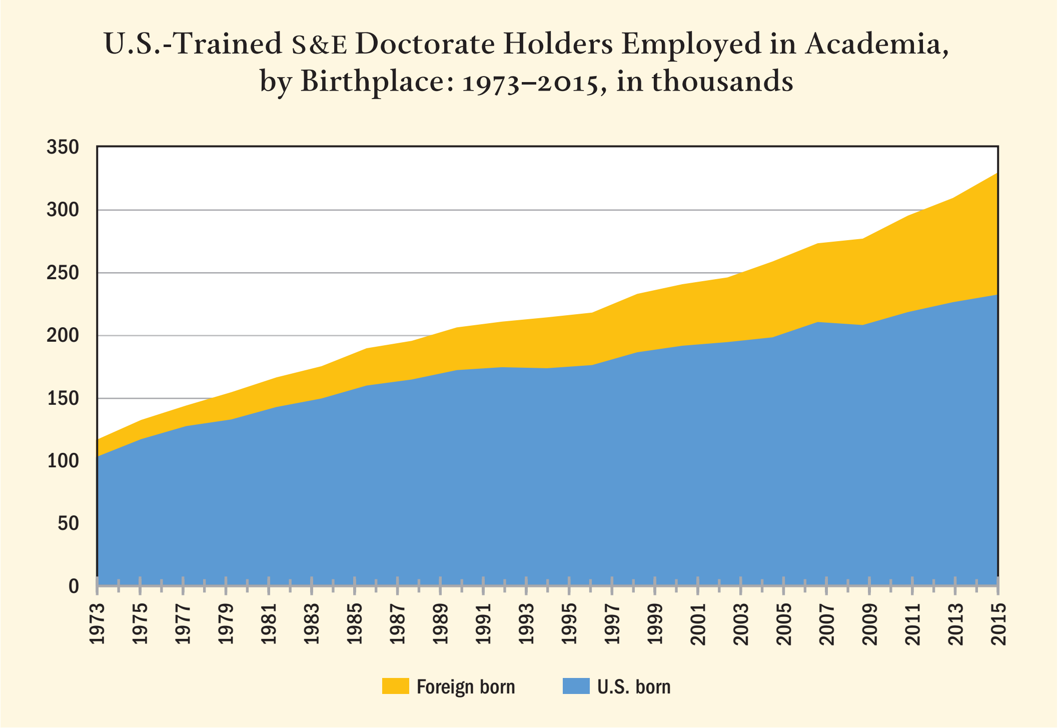

Figure 3-5

U.S.-Trained S&E Doctorate Holders Employed in Academia, by Birthplace: 1973 – 2015, in thousands

Source: Reproduced from Figure 5-16 in National Science Board, *Science & Engineering Indicators* 2018 (Washington, D.C.: National Science Foundation, 2018).

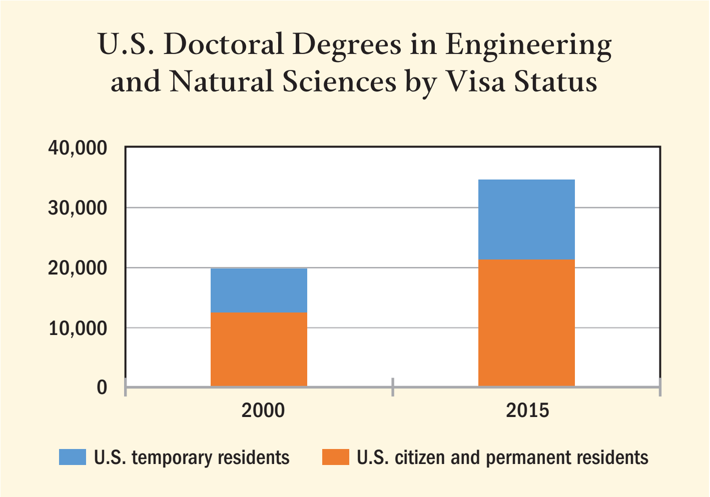

Figure 3-6

U.S. Doctoral Degrees in Engineering and Natural Sciences by Visa Status

Source: National Science Board 2018, Appendix Table 2-29.

countries have taken corresponding actions to control such activity, although these actions are ongoing and have not settled into clear policy, with the exception of the U.K.[175]

Most intellectual property generated in U.S. universities is shared widely, either through open publication or through patent disclosures.[176] U.S. intelligence agencies have nonetheless expressed concern that China's talent programs are, in part, designed to bring intellectual property to China by enticing U.S.-based scientists of all citizenships to spend time in China, set up laboratories there, or collaborate across borders with Chinese scientists.[177]

Taken together, the benefits of welcoming foreign-born individuals to the U.S. S&T enterprise far outweigh potential risks or disadvantages, and university leaders should continue to work with federal officials to promote the openness that is a key hallmark of American higher education. What are needed are prudent alertness and decisive action when U.S. law is violated, not blanket prohibitions. The principal security and commercial concern about Chinese intervention should be focused on the *application* of new knowledge, as opposed to the *creation* of new knowledge (i.e., fundamental research).

International cooperation in science has benefitted the United States throughout its history. Even cooperation with scientists in the Soviet Union during the Cold War helped advance U.S. science, while providing an avenue for diplomatic engagement.[178]

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175. Klint Finley, "Australia's Ban on Huawei Is Just More Bad News for China," *Wired*, August 24, 2018, https://www.wired.com/story/australias-ban-on-huawei-is-just-more-bad-news-for-china/; "The Huawei Indictment Tells a Story of Deceit and Corporate Espionage," *Washington Post*, January 29, 2019, https://www.washingtonpost.com/opinions/global-opinions/the-huawei-indictment-tells-a-story-of-deceit-and-corporate-espionage/2019/01/29/c2035abe-23f4-11e9-90cd-dedb0c92dc17_story.html; Jenny Leonard and Ian King, "Five Months after Huawei Export Ban, U.S. Companies Are Confused," *Bloomberg*, October 21, 2019, https://www.bloomberg.com/news/articles/2019-10-21/five-months-after-huawei-export-ban-u-s-companies-are-confused.

176. National Science Board, *Science and Engineering Indicators 2018*, 8-12 – 8-37, https://www.nsf.gov/statistics/2018/nsb20181/report/sections/invention-knowledge-transfer-and-innovation/invention-united-states-and-comparative-global-trends.

177. "About 1000plan.org," The Thousand Talents Plan, http://www.1000plan.org.cn/en/about.html; Lee C. Bollinger, "No, I Won't Start Spying on My Foreign-Born Students," *Washington Post*, August 30, 2019, https://www.washingtonpost.com/opinions/no-i-wont-start-spying-on-my-foreign-born-students/2019/08/29/01c80e84-c9b2-11e9-a1fe-ca46e8d573c0_story.html

178. Alan McDonald, "Scientific Cooperation as a Bridge across the Cold War Divide: The Case of the International Institute for Applied Systems Analysis (IIASA)," *Annals of the New York Academy of Sciences* 866 (1) (1998): 55 – 83, https://doi.org/10.1111/j.1749-6632.1998.tb09147.x.

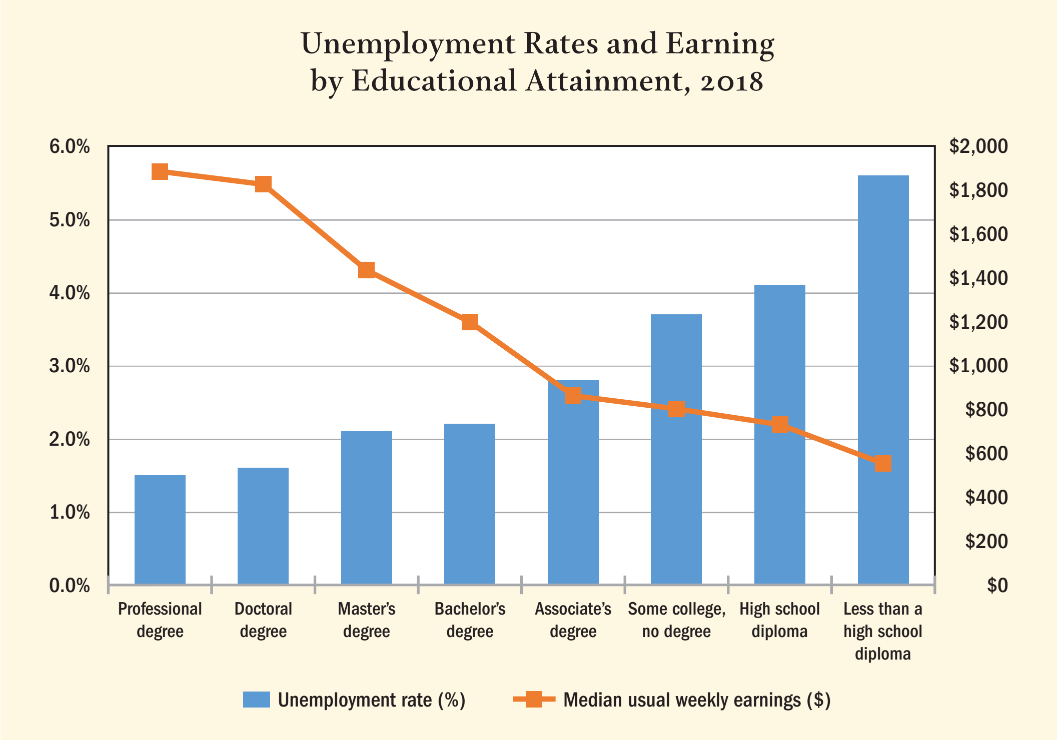

Figure 3-7

Unemployment Rates and Earning by Educational Attainment, 2018

Source: U.S. Bureau of Labor Statistics. 2019. "Current Population Survey," https://www.bls.gov/emp/chart-unemployment-earnings-education.htm.

Note: Data are for persons age 25 and older. Earnings are for full-time wage and salary workers.

3.3.1.2 U.S. Workforce

Wages and employment in the United States strongly correlate with education.[179] A recent study from the Federal Reserve Bank of San Francisco sets the value of a baccalaureate degree over a high school diploma at about $800,000 based on inflation-corrected discounted cash flows including debt.[180] While some still debate the payoff of various college or university degrees, particularly when student loans prove to be a burden later in life, it is still the overall case that salaries, properly discounted and adjusted for inflation, increase substantially with the level of education one achieves (Figure 3-7). Median salaries, compared with those associated with a high school diploma, range from approximately 65 percent higher for a bachelor's degree to more than double for a master's or other professional degree.

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[179] "Employment Projections," U.S. Bureau of Labor Statistics, last updated September 4, 2019, https://www.bls.gov/emp/documentation/education-training-system.htm.

[180] Mary C. Daly and Leila Bengali, "Is It Still Worth Going to College?" *FRBSF Economic Letter*, no. 2014-13 (May 5, 2014), http://www.frbsf.org/economic-research/publications/economic-letter/2014/may/is-college-worth-it-education-tuition-wages/.

Although there is no single definition of the STEM workforce, the American Immigration Council (AIC) uses a narrow definition of workers in the physical and life sciences, engineering, mathematics, and computer sciences. Demand for workers in the STEM fields, using the AIC definition, continues to be high, and compensation is accordingly large, averaging over 25 percent higher than non-STEM fields at the entry level.[181] A similar disparity is maintained throughout careers at comparable levels of educational attainment.[182] Nonetheless, some 47 percent of American adults now doubt the value of higher education, with 57 percent of younger adults (ages 18 – 34) questioning the value of a four-year degree.[183] This represents a seismic departure from the view held for over a century by much of the population.

The United States continues to be strongly dependent upon immigration of talented men and women to meet its needs for a STEM workforce (Figure 3-8). By the AIC measurement, in 2018, STEM workers made up 8 million, or 5 percent, of the U.S. workforce, with foreign-born workers making up approximately 24 percent of that fraction, at 2 million workers. Given the vital importance to the U.S. economy of continuing to attract talent from abroad, it is in the nation's interest to ensure that its laws, policies, and image abroad encourage legal immigration, especially of STEM students and workers.

> *"We educate the best and the brightest and then we don't give them a green card."*
>
> – Michael Bloomberg, former Mayor of New York City

3.3.1.3 China's Workforce

China's workforce is estimated to be nearly 800 million people.[184] China reports employing more STEM researchers than the United States, even after a downward adjustment in 2009 to meet OECD definitional standards (Figure 3-9). Since China annually awards far more S&E degrees than the United States,[185] the STEM workforce differential between the two countries will continue to widen significantly.

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[181] "Real-Time Insight into the Market for Entry-Level STEM Jobs and STEM Careers," Burning Glass Technologies, https://www.burning-glass.com/research-project/stem/.

[182] Ibid.

[183] Carrie Dann, "Americans Split on Whether 4-Year College Degree Is Worth the Cost," NBC News, September 7, 2017, https://www.nbcnews.com/politics/first-read/americans-split-whether-4-year-college-degree-worth-cost-n799336.

[184] "Labor Force, Total," The World Bank, https://data.worldbank.org/indicator/SL.TLF.TOTL.IN.

[185] National Science Board, *Science and Engineering Indicators 2018*, 8-12 – 8-37, https://www.nsf.gov/statistics/2018/nsb20181/report/sections/higher-education-in-science-and-engineering/undergraduate-education-enrollment-and-degrees-in-the-united-states.

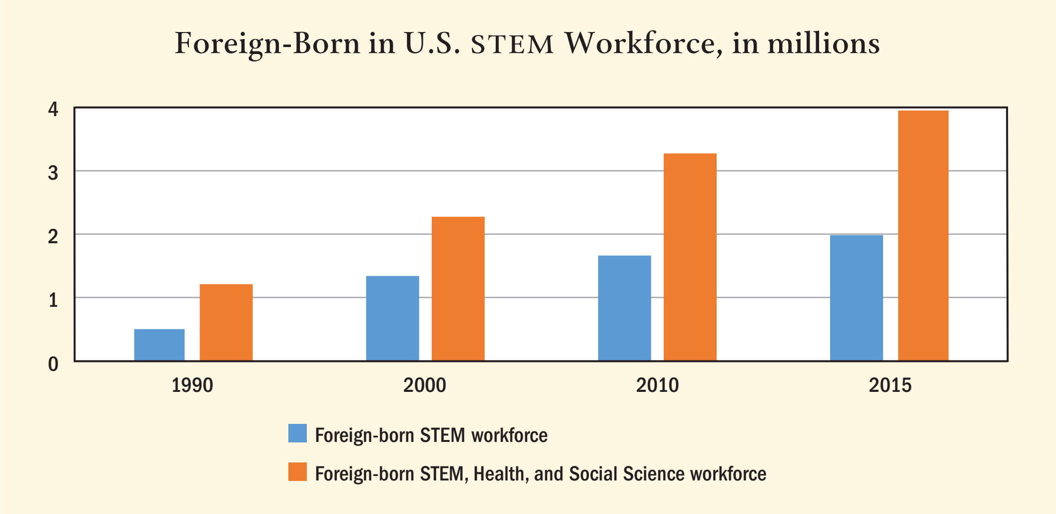

Figure 3-8

Foreign-Born in U.S. STEM Workforce, in millions

Source: American Immigration Council. 2018, "Foreign-Born STEM Workers in the United States," https://www.americanimmigrationcouncil.org/research/foreign-born-stem-workers-united-states.

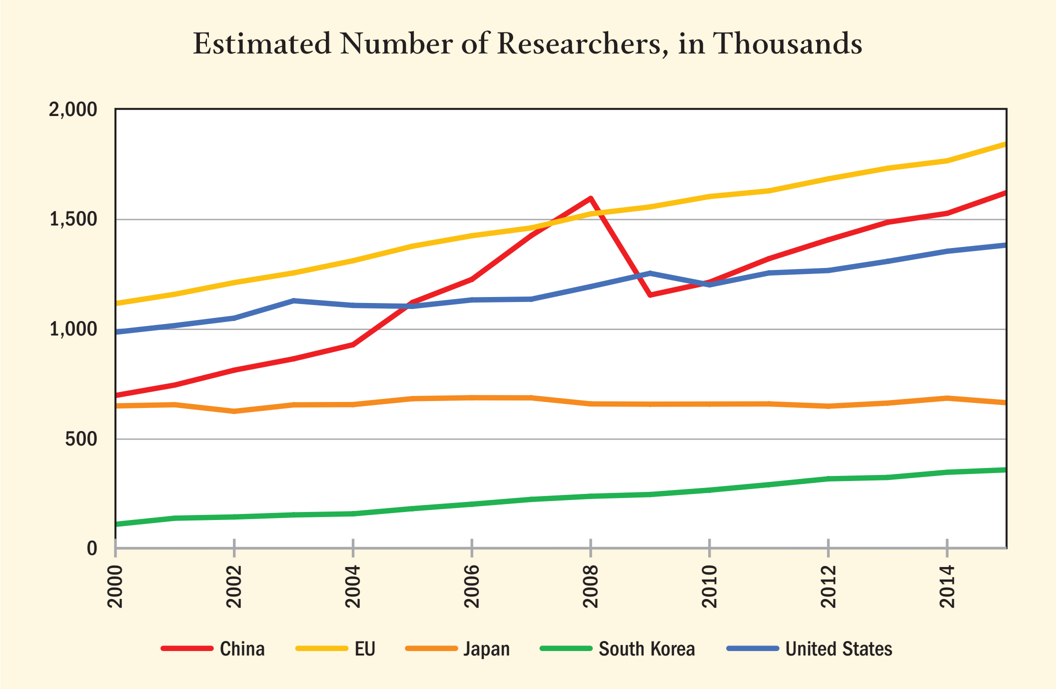

Figure 3-9

Estimated Number of Researchers, in Thousands

Source: Reproduced from Figure 3-38 in National Science Board, *Science & Engineering Indicators 2018* (Washington, D.C.: National Science Foundation, 2018).

China is aggressively recruiting STEM professionals from the United States and other nations through its Thousand Talents Program and similar initiatives intended to upgrade the quality of its scientific work, improve the stature of its universities, and bring foreign – especially American-educated – intellectual capital to China.[186] In 2018, a U.S. National Intelligence Council analysis put the number of "Thousand Talents" recruits from the United States at 2,629 – 44 percent of whom specialize in medicine, life, or health sciences; 22 percent in applied industrial technologies; 8 percent in computer sciences; and 6 percent each in aviation/aerospace and astronomy.[187] Pentagon officials have warned that such programs are a threat to the security and economy of the United States, arguing that retaining S&T talent is a crucial component of U.S. military leadership.[188]

3.3.2 *Knowledge Capital*

There is no agreed-upon single measure of knowledge capital. However, several indicators are available that taken together provide an illuminating picture of relative status and overall trends. The most common metrics include publications (number, citations, and quality) and patents.

3.3.2.1 Research Publications

A primary way of disseminating and evaluating the quality and impact of research results is through peer-reviewed journal publications and citation frequency of these papers, especially when these citations come from acknowledged scientific leaders. Thus, publications in highly cited journals can serve as one metric for research quality and impact.[189] In 2016, China overtook the United States in total number of research publications and now ranks second in the world, behind the EU (Figure 3-10a). The United States still publishes the most research publications in the top 1 percent of most-cited publications, but the number of Chinese articles in these journals is rapidly rising and has already surpassed the number of Indian and Japanese articles (Figure 3-10b).

The overall number of papers published by Chinese authors is not considered to be a particularly strong indicator of China's global standing in science since pressure to publish has tended to fuel

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[186] The Thousand Talents Plan, http://www.1000plan.org.cn/en/about.html.

[187] Yojana Sharma, "Panic over U.S. Scrutiny of Science Talent Programme," *University World News*, October 18, 2018, https://www.universityworldnews.com/post.php?story=20181018183445307.

[188] Bloomberg, "China's 'Thousand Talents' Plan Key to Seizing U.S. Expertise, Intelligence Officials Say," *South China Morning Post*, June 22, 2018, https://www.scmp.com/news/china/policies-politics/article/2152005/chinas-thousand-talents-plan-key-seizing-us-expertise.

[189] Ewen Callaway, "Beat It, Impact Factor! Publishing Elite Turns against Controversial Metric," *Nature* 535 (2016): 210–211, https://doi.org/10.1038/nature.2016.20224.

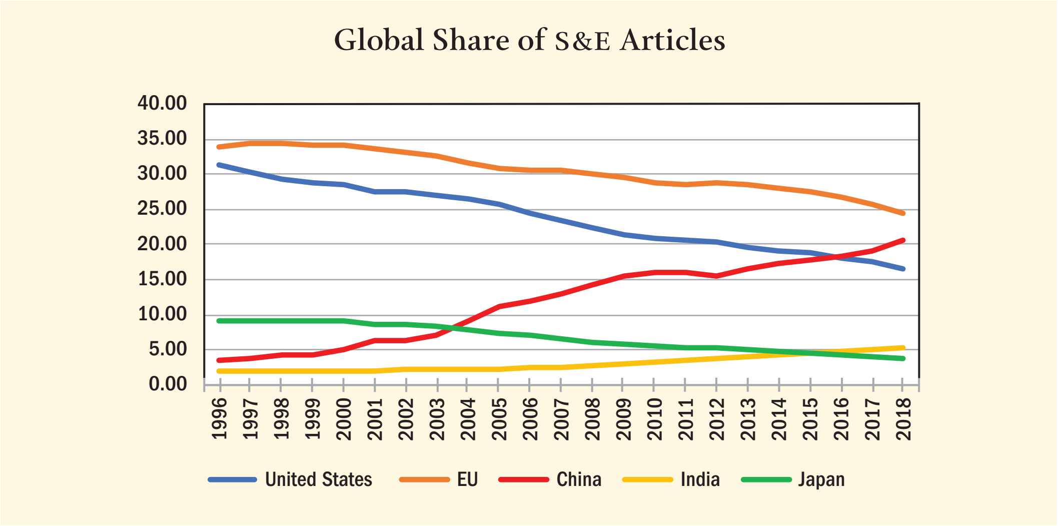

Figure 3-10a

Global Share of S&E Articles

Source: Reproduced from Figure 5a-3 in National Science Board SEI 2020, https://ncses.nsf.gov/pubs/nsb20206/data.

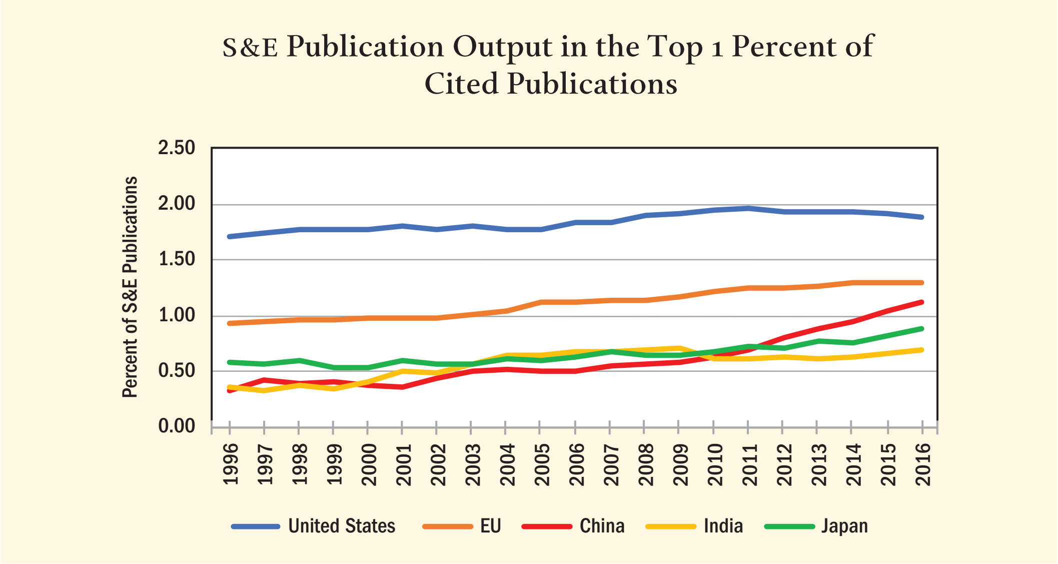

Figure 3-10b

S&E Publication Output in the Top 1% of Cited Publications

Source: Reproduced from Figure 5a-9 in National Science Board SEI 2020, https://ncses.nsf.gov/pubs/nsb20206/data.

low-quality journals and, on occasion, even outright fraud.[190] In 2017, the Chinese Ministry of Science and Technology announced that more than 100 papers (involving about 400 authors) had been retracted after the editors of one journal, *Tumor Biology*, found serious violations of peer review policies.[191]

Nonetheless, the rapid rise in the number of articles published by Chinese researchers in top-cited journals is a significant indicator that the quality of science in China is increasing (Figure 3-10b and 3-10c).

In a 2018 paper, "China's Overwhelming Contribution to Scientific Publication," Xingnan Xie and Richard Freeman examined research publications with Chinese authors and concluded that other studies have underestimated the impact of Chinese research. For example, Xie and Freeman argue that counting only authors with addresses in China misses Chinese authors with U.S. or other addresses and thus understates the true impact of Chinese researchers.[192] In addition, the Scopus database, used in most studies of scientific publications, includes only a few of the more than 4,000 journals publishing articles in Chinese. While citation counts may imply that these unincluded articles written in Chinese are likely lower-quality papers, some do contain important scientific results.[193] From their analysis, Freeman and Xie conclude:

> That China, one of the lowest income countries in the world at the turn of the 21st century, became a super-power in scientific knowledge in less than two decades is a remarkable development in the history of science. The way China deploys its newly developed scientific resources will drive the direction of science and technology into the foreseeable future and the direction of our increasingly knowledge-based economy. In the 19th century, Horace Greeley famously advised Americans to "Go West, young man, and grow up with the country." In the 21st century, science is going East and will grow up with China.[194]

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[190] David Cyranoski, "China Awaits Controversial Blacklist of 'Poor Quality' Journals," *Nature* 562 (2018): 461 – 472, https://doi.org/10.1038/d41586-018-07025-5.

[191] Normile, "China Cracks Down after Investigation Finds Massive Peer-Review Fraud."

[192] Qingnan Xie and Richard B. Freeman, "China's Overwhelming Contribution to Scientific Publications," 2018, https://scholar.harvard.edu/files/freeman/files/china_overwhelming_contribution_to_scientific_publications_ms_science_voxchina_xie-freeman_sept2018.pdf.

[193] Scopus, https://www.elsevier.com/solutions/scopus.

[194] Qingnan Xie and Richard B. Freeman, "China's Overwhelming Contribution to Scientific Publications," 2018, https://scholar.harvard.edu/files/freeman/files/china_overwhelming_contribution_to_scientific_publications_ms_science_voxchina_xie-freeman_sept2018.pdf.

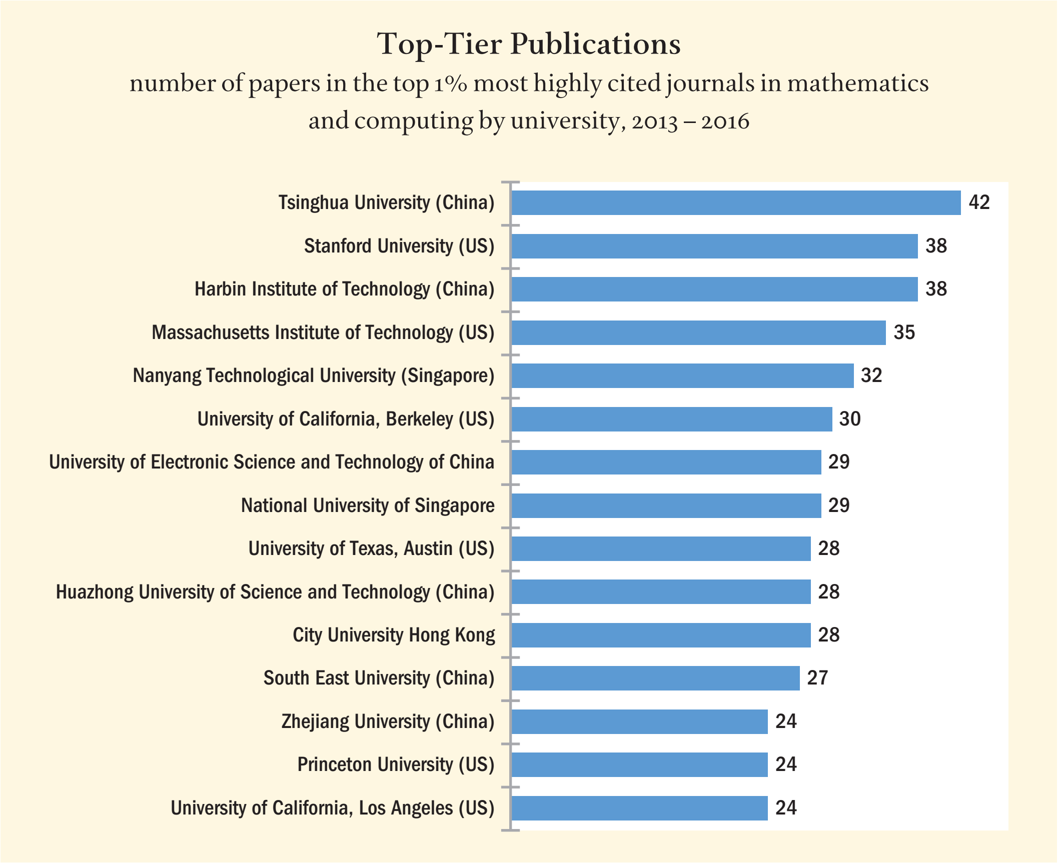

Figure 3-10c

Top-tier publications: number of papers in the top 1% most highly cited journals in mathematics and computing by university, 2013 – 2016

Source: *The Economist,* "Tsinghua University May Soon Top the World League in Science Research," 2018, https://www.economist.com/china/2018/11/17/tsinghua-university-may-soon-top-the-world-league-in-science-research.

3.3.2.2 Patents

The number of patents generated is one, albeit limited, measure of the effectiveness of the transfer of knowledge from research to practical application. The number of China's patent applications has increased over recent decades, eclipsing applications in the rest of the world (Figure 3-11). In 2015, China for the first time granted more patents than the United States (Figure 3-12). However, this indicator is not precise – national practices for granting patents vary, and a large fraction of Chinese patents, especially so-called design patents, are discarded after five years because their holders no longer wish to pay patent fees to protect designs deemed to be of low value.[195]

3.3.3 *Innovation Ecosystem*

> *"[T]he United States appears to be on a course that will lead to a declining, not growing, standard of living for our children and grandchildren."*
>
> – National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising above the Gathering Storm, Revisited – Rapidly Approaching Category* 5, 2010

For many years the United States has been considered to be the world's most competitive economy and a model of innovation that other countries have sought to emulate, based on such factors as a talented workforce, business dynamism, labor markets, and innovation.[196] Today, however, many nations are surpassing the United States in innovativeness.

By one metric, the Bloomberg Innovation Index, the United States is ranked eighth overall in the world. In some specific categories of this index, it ranks even lower – tenth in R&D intensity, measured as GDP percentage spent on R&D; 28th in researcher concentration, measured as the

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[195] Lulu Yilun Chen, "China Claims More Patents Than Any Country – Most Are Worthless," *Bloomberg*, September 26, 2018, https://www.bloomberg.com/news/articles/2018-09-26/china-claims-more-patents-than-any-country-most-are-worthless.

[196] Oliver Cann, "What Makes America the World's Most Competitive Economy?" World Economic Forum, October 16, 2018, https://www.weforum.org/agenda/2018/10/what-makes-america-the-world-s-most-competitive-economy/.

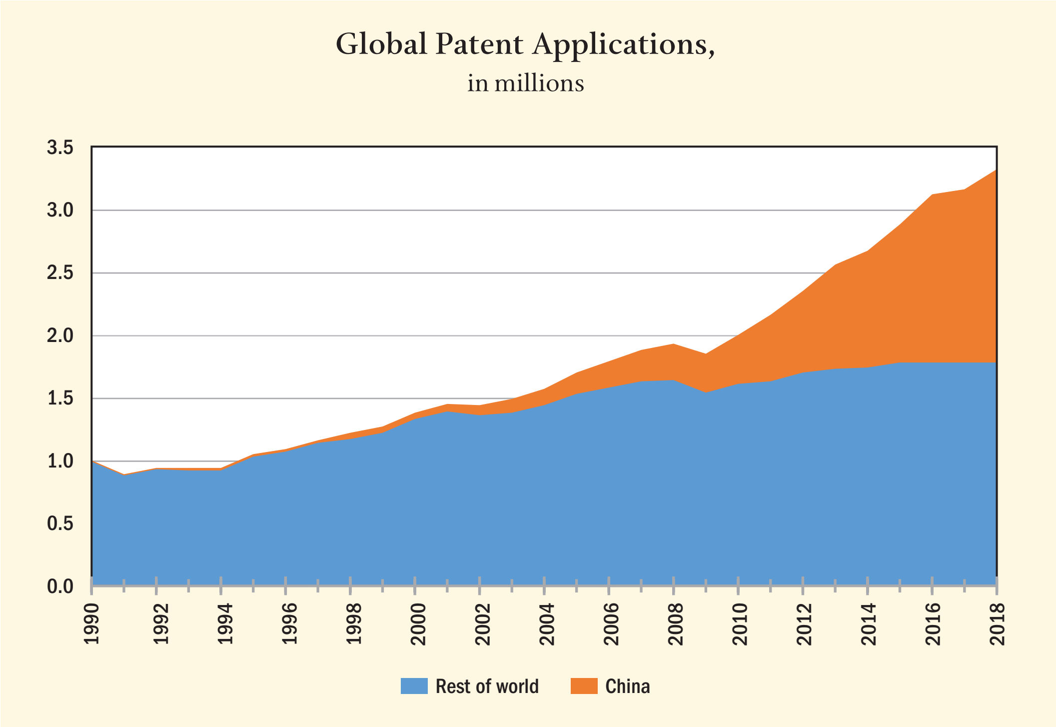

Figure 3-11

Global Patent Applications, in millions

Source: World Intellectual Property Organization, "WIPO Statistics Database," 2019, https://www3.wipo.int/ipstats/. Reproduced from *The Economist*, "The Chinese Century Is Well under Way," 2018, https://www.economist.com/graphic-detail/2018/10/27/the-chinese-century-is-well-under-way.

Note: Includes both Direct & PCT National Phase Entries.

percentage of professionals engaged in R&D per capita; 25th in manufacturing value added; and 43rd in tertiary efficiency, measured as the fraction of citizens receiving tertiary education.[197]

Of the U.S. decline, Robert D. Atkinson, president of the Information Technology and Innovation Foundation in Washington, D.C., said, "I see no evidence to suggest that this (downward) trend will not continue. . . . Other nations have responded with smart, well-funded innovation policies like better R&D tax incentives, more government funding for research, more funding for technology commercialization initiatives."[198]

As recently as 2008, the World Intellectual Property Organization (WIPO), an agency of the United Nations, ranked the United States as the most innovative country in its Global Innovation Index, based on its assessment of 80 indicators of innovation performance in 126 countries.[199] These metrics include political environment, education, infrastructure, and business sophistication. In 2017, the United States slipped to fourth place. In the WIPO's 2018 report, which focuses on energy innovation, the United States was ranked sixth, while China advanced to 17th place because of "an economy witnessing rapid transformation guided by government policy prioritizing research and development-intensive ingenuity."[200]

In *The Politics of Innovation*, Zachary Taylor reports on over 50 years of theory and research on national innovation and the factors that make some countries innovation leaders and others followers. He concludes that innovation depends upon how countries build networks – or inno-

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[197] Michelle Jamrisko and Wei Lu, "The U.S. Drops Out of the Top 10 in Innovation Ranking," *Bloomberg*, January 22, 2018, https://www.bloomberg.com/news/articles/2018-01-22/south-korea-tops-global-innovation-ranking-again-as-u-s-falls; Michelle Jamrisko, Lee J. Miller, and Wei Lu, "These Are the World's Most Innovative Countries," *Bloomberg*, January 22, 2019, https://www.bloomberg.com/news/articles/2019-01-22/germany-nearly-catches-korea-as-innovation-champ-u-s-rebounds. The index bases its ranking on the following criteria: "Postsecondary education: Number of secondary graduates enrolled in postsecondary institutions as a percentage of cohort; percentage of labor force with tertiary degrees; annual science and engineering graduates as a percentage of the labor force and as a percentage of total tertiary graduates" (Peter Coy and Wei Lu, "The Bloomberg Innovation Index," *Bloomberg*, 2015, https://www.bloomberg.com/graphics/2015-innovative-countries/). The United States is penalized by its fraction of high school dropouts (one-third) and six-year graduation rate of 40 – 60 percent from many state public universities.

[198] Michelle Jamrisko and Wei Lu, "The U.S. Drops Out of the Top 10 in Innovation Ranking."

[199] Cornell University, INSEAD, and WIPO, *Global Innovation Index 2018: Energizing the World with Innovation* (Geneva: WIPO, 2018), http://www.wipo.int/publications/en/details.jsp?id=4330; WIPO et al., "Global Innovation Index 2018: China Cracks Top 20. Top Rankings: Switzerland, Netherlands, Sweden, UK, Singapore, U.S.," press release PR/2018/819, July 10, 2018, http://www.wipo.int/pressroom/en/articles/2018/article_0005.html; Confederation of Indian Industry and INSEAD, *Global Innovation Index* 2008 – 2009 (INSEAD, 2009), https://www.globalinnovationindex.org/userfiles/file/GII-2008-2009-Report.pdf.

[200] Ibid.

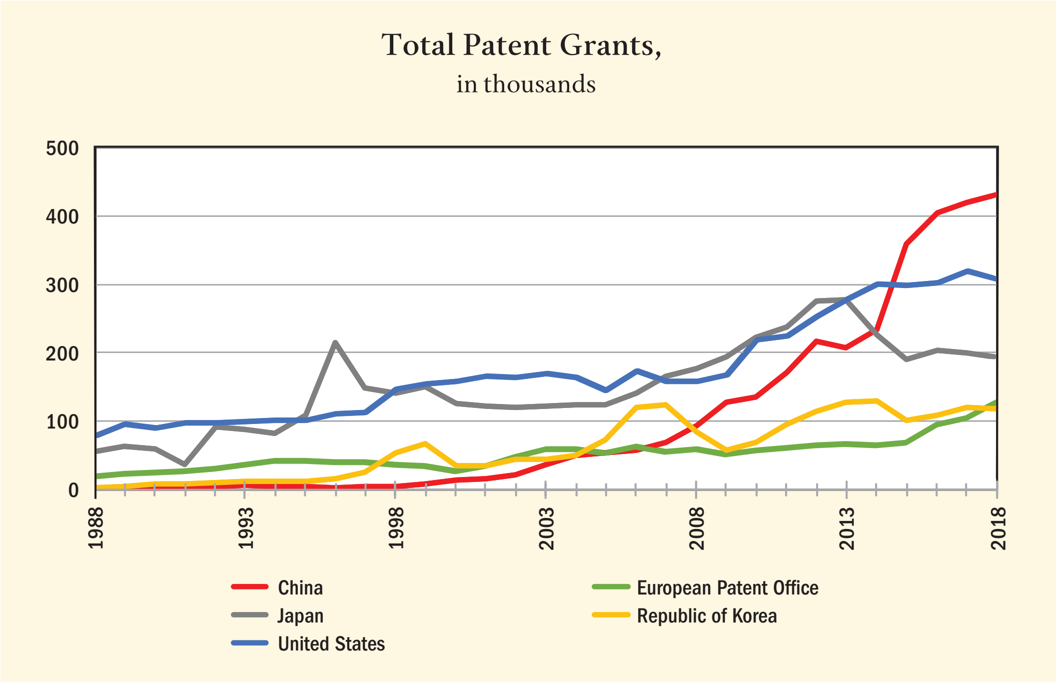

Figure 3-12

Total Patents Grants, in thousands

Source: World Intellectual Property Organization, "WIPO Statistics Database," 2019, https://www3.wipo.int/ipstats/index.htm?tab=patent.

Note: Includes both total patent grants and Patent Cooperation Treaty national phase entries.

vation ecosystems. "Countries that are able [to] bring together the science labor force, provide it with resources, and then build links between it and the business sector are most likely to be successful at innovation."[201]

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[201] "The Politics of Innovation: Why Some Countries Are Better Than Others at Science and Technology" (Event Summary), ITIF, https://itif.org/events/2018/06/21/politics-innovation-why-some-countries-are-better-others-science-and-technology. See also Zachary Taylor, *The Politics of Innovation: Why Some Countries Are Better Than Others at Science and Technology* (Oxford, UK: Oxford University Press, 2016).

3.3.4 *Financial Capital*

The United States, with an approximately $20 trillion GDP in 2018, has a larger economy than China based on currency exchange rates. But when adjusting for buying power using PPP-corrected GDP, China, with a PPP-corrected GDP of $25 trillion, already ranks number one in the world.[202] Some analyses project that China will also be the world's largest economy, when measured by currency exchange rates, by 2030.[203] The current total gross world product is estimated to be nearly $90 trillion at exchange rates. Adjusted for PPP, the figure becomes $128 trillion.[204] Now a major global competitor, China has grown its GDP by an historically unprecedented amount since it reformed its economy more than 40 years ago. A member of the World Trade Organization only since 2001, China has become a major business center of the world. From 2008 to 2018, the number of Chinese Global Fortune 500 companies rose from 29 to 120, while the number of U.S. companies fell from 153 to 126 (Figure 3-13).

In 2015, the United States devoted $497 billion (2.7 percent of GDP) to R&D (public and private), of which 62 percent came from business, 25 percent from the federal government, and 13 percent from other sources such as foundations, state governments, and universities (Table 3.1). The U.S. federal government's share of overall R&D funding has been declining for several decades. In 1962, federal funding accounted for two-thirds of the total national investment in R&D. Today it is less than one-fourth.[205]

In contrast, China devoted an estimated $445 billion (with PPP adjustment) to R&D in 2015, with 76 percent of the funds coming from business, 20 percent from the national government, and the remainder not specified.[206] However, in China the distinction between "public" and "private," especially with respect to business, is fundamentally different from that in the United States. The two countries differ in where R&D is performed and the type of R&D being supported (Table 3.1). U.S. universities' share of American R&D is roughly twice that of Chinese universities' share of Chinese R&D. And the United States devotes approximately twice the percentage of R&D funds

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[202] Noah Smith, "Who Has the World's No. 1 Economy? Not the U.S.," *Bloomberg*, October 18, 2017, https://www.bloomberg.com/opinion/articles/2017-10-18/who-has-the-world-s-no-1-economy-not-the-u-s.

[203] Paton, "World's Largest Economy in 2030 Will Be China."

[204] "Gross World Product," *Statistics Times*, http://statisticstimes.com/economy/gross-world-product.php; CIA, *The World Factbook*, https://www.cia.gov/library/publications/the-world-factbook/geos/xx.html.

[205] National Science Board, *Science and Engineering Indicators 2018*, figure 4-3, https://www.nsf.gov/statistics/2018/nsb20181/report/sections/research-and-development-u-s-trends-and-international-comparisons/recent-trends-in-u-s-r-d-performance.

[206] "2016 Global R&D Funding Forecast," *R&D Magazine*, Winter 2016, supplement, https://www.iriweb.org/sites/default/files/2016GlobalR&DFundingForecast_2.pdf.

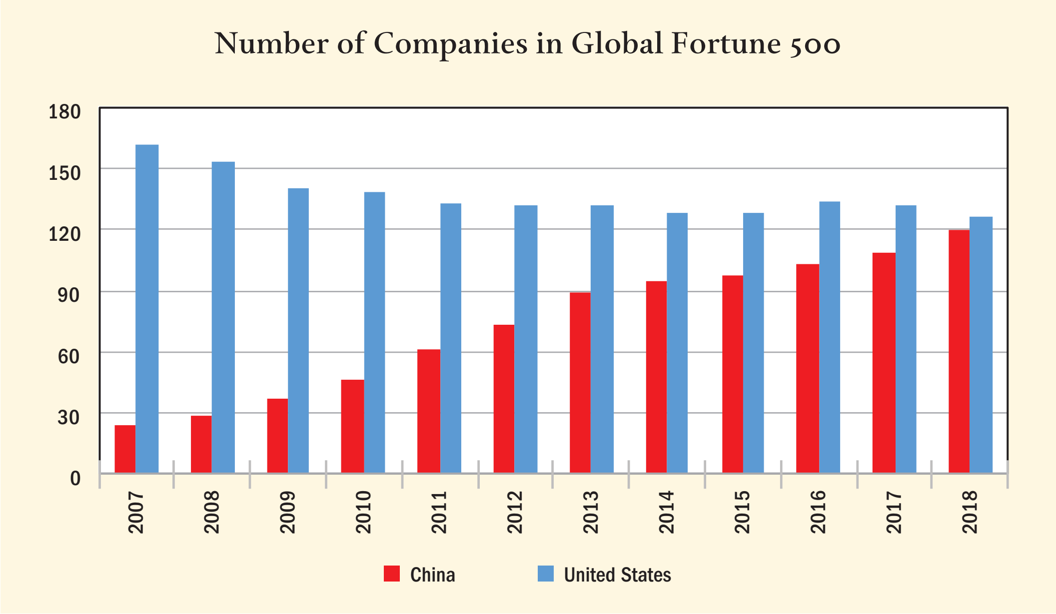

Figure 3-13

Number of Companies in Global Fortune 500

Source: “Global 500,” *Fortune*, https://fortune.com/global500/.

National R&D by Performance, Sector, and Character of Work in 2016 (percent)

		United States	China
By Performer	Business Enterprise	71.8	76.8
	Government	11.0	16.2
	Higher Education	13.3	7.0
	Private Nonprofit	4.0	0.0
By Funder	Business Enterprise	62.3	76.1
	Government	25.1	20.0
	Higher Education	3.7	0.0
	Private Nonprofit	3.8	0.0
	Other Sources	5.2	0.7
By Type of Work	Basic	17.2	5.1
	Applied	19.4	10.8
	Development	63.4	84.2

Table 3.1

National R&D by Performance, Sector, and Character of Work in 2016 (percent)

Source: “OECD Science, Technology and R&D Statistics,” OECD iLibrary, https://doi.org/10.1787/data-00182-en.

to research as does China. The ratio is even larger for fundamental research. China is aware of this imbalance and has flagged research, especially fundamental research, as a particularly high priority in its current five-year plan.[207] The terms *fundamental* (basic) and *applied* are imprecise, but at least qualitative comparisons can be made.

Collectively, companies in the United States support a great deal of domestic R&D. In 2016, U.S. industry reported spending $375 billion on R&D activities, 86 percent ($321 billion) of which derived from their own funds; another 6 percent from the federal government; and the remainder from other sources such as state governments, universities, and other domestic and foreign entities.[208] Companies spent $289 billion (77 percent) on development, $61 billion (16 percent) on applied research, and $25 billion (7 percent) on "basic" research considered to be related to the companies' business interests.[209]

Accounting practices in the United States generally require that R&D be expensed rather than capitalized (as an asset). This tends to discourage companies from pursuing such work.[210] The accounting practice has presumably been required to assure financial conservatism in a firm's financial reporting in the face of the risk that R&D activity often entails. In the United States, as publicly held companies increasingly favor short-term gains in stock price over long-term returns on investments, this also discourages investment in research. It has thus increasingly fallen to the U.S. federal government and other sources, including philanthropy, to ensure that the United States continues to be a country of exploration and scientific discovery.[211]

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207. Kathleen McLaughlin, "Science Is a Major Plank in China's New Spending Plan," *Science*, March 7, 2016, https://www.sciencemag.org/news/2016/03/science-major-plank-china-s-new-spending-plan.

208. Raymond M. Wolfe, "Businesses Spent $375 Billion on R&D Performance in the United States in 2016," NCSES InfoBrief, NSF 18-312, September 2018, https://www.nsf.gov/statistics/2018/nsf18312/.

209. Ibid.

210. "IFRS vs. US GAAP: R&D Costs," KPMG, https://advisory.kpmg.us/articles/2017/ifrs-vs-us-gaap-rd-costs.html.

211. Beatriz Pessoa de Araujo and Adam Robbins, "The Modern Dilemma: Balancing Short- and Long-Term Business Pressures," Harvard Law School Forum on Corporate Governance, June 20, 2019, https://corpgov.law.harvard.edu/2019/06/20/the-modern-dilemma-balancing-short-and-long-term-business-pressures/; Ben S. Bernanke, "Promoting Research and Development: The Government's Role" (speech at the New Building Blocks for Jobs and Economic Growth conference, Washington, D.C., May 16, 2011), https://www.federalreserve.gov/newsevents/speech/bernanke20110516a.htm.

> *"Federal investments in science pay off – they produce cutting-edge ideas and a highly skilled work force. The ideas and personnel then feed into high-tech industries to drive the U.S. economy. It's a straightforward relationship : Industry is attentive to immediate market pressures ; the federal government makes the adventurous investments in university-based research that ensures long-term competitiveness. So far, it's been a powerful tandem."*
>
> – Allan Bromley, science advisor to President George H. W. Bush

3.3.4.1 U.S. R&D Spending

In recent decades, the U.S. federal government's funding of R&D has decreased markedly, although there has been some recovery in the past few years. One indicator of the priority that the government's policy-makers place on science and technology is the fraction of the federal budget the president and Congress devote to R&D. During the Cold War, federal R&D funding peaked at approximately 12 percent of total federal spending (outlays), with nondefense R&D being about 6 percent (Figure 3-14a). At the height of the Apollo Lunar Program, R&D peaked at 17 percent of federal discretionary spending (excluding entitlements and interest on the national debt), and *nondefense* R&D peaked at nearly 25 percent of *nondefense* discretionary spending (Figure 3-14b).

Following the completion of the Apollo Program, and then as the Cold War wound down, federal spending on R&D dropped steadily before reaching a relatively steady plateau. Over the past four decades, federal R&D spending as a fraction of the overall federal budget has narrowly varied between 4 and 5 percent of total spending and between 10 and 12 percent of discretionary spending. Nondefense R&D spending has remained approximately 2 percent of total federal spending (and approximately 10 percent of nondefense discretionary spending) for over four decades.

Yet another indicator of the importance America's policy-makers assign to R&D as a long-term investment in the country's S&T enterprise and future economic growth is the level of federal R&D spending as a percentage of the nation's GDP (Figure 3-15a). Since the end of the Cold War, federal R&D spending by this measure has been reduced by more than a factor of two, from 2 percent at its peak to less than 1 percent in recent years.

The fluctuations in federal R&D funding that have occurred over the four decades from 1976 to 2016 were primarily due to increases in defense R&D during two periods – the Ronald Reagan and George W. Bush administrations – when the overall defense budgets experienced large increases. Overall, federal R&D spending has grown (in constant dollars) by about 1.5 percent per year over the last four decades (Figure 3-15b).

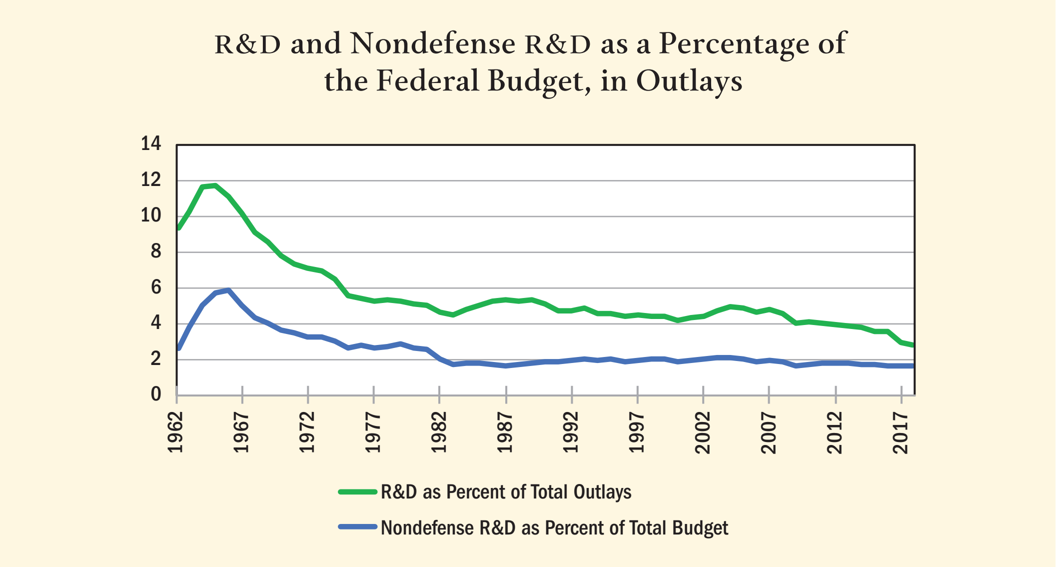

Figure 3-14a

R&D and Nondefense R&D as a Percentage of the Federal Budget, in Outlays

Source: American Association for the Advancement of Science, “Historical Trends in Federal R&D,” 2019, https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd.

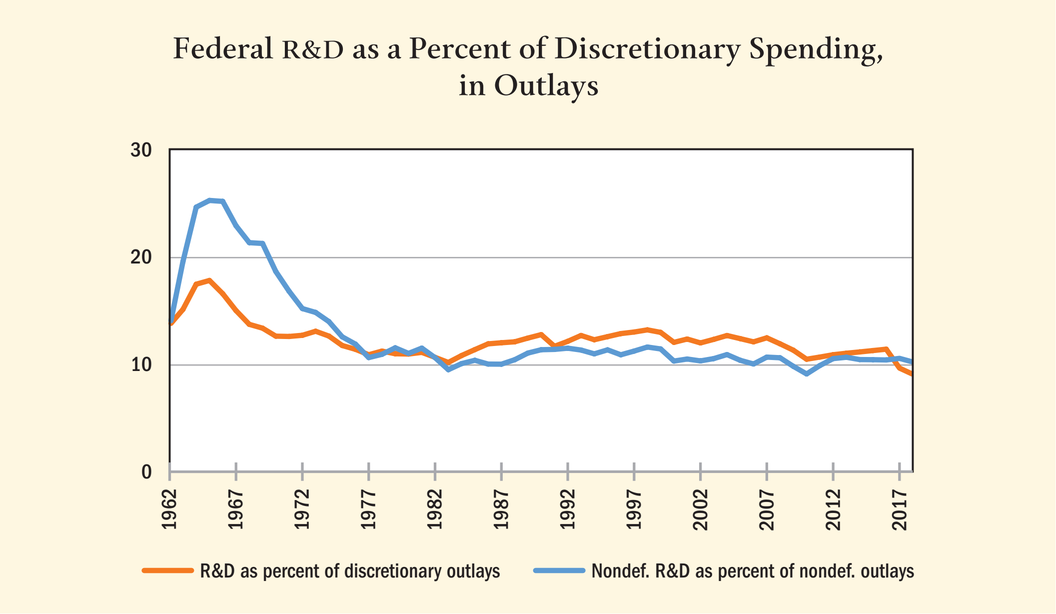

Figure 3-14b

Federal R&D as a Percent of Discretionary Spending, in Outlays

Source: American Association for the Advancement of Science, “Historical Trends in Federal R&D,” 2019, https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd.

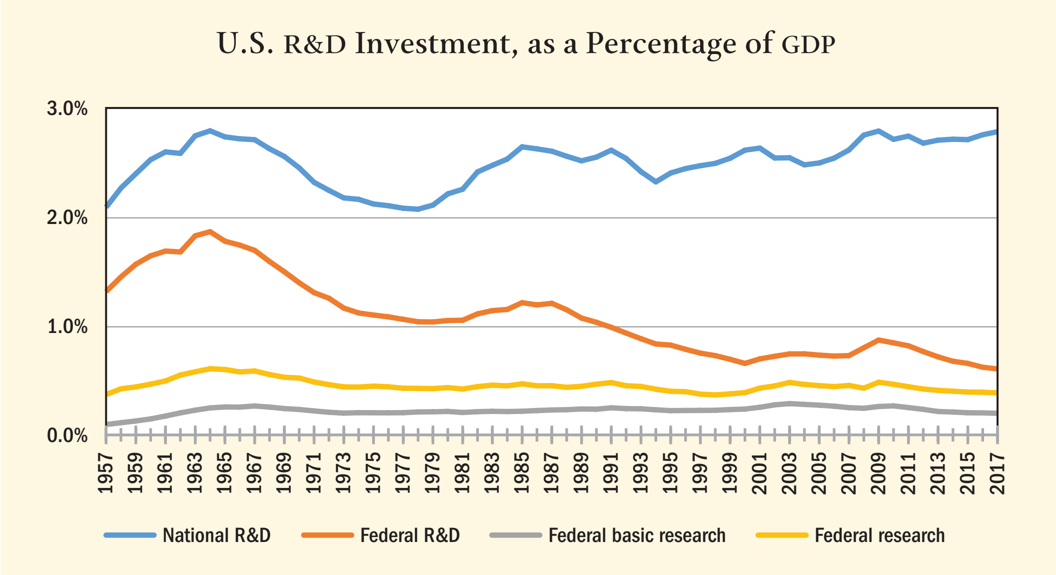

Figure 3-15a

U.S. R&D Investment, as a Percentage of GDP

Source: National Science Foundation National Center for Science and Engineering Statistics, "National Patterns of R&D Resources: 2016 – 17 Data Update," 2019, . https://ncses.nsf.gov/pubs/nsf19309/#general-notes&section2192.

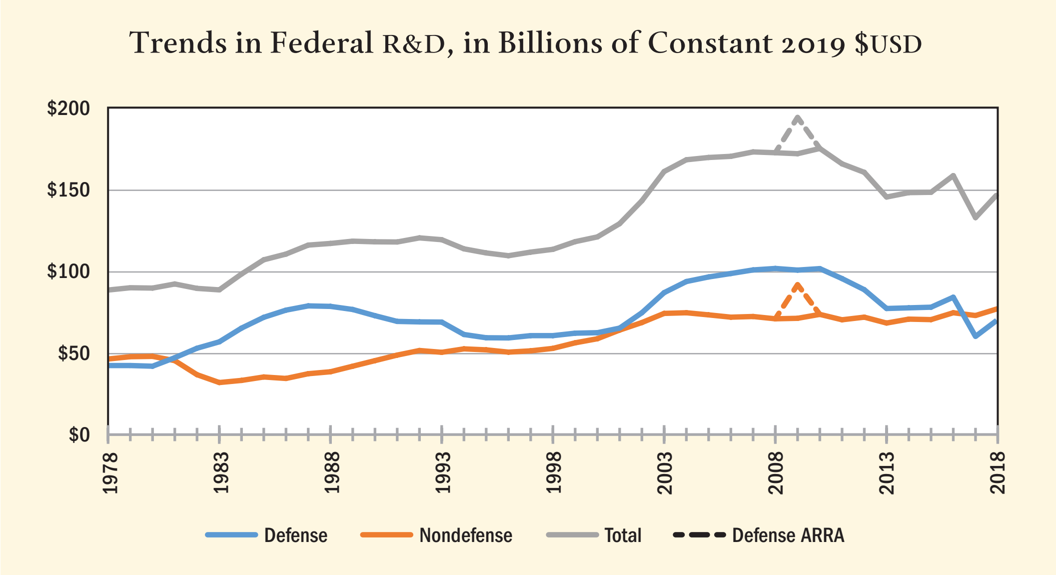

Figure 3-15b

Trends in Federal R&D, in Billions of Constant 2019 $USD

Source: American Association for the Advancement of Science, "Historical Trends in Federal R&D," 2019, https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd.

Note: Dashed lines represent appropriations from the American Recovery and Reinvestment Act of 2009. R&D was redefined for FY2017 to exclude DOD's late-stage development, testing, and evaluation "development" category.

In 2015, total federal R&D funding was 0.8 percent of GDP. Federal spending on research was about 0.4 percent of GDP, split roughly in half between fundamental and applied research. While the overall research fraction, 0.4 percent of GDP, has varied from year to year, it has remained basically unchanged for 40 years. That is, federal spending on research has closely correlated with GDP growth for four decades, independent of changes in geopolitical circumstances, economic events, research opportunities, or other factors (Figure 3-15a).[212]

Federal R&D activities are funded by several defense and nondefense agencies that have distinct missions, statutory authority, and base budgets that reflect broad national needs and the political priorities of the moment (Figure 3-16a). The mix of basic research, applied research, and development differs widely among the departments and agencies (Figure 3-16b), as does the interpretation of the definitions of these categories. For many disciplines of science and engineering – for example, materials research, computing, some areas of biomedical research, and new multidisciplinary and transdisciplinary fields – both fundamental and applied research are being pursued in the same laboratory by the same investigators.[213]

Defense R&D funding correlates closely with the overall defense budget, which experienced significant growth periods after the launch of *Sputnik 1* and during the Reagan and George W. Bush administrations, and is a priority during the present administration.[214] DOD uses seven categories to characterize its R&D activities: basic research (6.1); applied research (6.2); advanced technology development (6.3); advanced component development and prototypes (6.4); system development and demonstration (6.5); research, development, test, and evaluation (6.6); and operational systems development (6.7). Prior to fiscal year (FY) 2017, defense R&D spending was primarily focused (approximately 90 percent) on development, as defined by the White House Office of Management and Budget (OMB), which included categories 6.3 through 6.7. Since the OMB redefined *development* to exclude the "operational systems development" category (6.7), DOD's development budget line has dropped considerably, making comparisons with earlier years difficult. However, the $20 billion drop in defense R&D spending from FY2016 to FY2017 is largely attributable to OMB's redefinition of *development*.[215] The FY2019 DOD R&D budget was approximately $70 billion, or approximately 10 percent of the defense budget, and included $2.5 billion for basic research (6.1); $6 billion for applied research (6.2); and $7.4 billion

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212. The apparent drop in defense R&D in FY2017 was due to a change in DOD's definition of *development*.

213. Alvin Powell, "The False Choice of Basic vs. Applied Research," Harvard John A. Paulson School of Engineering and Applied Sciences, January 3, 2017, https://www.seas.harvard.edu/news/2017/01/false-choice-of-basic-vs-applied-research.

214. Dinah Walker, "Trends in U.S. Military Spending," Council on Foreign Relations, July 15, 2014, https://www.cfr.org/report/trends-us-military-spending.

215. Congressional Research Service, *Federal Research and Development Funding: FY2018*, CRS Report 7-5700 (Washington, D.C.: Congressional Research Service, 2018), https://fas.org/sgp/crs/misc/R44888.pdf.

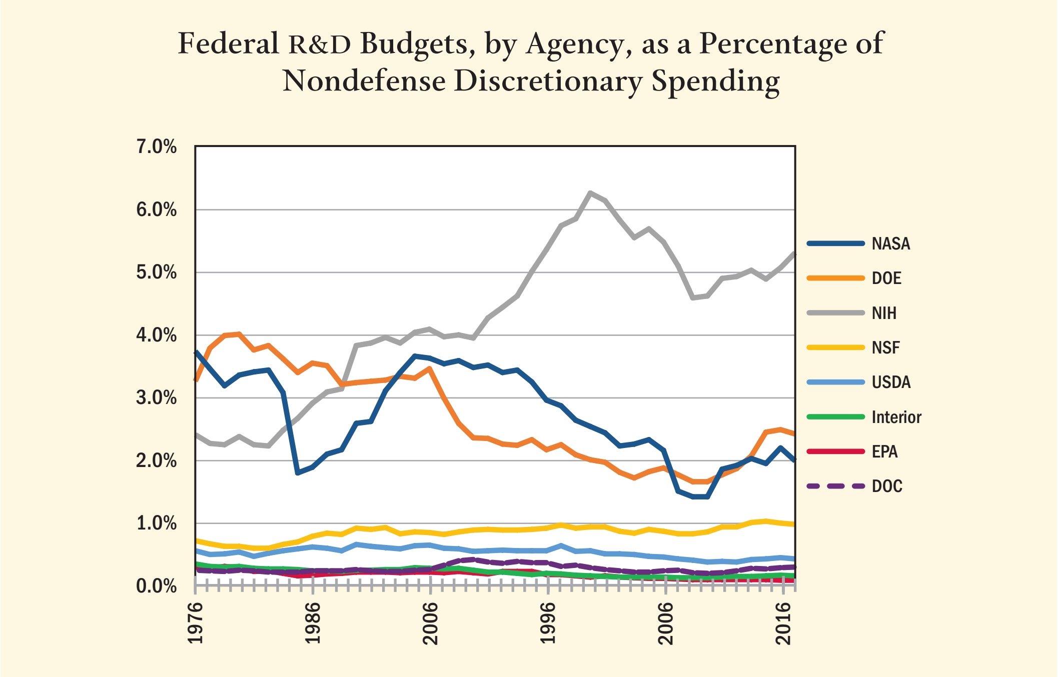
Federal R&D Budgets, by Agency, as a Percentage of Nondefense Discretionary Spending

Figure 3-16a

Federal R&D Budgets, by Agency, as a Percentage of Nondefense Discretionary Spending

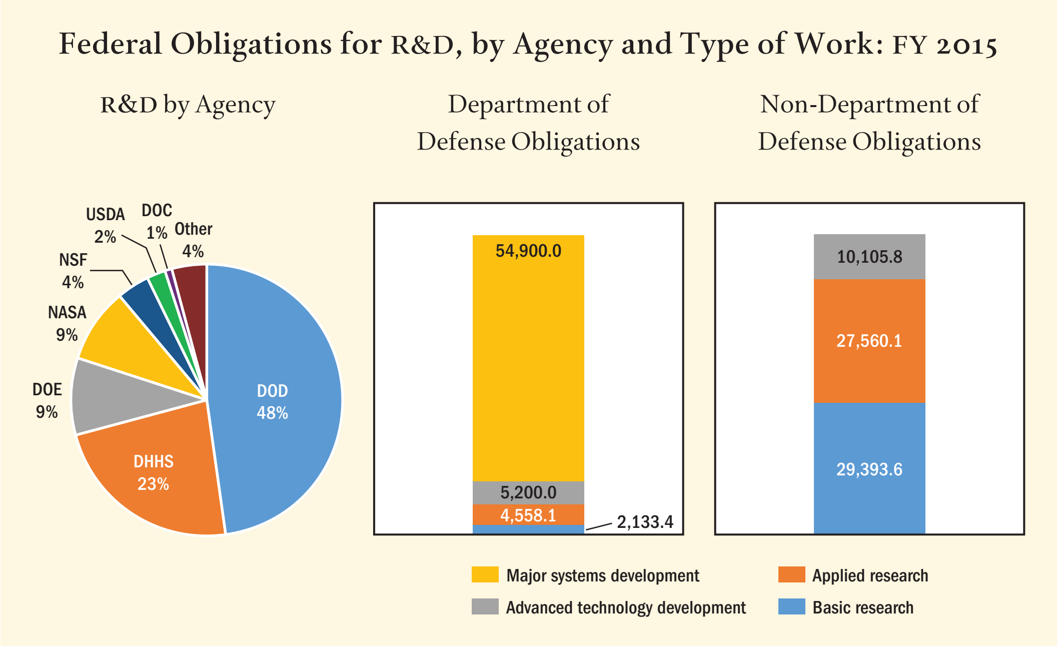
Federal Obligations for R&D, by Agency and Type of Work: FY 2015

Figure 3-16b

Federal Obligations for R&D, by Agency and Type of Work: FY 2015 for advanced technology development (6.3).[216] DOD research is largely focused on the physical sciences, mathematics, and computer sciences, through the Office of Naval Research, Air Force Office of Scientific Research, Army Research Office, and the Defense Advanced Research Projects Agency (DARPA). DOD also currently supports approximately $2 billion of medical research related to military missions.

Of total federal *nondefense* discretionary spending in FY2019, about 10 percent, or approximately $80 billion, is directed to nondefense R&D. Approximately half of all federal nondefense discretionary R&D funding supports biomedical research through the National Institutes of Health (NIH), and the NIH has increased its budget by 40 percent over the past five years, which represents a partial recovery from earlier reductions (Figure 3-16a).[217] Federally funded nondefense R&D has experienced about the same slow growth as total R&D funding, roughly tracking GDP. Both defense and nondefense R&D received significant one-time increases from the American Recovery and Reinvestment Act (ARRA) stimulus package in FY2009.

The administration proposed deep cuts in nondefense R&D in the president's FY2020 budget request; however, Congress rejected those cuts and provided significant budget increases over the FY2019 levels for most agencies that support R&D.[218]

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[216] "Updated FY 2019 Budget Tables," American Association for the Advancement of Science, https://www.aaas.org/page/updated-fy-2019-budget-tables.

[217] National Science Board, *Science and Engineering Indicators 2018*, 4-74 – 4-103, https://nsf.gov/statistics/2018/nsb20181/report/sections/research-and-development-u-s-trends-and-international-comparisons/recent-trends-in-federal-support-for-u-s-r-d; Jocelyn Kaiser, "Senate Bill Would Give NIH $3 Billion in 2020, or 7.7% Boost," *Science*, September 18, 2019, https://www.sciencemag.org/news/2019/09/senate-bill-would-give-nih-3-billion-2020-or-77-boost.

[218] "Trump, Congress Approve Largest U.S. Research Spending Increase in a Decade," *Science*, March 23, 2018, https://www.sciencemag.org/news/2018/03/updated-us-spending-deal-contains-largest-research-spending-increase-decade.

3.3.4.2 Chinese R&D Spending

> *"Great scientific and technological capacity is a must for China to be strong and for people's lives to improve. . . . In seeking to become a world-leading S&T power, China aims to speed up S&T innovations in all fields and seize the initiative in global S&T competition."*
>
> – Chinese President Xi Jinping, at the 2016 biennial conference of the Chinese Academy of Sciences (CAS) and the Chinese Academy of Engineering (CAE), and the national congress of the China Association for Science and Technology (CAST)

China's spending on R&D as a percentage of GDP, unlike America's, has dramatically increased since 2000. R&D spending in constant dollars increased in China by 18 percent per year from 2000 to 2012, albeit from a lower initial base, compared with only 4 percent per year growth for the United States (Figure 1-2). In 2015, China allocated about $400 billion (with PPP conversion) for overall R&D, surpassing the EU.[219] And in 2018, China was projected to have passed the United States in overall R&D investment (with PPP conversion).[220] Although China's economic growth has recently slowed, by placing a high priority on science and technology it has continued to substantially increase funding for R&D.[221] In the past, China has focused much more on development than on research – and even less so on fundamental research – but it has recognized this imbalance and is now increasing fundamental (basic) research funding.[222]

China's former minister of science and technology, Wan Gang, reported that in 2017 China spent 1.76 trillion yuan/$248B (2.15 percent GDP) on R&D, up 71 percent from 2012, thus continuing the nation's double-digit percentage increases.[223] To eliminate its dependence on the United

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[219] "R&D Expenditure," Eurostat: Statistics Explained, last modified September 2019, https://ec.europa.eu/eurostat/statistics-explained/index.php/R_%26_D_expenditure.

[220] In spite of unique limitations on the use of either PPP or exchange rate conversions, virtually all analysts agree that the crossover in national investments in R&D will occur within just a few years if it has not already happened.

[221] "China Economic Outlook," FocusEconomics, last updated January 28, 2020, https://www.focus-economics.com/countries/china.

[222] Teddy Ng and Jane Cai, "China's Funding for Science and Research to Reach 2.5 Per Cent of GDP in 2019," *South China Morning Post*, March 10, 2019, https://www.scmp.com/news/china/science/article/2189427/chinas-funding-science-and-research-reach-25-cent-gdp-2019.

[223] "China Spends $279 Bln on R&D in 2017: Science Minister," Reuters, February 26, 2018, https://www.reuters.com/article/us-china-economy-r-d/china-spends-279-bln-on-rd-in-2017-science-minister-idUSKCN1GB018.

States for computation hardware, China is investing tens of billions of dollars in arguably the most important enabling element of the ongoing technological revolution, the semiconductor integrated circuit, through the recent establishment of its Integrated Circuit Investment Fund. Not surprisingly, then, about 50 percent of China's R&D funds come from investments by the nation's 136,000 private tech companies (although the distinction between "private" and government firms is often vague).[224]

China's current five-year plan (FYP) singles out innovation and R&D for special attention. According to a February 2018 report by the U.S. China Economic and Security Review Commission, China's government plans to use innovation to rebalance the economy to ensure growth is more sustainable and based on higher-value-added manufacturing and domestic consumption. The 13th FYP also broadens the Chinese government's stated commitment to innovation, noting:

> Innovation is a cornerstone of China's development strategy in the 13th FYP and will be an important component of moving Chinese manufacturing up the value-added manufacturing chain and enhancing its future global competitiveness and technological edge. Under the 13th FYP, by 2020 the government seeks to increase its global innovation ranking from 18 to 15, the share of R&D spending as a percent of gross domestic product (GDP) from 2.1 to 2.5, the number of patents filed per 10,000 people from 6.3 to 12, and the number of personnel in R&D.[225]

The plan sets a goal of enhancing China's STEM base by increasing the share of the population with scientific degrees from 6.2 percent in 2015 to 10 percent by 2020 and by increasing the number of R&D personnel per 10,000 people employed from 48.5 in 2015 to 60 in 2020.[226]

China is also investing in scientific infrastructure as well as its people and academic institutions. As but one example, the Shanghai Synchrotron Radiation Facility is one of the most advanced third-generation light sources in the world, supporting over 10,000 users from throughout the world.

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[224] Ibid.; Xinhua, "China's R&D Spending Increases over Five Years: Minister," *China Daily*, January 10, 2018, http://www.chinadaily.com.cn/a/201801/10/WS5a554e68a3102e5b17371b3c.html; Ashley Feng, "We Can't Tell if Chinese Firms Work for the Party," *Foreign Policy*, February 7, 2019, https://foreignpolicy.com/2019/02/07/we-cant-tell-if-chinese-firms-work-for-the-party/.

[225] Katherine Koleski, *The 13th Five-Year Plan* (Washington, D.C.: U.S.-China Economic and Security Review Commission, February 14, 2017), https://www.uscc.gov/sites/default/files/Research/The%2013th%20Five-Year%20Plan_Final_2.14.17_Updated%20(002).pdf.

[226] Denise Hruby, "Why China Needs Your Scientific Expertise," *Nature* 553 (2018): S2 – S3, https://doi.org/10.1038/d41586-018-00536-1.

Left : Artist rendition of quantum satellite Micius, from *Science*.
Right : Shanghai Synchrotron Radiation Facility. Source : Getty Images.

A TIMELY EXAMPLE: ARTIFICIAL INTELLIGENCE AND 5G TECHNOLOGY IN THE UNITED STATES AND CHINA

> *"We're going to be able to ask our computers to monitor things for us, and when certain conditions happen, are triggered, the computers will take certain actions and inform us after the fact."*
>
> – Steve Jobs, former CEO of Apple

> *"All of us are going where the high IQ's are."*
>
> – Bill Gates, Founder of Microsoft Corporation

> *"Whoever becomes the leader in this sphere [AI] will become the ruler of the world."*
>
> – Vladimir Putin, President of Russia

AI and 5G networking are particularly important examples of rapidly developing areas of technology where R&D, innovation, and market deployment are all global challenges. In the United States, aggressive efforts in AI are being led primarily by the private sector, building upon decades-long federal investments in fundamental (basic) research into topics such as high-performance computing and complex modeling.[227] Today, American companies like Google and Amazon lead the world in applications of AI to e-commerce.[228] Google's parent company, Alphabet, recently won the biennial "protein folding" competition – predicting the shape of long protein molecules – with the company's DeepMind AI lab.[229] The lab's computers previously made headlines by defeating world experts in the complicated game of Go.[230] Medical researchers are predicting that AI will prove a useful tool in future drug discovery and

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[227] "Artificial Intelligence (AI) at NSF," National Science Foundation, last updated June 25, 2019, https://nsf.gov/cise/ai.jsp.

[228] "Machine Learning on AWS," Amazon Web Services, https://aws.amazon.com/machine-learning/; Google AI, https://ai.google/.

[229] Andrew Senior et al., "AlphaFold: Using AI for Scientific Discovery," DeepMind Blog, January 15, 2020, https://deepmind.com/blog/article/alphafold.

[230] Elizabeth Gibney, "Self-Taught AI Is Best Yet at Strategy Game Go," *Nature*, October 18, 2017, https://www.nature.com/news/self-taught-ai-is-best-yet-at-strategy-game-go-1.22858.

will speed up many aspects of diagnostics and treatment.[231] However, a challenge facing U.S. companies is the chronic shortage of technically trained workers. To find needed human capital, Google and other companies are expanding their operations abroad, where AI talent continues to expand.[232] The present AI talent shortage is a harbinger of the talent problems that will plague the United States throughout this century if current trends prevail. Prototype facilities and, eventually, factories not uncommonly follow the location of research laboratories.

For the U.S. government, rapid response to a fast-developing challenge like AI is problematic. Making significant changes in R&D budget lines commonly takes nearly two years and generally requires several agencies with different missions to align their R&D efforts with other priorities within their purview. In 2019, President Donald Trump signed an executive order establishing a new American AI Initiative that will "focus the resources of the Federal government to develop AI in order to increase our Nation's prosperity, enhance our national and economic security, and improve quality of life for the American people."[233] The administration identifies R&D investments in quantum information, strategic computing, and AI as budget priorities in the FY2020 guidance memo sent by the White House Office of Science and Technology Policy (OSTP) and OMB to federal agencies.[234]

Various federal agencies support AI R&D. DOD established the Joint Artificial Intelligence Center to accelerate the development of new AI enabled capabilities.[235] DARPA indicated that it will invest $2 billion in an AI Next Campaign to create the "next wave of AI technologies."[236] Presumably, given the Pentagon's concerns about the national security implications of the United States falling behind in AI, other defense agencies will also direct funding to AI R&D. The National Science Foundation spends an estimated $100 million annually in fundamental AI research,

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[231] Cade Metz, "Making New Drugs with a Dose of Artificial Intelligence," *The New York Times*, February 6, 2019, https://www.nytimes.com/2019/02/05/technology/artificial-intelligence-drug-research-deepmind.html.

[232] Ibid.

[233] Donald J. Trump, "Executive Order on Maintaining American Leadership in Artificial Intelligence," February 11, 2019, https://www.whitehouse.gov/presidential-actions/executive-order-maintaining-american-leadership-artificial-intelligence/.

[234] Mick Mulvaney and Michael Kratsios, Memorandum, "FY 2020 Administration Research and Development Budget Priorities," M-18-22, July 31, 2018, https://www.whitehouse.gov/wp-content/uploads/2018/07/M-18-22.pdf.

[235] "Vision: Transform the DoD through Artificial Intelligence," Department of Defense Joint Artificial Intelligence Center, https://dodcio.defense.gov/About-DoD-CIO/Organization/JAIC/.

[236] "AI Next Campaign," DARPA, https://www.darpa.mil/work-with-us/ai-next-campaign; "DARPA Announces $2 Billion Campaign to Develop Next Wave of AI Technologies," DARPA, September 7, 2018, https://www.darpa.mil/news-events/2018-09-07.

and other nondefense agencies such as NIH have also identified AI opportunities.[237] The OSTP/OMB R&D priorities memorandum, which gave guidance to the agencies as they prepared their FY2020 budgets, emphasizes AI as a particularly high priority, saying "agencies should invest in fundamental and applied AI research, including machine learning, autonomous systems, and applications at the human-technology frontier. Agencies should prioritize QIS [Quantum Information Science] R&D, which will build the technical and scientific base necessary to explore the next generation of QIS theory, devices, and applications."[238]

A select committee on AI, under the White House National Science and Technology Council (NSTC), has been charged with coordinating AI and updating the 2016 National AI R&D Strategic Plan.[239] The NSTC has the capability to form a coherent and integrated federal AI plan, as it has done for nanotechnology, and to contain other interagency R&D initiatives, but that will require several agencies agreeing to coordinate their annual budget requests.

China, South Korea, Britain, France, and Canada are also accelerating their work in AI. In July 2017, China announced its intention to become the world leader in AI with a goal to create a $150 billion industry by 2030.[240] Two Chinese cities have announced plans to invest the equivalent of tens of billions of dollars in AI.[241] In 2019, China announced 400 new university majors specifically focused on big data, AI, and robotics.[242] Experts in AI are concerned that China could lead the world in important applications such as surveillance systems, autonomous weapons, driverless cars, Internet services – essentially everything from consumer products to healthcare to warfare.[243] China has several obvious advantages: a large and rapidly growing well-educated

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[237] "Statement on Artificial Intelligence for American Industry," National Science Foundation, press statement 18-005, May 10, 2018, https://www.nsf.gov/news/news_summ.jsp?cntn_id=245418; "Artificial Intelligence, Machine Learning, and Deep Learning," National Institute of Biomedical Imaging and Bioengineering, https://www.nibib.nih.gov/research-funding/machine-learning.

[238] Mulvaney and Kratsios, "FY 2020 Administration Research and Development Budget Priorities."

[239] "Charter of the National Science and Technology Council Select Committee on Artificial Intelligence," https://epic.org/SelectCommitteeonAI.pdf.

[240] Paul Mozur, "Beijing Wants A.I. to Be Made in China by 2030," *The New York Times*, August 7, 2018, https://www.nytimes.com/2017/07/20/business/china-artificial-intelligence.html; Meng Jing, "Tianjin City in China Eyes US$16 Billion Fund for AI Work, Dwarfing EU's Plan to Spend US$1.78 Billion," *South China Morning Post*, May 16, 2018, https://www.scmp.com/tech/innovation/article/2146428/tianjin-city-china-eyes-us16-billion-fund-ai-work-dwarfing-eus-plan.

[241] Jing, "Tianjin City in China Eyes US$16 Billion Fund for AI Work."

[242] Chen Xi, "China to Open 400 Big Data, AI Majors in Universities for Global Competition," *People's Daily Online*, February 27, 2019, http://en.people.cn/n3/2019/0227/c202936-9550508.html.

[243] Sarah O'Meara, "Will China Overtake the U.S. in Artificial Intelligence Research?" *Scientific American*, August 24, 2019, https://www.scientificamerican.com/article/will-china-overtake-the-u-s-in-artificial-intelligence-research/.

STEM workforce; the ability to direct large amounts of funding to AI; and a large population that enables the creation of large databases for machine learning, including in such areas as commerce and medicine.

U.S. and Chinese researchers working together developed a system to diagnose childhood illnesses such as meningitis, influenza, asthma, and gastrointestinal disease using a large database of 1.3 million patients who had visited Chinese pediatric hospitals over an 18-month period.[244] While AI will not replace the role of the physician, it could prove to be a valuable diagnostic tool. This is a good example of the importance of encouraging joint research between researchers in the United States and many other countries, including China.

The ubiquitous impact of AI will become increasingly apparent as 5G networking, with theoretical data rates as high as 100 times greater than current 4G capability, becomes widely available.[245] 5G competition has also increased from the Chinese companies ZTE Technology and Huawei. [246] Huawei, with $100 billion in revenues, has in the past three decades become one of the world's leading sellers of smartphones, recently passing Apple as #2 (South Korea's Samsung remains #1).[247] Huawei is also a leading provider of Internet services across the globe and is moving aggressively to install 5G technology based on its own hardware and systems.[248]

The United States, Britain, and other countries have expressed concerns that China's investment in 5G technology presents a serious security risk. The United States has banned the federal government and government contractors from using Huawei's services and technologies and is pressuring other countries to do likewise.[249] The concern is that as information and physical objects are increasingly becoming connected to the "internet of things," whoever controls the Internet, with its possible backdoors and other hidden features, will control much of the world's

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[244] Huiying Liang et al., "Evaluation and Accurate Diagnoses of Pediatric Diseases Using Artificial Intelligence," *Nature Medicine* 25 (3) (2019): 433, https://doi.org/10.1038/s41591-018-0335-9.

[245] Sacha Kavanagh, "How Fast IS 5G?" 5G.co.uk, https://5g.co.uk/guides/how-fast-is-5g/.

[246] Li Tao, "ZTE Secures More Than 25 Commercial 5G Network Contracts as It Steps Up Turnaround Efforts," *South China Morning Post*, June 25, 2019, https://www.scmp.com/tech/gear/article/3016032/zte-secures-more-25-commercial-5g-network-contracts-it-steps-turnaround.

[247] "Huawei Overtakes Apple as World No. 2 Smartphone Seller, Gains Ground in China," Reuters, July 30, 2018, https://www.reuters.com/article/us-huawei-revenue/huawei-overtakes-apple-as-world-no-2-smartphone-seller-gains-ground-in-china-idUSKBN1KL0BN.

[248] Arjun Kharpal, "Huawei Touts More Than 50 Contracts for 5G as U.S. Pressure Continues to Mount," CNBC, September 3, 2019, https://www.cnbc.com/2019/09/03/huawei-touts-more-than-50-contracts-for-5g-as-us-pressure-mounts.html.

[249] Steve Lohr, "U.S. Moves to Ban Huawei From Government Contracts," *The New York Times*, August 7, 2019, https://www.nytimes.com/2019/08/07/business/huawei-us-ban.html.

assets and activities.[250] However, Cisco's most recent Visual Networking Index report predicts that in 2022 North America will be ahead of Asia in advancing 5G penetration (i.e., in the percentage of mobile devices with 5G technology) while offering the caveat that a number of obstacles will need to be overcome along the way.[251] These include uncertainties in federal infrastructure policy and the current U.S. stance on contracts with certain foreign technology firms.[252]

The United States and China are in an ongoing race to develop high-performance supercomputers, which are used for weapons design and code-breaking, among other purposes. Although the United States is currently home to the second-fastest supercomputer, which is located at the Oak Ridge National Laboratory in Tennessee, China builds the most supercomputers in the world and as of 2018 possessed 206 of the top 500 supercomputers in existence.[253] The U.S. Department of Energy is currently building a $500 million machine for the Argonne National Laboratory. This machine is scheduled to be delivered in 2021 and is predicted to be capable of "exascale" performance, or more than a quintillion calculations per second, the first American machine with this capability and the fastest supercomputer in the world.[254]

3.4 A LOOMING THREAT TO U.S. FEDERAL SUPPORT OF R&D

The arguments for increased investment in R&D are compelling, especially for the basic research funded by the federal government and largely conducted in America's universities and national laboratories. While R&D funding is a small element of the overall federal budget (Figure 3-17) and the nation's GDP, looming budget trends may severely constrain future presidents and Congresses when making annual budget allocations to discretionary programs, including R&D. On the other hand, total federal research (basic and applied) is a relatively

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[250] Tam Harbert, "Practical Uses of the Internet of Things in Government Are Everywhere," *Government Technology*, January/February 2017, https://www.govtech.com/network/Practical-Uses-of-the-Internet-of-Things-in-Government-Are-Everywhere.html.

[251] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017 – 2022," white paper, February 2019, https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-738429.html.

[252] Brian Fung, "The Race to 5G Wireless Tech Is On: A Report Finds Americans May Have an Early Lead," *Washington Post*, February 19, 2019, https://www.washingtonpost.com/technology/2019/02/19/race-g-wireless-tech-is-report-finds-americans-have-an-early-lead/.

[253] Steve Lohr, "China Extends Lead as Most Prolific Supercomputer Maker," *The New York Times*, June 25, 2018, https://www.nytimes.com/2018/06/25/technology/china-supercomputers.html.

[254] Don Clark, "Racing Against China, U.S. Reveals Details of $500 Million Supercomputer," *The New York Times*, March 18, 2019, https://www.nytimes.com/2019/03/18/technology/china-us-500-million-supercomputer.html.

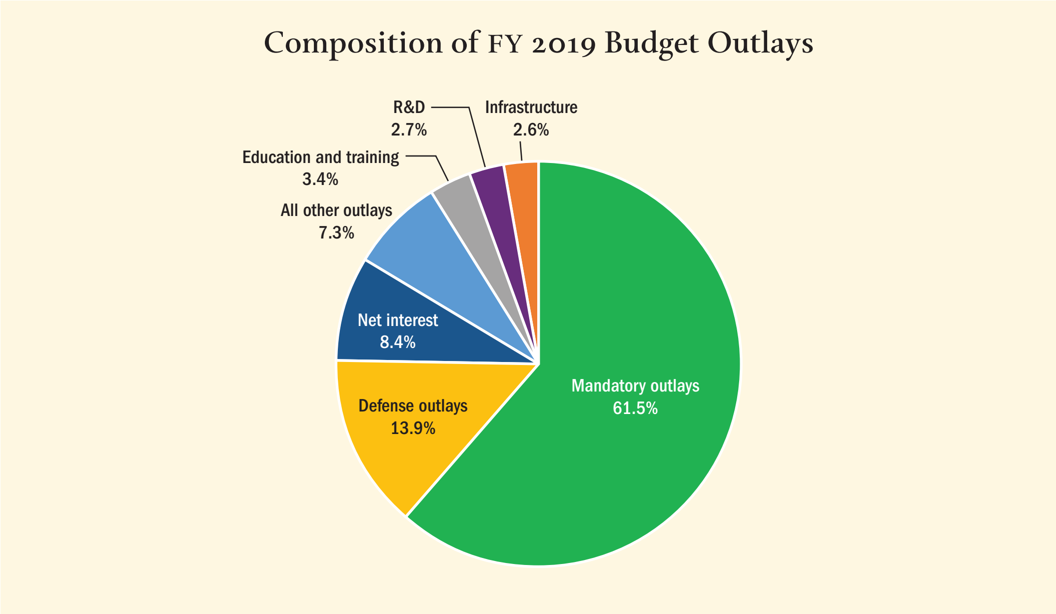

Figure 3-17

Composition of FY2019 Budget Outlays

Source: "AAAS Federal R&D Budget Dashboard," https://www.aaas.org/programs/r-d-budget-and-policy/federal-rd-budget-dashboard.

small fraction of GDP (0.4 percent) and of total annual federal spending (2 percent), so even if doubled it would still be relatively modest in the overall scale of the national economy.

In recent years, the administration and Congress have shown little concern for the large annual federal budget deficits and growing national debt, but history and COVID-19–related expenditures suggest this may have to change, and fundamental economics also suggests it will change. When policy-makers must focus on reducing deficits and, ultimately, the national debt, research funding will be particularly vulnerable. Many federal budget areas, especially those offering near-term benefits, are backed by powerful political constituencies. Science, with the possible exception of health science, has no such advantage.

The existential threat to R&D – and to federal functions as a whole – is the rapidly increasing gap between federal revenues and outlays (Figure 3-18). The cost of addressing COVID-19 will significantly exacerbate this budgetary threat.

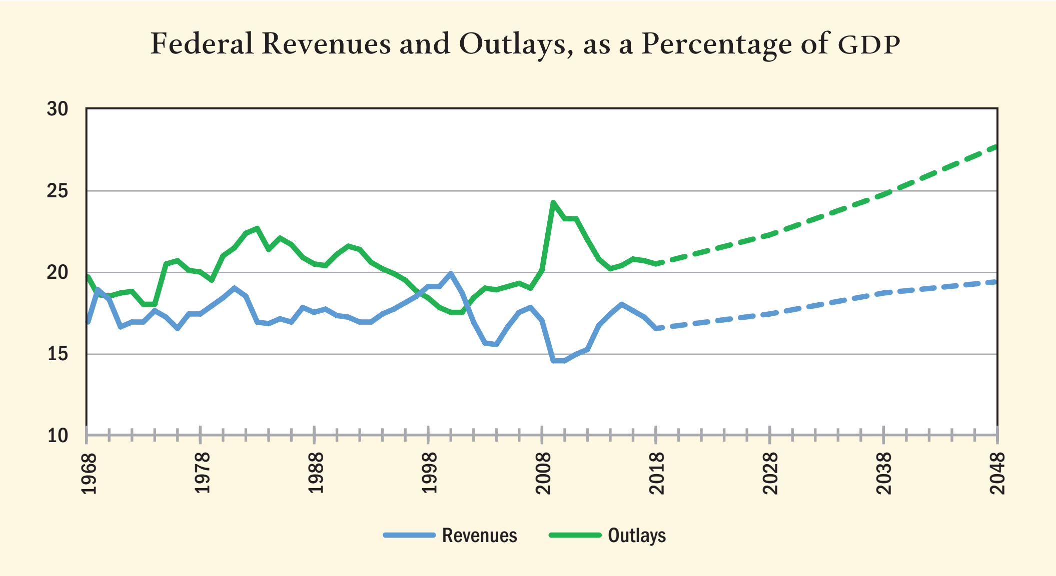

Figure 3-18

Federal Revenues and Outlays, as a Percentage of GDP

Source: Historical data taken from Table E-1 in Congressional Budget Office, "The Budget and Economic Outlook: 2018 to 2028," 2018, https://www.cbo.gov/publication/53651. Projections to 2048 taken from Table 1 in Congressional Budget Office, "The 2018 Long-Term Budget Outlook," 2018, https://www.cbo.gov/publication/53919.

The gap between revenues and expenditures is reflected in annual deficits and growing cumulative debt, the latter of which in turn leads to higher expenditures for interest on that debt, further compounding the budgetary dilemma (Figure 3-19).

The U.S. national debt was about $22 trillion at the end of February 2019, somewhat larger than the nation's GDP, representing an increase of nearly 7 percent from the previous year.[255] As of 2018, much of that debt ($6.9 trillion, or 32 percent) is held by U.S. investors, nongovernment institutions, and individuals. The U.S. government's share of debt ownership is mostly in the form of Social Security and pension obligations ($5.7 trillion, or 27 percent); and the Federal

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[255] Bill Chappell, "U.S. National Debt Hits Record $22 Trillion," NPR, February 13, 2019, https://www.npr.org/2019/02/13/694199256/u-s-national-debt-hits-22-trillion-a-new-record-thats-predicted-to-fall.

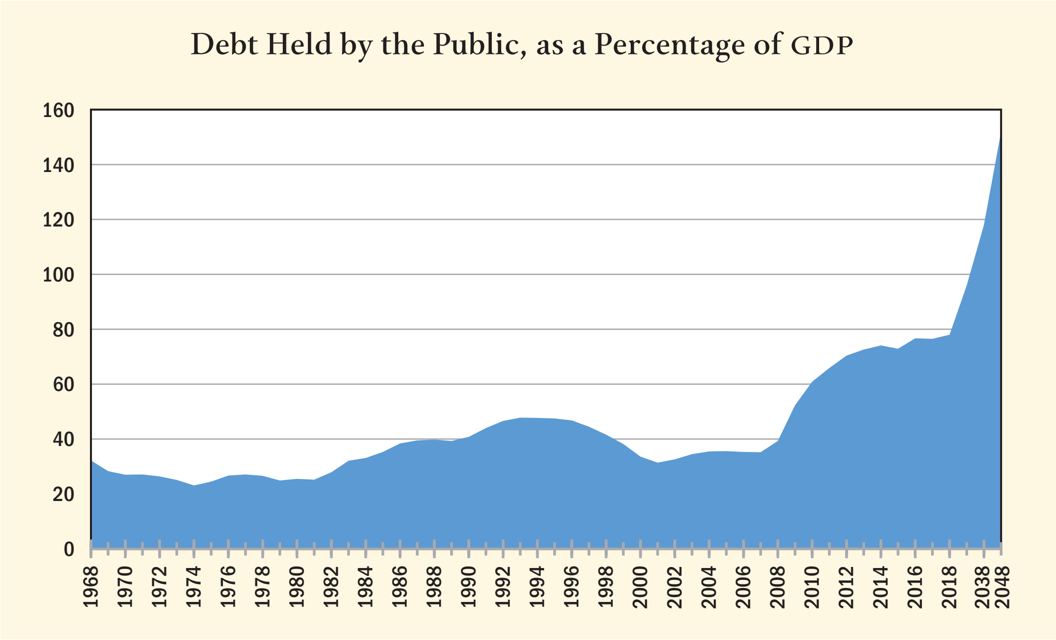

Figure 3-19

Debt Held by the Public, as a Percentage of GDP

Source: Historical data taken from Table E-1 in Congressional Budget Office, "The Budget and Economic Outlook: 2018 to 2028," 2018, https://www.cbo.gov/publication/53651. Projections to 2048 taken from Table 1 in Congressional Budget Office, "The 2018 Long-Term Budget Outlook," 2018, https://www.cbo.gov/publication/53919.

Reserve holds an additional $2.4 trillion, or 11 percent.[256] Foreign investors account for $6.2 trillion, or 29 percent of the total. The two largest foreign debt holders are China ($1.2 trillion, or 5.6 percent) and Japan ($1.0 trillion, or 4.9 percent).[257]

The CBO estimated the deficit for FY2018 to be $895 billion, up 33 percent in a single year. This is attributed to decreased corporate tax payments (due to the tax reform bill), increased spending on major entitlement programs, and increased interest payments on the national debt. The CBO

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[256] Ibid.; Jeffry Bartash, "Here's Who Owns a Record $21.21 Trillion of U.S. Debt," *MarketWatch*, August 23, 2018, https://www.marketwatch.com/story/heres-who-owns-a-record-2121-trillion-of-us-debt-2018-08-21.

[257] Jeffry Bartash, "Here's Who Owns a Record $21.21 Trillion of U.S. Debt."

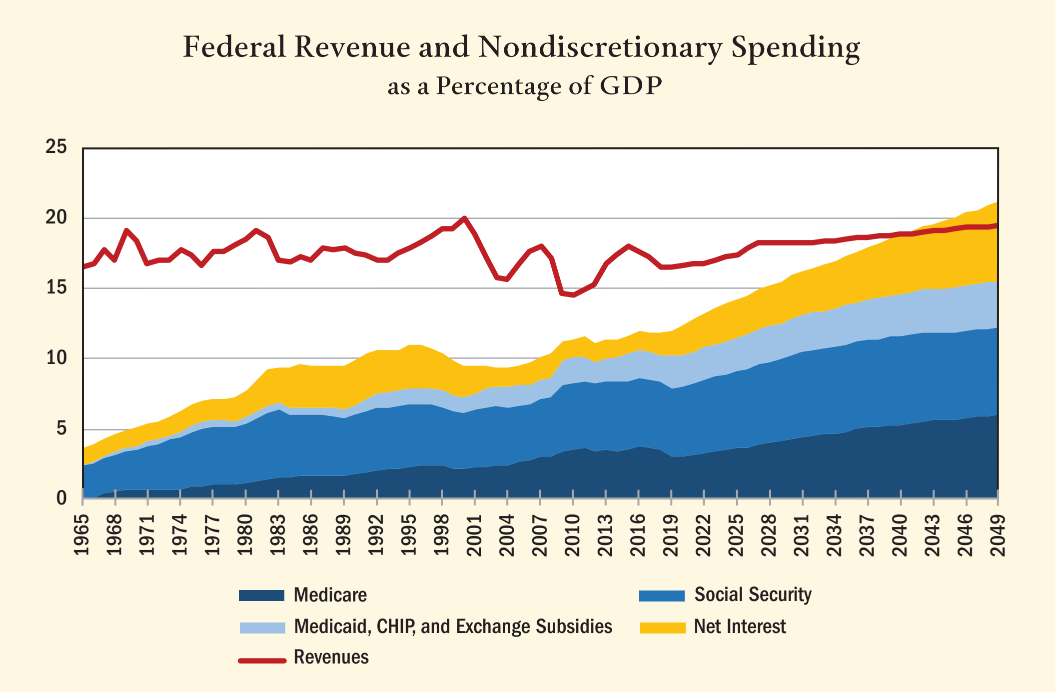

Figure 3-20

Federal Revenue and Nondiscretionary Spending, as a Percentage of GDP

Source: Congressional Budget Office, https://www.cbo.gov/about/products/budget-economic-data, accessed January 23, 2020.

also projects a cooling of the U.S. economy from 3.1 percent real GDP growth in FY2018, to 2.4 percent in FY2019, to under 2 percent in the following years.[258]

Quoting the CBO:

> At 78 percent of GDP, federal debt held by the public is now at its highest since shortly after World War II. If current laws generally remained unchanged, CBO projects growing budget deficits would boost that debt sharply over the next 30 years; it would approach 100 percent of GDP by the end of the next decade and 152 percent by 2048. That amount would be the highest in the nation's history by far. Moreover, if lawmakers changed current law to maintain certain policies now in place – preventing a significant increase in individual income taxes in 2026, for example – the result would be even larger increases in debt. The prospect of large and growing debt poses substantial risks for the nation and presents policymakers with significant challenges.[259]

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[258] CBO, *An Update to the Economic Outlook: 2018 to 2028* (Washington, D.C.: CBO, 2018), https://www.cbo.gov/publication/54318.

[259] CBO, *The 2018 Long-Term Budget Outlook* (Washington, D.C.: CBO, 2018), https://www.cbo.gov/publication/53919.

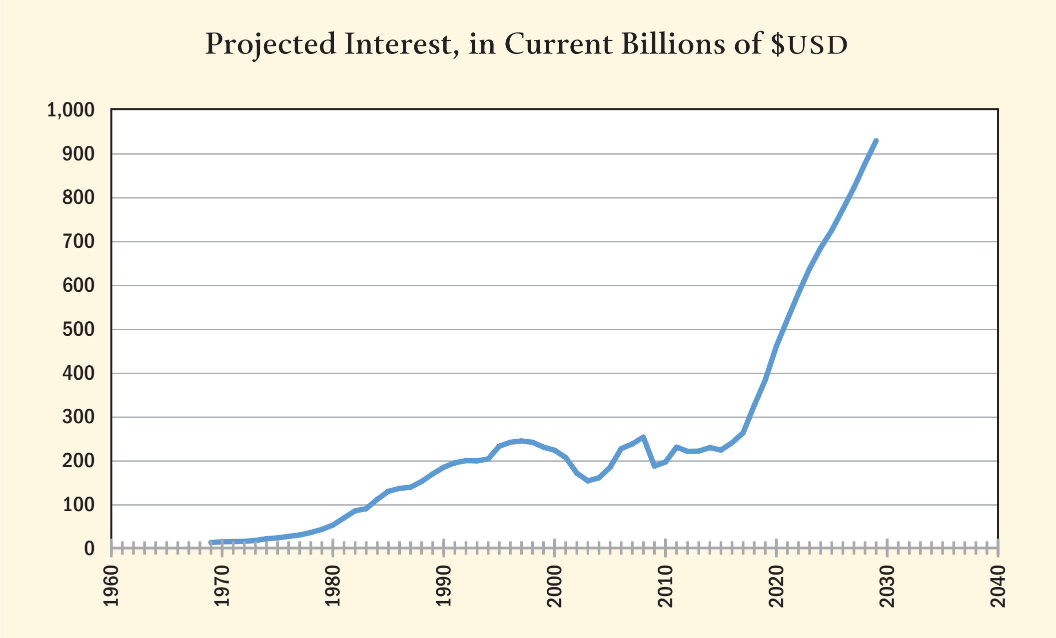

Figure 3-21

Projected Interest, in Current Billions of $USD

Source: Congressional Budget Office, "The Budget and Economic Outlook: 2019 to 2029," 2019, https://www.cbo.gov/publication/54918.

The above assessment was, of course, made without consideration of the budgetary consequences of the COVID-19 response.

Nondiscretionary ("mandatory") spending (interest on the debt and already legislated "entitlements") remains dangerously close to overtaking total revenues (Figure 3-20). When it does, discretionary expenses – defense, health, infrastructure, agriculture, education, and R&D – will all have to be funded either by borrowing or tax increases, the former thereby further increasing annual deficits and debt and concomitant interest payments (Figure 3-21).

Unless research, and R&D more broadly, emerge as much higher priorities than has been typical of recent decades, future budgets will, at best, likely mirror trends in overall nondefense discretionary spending. The result will be that federal support of science and technology – including all categories of R&D – will begin an accelerated downward slide.

Chapter 4

America at a "Tipping Point" – The Decision to Compete . . . or Not to Compete

> *"Out-innovating them is the way to beat China. And to do everything that we do in this country to support innovative policy, that drives innovation and new products and more jobs and creates jobs. You can't – you can't put a wall up around here. We tried that in the '30s. It didn't work."*
>
> – Jack Welch, former Chairman and CEO of General Electric

> *"My partners and I found the best fuel cells, the best energy storage, and the best wind technologies were all born outside the United States. . . . [W]e need to restock the cupboard or be left behind."*
>
> – John Doerr, Partner at Kleiner Perkins

The United States is today at a "tipping point" with regard to its ability to compete globally. Decisions made in the next few years will determine what kind of country America will leave to future generations. A decision to compete will require a renewed commitment to enhancing the four essential elements of American innovation: human capital, knowledge capital, an ecosystem that promotes innovation, and financial capital.

Competing globally is founded upon access to quality jobs for all Americans who aspire to hold them. Given the knowledge and skills demanded by most high-quality jobs, a much larger fraction of young adults will need, in the next two decades, to have completed at least the equivalent of an undergraduate education that includes a grounding in STEM. U.S. companies report that a substantial share of applicants for open positions, in addition to needing science and mathematics skills, also require additional writing and oral communication skills, as well as experience working with others to solve problems. A grounding in the humanities will thus continue to be a vital part of education. Similarly, the nation's education system needs to reinvigorate its once strong diversity of career tracks, which requires certified training and apprenticeship programs that relate to newly emerging technologies, particularly in STEM.

If the United States meets the above challenge by assigning STEM a higher priority in the future than it has in recent decades, the nation will be able to provide an abundance of quality, high-paying jobs for skilled American workers. If the United States seriously addresses the many challenges now being confronted by its system of education, from pre-K–12 through its colleges and universities, particularly its public institutions, an abundance of skilled workers – women and men from all backgrounds – will be qualified to fill those jobs. If the United States modifies its immigration laws to permit talented students trained in America to remain and work in America, the nation's workforce will be strengthened. If the United States streamlines its ponderous taxation and regulatory systems, it will have an ecosystem in which innovation and job creation can flourish. And if the federal government assigns higher priority to funding the full range of R&D than it has in recent decades, including a sustainable growth path for funding basic research, America's outstanding researchers from across the country will ensure that the United States remains ahead in scientific discovery.

But none of these suppositions is assured if the United States does not shift toward decisive action. The direction America has drifted in recent decades suggests a country that is neither investing in a future as a major global competitor in science and technology, innovation, and commerce, with an abundance of quality high-paying jobs, nor cultivating a cadre of skilled young adults to fill such jobs. Meeting these challenges will require major, even radical, changes in government policies and priorities at the federal, state, and local levels, along with constructive responses by U.S. businesses and academia.

The last time federal research funding seemed to be on a sustainable path was the roughly two decades between the mid-1970s and the mid-1990s.[260] Federal funding of basic research grew by about 4 percent per year in real terms, while increasing from approximately 0.16 to 0.2 percent of GDP, throughout that period (Figure 4-1). In recent decades, there have been funding spurts (e.g., the five-year doubling of NIH funding from 1998 – 2003 and the ARRA stimulus), but overall the funding pattern has been turbulent and inconsistent with the goal of remaining a serious global competitor in scientific discovery, innovation, and, ultimately, economic competitiveness and all that it supports (Figure 4-1).

The American Academy of Arts and Sciences' 2014 *Restoring the Foundation* report included a recommendation that the United States return to its earlier policy of sustained real growth in federal funding of fundamental research of at least 4 percent per year in constant dollars with a long-term goal of increasing its funding from 0.2 to 0.3 percent of GDP. But even with strong support from many members of Congress, the challenges of prioritizing research are imperiled by the very structure of an appropriations process that does not allow a national focus on research funding per se. Even if the nation's leadership were unanimously in agreement that research should be a much higher priority, the federal budget has no single line item for research or development, Congress has no single oversight committee for research or development, and every budget, even the most favorable, is meaningful for only a single year. Instead there are thousands of budget categories in the budgets of dozens of federal agencies that support differing forms of research overseen by separate congressional subcommittee jurisdictions – all with a one-year budget. If federally funded research is to be truly designated as a national high priority, agencies will need to be directed to ensure that their budget submissions reflect that policy, and those submissions will need to be closely coordinated.

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[260] American Academy of Arts and Sciences, *Restoring the Foundation*.

Funding is not the only limiting aspect to the nation's ability to meet the rapidly emerging competitiveness challenge from China and other parts of the world. The list beyond funding is both long and daunting.

- America's system of pre-K–12 schools utterly fails to provide the majority of the nation's young people access to a globally competitive education, particularly in the STEM fields.
- Support by the states for their public universities is dwindling, forcing education out of reach of an increasing number of American families due to rising net tuition and fees.
- Some policies of government, universities, and industry have become barriers to research collaboration and productivity.
- Immigration policies discourage talented foreign-born scientists, engineers, and other STEM professionals – and their families – from joining the U.S. workforce even after receiving advanced degrees from U.S. universities.

While a few of these shortcomings are relatively recent, most have been present and recognized for many years. The National Academies of Sciences, Engineering, and Medicine's *Rising above the Gathering Storm*, now well over a decade old, raised the alarm about threats to American competitiveness.[261] That report, responding to a bipartisan request of the U.S. Congress, was prepared by a group of 20 individuals, including university presidents, CEOs of major corporations, former presidential appointees, and three Nobel Laureates. Following completion of the group's work, two of its members took key positions in President Obama's cabinet. Its findings are still relevant:

> It is easy to be complacent about U.S. competitiveness and preeminence in science and technology. We have led the world for decades, and we continue to do so in many research fields today. But the world is changing rapidly, and our advantages are no longer unique. Some will argue that this is a problem for market forces to resolve – but that is exactly the concern. Market forces are already at work moving jobs to countries with less costly, often better educated, highly motivated workforces and friendlier tax policies.[262]

In light of the issues highlighted in the *Gathering Storm* report, President George W. Bush launched the American Competitiveness Initiative, which was accompanied by increases in federal

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[261] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (Washington, D.C.: National Academies Press, 2007), https://doi.org/10.17226/11463.

[262] Ibid.

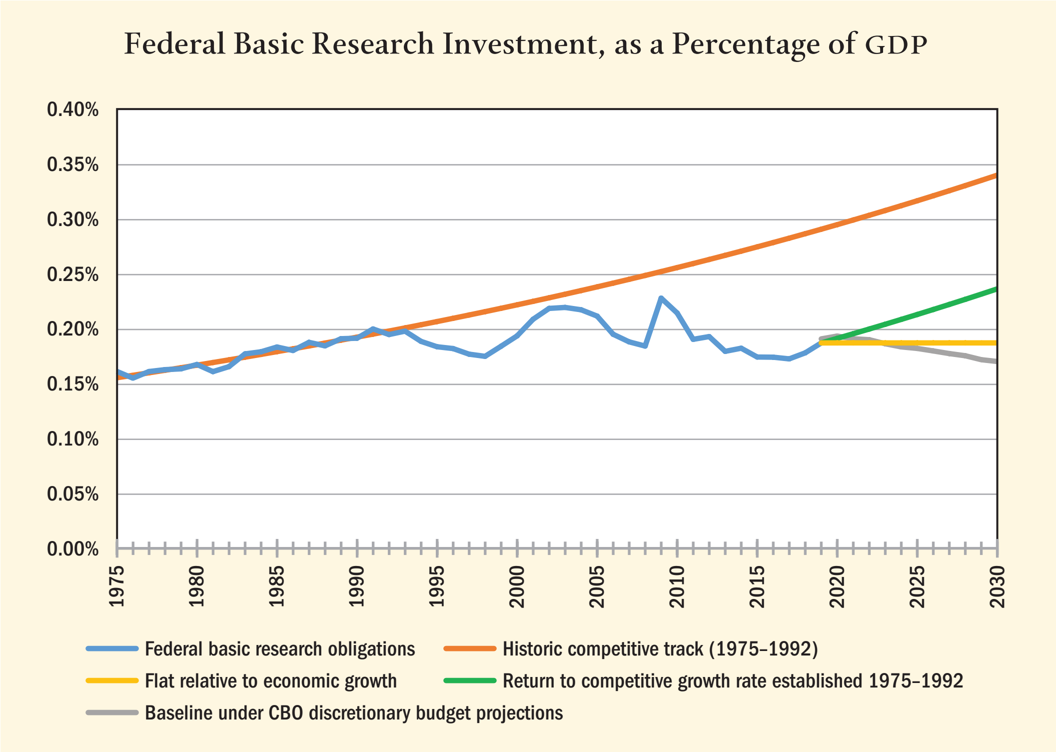

Figure 4-1

Federal Basic Research Investment, as a Percentage of GDP

Sources: NCSES, https://ncsesdata.nsf.gov/fedfunds/2018; CBO, https://www.cbo.gov/system/files/2019-06/55331LTBO-2.pdf.

Note: Baseline calculated assuming R&D budgets continue to be directly proportional to total discretionary outlays, as they have for decades.

research funding in the FY2007 budget request to Congress.[263] Congress responded by passing the America Competes Acts of 2007 and 2010, which addressed not only research funding but STEM education and other related issues.[264] President Obama similarly implemented recommendations from the *Gathering Storm* report, but, following the 2008 financial crisis and the end of the stimulus initiative (the American Recovery and Reinvestment Act of 2009), concerns about the national debt led to the severe spending constraints imposed by the Budget Control Act of 2011.[265] Subsequently, the Bipartisan Budget Act of 2019 increased discretionary spending limits and suspended the debt limit for FY2020 and FY2021.[266] Discretionary spending increased in real terms by 8.3 percent from FY2013 to FY2018, and federal spending on basic research increased in real terms by 10 percent over the same period. However, voices in Congress are again, and justifiably so, beginning to express serious concerns about large deficits and projected increases in the national debt. But with each passing year, potential solutions become increasingly daunting.

The 2010 "five-year" update of the *Gathering Storm* report concluded that much remained to be done and that America's competitive position had further deteriorated during the intervening years.[267] Now, nearly a decade later – despite congressional acts and presidential initiatives – the storm has only intensified.

> *"Unless government and business take firm actions to improve education, create a culture of investment and job creation in this country, then the next Intel or the next big thing will not be invented here. Jobs will not be created here. And wealth will not accrue here."*
>
> – Paul Otellini, former CEO of Intel Corporation,
> at the Technology Policy Institute's Aspen Forum, August 2011

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[263] George W. Bush, "American Competitiveness Initiative: President's Letter," February 2, 2006, https://georgewbush-whitehouse.archives.gov/stateoftheunion/2006/aci/index.html.

[264] "America COMPETES Act," *Wikipedia*, last modified October 2, 2019, https://en.wikipedia.org/wiki/America_COMPETES_Act.

[265] "American Recovery and Reinvestment Act of 2009," *Wikipedia*, last modified January 24, 2020, https://en.wikipedia.org/wiki/American_Recovery_and_Reinvestment_Act_of_2009; "Budget Control Act of 2011," Wikipedia, last modified January 20, 2020, https://en.wikipedia.org/wiki/Budget_Control_Act_of_2011; https://www.gpo.gov/fdsys/pkg/PLAW-112publ25/html/PLAW-112publ25.htm.

[266] Bipartisan Budget Act of 2019, H.R. 3877, 116th Cong. (2019), https://www.congress.gov/bill/116th-congress/house-bill/3877/text.

[267] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising above the Gathering Storm, Revisited: Rapidly Approaching Category 5* (Washington, D.C.: National Academies Press, 2010), https://doi.org/10.17226/12999.

"The history of modernization is in essence a history of scientific and technological progress. 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."

– Wen Jiabao, Premier of the People's Republic of China,
Science Magazine, October 2008

Developments at home and abroad have placed the United States at a truly precarious juncture with regard to its future global competitiveness. As China and other countries increasingly identify science and technology as one of their highest national priorities and devote increasing portions of their budgets to R&D, anticipating returns on investment in the long run, it is imperative that the United States respond – positively. This is now a matter of urgency. American national and economic security and the quality of life of all Americans hang in the balance.

Thomas Friedman, in his provocative book *The World is Flat*, argues:

> [T]he two greatest dangers we Americans face are an excess of protectionism . . . in search of personal security . . . and excessive fears of competing . . . that prompt us to wall ourselves off, in search of economic security. We Americans will have to work harder, run faster, and become smarter to make sure we get our share. But let us not underestimate our strengths or the innovation that could explode from the flat world when we really do connect all of the knowledge centers together. On such a flat earth, the most important attribute you can have is creative imagination – the ability to be first on your block to figure out how all these enabling tools can be put together in new and exciting ways to create products, communities, opportunities, and profits. That has always been America's strength, because America was, and for now still is, the world's greatest dream machine.[268]

Being "first on the block" will require a renewed and sustained national commitment – in government, higher education, and the private sector.

4.1 REAFFIRMING THE 2014 RECOMMENDATIONS

The committee reasserts the prescriptions and implementing actions offered in the American Academy's 2014 *Restoring the Foundation* report (see appendix).[269] To account for events

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[268] Thomas L. Friedman, *The World is Flat* (New York: Farrar, Straus and Giroux, 2005).

[269] American Academy of Arts and Sciences, *Restoring the Foundation.*

that have transpired over the past five years, the committee urges that particular attention be devoted to the following recommendations:

- The nation should increase total R&D investment (public and private) as a fraction of GDP from 2.7 percent to at least 3.0 percent within five years and to 3.3 percent within ten years [RtF1 Action 1.1].
    - Several recent U.S. presidents have called for significant increases in funding for R&D, including Presidents Reagan,[270] Clinton,[271] George W. Bush, and Obama.[272] In 2009, President Obama stated that total national R&D investment should surpass 3 percent of GDP.[273] R&D investment, however, has continued to vary between 2.4 and 2.7 percent for over 30 years. Given the impact of R&D on the nation's economy, national security, and the accelerating global competition, the R&D target should be increased to at least 3.3 percent, a figure more competitive with leading countries.
- Federal funding for basic research should be increased at a sustained real growth rate of at least 4 percent per year, with the goal of raising federal basic research funding as a percentage of GDP by 50 percent from the present 0.2 percent to 0.3 percent [RtF1 Action 1.1].
    - Basic research in STEM fields – especially research funded by the federal government – will continue to yield major discoveries that revolutionize technology and fuel innovation. But increases in basic research funding should not come at the expense of applied research. Ideally, investments in the latter would increase at approximately the same rate – the boundary between basic and applied research in many fields is not sharp.
- OSTP, in cooperation with OMB and government funding agencies, should prepare a rolling five-year integrated federal R&D funding plan for each of the agencies that support R&D, including overall funding targets for the three categories basic research, applied research, and development [RtF1 Action 1.4].
    - Each federal agency plans its allocation of funds for R&D in the context of its unique mission and institutional constraints. But an overall federal strategy for supporting

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[270] "President Reagan on Basic Research," *FYI: Science Policy News from AIP*, no. 102 (August 26, 2011), https://www.aip.org/fyi/2011/president-reagan-basic-research.

[271] Rex Dalton, "Clinton Proposes $2.8 Billion Increase in Science Funding," *Nature* 403 (2000): 349, https://doi.org/10.1038/35000362.

[272] Bush, "American Competitiveness Initiative."

[273] "Obama: 3% of GDP for R&D," *FYI: Science Policy News from AIP*, no. 49 (April 27, 2009), https://www.aip.org/fyi/2009/obama-3-gdp-rd.

  the priority of science and engineering requires planning across government. The role of OSTP in the annual budget process is advisory, but OSTP works closely with OMB on the parts of the president's budget that relate to science and technology. The cabinet-level NSTC, which includes the directors of OSTP and OMB, is a critical element in achieving RtF1 Action 1.4.

- A capital budgeting process should be established to provide resources for federally funded R&D facilities [RtF1 Action 1.3].
  - Corporations and other institutions have many decades of experience that demonstrate the value of capital budgeting, based on evaluating the long-term impact of investments. Multiyear budgeting for the construction and updating of large R&D facilities, including procurement of major research equipment, would avoid wasteful year-to-year fluctuations in agency appropriations.
- U.S. R&D budgets should be appropriated on (at least) a two-year cycle, rather than annually [RtF1 Action 1.2].
  - Quality research is not carried out in one-year segments, and the agencies that support research can best serve the nation's interest in advancing scientific knowledge by having longer time horizons for making investments. Large year-to-year fluctuations in appropriations waste money and are inimical to the performance of quality research.
- The number of H1-B visas should be doubled, and immediate family members of recipients appropriately accommodated [RtF1 Action 3.7].
  - The U.S. S&T enterprise will require additional talent. Much of that talent, at least in the decade ahead, will have to come from abroad as it has in the past. Young men and women throughout the world continue to be attracted to America's universities, and the United States should institute policies that encourage these individuals to remain in America after receiving their education and to contribute as members of the U.S. STEM workforce.
- Regulations, policies, and reporting requirements currently imposed on the conduct of R&D should be reviewed with the purpose of eliminating constraints that do not offer demonstrable benefits [RtF1 Action 2.2a].
  - Over a period of decades, many well-intentioned rules, regulations, and other polices have been put in place that reduce the productivity of the nation's researchers but offer little or no benefit. Several well-researched reports have described these in

detail and have offered specific policy reforms.[274] Further studies are not needed; it is time for action by the federal agencies, the OMB, and, in some cases, Congress.

  - As new policies are considered by the nation's universities and federal agencies to ensure the proper protection of intellectual property, while continuing to encourage foreign-born students and science and engineering researchers to study and establish careers in the United States, any new regulations should not place additional burdens on researchers and institutions.

- Universities should revise their policies on intellectual property to better reflect the original intent of the 1980 Bayh-Dole Act. The act was designed to help ensure that the public received the benefits of federally funded R&D by giving universities ownership of the intellectual property produced by their faculty and encouraging universities to share their discoveries and inventions with industry through patents and licensing agreements. Companies and universities should implement mechanisms that enable more effective partnerships and especially encourage transdisciplinary research collaborations. The federal government should clarify and, if necessary, revise tax laws to encourage stronger university-industry partnerships [**RtF1 Action 3.2**].[275]
  - Over many decades, laws, rules, and other policies and practices have accumulated that hinder university-industry partnerships that have the potential to be far more powerful components of the nation's innovation and global competitive strategy.

4.2 2020 RECOMMENDATIONS

To the recommendations originally made in the 2014 *Restoring the Foundation* report and reiterated above, which focused on R&D priorities, we append the following recommendations focused on strengthening U.S. STEM education and the American workforce:

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[274] National Science Board, *Reducing Investigators' Administrative Workload for Federally Funded Research*, NSB-14-18 (Arlington, VA: National Science Foundation, 2014), https://www.nsf.gov/pubs/2014/nsb1418/nsb1418.pdf; National Academies of Sciences, Engineering, and Medicine, "Optimizing the Nation's Investment in Academic Research: A New Regulatory Framework for the 21st Century," https://www.nap.edu/catalog/21824/optimizing-the-nations-investment-in-academic-research-a-new-regulatory.

[275] For additional recommendations, see ARISE II – *Advancing Research In Science and Engineering: The Role of Academia, Industry, and Government in the 21st Century* (Cambridge, MA: American Academy of Arts and Sciences, 2014), https://www.amacad.org/project/arise-ii-advancing-research-science-and-engineering-role-academia-industry-and-government.

- The recommendations in the 2005 National Academies of Sciences, Engineering, and Medicine's *Gathering Storm* report pertaining to pre-K–12 education should be implemented, including creating each year 10,000 federally funded four-year scholarships in STEM fields to be competitively awarded to U.S. citizens in exchange for a commitment to teach STEM in a public school for at least five years following graduation.
    - The nation's pre-K–12 public education system has been in crisis for decades, and the urgent need to improve student achievement was one of the seven priorities listed in the "Innovation: An American Imperative" call to action that was supported by over 500 organizations across the country.[276] The National Academies of Sciences, Engineering, and Medicine, in its *Gathering Storm* report, laid out a strategy to address this crisis.[277]
    - States should return to providing sustained public university funding per full-time equivalent (FTE) student at least at the level in place in real dollars prior to the 2008 recession.
    - Restoring state funding for universities will enable those institutions to better serve the educational needs of the state's citizens, raise the skill level of the workforce; support full employment; form stronger partnerships with local companies; and contribute to the country's overall S&T enterprise.
- The recent tax placed on the earnings of endowments of (private) universities represents an altogether counterproductive trend and should be repealed promptly.
    - Repealing this punitive tax will help universities control tuition, provide more financial aid, and maintain modern research and teaching facilities. Doing so will also, hopefully, discourage further such narrowly targeted, counterproductive approaches.

The committee is acutely aware of the budgetary constraints faced by the federal government and the trend toward growing deficits. Many of the committee's recommendations will require additional funding. But the committee does not accept the notion that, for example, the recommended additional 0.1 percent of GDP cannot be allocated to the federally funded basic research that is so vital to the health, security, and overall well-being of Americans.

The issue at hand is principally one of priority.

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[276] *Innovation: An American Imperative,* www.innovationimperative.org.

[277] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future.*

> *"If you do not change direction, you may end up where you are heading."*
>
> – Attributed to Lao Tzu

A FINAL OBSERVATION

To predict, with any confidence, what new capabilities science and technology will bring in the decades ahead is impossible. But to see how different our lives would be today without the contribution of science and technology in the past decades is not so difficult: no smartphones, high-definition TV, laptops, electric and hybrid cars, magnetic resonance imaging, artificial joints, stents, laser eye surgery, or vaccines for diseases such as polio. Nor would the world have e-commerce, GPS in its cars, or cures for hepatitis C. Without advances in science and technology and private-sector innovation, the world will not develop cleaner methods of power generation, adapt to climate change, or conquer future diseases. And without advances in science, COVID-19 will not be conquered.

The committee preparing this report has sought to balance, insofar as possible, the critical need for enhanced investment in research and development with the severe budgetary pressures that will be faced in the years ahead.

Not every scientific discovery or technological innovation will have its origin in the United States, nor does it need to do so. This makes international scientific cooperation vital to American interests. But unless the United States remains a leading contributor to the discovery of new knowledge and has the capacity and the will to translate that knowledge into applications, Americans will be left behind, isolated, and increasingly impoverished in a 21st-century world powered by science and technology. A great opportunity will have been lost.

APPENDIX A

Recommendations from *Restoring the Foundation*

Prescription 1

Secure America's Leadership in Science and Engineering Research – Especially Basic Research – by Providing Sustainable Federal Funding and Setting Long-Term Investment Goals

ACTION 1.1 – We recommend that the President and Congress work together to establish a sustainable real growth rate of *at least* 4 percent in the federal investment in basic research, approximating the average growth rate sustained between 1975 and 1992. This growth rate would be compatible with a target of at least 0.3 percent of GDP for federally supported basic research by 2032 (one-tenth the national goal for combined public and private R&D investment adopted by several U.S. presidents). We stress that an increase in support for basic research should not come at the expense of investments in applied research or development, both of which will remain essential for fully realizing the societal benefits of scientific discoveries and new technologies that emerge from basic research.

We further recommend that, as the U.S. economy improves, the federal government strive to exceed this growth rate in basic research, with the goal of returning to the sustainable growth path for basic research established between 1975 and 1992.

Productive first steps include:

- Establishment of an aggressive goal of *at least* 3.3 percent GDP for the total national R&D investment (by all sources) and a national discussion of the means of attaining that goal;
- Strong reauthorization bills, following the model set by the 2007 and 2010 America COMPETES Acts,[278] that authorize the investments necessary to renew America's commitment to science and engineering research and STEM education and reinforce the use of expert peer review in determining the scientific merit of competitive research proposals in all fields;
- Appropriations necessary to realize the promise of strong authorization acts; and
- A "Sense of the Congress" resolution affirming the importance of these goals as a high-priority investment in America's future.

ACTION 1.2 – We recommend that the President and Congress adopt *multiyear appropriations* for agencies (or parts of agencies) that primarily support research and graduate STEM education.

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[278] *America COMPETES Act*, Public Law 110-69, H.R. 2272, 110th Congress (January 4, 2007); and *America COMPETES Reauthorization Act of 2010*, Public Law 111-358, H.R. 5116, 111th Congress (January 4, 2011).

Providing research agencies with advanced notice of pending budgetary changes would allow them to adjust their grant portfolios and the construction of new facilities accordingly. The resulting efficiency gains would reduce costs while enhancing research productivity.

ACTION 1.3 – We recommend that the White House Office of Management and Budget (OMB) establish a *strategic capital budget process* for funding major research instrumentation and facilities, ideally in the context of a broader national capital budget that supports investment in the nation's infrastructure; and that enabling legislation specifically preclude earmarks or other mechanisms that circumvent merit review.

ACTION 1.4 – We recommend that the President include in the annual budget request to Congress a rolling long-term (five-to-ten-year) plan for the allocation of federal R&D investments – especially funding for major instrumentation that requires many years to plan and build.

Prescription 2

Ensure that the American People Receive the Maximum Benefit from Federal Investments in Research

ACTION 2.1 – We recommend that the President publish a biennial "State of American Science, Engineering & Technology" report giving the administration's perspective on issues such as those addressed by the *Science and Engineering Indicators* and related reports published by the National Science Foundation (NSF) National Science Board (NSB),[279] and with input from the federal agencies that sit on the President's National Science and Technology Council (NSTC). The report, if released with the President's budget, would provide information useful for both the appropriations and authorization legislative processes.

ACTION 2.2 – We recommend the following actions to enhance the productivity of America's researchers, particularly those based at universities:

> **ACTION 2.2a** – We recommend that the White House Office of Science and Technology Policy and Office of Management and Budget lead an effort to streamline or eliminate

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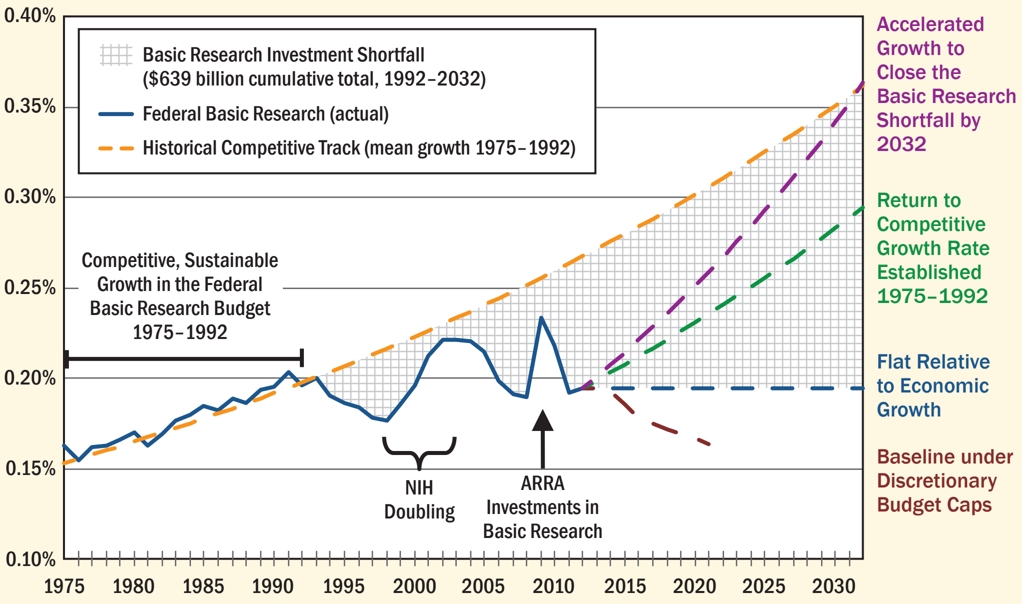
[279] The statutory authority of the NSB is included under U.S. Code 42, Chapter 16, Paragraph 1863, http://www.law.cornell.edu/uscode/text/42/chapter-16: "Report to President; submittal to Congress: (1) The Board shall render to the President and the Congress no later than January 15 of each even numbered year, a report on indicators of the state of science and engineering in the United States; (2) The Board shall render to the President and the Congress reports on specific, individual policy matters within the authority of the Foundation (or otherwise as requested by the Congress or the President) related to science and engineering and education in science and engineering, as the Board, the President, or the Congress determines the need for such reports."

Federal Basic Research Investment as a Share of GDP



Getting U.S. Basic Research Back on Track

Should federal obligations for basic research (blue) flatline relative to economic growth, the United States will by 2032 have accumulated a $639 billion shortfall (cross-hatch) in federal support of basic research relative to the 4.4 percent average annual real growth trend (orange) established during the period of 1975 to 1992. This committee recommends that the nation return to this historical competitive growth rate (green), with the ultimate goal of fully closing the basic research shortfall (purple) as the economy improves.

Data Sources: Federal obligations for basic research from 1975 to 2012 are from the National Science Board, *Science and Engineering Indicators 2014* (Arlington, VA: National Science Foundation, 2014), Appendix Table 4-34, "Federal Obligations for R&D and R&D Plant, by Character of Work: FYs 1953–2012." Basic research funding baseline projections are based on the nondefense discretionary funding levels from Office of Management and Budget, *Fiscal Year 2015 Budget of the U.S. Government* (Washington, D.C.: Office of Management and Budget, 2014), Table S-10, "Funding Levels for Appropriated ('Discretionary') Programs by Category," whose baseline levels assume Joint Committee enforcement cap reductions are in effect through 2021. GDP projections assume an average real annual growth rate of 2.2 percent until 2020 and 2.3 percent from 2020 to 2030, according to Jean Chateau, Cuauhtemoc Rebolledo, and Rob Dellink, "An Economic Projection to 2050: The OECD 'ENV-Linkages' Model Baseline," *OECD Environment Working Papers*, No. 41 (Paris: OECD Publishing, 2011), Table 4, https://doi.org/10.1787/5kgondkjvfhf-en.

practices and regulations governing federally funded research that have become burdensome and add to the universities' administrative overhead while failing to yield appreciable benefits.

ACTION 2.2b – We recommend that universities adopt "best practices" targeted at capital planning, cost-containment efforts, and resource sharing with outside parties, such as those described in the 2012 National Research Council (NRC) report *Research Universities and the Future of America*.[280]

ACTION 2.2c – We recommend that universities and the National Institutes of Health (NIH) gradually adopt practices to foster an appropriately sized and sustainable biomedical research workforce.[281] Key goals should include reducing the length of graduate school and postdoctoral training and shifting support for education to training grants and fellowships; providing funding for master's degree programs that may provide more appropriate training for some segments of the biomedical workforce now populated by Ph.D.s; enhancing the role of staff scientists in university laboratories and core facilities; reducing the percentage of faculty salaries supported solely by grants; and securing a renewed commitment from senior scientists to serve on review boards and study sections.

ACTION 2.2d – We recommend that the President and Congress reaffirm the principle that competitive expert peer review is the best way to ensure excellence. Hence, peer review should remain the mechanism by which federal agencies make research award decisions, and review processes and criteria should be left to the discretion of the agencies themselves. In the case of basic research, scientific merit – based on the opinions of experts in the field – should remain the primary consideration for awarding support.

ACTION 2.2e – We recommend that the research funding agencies intensify their efforts to reduce the time that researchers spend writing and reviewing proposals, such as by expanding the use of pre-proposals, providing additional feedback from program officers, allowing authors to respond to reviewers' comments, further normalizing procedures across the federal government, and experimenting with new approaches to streamline the grant process.

ACTION 2.3 – We recommend that the National Academies, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences convene a series of meetings of nongovernmental organizations and professional societies that focus on science

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[280] National Research Council, *Research Universities and the Future of America: Ten Breakthrough Actions Vital to Our Nation's Prosperity and Security* (Washington, D.C.: The National Academies Press, 2012).

[281] While the situation is particularly acute for the biomedical research workforce, mismatches between supply and demand also exist in other fields, such as computer science. Therefore, other federal agencies might also examine how their programs and priorities affect the workforce.

and engineering research, for the purpose of establishing a formal task force, alliance, or new organization to:

- Develop a common message about the nature and importance of science and engineering research that could be disseminated by all interested organizations;
- Elevate science and technology issues in the minds of the American public, business community, and political figures, and restore appropriate public trust;
- Ensure that the recommendations offered by existing science and technology policy organizations, academies, and other advisory bodies remain current and available to institutional leaders and policy-makers in all sectors;
- Cooperate with organizations that are focused on business and commerce, national and domestic security, education and workforce, health and safety, energy and environment, culture and the arts, entertainment, and other societal interests and needs to encourage a discussion of the role of science, engineering, and technology in society; and
- Offer assistance – in real time – to federal and state government, universities, private foundations, and leaders in business and industry to help with implementation of policy reforms.

ACTION 2.4 – In order to have direct access to current information and analysis of important science and technology policy issues, we urge Congress to: 1) significantly expand the science, engineering, and technology assessment capabilities of the Government Accountability Office (GAO), including the size of the technical staff, or alternatively to establish and fund a new organization for that purpose; and 2) explore ways to tap the expertise of American researchers in a timely and non-conflicted manner. In particular, consideration should be given to ways in which either the GAO or another organization with scientific and technical expertise could use crowdsourcing and participatory technology assessment to rapidly collect research, data, and analysis related to specific scientific issues.

Prescription 3

Regain America's Standing as an Innovation Leader by Establishing a More Robust National Government-University-Industry Research Partnership

ACTION 3.1 – We recommend that the President or Vice President convene a "Summit on the Future of America's Research Enterprise" with participation from all government, university, and industry sectors and the philanthropic community. The Summit should have the bold action agenda to: assess the current state of science and engineering research in the United States in a global twenty-first-century context; review successful approaches to bringing each sector into closer collaboration; determine where further actions are needed to encourage collaboration; and form a new compact to ensure that the United States remains a leader in science, engineering, technology, and medicine in the coming decades.

ACTION 3.2 – We recommend that the nation's research universities:

- Experiment with new intellectual property policies and practices that favor the creation of stronger research partnerships with companies over the maximization of revenues;
- Adopt innovative models for technology transfer that can better support the universities' mission to produce and export new knowledge and educate students;
- Enhance early exposure of graduate students (including doctoral students) to a broad range of non-research career options in business, industry, government, and other sectors, and ensure that they have the necessary skills to be successful;
- Expand professional master's degree programs in science and engineering, with particular attention to students interested in non-research career options; and
- Increase permeability across sectors through research collaborations and faculty research leaves.

ACTION 3.3 – We recommend that the President and Congress, in consultation with leaders of the nation's research universities and corporations, consider legislation to remove lingering barriers to university-industry research cooperation, and specifically:

- Help universities overcome impediments to experimenting with new technology transfer policies and procedures that emphasize objectives (such as the creation of new companies and jobs), outcomes, and best practices (such as processes that minimize the time and cost of licensing); and
- Amend the U.S. tax code to encourage closer university-industry cooperation. For example, in the case of industry-funded research conducted in university buildings financed with tax-exempt bonds, the tax code should be amended to allow universities to enter into advance licensing agreements with industry.

ACTION 3.4 – We recommend that the federal agencies that operate or provide major funding for national laboratories[282] review their current missions, management, and operations, includ-

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[282] As used here, *national laboratories* include intramural laboratories and centers at the Department of Energy (DOE), Department of Defense (DOD), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), National Institute of Standards and Technology (NIST), United States Department of Agriculture (USDA), and the National Institutes of Health (NIH).

ing the effectiveness of collaborations with universities and industry, and phase in changes as appropriate. While consultation with these laboratories is critical in carrying out such reviews, the burden of reviews and other agency requirements is already heavy and should, over time, be reduced.

ACTION 3.5 – We recommend that corporate boards and chief executives give higher priority to funding research in universities and work with university presidents and boards to develop new forms of partnership: collaborations that can justify increased company investments in university research, especially basic research projects that provide new concepts for translation to application and are best suited for training the next generation of scientists and engineers.

ACTION 3.6 – We strongly urge Congress to make the Research and Experimentation (R&E) Tax Credit permanent, as recommended by the President's Council of Advisors on Science and Technology (PCAST), the National Academies, the Business Roundtable, and many others. Doing so would provide an incentive for industry to invest in long-term research in the United States, including collaborative research with universities such as that recommended under Action 3.5.

ACTION 3.7 – We support the recommendation made by many other organizations, including the President's Council of Advisors on Science and Technology and the National Academies,[283] both to increase the number of H-1B visas and to reshape policies affecting foreign-born researchers in order to attract and retain the best and brightest researchers. Productive steps include allowing foreign students who receive a graduate degree in STEM disciplines from a U.S. university to receive a green card (perhaps contingent on receiving a job offer) and stipulating that each employment-based visa automatically covers a worker's spouse and children.

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[283] See President's Council of Advisors on Science and Technology, *Transformation and Opportunity: The Future of the U.S. Research Enterprise* (Washington, D.C.: Executive Office of the President of the United States, 2012); Institute of Medicine, National Academy of Sciences, and National Academy of Engineering, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (Washington, D.C.: The National Academies Press, 2007); and National Research Council, *Research Universities and the Future of America*.

APPENDIX B

Signatories to *Innovation: An American Imperative*

Academy of Radiology Research
Acoustical Society of America
Advanced Informatics and Medical Solutions LLC
Advanced Micro Devices (AMD)
Advanced Technical Intelligence Association
Aerospace Industries Association
Agricultural and Applied Economics Association
Aizoon Technology Consulting
AJES LifeSciences
Alabama A&M University
Alliance for Science & Technology Research in America (ASTRA)
Alpha-1 Biologics
Alpha-1 Foundation
American Academy of Arts & Sciences
American Anthropological Association
American Association for Dental Research
American Association for the Advancement of Science (AAAS)
American Association for the Study of Liver Diseases
American Association of Colleges of Pharmacy
American Association of Mycobacterial Diseases
American Association of Petroleum Geologists
American Association of Physical Anthropologists
American Association of Physicists in Medicine
American Association of Physics Teachers
American Association of State Colleges and Universities
American Astronomical Society
American Chemical Society
American Council on Education
American Dairy Science Association
American Dental Education Association
American Educational Research Association
American Geophysical Union
American Geosciences Institute
American Institute for Medical and Biological Engineering
American Institute of Aeronautics and Astronautics
American Institute of Chemists
American Institute of Physics
American Mathematical Society
American Meteorological Society
American Physical Society
American Physiological Society
American Phytopathological Society
American Political Science Association
American Psychological Association
American Society for Biochemistry and Molecular Biology
American Society for Engineering Education
American Society for Microbiology
American Society for Nutrition
American Society of Agronomy
American Society of Animal Science
American Society of Mechanical Engineers (ASME)
American Society of Plant Biologists
American Sociological Association
American Veterinary Medical Association
Ames Chamber of Commerce
Anchorage Economic Development Corporation
Ann Arbor/Ypsilanti Regional Chamber
Applied DNA Sciences, Inc.
Applied Materials, Inc.
Archaeological Institute of America
Arizona-Nevada Academy of Science
Arizona State University

Arkansas Research Alliance
Arkansas State University
ASHRAE
Associated Industries of Florida
Association for Information Science and Technology
Association for Psychological Science
Association for Women in Mathematics
Association for Women in Science
Association of American Geographers
Association of American Medical Colleges (AAMC)
Association of American Universities (AAU)
Association of American Veterinary Medical Colleges
Association of Independent Research Institutes
Association of Public and Land-Grant Universities (APLU)
Association of Research Libraries
Association of University Technology Managers
Auburn University
Austin Chamber of Commerce
Avanti Biosciences Inc.
Battelle
Bay Area Council
Binghamton University, State University of New York
Biocogent LLC
BioForward
Biophysical Society
BioStrategies LC
Biotechnology Industry Organization (BIO)
Blood Cell Technologies
Boeing Company
Boise State University
Bonded Energy Solutions
Boston University
Botanical Society of America
Boulder Chamber of Commerce
Brandeis University
Brides Energy
Brookhaven Chambers of Commerce Coalition
Brookhaven Technology Group
Brown University
Buffalo Niagara Partnership
Buncee, LLC
Business & Industry Association of New Hampshire
Business-Higher Education Forum
CA Technologies
California Institute of Technology
California Polytechnic State University
California State Polytechnic University, Pomona
California State University at Bakersfield
California State University Maritime Academy
California State University, Channel Islands
California State University, Chico
California State University, Dominguez Hills
California State University, East Bay
California State University, Fresno
California State University, Fullerton
California State University, Long Beach
California State University, Los Angeles
California State University, Northridge
California State University, Sacramento
California State University, San Bernardino
California State University, San Marcos
California State University System
Carnegie Mellon University
Cary Institute of Ecosystem Studies
Case Western Reserve University
Center for Policy on Emerging Technologies
Central National Gottesman Inc.

Chamber of Business & Industry of Centre County (CBICC)
Chem-Master International, Inc.
ChemCubed
Chermac Energy Corporation
Chroma Research Labs, Inc.
City University of New York (CUNY)
ClearPointe
Clemson University
Cleveland State University
Coalition for National Science Funding (CNSF)
Coalition for National Security Research (CNSR)
Coalition for the Life Sciences
Coalition of Urban Serving Universities
College of William and Mary
Colorado School of Mines
Colorado State University
Columbia University
Computing Research Association
Consortium for Ocean Leadership
Consortium of Social Science Associations (COSSA)
Cornell University
Council of Graduate Schools
Council of Scientific Society Presidents
Council on Competitiveness
Council on Governmental Relations (COGR)
Crop Science Society of America
Cultivation Corridor
Delaware State University
DII, LLC
Duke University
Earthquake Engineering Research Institute
East Carolina University
Ecological Society of America
EDUCAUSE
Electrochemical Society
Emory University
Energy Sciences Coalition
Energystics, LTD
Entomological Society of America
EPICenter Memphis
Eugene Area Chamber of Commerce
Ewbank Geo Testing, LLC
Federation of American Societies for Experimental Biology
Federation of Animal Science Societies (FASS)
Federation of Associations in Behavioral & Brain Sciences
FertiLab
Festo Didactic Inc.
FlightPartner Technologies, Inc.
Florida Agricultural & Mechanical University
Florida Atlantic Research and Development Authority
Florida International University
Florida State University
Foundation for Science and Disability
Frontier Electronic Systems Corp.
General Capacitor, LLC
Genetics Society of America
Geological Society of America
George Mason University
Georgia Institute of Technology (Georgia Tech)
Georgia Regents University (Augusta University)
Georgia Research Alliance
Georgia State University
Ghidorah Holdings, LLC
Google LLC
Graphene 3D Lab Inc.
Greater Boston Chamber of Commerce
Greater Des Moines Partnership

Greater Madison Chamber of Commerce
Greater Manchester Chamber of Commerce
Greater Philadelphia Chamber of Commerce
Greater Pittsburgh Chamber of Commerce
Greater Port Jefferson Chamber of Commerce
Greater Providence Chamber of Commerce
Harvard University
Hawaii Academy of Science
Haze Inc
Hepatitis B Foundation
Hewlett-Packard (HP)
Human Factors and Ergonomics Society
Humboldt State University
IBM Corporation
iCell Gene Therapeutics
Idaho Academy of Science and Engineering
ImmunoMatrix, LLC
IMSzema Solutions
Indiana University
Industrial Research Institute
Infineon Technologies
Information Technology Industry Council (ITI)
Innovation Associates
Institute of Electrical and Electronics Engineers (IEEE-USA)
Institute of Food Technologists
Intel Corporation
International Economic Development Council
International Society for Educational Planning
International Society for the Systems Sciences
International Technology and Engineering Educators Association
Iontraxx LLC
Iowa State University
Iowa State University (ISU) Research Park
IPC- Association Connecting Electronics Industries
iStart Valley
Jasmine Universe, LLC
Jefferson Science Associates, LLC
John Deere
Johns Hopkins University
Kansas State University
Kansas State University Institute for Commercialization
Kent State University
Kentucky Academy of Science
Lambert Construction Company
Lehigh University
Linguistic Society of America
Little Rock Regional Chamber of Commerce
Lockheed Martin Corporation
Long Island University (LIU)
Louisiana State University
Louisiana Tech University
Lowell Observatory
Maine State Chamber of Commerce
Manhattan Area Chamber of Commerce (KS)
Manhattan Chamber of Commerce (NY)
Massachusetts Biotechnology Council
Massachusetts Institute of Technology (MIT)
Massachusetts Life Sciences Center
Materials Research Society
Mathematical Association of America
Merck & Co., Inc
Meritage Midstream Services
Miami Dade College
Miami University
Michigan State University
Michigan Technological University
Micron Technology Inc.

Microscopy Society of America
Microsoft Corporation
Middle Tennessee State University
Millennial Materials and Devices Inc.
MindWick
Minnesota SBIR
Mississippi State University
Missouri University of Science and Technology (Missouri S&T)
Mobileware Inc.
modelizeIT Inc
Montana State University
Museum of Science Boston—National Center for Technological Literacy
National Alliance for Eye and Vision Research
National Association of Colleges and Employers (NACE)
National Association of Geoscience Teachers
National Association of Graduate-Professional Students
National Association of Manufacturers
National Association of Marine Laboratories
National Center for Science Education
National Coalition for Food and Agricultural Research
National Council for Science and the Environment
National Defense Industrial Association
National Ground Water Association
National Science Education Leadership Association
National Science Teachers Association
NeoMatrix Therapeutics
New England Council
New Jersey Business and Industry Association (NJBIA)
New Mexico State University
New York University
NextThought, LLC
North Carolina A&T State University
North Carolina Academy of Science
North Carolina State University
North Dakota State University
Northeastern University
Northern Illinois University
Northrop Grumman Corporation
Northwestern University Feinberg School of Medicine
Novartis Corporation
Oakland University
Ohio State University
Ohio University
Oklahoma Academy of Science
Oklahoma State University
Oklahoma State University College of Engineering
Oklahoma State University, Unmanned Systems Research Institute
ON Semiconductor
ONAMI
Optical Society of America (OSA—The Optical Society)
Orange County Business Council
Oregon State University
Pace University
Parapsychological Association
Pennsylvania State University
Phillips 66
Phiston Technologies
Polynova Cardiovascular, Inc.
Population Association of America
Portland State University
Poultry Science Association
PPG Industries, Inc.
Prairie View A&M University
Princeton University
Principal Financial Group

Procter & Gamble Company- P&G
ProGen LifeSciences
QB Sonic, Inc.
Qualcomm
Re-Nuble
Regional Accelerator Innovation Network (RAIN) Eugene
Rensselaer Polytechnic Institute (RPI)
Research!America
Rice University
Rochester Institute of Technology (RIT)
Royal Dutch Shell plc
Rutgers, the State University of New Jersey
Sage Publications
San Diego Regional Economic Development Corporation
San Diego State University
San Francisco State University
San Jose State University
Saniteq LLC
SchoolSource Technologies
Semiconductor Equipment & Materials International (SEMI)
Semiconductor Industry Association (SIA)
Semiconductor Research Corporation
Sigma Xi, the Scientific Research Society
Silicon Valley Leadership Group
Small Business Technology Council
Society for in Vitro Biology
Society for Industrial and Applied Mathematics (SIAM)
Society for Industrial and Organizational Psychology
Society for Neuroscience
Society for the Study of Evolution
Society of Toxicology
Softheon
Soil Science Society of America
Sonoma State University
South Dakota School of Mines
South Dakota State University
Southeastern Universities Research Association (SURA)
Southern Illinois University System
SPIE
SRI International
Stanford University
State Science & Technology Institute (SSTI)
State University of New York System (SUNY)
Stillwater Chamber of Commerce
Stony Brook Building Science, LLC
Stony Brook University, State University of New York
STS Global
Sulfcrete
Sullstice
Supporters of Agricultural Research Foundation
SynchroPET
Syracuse University
TargaGenix, Inc.
Task Force on American Innovation (TFAI)
Teaching Institute for Excellence in STEM (TIES)
Technology Association of Georgia
Techvision21
Temple University
Texas A&M University
Texas Instruments Incorporated
Texas State University
Texas Tech University
The InterTech Group
Theragnostic Technologies Inc.
ThermoLift, Inc.
The Science Coalition
The Webb Group

Tri-Cities Washington Economic Development Council (TRIDEC)
TRITEC Real Estate Company, Inc.
Tufts University
Tulane University
UNAVCO
Unique Technical Services LLC
United for Medical Research
Universities Research Association
University at Albany, State University of New York
University at Buffalo, State University of New York
University City Science Center
University Corporation for Atmospheric Research
University Economic Development Association (UEDA)
University of Akron
University of Alabama
University of Alabama at Birmingham
University of Alabama System
University of Alaska
University of Alaska, Fairbanks
University of Arizona
University of Arkansas
University of Arkansas at Little Rock
University of California, Berkeley
University of California, Davis
University of California, Irvine
University of California, Los Angeles
University of California, Merced
University of California, Riverside
University of California, San Diego
University of California, San Francisco
University of California, Santa Barbara
University of California, Santa Cruz
University of California System
University of Central Florida
University of Chicago
University of Cincinnati
University of Colorado at Boulder
University of Colorado at Colorado Springs
University of Colorado at Denver
University of Colorado Denver and Health Sciences Center
University of Colorado Anschutz Medical Campus
University of Connecticut
University of Delaware
University of Florida
University of Georgia
University of Hawaii at Manoa
University of Hawaii System
University of Idaho
University of Illinois
University of Illinois at Chicago
University of Illinois at Urbana-Champaign
University of Iowa
University of Kansas
University of Kentucky
University of Louisville
University of Maryland
University of Maryland, Baltimore
University of Maryland Eastern Shore
University of Maryland University College
University of Massachusetts Amherst
University of Massachusetts Boston
University of Massachusetts System
University of Memphis
University of Miami
University of Michigan
University of Minnesota
University of Mississippi
University of Missouri
University of Missouri – Columbia
University of Missouri-Kansas City
University of Missouri – St. Louis

University of Montana
University of Nebraska
University of Nevada, Reno
University of New Hampshire
University of New Mexico
University of North Carolina
University of North Carolina at Chapel Hill
University of North Carolina at Charlotte (UNC Charlotte)
University of North Carolina at Greensboro (UNCG)
University of North Carolina Wilmington
University of North Texas
University of Notre Dame
University of Oklahoma
University of Oregon
University of Pennsylvania
University of Pittsburgh
University of Rhode Island
University of Rochester
University of South Carolina
University of South Dakota
University of South Florida
University of Southern California
University of Tennessee
University of Tennessee, Knoxville
University of Texas at Austin
University of Texas System
University of Toledo
University of Vermont
University of Virginia
University of Washington
University of Wisconsin – Madison
University of Wisconsin-Milwaukee
University of Wisconsin System
University of Wyoming
Utah State University
Vanderbilt University
Van Fleet & Associates
Vascular Simulations LLC
Vela Therapeutics LLC
Vermeer Corporation
Virginia Commonwealth University
Virginia Polytechnic Institute & State University (Virginia Tech)
Vitatex Inc.
Washington State University
Washington State University Tri-Cities
Washington University in St. Louis
Wayne State University
Weather Decision Technologies. Inc.
Weathernews Inc.
Web4Sign Corporation
Western Massachusetts Economic Development Council
Western Michigan University
West Virginia State University
West Virginia University
Wichita State University
Wisconsin Technology Council
Woods Hole Oceanographic Institution
Yale University
Zuznow

Appendix C

Committee Biographies

Norman R. Augustine (Cochair) is retired Chairman and CEO of Lockheed Martin Corporation and a former lecturer with the rank of Professor at Princeton University as well as a former Under Secretary of the U.S. Army. He served as a member of the President's Council of Advisors on Science and Technology for sixteen years, as Chair of the Review of United States Human Space Flight Plans Committee, and as Chair of two reviews of U.S. activities in Antarctica. He also served as Chair of the National Academies committee that produced the report *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*. He is a member of the American Philosophical Society and the National Academy of Sciences and a member and a former Chairman of the National Academy of Engineering. He served as Chairman and Principal Officer of the American Red Cross for nine years, Chairman of the Aerospace Industries Association, Chairman of the Defense Science Board, and President of the Association of the U.S. Army. He is a former President of the American Institute of Aeronautics and Astronautics and the Boy Scouts of America. He has also served as a member of the Board of Directors of ConocoPhillips, Black & Decker, and Proctor & Gamble. He chaired the NIH Scientific Management Review Board, is a Trustee Emeritus of Johns Hopkins University, and a former member of the Board of Trustees of Colonial Williamsburg, Princeton University, and MIT. He is a former Regent of the University Systems of Maryland and a member of the Council on Foreign Affairs and the Explorers Club. He authored or coauthored several books, including *Augustine's Laws* and *Shakespeare in Charge*. He received bachelor's and master's degrees from Princeton University and was elected a Fellow of the American Academy of Arts and Sciences in 1992.

Neal Lane (Cochair) is the Malcolm Gillis University Professor Emeritus and Professor Emeritus of Physics and Astronomy at Rice University, where he is currently a Senior Fellow in Science and Technology Policy at the James A. Baker III Institute for Public Policy. He served in the federal government as Assistant to the President for Science and Technology and Director of the White House Office of Science and Technology Policy from 1998 to 2001, and as Director of the National Science Foundation from 1993 to 1998. From mid-1984 to 1986, he served as Chancellor of the University of Colorado at Colorado Springs. He is a fellow of the American Physical Society, the American Association for Advancement of Science, the Association for Women in Science, and a member of the American Association of Physics Teachers. He has received the National Academy of Sciences Public Welfare Medal (2009), the American Institute of Physics K.T. Compton Medal (2009), the Association of Rice Alumni Gold Medal, and the Distinguished Friend of Science Award from the Southeastern Universities Research Association. In 2013, the National Science Board presented Lane with the Vannevar Bush Award, which recognizes exceptional, lifelong leaders who have made substantial contributions to the nation through public service activities in science, technology, and policy. He has received numerous honorary degrees and other recognitions and was elected a Fellow of the American Academy of Arts and Sciences in 1995. He has served as Chair of the Academy's Initiative on Science, Engineering, and Technology and as Vice Chair of the Academy's Council (member from 2004 to 2010). He has also participated in several Academy projects, including New Models of Federal Funding of Science (2009–2010), Reconsidering the Rules of Space (2009), and Risks and Benefits of Alternative Energy Sources (2009). He was a member of the Committee on Studies (2005–2006) and the Committee on International Security Studies (2005–2006). Lane has testified before House and Senate committees on behalf of various Academy projects, including ARISE, Reconsidering the Rules of Space, and New Models of Federal Funding. With George Abbey, he coauthored the research paper "United States Space Policy: Challenges and Opportunities" (2005).

Nancy C. Andrews is Dean Emerita of the School of Medicine and Vice Chancellor Emerita for Academic Affairs at Duke University in the United States. She is also Nanaline H. Duke Professor of Pediatrics and Professor of Pharmacology and Cancer Biology. Prior to joining Duke, she served as Director of the Harvard-MIT M.D.-Ph.D. program and was Dean for Basic Sciences and Graduate Studies and Professor of Pediatrics at the Harvard Medical School. From 1993 to 2006, Dr. Andrews was a biomedical research investigator of the Howard Hughes Medical Institute. Her research laboratory has been continuously funded by the U.S. National Institutes of Health, studying iron homeostasis and mouse models of human diseases. Over her research career, she has provided critical insight into iron metabolism. Using molecular genetics, she identified proteins that regulate the absorption of dietary iron and transport of iron from the intestine to other cells. Dr. Andrews also identified the role of the peptide hepcidin in redistributing iron in iron overload and inflammatory states, elucidating the pathophysiology of genetic hemochromatosis and the anemia of chronic disease. Dr. Andrews received her B.S. and M.S. in Molecular Biophysics and Biochemistry from Yale University, her Ph.D. in Biology from the Massachusetts Institute of Technology, and her M.D. from the Harvard Medical School. She completed her residency and fellowship training in pediatrics and hematology/oncology at the Children's Hospital in Boston and the Dana-Farber Cancer Institute, both in the United States, and served as an attending physician at both institutions. Dr. Andrews served as President of the American Society of Clinical Investigation. She was elected as a Fellow of the American Association for the Advancement of Science and to membership in the National Academy of Sciences, the National Academy of Medicine, and the American Academy of Arts and Sciences. She currently serves on the Council of the National Academy of Sciences and on the Board of Directors of the American Academy of Arts and Sciences. She is also a member of the Boards of Directors of Novartis International AG and Charles River Laboratories as well as the MIT Corporation.

Thomas R. Cech is Distinguished Professor of Biochemistry at the University of Colorado Boulder. He has also served as Executive Director of the University of Colorado BioFrontiers Institute (2009–2020). He is the former President of the Howard Hughes Medical Institute, where he remains an Investigator. He was awarded the Nobel Prize in Chemistry in 1989 for the discovery that RNA could be a biocatalyst. His research group now studies the enzyme telomerase – the upregulation of which contributes to multiple cancers – and long noncoding RNAs involved in the regulation of gene expression in humans. He is an elected member of the American Academy of Arts and Sciences, the National Academy of Sciences, the National Academy of Medicine, and the European Molecular Biology Organization.

Steven Chu is the William R. Kenan, Jr., Professor of Physics and Professor of Molecular & Cellular Physiology in the Medical School at Stanford University. He has published over 280 papers in atomic and polymer physics, biophysics, biology, bio-imaging, batteries, and other energy technologies. He holds fifteen patents and an additional nine patent disclosures or filings since 2015. Dr. Chu was the 12th U.S. Secretary of Energy from January 2009 until the end of April 2013. As the first scientist to hold a Cabinet position and the longest serving Energy Secretary, he recruited outstanding scientists and engineers into the Department of Energy. He began several initiatives, including ARPA-E (Advanced Research Projects Agency – Energy) and the Energy Innovation Hubs, and was personally tasked by President Obama to assist BP in stopping the Deepwater Horizon oil leak. Prior to his Cabinet post, he was Director of the Lawrence Berkeley National Laboratory, where he was active in pursuit of alternative and renewable energy technologies, and Professor of Physics and Applied Physics at Stanford University, where he helped launch Bio-X, a multidisciplinary institute combining the physical and biological sciences with medicine and engineering. Previously, he was head of the Quantum Electronics Research Department at AT&T Bell Laboratories. Dr. Chu is the co-recipient of the 1997 Nobel Prize in Physics for his contributions to laser cooling and atom trapping, and he has received numerous other awards. He is a member of the National Academy of Sciences, the American Philosophical Society, the American Academy of Arts and Sciences, and the Academia Sinica, and is a foreign member of the Royal Society, the Royal Academy of Engineering, the Chinese Academy of Sciences, the Korean Academy of Sciences and Technology, and the National Academy of Sciences, Belarus. He is the President-Elect of the American Association for the Advancement of Science. He received an A.B. degree in mathematics and a B.S. degree in physics from the University of Rochester, and a Ph.D. in physics from the University of California, Berkeley, as well as thirty-two honorary degrees.

Jared Cohon, President Emeritus, University administrator, civil engineer, professor, and government adviser, served as Carnegie Mellon University's eighth president from 1997 to 2013. During his presidency, Carnegie Mellon expanded globally and contributed significantly to Pittsburgh's economic resurgence. Prior to Carnegie Mellon, he was dean of the School of Forestry and Environmental Studies and professor of environmental systems analysis at Yale University. Before Yale, he rose through the faculty ranks at Johns Hopkins University to become associate dean of engineering and vice provost for research. An expert in environmental systems analysis, Cohon has served the nation in many roles: as Legislative Assistant to the late Senator Daniel Patrick Moynihan; as chairman of the Nuclear Waste Technical Review Board (appointed by President Bill Clinton); as a member of the Homeland Security Advisory Council (appointed by President George W. Bush and reappointed by President Barack Obama); and as chair of several

National Research Council Committees. He was elected to the American Academy of Arts and Sciences and the National Academy of Engineering in 2012.

James J. Duderstadt is President Emeritus and University Professor of Science and Engineering at the University of Michigan. A graduate of Yale and Caltech, Dr. Duderstadt's interests include nuclear science, applied physics, computer simulation, science policy, and higher education. He currently teaches science and technology policy at Michigan while chairing the National Academies Division on Policy and Global Affairs and directing the Millennium Project, a research center concerned with the impact of over-the-horizon technologies on society. Dr. Duderstadt has served on or chaired many public and private boards, including the National Science Board; numerous committees of the National Academies, including the Executive Council of the National Academy of Engineering and chairing its Division of Policy and Global Affairs; the Glion Colloquium (Switzerland); the Nuclear Energy Advisory Committee of the Department of Energy; the Intelligence Science Board; and as a director of business organizations such as Unisys, CMS Energy, the University of Michigan Hospitals, and the Big Ten Athletic Conference. He was elected to the American Academy of Arts and Sciences in 1993.

Mark C. Fishman is Professor of Stem Cell and Regenerative Biology at Harvard University, where he is affiliated with the Harvard Stem Cell Institute, and Chief of the Pathways Clinical Service at the MGH for patients with complex medical disorders. His current research focus is on the genes that guide social behavior, using genetics of the zebrafish. He served as President of the Novartis Institutes for BioMedical Research (NIBR) and as a member of the company's Executive Committee from 2002 to 2016. Prior to 2002, Dr. Fishman was a professor of medicine at Harvard Medical School and chief of cardiology and founding director of the Cardiovascular Research Center at the Massachusetts General Hospital. As a clinician and scientist, he is recognized in the fields of genetic and molecular cardiology, with a principal focus on embryonic heart development. He is best known for his studies in developmental genetics that introduced the zebrafish as a model for gene discovery. The author or coauthor of more than 160 publications, Dr. Fishman is the coauthor of the best-selling textbook *Medicine*. He serves on several editorial boards and has worked with national policy and scientific committees, including those at NIH and the Wellcome Trust. He has been honored with many awards and distinguished lectureships, and is a member of the National Academy of Medicine (formerly the Institute of Medicine), where he served on its governing Council. He has also served as a trustee of the Marine Biological Laboratory in Woods Hole and is a board member of the Coalition for the Life Sciences, an advocacy group. Fishman received the B.A degree (1972) from Yale University and the M.D. (1976) from Harvard Medical School. He completed his Internal Medicine Residency, Chief Residency, and Cardiology training at Massachusetts General Hospital, and did postdoctoral research training at the National Institutes of Health. He was elected a Fellow of the American Academy of Arts and Sciences in 2002. He is a committee member of the New Models for U.S. Science and Technology Policy project, and worked, with Fellow Nancy Andrews, to develop further the recommendations of *Restoring the Foundation* and implement them. On February 24, 2015, he participated in a Stated Meeting held at Duke University on "The Unstable Biomedical Research Ecosystem: How Can It Be Made More Robust?"

Sylvester James Gates, Jr. is an expert on supergravity, an area of theoretical physics dealing with the extension of the General Theory of Relativity to allow for quantum variables in spacetime. He played a prominent role in developing the superspace description of supergravity in four dimensions, created Superstring Theory: The DNA of Reality, a video collection, and authored *L'arte della Fisica*. A second book on superspace (with Grisaru, Rocek, and Siegel) is an important reference. He contributed to the understanding of alternative superspace formulations of field theories. His work on supersymmetric sigma models in two dimensions with ordinary and twisted supermultiplets gave one of the starting points for the celebrated theory of mirror symmetry. He worked to improve opportunities for all students, including minorities, in physics. He was a Member of the U.S. President's Council of Advisors on Science and Technology (PCAST) and the Maryland State Board of Education. He is a Fellow of several scientific societies: American Association for the Advancement of Science, American Physical Society, and National Society of Black Physicists. He is also a member of the American Academy of Arts and Sciences. He served as a consultant for U.S. government agencies (National Science Foundation, Department of Energy, Department of the Defense) and corporations (Educational Testing Services, Time-Life Books) and speaks nationally and internationally to diverse audiences on issues of education, development, diversity, research, and physics. He established a research direction that led to uncovering links between physics, mathematics, art, and computer codes. In 2017, Professor Gates was elected to the office of the Vice President of the American Physical Society (APS) and is scheduled to be its President in 2021.

Bart Gordon is former Representative for the state of Tennessee in the United States House of Representatives and current Partner at K&L Gates. He served as a congressman for twenty-six years, from 1985 to 2011, and as Chairman of the House Committee on Science and Technology from 2007 to 2011. He was also a Senior Member of the House Committee on Energy and Commerce, and served on the House Committee on Financial Services and the House Committee on Rules, Transatlantic Parliamentary Dialogue, and NATO Parliamentary Assembly.

M.R.C. Greenwood is President Emerita of the University of Hawaii. She is also Chancellor Emerita of the University of California, Santa Cruz, and Distinguished Professor Emerita of Nutrition at the University of California, Davis. She served as Associate Director for Science in the White House Office of Science and Technology Policy during the Clinton administration. She was also President of the American Association for the Advancement of Science in 1999. In addition, she has served as Chair of the Policy and Global Affairs division of the National Academy of Sciences, as President of the North American Association for the Study of Obesity (now the Obesity Society), and as President of the American Society of Clinical Nutrition. She currently consults on higher education, science policy and nutrition, women's health issues, and other national issues. She is also working on a book. She is a member of the National Academy of Medicine of the National Academies. She was elected a Fellow of the American Academy of Arts and Sciences in 2005.

John L. Hennessy is The James and Lynn Gibbons Professor of Electrical Engineering and Computer Science and the Shriram Family Director of the Knight-Hennessy Scholars. He was elected a Fellow of the American Academy of Arts and Sciences in 1995, and is a Member of the National Academy of Engineering and the National Academy of Sciences. He previously served as President of Stanford University (2000–2016), Dean of Stanford's School of Engineering (1996–1999), and Provost (1999–2000), and he was the Willard and Inez Kerr Bell Professor of Electrical Engineering and Computer Science (1987–2004). A pioneer in computer architecture, Hennessy has focused his research on a computer architecture known as RISC (Reduced Instruction Set Computing), a technology that has revolutionized the computer industry by increasing performance while reducing costs; he and David Patterson were awarded the 2017 ACM Turing Prize for their contributions. He has cofounded two companies: MIPS Computer Systems Inc. (1984) and Atheros Communications (1998). Hennessy is a chairman of the board of Alphabet (Google's parent company) and a member of the board of the Gordon and Betty Moore Foundation. In 2005, Hennessy received the Founders Award from the American Academy of Arts and Sciences. In 2010, the 14th Dalai Lama conferred a Khata, a ceremonial Tibetan scarf, on Dr. Hennessy, and in 2012, he received the IEEE's Medal of Honor. In 2013, he received Carnegie Corporation's Academic Leadership Award.

Charles O. (Chad) Holliday Jr. was elected Chairman of Royal Dutch Shell in May 2015. He previously served as Chairman of the Board of Bank of America and as Chairman and CEO of DuPont, the company he retired from after thirty-six years of service. Chad started at DuPont as an engineer in manufacturing and served in multiple roles at seven different locations, including as President of DuPont Asia Pacific based in Tokyo. He was named CEO in 1998 and served in that role for eleven years. Chad currently serves on the boards of Deere & Company and Hospital Corporation of America (HCA). He is a licensed Professional Engineer and a member of the U.S. National Academy of Engineering, the UK Royal Society of Engineering, and the American Academy of Arts and Sciences. He previously served as Chairman of the following organizations: U.S. Council on Competitiveness, United Nations Sustainable Energy for All, World Business Council for Sustainable Development, Catalyst, U.S. Business Council, and the U.S. National Academy of Engineering. He graduated from the University of Tennessee with a bachelor's degree in industrial engineering. He received honorary doctorates from Polytechnic University Brooklyn, New York, Washington College Chestertown, Maryland, and the University of Tennessee Knoxville, Tennessee.

Peter S. Kim is the Virginia and D.K. Ludwig Professor of Biochemistry at Stanford University School of Medicine, Institute Scholar at Stanford ChEM-H, and Lead Investigator of the Infectious Disease Initiative at the Chan Zuckerberg Biohub. From 2003 to 2013, he was President of Merck Research Laboratories at Merck & Co., Inc. From 2001 to 2003, he was Executive Vice President at Merck. Earlier, he was a faculty member at MIT (1988–2001), a member of the Whitehead Institute for Biomedical Research (1985–2001), and an Investigator of the Howard Hughes Medical Institute (1997–2001). Kim has a special interest in viral membrane fusion, which allows infection of cells. He has designed compounds that stop membrane fusion by the AIDS virus, thereby preventing it from causing infection, and has pioneered efforts to develop an HIV vaccine based on similar principles. While at Merck, he oversaw the development of more than twenty new medicines, including treatments for diabetes, cancer, HIV, and hepatitis C, and vaccines against cervical cancer and shingles. Kim received the A.B. degree (1979) in chemistry from Cornell University and the Ph.D. (1985) in biochemistry from Stanford University. He was elected a Fellow of the American Academy of Arts and Sciences in 2008, and is a member of the National Academy of Sciences, the National Academy of Medicine, and the National Academy of Engineering.

Richard A. Meserve is the President Emeritus of the Carnegie Institution for Science. He previously was Chairman of the U.S. Nuclear Regulatory Commission and a partner in the Washington, D.C., law firm Covington & Burling LLP. He now serves on a part-time basis as Senior Of Counsel with the firm. He has a JD from Harvard Law School and Ph.D. in applied physics from Stanford University. Early in his career he served as law clerk to Supreme Court Justice Harry A. Blackmun and to Massachusetts Supreme Judicial Court Judge Benjamin Kaplan and as legal counsel to the President's Science Adviser. He has served on or chaired numerous committees involving legal/technical issues, including many convened by the National Academies of Sciences, Engineering, and Medicine. Among other activities, he is the former President of the Board of Overseers of Harvard University and Chairman of the International Nuclear Safety Group (chartered by the International Atomic Energy Agency). He is a member of the National Academy of Engineering, formerly serving as a member of its Council, is a member of the American Philosophical Society, and is a Foreign Member of the Russian Academy of Sciences. He was elected a Fellow of the American Academy of Arts and Sciences in 1994, and served on its Council and Trust. He is also a member of the advisory committee to its Global Nuclear Future Initiative and chaired the Public Face of Science Initiative.

C.D. Mote, Jr. served as President of the University of Maryland, College Park from September 1998 till August 2010. He served as President of the National Academy of Engineering for six years beginning on July 1, 2013, after which he returned to his position as Regents Professor and Glenn L. Martin Institute Professor of Engineering at the University of Maryland. From 1967 to 1991, Mote was a professor in mechanical engineering at the University of California, Berkeley, and served as Vice Chancellor at Berkeley from 1991 to 1998. He was also President of the UC Berkeley Foundation and led a comprehensive capital campaign for Berkeley that raised $1.4 billion. He is internationally known for research on the dynamics of gyroscopic systems and the biomechanics of snow skiing, including work to produce thinner and safer saw blades for the wood industry, and improvements in ski bindings to reduce knee injuries. His tenure at the University of Maryland witnessed a significant effort at increasing private fundraising. In particular, Mote implemented a building campaign to both refurbish aging university buildings and expand facilities. He was elected a Fellow of the American Academy of Arts and Sciences in 2004 and is a member of the National Academy of Engineering and its Council. Mote is a leader in the national dialogue on higher education and his analyses of shifting funding models have been featured in local and national media. He has testified on major educational issues before Congress, representing the University and higher education associations on the problem of visa barriers for international students and scholars and on deemed export control issues. He has been asked to serve on a high-level National Academies Committee appointed at the request of the Senate Energy Subcommittee of the Senate Energy and Natural Resources Committee to identify challenges to United States leadership in key areas of science and technology and to be a member of the Leadership Council of the National Innovation Initiative, an activity of the Council on Competitiveness. He has served as vice chair of the Department of Defense Basic Research Committee. In 2004–2005, he served as President of the Atlantic Coast Conference.

Venkatesh "Venky" Narayanamurti is the Benjamin Peirce Professor of Technology and Public Policy, Engineering and Applied Sciences, and Physics, *Emeritus* at Harvard University. He has served on numerous advisory boards of the federal government, research universities, and industry. He was formerly the John L. Armstrong Professor and Founding Dean of the School of Engineering and Applied Sciences, Professor of Physics and Dean of Physical Sciences at Harvard. From 2009–2015, he served as the Director of the Science, Technology, and Public Policy Program at the Harvard Kennedy School's Belfer Center. He served as Dean of the UCSB College of Engineering from 1992–1998, as Vice President for Research at Sandia National laboratories (1987–1992), and spent much of his scientific research career at AT&T Bell Laboratories (1968–1987). He obtained his Ph.D. in physics from Cornell University in 1965, and he has an Honorary Doctorate from Tohuku University (2009). He is the author of more than 240 scientific papers in different areas of condensed matter and applied physics and technology innovation policy. He is a Fellow of the American Academy of Arts and Sciences, Indian Academy of Science, Indian National Academy of Engineering, IEEE, and AAAS and is an elected member of the U.S National Academy of Engineering , the Royal Swedish Academy of Engineering Sciences, and the World Academy of Sciences. He served as NAE Foreign Secretary from 2011–2015 and is currently on the Board of Directors and the Council of the American Academy of Arts and Sciences. In 2018, he received the Arthur Bueche Award of the NAE "for seminal contributions to condensed matter physics and visionary leadership of multi-disciplinary research in industry, academia, and national labs that generated research and engineering advances."

Maxine L. Savitz is an expert in energy efficiency research and development (R&D) and products in the transportation, industry, and buildings sectors; aerospace technology; and integration of R&D between laboratories and business units. From 1979–1983, Dr. Savitz served as the Deputy Assistant Secretary for Conservation at the U.S. Department of Energy (DOE). She received the Outstanding Service Medal from the Department of Energy in 1981. Prior to her DOE service, she was program manager for Research Applied to National Needs at the National Science Foundation. Following her government service, she served in executive positions in the private sector, including as President of Lighting Research Institute, Assistant to the Vice President for Engineering at The Garrett Corporation, and General Manager of Allied Signal Ceramic Components. She retired from the position of General Manager for Technology Partnerships at Honeywell. Dr. Savitz served two terms (2006–2014) as Vice President of the National Academy of Engineering. She has served on numerous NASEM studies, boards, and committees. She was elected a Fellow of the American Academy of Arts and Sciences in 2013. She served on the President's Council of Advisors for Science and Technology, 2009–2017, and was Co-Vice Chair from 2010–2017. She is currently a member of an ad hoc subgroup of former members of President Obama's PCAST. Dr. Savitz was appointed to the National Science Board in 1998–2004. She is a member of advisory bodies for Pacific Northwest National Laboratory and Fermi National Laboratory. She has been a member of the Secretary of Energy Advisory Board, the Laboratory Operations Board, and advisory committees at Oak Ridge National Laboratory and Sandia National Laboratory. She has previously served on the board of directors of the Electric Power Research Institute, the Draper Laboratory, American Council for an Energy-Efficient Economy, and the Energy Foundation. Dr. Savitz received a B.A. in Chemistry from Bryn Mawr College and a Ph.D. in Organic Chemistry from the Massachusetts Institute of Technology.

Robert F. Sproull is the Adjunct Professor of Computer Science at the University of Massachusetts Amherst, where he is also on the Advisory Board. Prior to his teaching career, he was the former Vice President and Director of Oracle Labs from 1990–2010. He previously served as Associate Professor in Computer Science at Carnegie Mellon University, a research staff member of Xerox Palo Alto Research Center, and Technology Partner of Advanced Technology Ventures. Throughout his career, he wrote *Logical Effort* and coauthored *Principles of Interactive Computer Graphics*. He was honored as a member of the National Academy of Engineering, where he was Chair of the Computer Science and Telecommunications Board. He also served as Director of Applied Microcircuits Corp. and on the U.S. Air Force Scientific Advisory Board. Sproull was a fellow of the American Association for the Advancement of Science. The American Academy of Arts and Sciences inducted him as a Fellow in 2002. He received his Ph.D. and M.S. in Computer Science from Stanford University and A.B. in Physics from Harvard College.

Subra Suresh is President and Distinguished University Professor at Nanyang Technological University, Singapore. He has previously served as Director of the U.S. National Science Foundation; President of Carnegie Mellon University; and Dean of MIT's School of Engineering.

Suresh is an elected member of all three branches of the U.S. National Academies – Engineering, Sciences, and Medicine – as well as the American Academy of Arts and Sciences and the National Academy of Inventors. He has also been elected as a foreign member of major science and/or engineering academies in China, France, Germany, India, Spain, and Sweden, and awarded eighteen honorary doctorate degrees from institutions around the world. Suresh has authored three books, over three hundred research articles, and thirty patent applications, covering the properties of engineered and biological materials and their implications for human diseases, and co-founded a technology startup. Suresh's recent honors include the 2020 ASME Medal, the highest honor from the American Society of Mechanical Engineers; election in 2018 as an Honorary Fellow of St. Hugh's College at Oxford University; the 2015 Industrial Research Institute Medal; the 2013 Benjamin Franklin Medal in Mechanical Engineering and Materials Science; the 2012 Timoshenko Medal and the 2011 Nadai Medal of ASME; the 2011 Padma Shri Award, one of the highest civilian honors from the President of India; and the 2007 Gold Medal of the Federation of European Materials Societies (the first non-European to receive this highest honor). As Director of NSF, Suresh founded the NSF Innovation Corps (I-Corps) program in 2011 to develop an innovation ecosystem across the United States that is built on scientific discoveries supported by NSF. This program has been replicated by other organizations, including the National Institutes for Health and the Advanced Research Projects Agency for Energy (ARPA-E) in the United States, the National Research Foundation of Singapore, and the National Science Foundation of Ireland. Within the first six years, I-Corps supported more than 1,200 innovation teams from 248 universities and led to the creation of more than 577 companies. Suresh is an independent Director of the Board of HP Inc. (HPQ) in Palo Alto, CA, and of the Singapore Exchange (SGX); a member of the Board of the National Research Foundation (NRF) and of the Agency for Science, Technology and Research (ASTAR), Singapore; a Senior Advisor to Temasek International Pte Ltd, Singapore; and a member of the Future Economy Council chaired by Singapore's Minister of Finance.

Shirley M. Tilghman was on the faculty of Princeton University for fifteen years before serving as President from May 2001 to July 2013. She is now President and Professor of Molecular Biology and Public Affairs Emerita. Prior to becoming President, Tilghman's research was focused on mammalian developmental genetics, and she now writes on science and education policy. At Princeton she was an Investigator of the Howard Hughes Medical Institute and the founding director of the University's Lewis-Sigler Institute for Integrative Genomics. Tilghman's presidency placed an emphasis on increasing the diversity of Princeton's faculty and students; widening access to the university through improvements to its generous financial aid program and the elimination of admission through "early decision"; fostering a multidisciplinary approach to teaching and research; and strengthening the university's international perspective through a wide range of initiatives – from the Global Scholars Program, which brings international scholars to campus on a recurring basis, to the Bridge Year Program, which gives incoming freshmen an opportunity to defer their studies for a year in order to devote themselves to public service overseas. She also oversaw the establishment of a sixth residential college at Princeton, Whitman College. In 2002, Tilghman was one of five winners of the L'Oréal-UNESCO Award for Women in Science. Other awards include the Princeton's President's Award for Distinguished Teaching (1996), the Lifetime Achievement Award from the Society for Developmental Biology (2003), and the Genetics Society of America Medal (2007). Tilghman is a member of the American Philosophical Society, the National Academy of Sciences, the National Academy of Medicine (formerly the Institute of Medicine), and the Royal Society of London. In 2014, she became an Officer of the Order of Canada. She also serves as a trustee of Amherst College, the Institute for Advanced Study, and the Simons Foundation, and is a Fellow of the Harvard Corporation. In 2015, she was President of the American Society for Cell Biology. Tilghman received the B.Sc. degree (1968) in chemistry from Queen's University in Kingston, Ontario and the Ph.D. in biochemistry from Temple University after two years of teaching secondary school in Sierra Leone, West Africa. She was elected a Fellow of the American Academy of Arts and Sciences in 1990 and served on the Class II:1 membership panel. She now serves on the Board of Directors of the American Academy of Arts and Sciences.

Jeannette M. Wing is Avanessians Director of the Data Science Institute and Professor of Computer Science at Columbia University. She came to Columbia in July 2017 from Microsoft, where she served as Corporate Vice President of Microsoft Research, overseeing a global network of research labs. She is widely recognized for her intellectual leadership in computer science, particularly in trustworthy computing. Her seminal essay, "Computational Thinking," was published more than a decade ago and is credited with helping to establish the centrality of computer science to problem-solving in fields where previously it had not been embraced. Before joining Microsoft, she held positions at Carnegie Mellon University and at the National Science Foundation. She served Carnegie Mellon as Head of the Department of Computer Science and as Associate Dean for Academic Affairs of the School of Computer Science. At the National Science Foundation, she was Assistant Director of the Computer and Information Science and Engineering Directorate, where she oversaw the federal government's funding of academic computer science research. Her areas of research expertise include security and privacy; formal methods; programming languages; and distributed and concurrent systems. She has been recognized with distinguished service awards from the Computing Research Association and the Association for Computing Machinery. She is a Fellow of the American Academy of Arts and Sciences, American Association for the Advancement of Science, the Association for Computing Machinery, and the Institute of Electrical and Electronic Engineers. She holds bachelor's, master's, and doctoral degrees from MIT.

Elias Zerhouni, a native of Algeria where he received his basic education and training, spent his career at Johns Hopkins University and Hospital. He is currently Emeritus Professor of Radiology and Biomedical Engineering and senior adviser for Johns Hopkins Medicine. He served as

Chair of the Russell H. Morgan Department of Radiology and Radiological Sciences, Vice Dean for Research, and Executive Vice Dean of the School of Medicine from 1996 to 2002 before his appointment as Director of the National Institutes of Health of the United States of America from 2002 to 2008. He was a presidential science envoy from 2009 to 2010 as well as Senior Fellow at the Bill and Melinda Gates Foundation. From 2011 to 2018 he was president of global R&D for Sanofi, a pharmaceutical company. He is a member of the National Academy of Medicine and the National Academy of Engineering. Among his many honors, he received the prestigious Legion of Honor medal from the French National Order in 2008. He was appointed as Chair of Innovation at the Collège de France and elected to membership at the French Academy of Medicine. He is a board member of the Lasker Foundation, the Foundation for NIH, and Research America.

APPENDIX D

Comparison of U.S. and China Gross R&D Investment with PPP Update

In this report, we use purchasing power parity (PPP), as defined by the Organisation for Economic Co-operation and Development (OECD), to compare China's investments in R&D and research with those of the United States. The intended purpose of PPP is to take into account differences in the actual costs of a bundle of goods and services in different countries (see footnote 138 on page 65). While economists debate the use of PPP for different kinds of national expenditures, it is widely used for comparisons between different countries.

Figure 1 on page 13 of this report is a comparison of the national R&D investments (public and private) of the United States and China, where the latter's spending has been adjusted by applying the purchasing power parity (PPP) currency conversion, reported by the OECD, as of the time this report was being written. Linear projections reported by the National Science Board, based on data from their 2018 and 2020 *Science and Engineering Indicators*, suggested that a crossing of the China and U.S. curves could occur as early as 2018. However, in 2020 the OECD revised their PPP currency conversion for China, https://stats.oecd.org/Index.aspx?DataSetCode=MSTI_PUB. The new comparison pushes the crossing point further into the future, as shown in Figure 5 on page 151. We have not attempted a projection of the new curve beyond 2018, the last year reported by the OECD.

The OECD changes do not affect the analysis and findings in this report in any significant way. The arguments for sustainable real growth in federal research funding are not changed nor are the recommendations in this report.

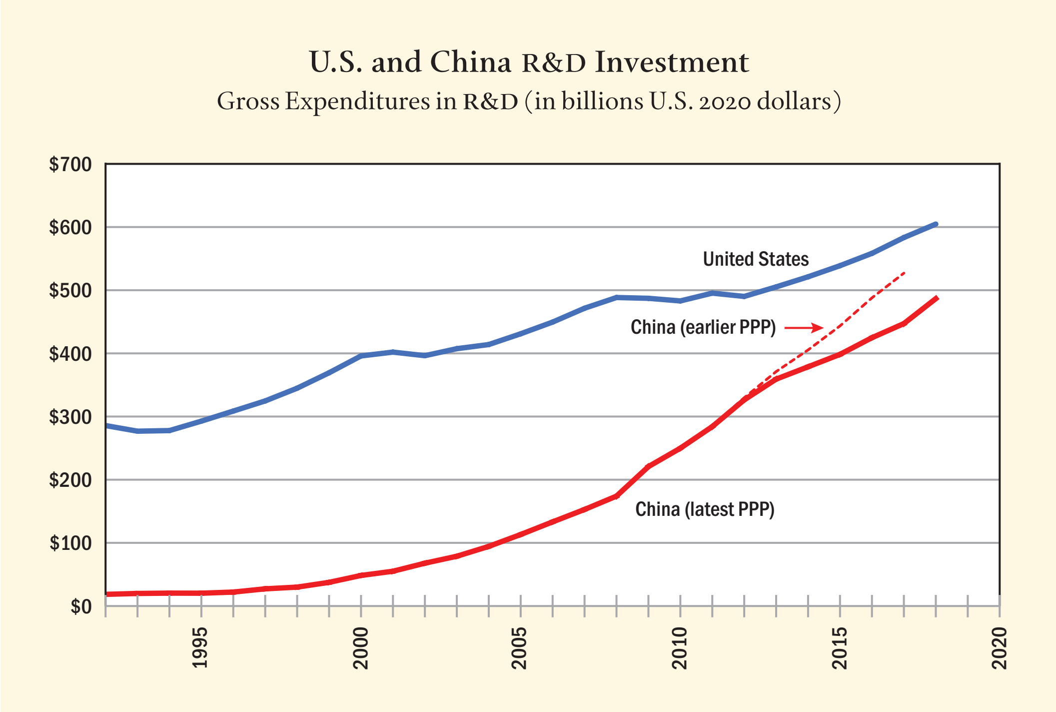

Figure 5

U.S. and China R&D Investment, Gross Expenditures in R&D (in billions U.S. 2020 dollars)

Sources: OECD. 2020. "Main Science and Technology Indicators," OECD Science, Technology and R&D Statistics (database); and National Science Board, "Statement on Global R&D Investment NSB-2018-9," February 17, 2018.

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