Benchmarks 2019

Second Place America?

Increasing Challenges to U.S. Scientific Leadership

A Report by the Task Force on American Innovation

May 2019

ABOUT THE TASK FORCE ON AMERICAN INNOVATION

The Task Force on American Innovation (TFAI) is a non-partisan alliance of leading American companies and business associations, research university associations, and scientific societies. Established in 2004, TFAI supports federally-funded scientific research and promotes its benefits to America's economy and national security. TFAI is particularly concerned with research and educational funding in the physical sciences and engineering at the Department of Defense, the National Science Foundation, the Department of Energy's Office of Science, the National Institute of Standards and Technology, and NASA.

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List of Key Technical Terms

Applied Research – "Original investigation undertaken in order to acquire new knowledge. Applied research is, however, directed primarily towards a specific practical aim or objective." (OMB Circular No. A-11, 2018, Sec. 84)

Basic Research – "Experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts. Basic research may include activities with broad or general applications in mind, such as the study of how plant genomes change, but should exclude research directed towards a specific application or requirement, such as the optimization of the genome of a specific crop species." (OMB Circular No. A-11, 2018, Sec. 84)

Citation – A reference to a published work in articles, books, or other sources. A primary purpose of citations is to attribute prior or unoriginal work and ideas to the original sources.

Development – "Creative and systematic work, drawing on knowledge gained from research and practical experience, which is directed at producing new products or processes or improving existing products or processes. Like research, experimental development will result in gaining additional knowledge." (OMB Circular No. A-11, 2018, Sec. 84)

Exascale Computing – Refers to computing systems capable of at least one exaFLOPS (FLOPS is a measure of computer performance), or a quintillion calculations per second. Such capacity represents a thousand fold increase over the first petascale (one quadrillion FLOPS per second) computer that came into operation in 2008.

Lost Einsteins – Refers to, "people who would have had highly impactful inventions had they been exposed to careers in innovation as children."[1]

Patent – An exclusive right granted for an invention, whether a product or a process, that offers a new way of doing something. Patents are granted in exchange for an enabling public disclosure of the invention.

Physical Sciences – The branch of natural science that studies non-living systems, in contrast to life science. Physical science fields include physics, astronomy, chemistry, and earth science.

Private R&D – R&D carried out by industry and business firms, for mostly private gain, in sectors such as pharmaceuticals, aerospace, and telecommunications.

Public R&D – Encompasses the wide range of government-funded R&D programs that benefit society as a whole, from cancer research to weather forecasting to food safety studies.

Research Intensity – R&D expenditures relative to total GDP. A standard metric used to assess a country's level of innovative activity.

Researchers – "Professionals engaged in the conception or creation of new knowledge, products processes, methods, and systems, and in the management of the projects concerned."[2] (OECD)

Research Publication – Scientific work that is usually peer-reviewed and published in an academic or scholarly journal, in distinct fields such as the natural sciences, social sciences, and humanities.

Skilled Technical Work – "To be considered a skilled technical occupation, two criteria must be met:

1. the occupation requires a high level of knowledge in a technical domain
2. and does not require a bachelor's degree for entry."[3] (NASEM)

Triadic Patent – A set of corresponding patents filed at the European Patent Office, the Japanese Patent Office, and the U.S. Patent and Trademark Office, for the same invention.

Introduction

The United States has a rich history of global leadership in science and technology. From the lightbulb to the transistor to the internet and search engine, American scientists and innovators have led the way in taking discoveries from the lab to the market and improving quality of life. Much of this success is due to the unique partnership between the federal government, universities, and private industry. This innovation ecosystem has allowed for the generation of new knowledge and foundational ideas helping make the U.S. the world leader in many scientific and technological fields. It has also helped to attract the best and brightest students and scholars from around the world to come to the U.S. to study, work, and contribute to advancing U.S. scientific research and our economy.

However, America's competitive edge is now at stake, as China and other countries are rapidly increasing investments in research and workforce development in order to assume positions of global leadership. Our nation risks falling perilously behind in the basic scientific research that drives innovation, as our global competitors increase support for cutting-edge research and push to the forefront in fields such as artificial intelligence (AI), robotics, aerospace, advanced manufacturing, and the next generation of telecommunications networks.

Our competitors' increasing basic research investments and production of new advanced technologies poses an escalating challenge to U.S. scientific leadership. Not only are European countries and China upping their game in industries like nanotechnology and supercomputing, they are also attracting the best and brightest students and scholars to close the technological and innovation gap.

Maintaining America's global leadership status is critical to national security as well as to future economic growth and prosperity. However, the diminishing presence of the U.S. within the global share of research and development (R&D) is a threat to the nation's scientific enterprise, indicating a lack of federal commitment to scientific research programs at agencies, such as the Departments of Defense (DOD) and Energy (DOE), National Science Foundation (NSF), National Institutes of Health (NIH), National Aeronautics and Space Administration (NASA), and the National Institute of Standards & Technology (NIST). This lack of commitment could lead to decreased economic competitiveness as well as negative impacts on our domestic workforce and industries.

The U.S. must continue to develop and support an innovation economy that, "collaborates with allies and partners, improves STEM education, draws on an advanced technical workforce, and invests in early-stage research and development," according to the latest U.S. National Security Strategy (NSS).[4] Further, the NSS asserts that the nation must continue to be the destination of choice for the "innovative and the inventive, the brilliant and the bold."[5]

In order to sustain global leadership, the U.S. needs to capitalize on its tremendous assets and make technological pre-eminence a national priority.[6] This can be achieved through the development and execution of a competitive strategy that includes increased funding for scientific research and human capital development, targeting investments in new programs to grow, attract, and retain domestic and international STEM talent.

The Task Force on American Innovation (TFAI) has a history of assembling and examining benchmarks to assess America's international standing in science and technology. This report builds on past TFAI reports, beginning with the first Benchmarks Report released in 2005, which highlighted that, "the United States still leads the world in research and discovery, but our advantage is rapidly eroding, and our global competitors may soon overtake us." Since this report, additional TFAI analyses in 2006 and 2012 found a continuation of the 2005 trends and called for the U.S. to strengthen the workforce and innovation ecosystem. In the 14 years since the first TFAI report, original trends persist and the U.S. continues to lose ground to other nations in investments in science, technology, and talent.

TFAI, therefore, reiterates its past statements and calls for strong and sustained commitments to increasing federal investments in the underpinning scientific research and human talent that drives the U.S. economy forward and fuels American innovation.

Investing in Scientific Research: An American Imperative

In 2014, the American Academy of Arts and Sciences released a report titled, "*Restoring the Foundation: The Vital Role of Research in Preserving the American Dream.*" One of the report's core recommendations was to provide steady and sustained real funding growth of at least four percent for the basic scientific research performed at major federal research agencies. The report notes that, "*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.*"

In June 2015, the heads of nine major U.S. corporations called on Congress to enact the funding and policy recommendations made in the *Restoring the Foundation* report. Their accompanying statement, *Innovation: An American Imperative*, has since been endorsed by over 500 leading industry, higher education, science, and engineering organizations, including the Task Force on American Innovation.

The statement notes that, "*now is not the time to rest on past success…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.*"

To ensure that the United States remains the global innovation leader, the Task Force on American Innovation urges Congress and the Administration to take the concerns raised by the Restoring the Foundation report seriously, along with the alarming trends highlighted by the benchmarks examined in this TFAI report.

Research & Development Investment Benchmarks

1

Why does public R&D matter? In many countries, the primary investor in R&D is industry, but government also plays an important role. In reality, the functions served by industrial R&D and government R&D are fairly different. Industrial R&D is generally more geared toward applied research and development, which tends to be shorter-term, more incremental, and results in private benefits. In contrast, public sector R&D is oriented around basic research – fundamental knowledge that underlies innovation – which tends to be higher risk, longer-term, and has much broader and far-reaching societal benefits. This is especially true of non-defense U.S. research agencies including NSF, NIH, and DOE's Office of Science, which account for the bulk of federal non-defense research expenditures.

Public and private industry R&D are synergistic and complementary to one another. Government investment serves as a catalyst for industrial investment and spurs projects that would not have taken place otherwise, or at a smaller or slower scale.[7] Public R&D has been found to stimulate additional patenting from industry; for instance, one study found a $1 increase in NIH basic research led to a more than $8 increase in pharmaceutical industry R&D funding after a multi-year lag, and a $1 increase in NIH clinical research led to a greater than $2 increase in private pharmaceutical industry investment after a shorter lag. Nearly one-third of all NIH grants can be indirectly linked to a later commercial patent.[8]

The U.S. federal government is also the primary funder of university-based research, accounting for 51 percent of university R&D expenditures in 2016 according to NSF's National Center for Science and Engineering Statistics.[9] Federal funding of university-based research has been found to stimulate more new and disruptive technologies than funding from other sources.[10]

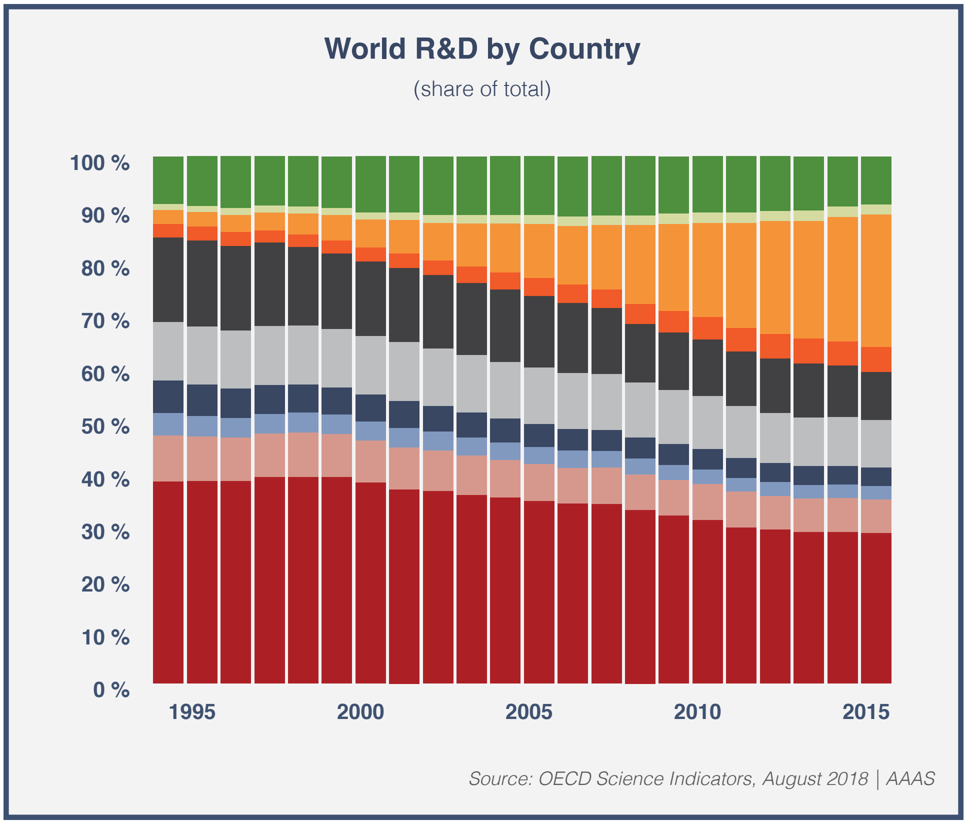
The U.S. Share of Global R&D has Declined. In 1995, the United States accounted for 38.3 percent of global R&D. As of 2016, the U.S. share had declined to 28.5 percent (see **GRAPH 1.1**). This decline is partly due to increasing investments from smaller nations such as Spain, Ireland, Israel, and Norway. But the biggest drivers behind the declining U.S. share of R&D are greater investments by Taiwan, South Korea, and China. Taiwan and South Korea have more than quadrupled their investments in R&D since 1995, while China will likely catch the U.S. in total R&D expenditures within the next few years (see **GRAPH 1.2**).

GRAPH 1.1

World R&D by Country

(share of total)

- Rest of World
- Taiwan
- China
- Korea
- Japan
- Other EU
- France
- UK
- Germany
- USA



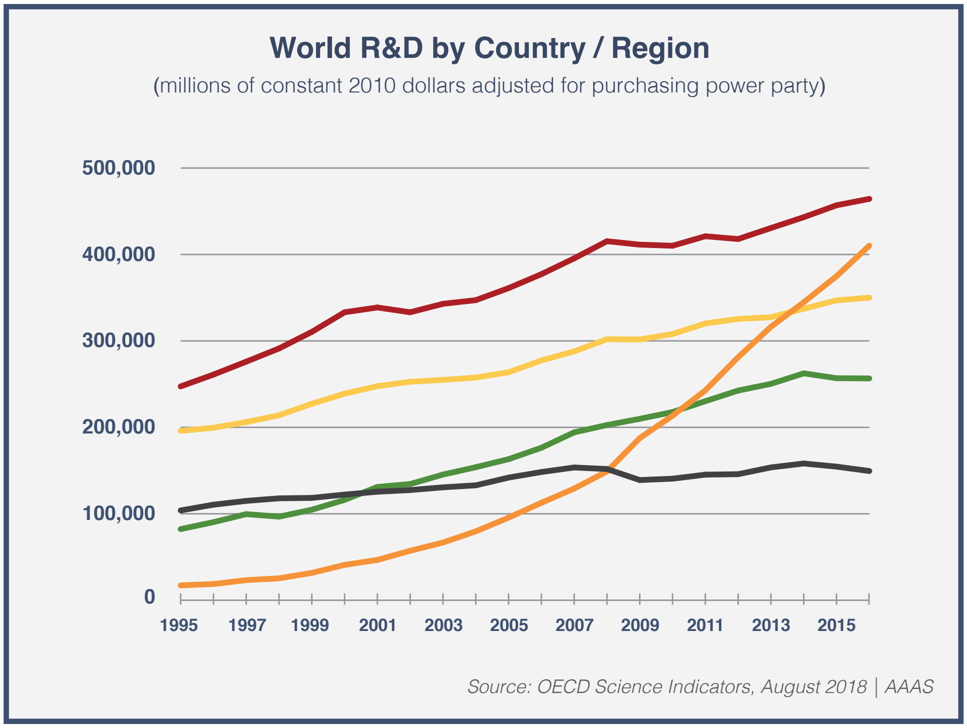
GRAPH 1.2

World R&D by Country/Region

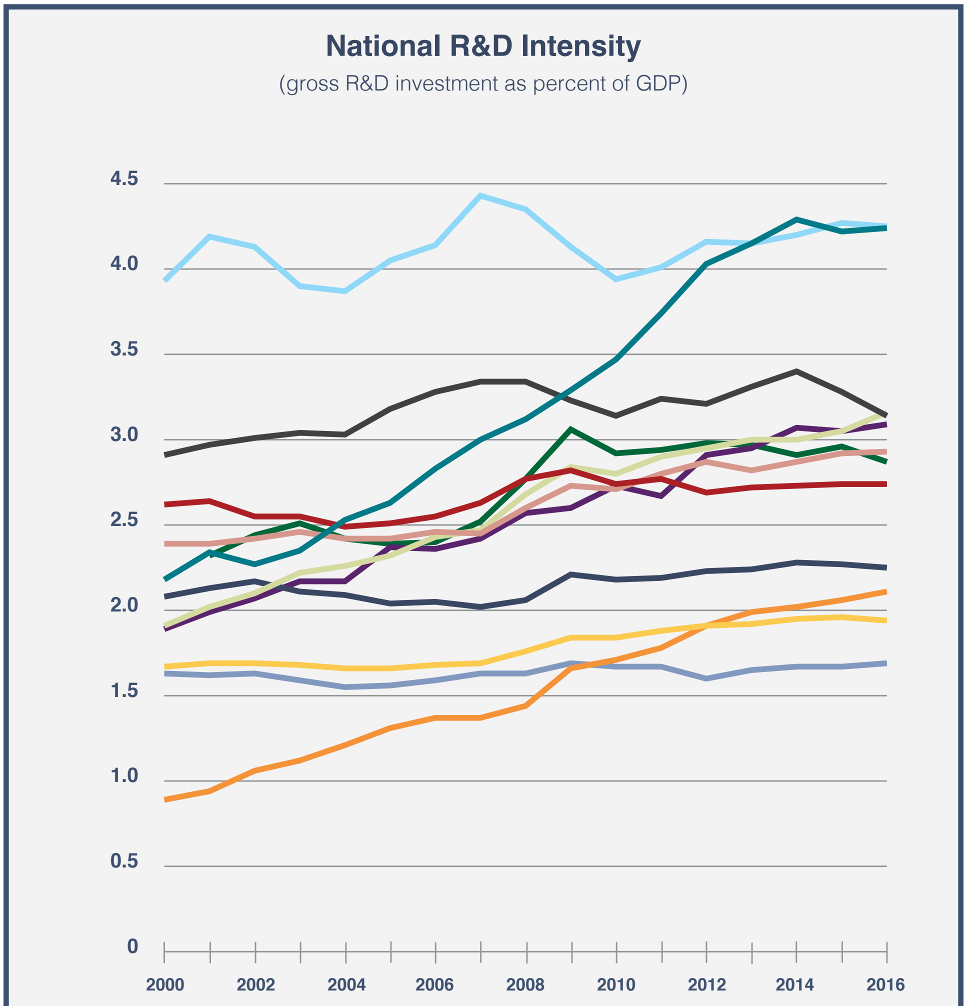
(millions of constant 2010 dollars adjusted for purchasing power party)

- USA
- China
- EU-28*
- Japan
- Rest of World

** For this report, the term 'EU-28' refers to the 28 member states of the European Union as of early 2019: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom*



Global Research Intensity is Rising – and the U.S. Has Fallen to 10th Place. Research intensity, or R&D expenditures relative to total GDP, is one standard metric used to assess a country's level of innovative activity. As of 1995, the U.S. ranked fourth on this metric with total R&D expenditures at 2.4 percent of GDP, trailing Sweden, Japan, and Israel. As of 2016, the U.S. had slipped to tenth (see GRAPH 1.3; note not all countries shown). Countries that have now surpassed the U.S. over this time period include Korea, Denmark, Taiwan, Austria, Germany, and Finland. The U.S. also barely cracks the top 10 in basic research as a share of GDP. Although total American basic research spending remains largest in the world for now, the share is declining relative to the size of the U.S. economy and the rest of the world's share. As basic research spending erodes, so does the foundation for applied research and development investments.



Source: OECD, Main Science and Technology Indicator, August 2018 | AAAS

GRAPH 1.3

National R&D Intensity

(gross R&D investment as percent of GDP)

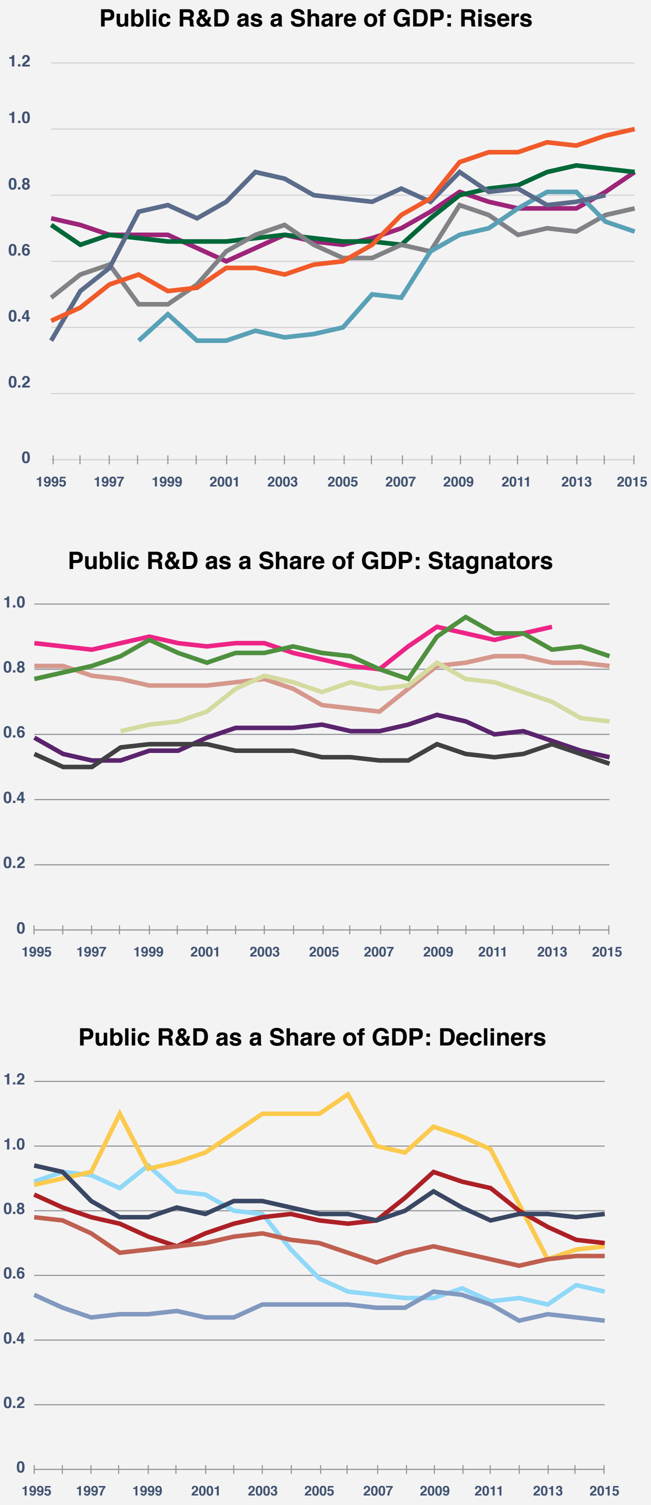
- South Korea
- Israel
- Japan
- Taiwan
- Austria
- Germany
- Denmark
- USA
- France
- EU-28
- China
- UK

The U.S. is among a small group of countries with declining public R&D investment. Public sector R&D encompasses the wide range of government-funded programs that benefit society as a whole, from cancer research to weather forecasting to food safety studies. Of the 36 countries for which the Organization for Economic Cooperation and Development (OECD) has relatively complete data since the 1990s, 24 countries have managed to at least slightly increase their public R&D investments relative to gross domestic product, and more than a dozen of these countries have managed to achieve increases greater than 20 percent. South Korea has managed to more than double public R&D as a share of GDP since 1995 (see **GRAPH 1.4**). Another group of countries has managed to mostly sustain their public investments in R&D, or at least limit relative decline since 1995. This group includes R&D powerhouses Germany, Japan, and Taiwan.

At the bottom of the list, however, are a handful of countries that have seen public R&D investment as a share of GDP decline by over 15 percent since 1995, including the U.S. According to OECD data, the U.S. publicly-funded R&D as a share of GDP has declined from 0.85 percent in 1995 to 0.70 percent as of 2015. This relative decline ranks the U.S. fifth from the bottom over this period.

GRAPH 1.4

Public R&D as a Share of GDP



Source: OECD Science & Technology Indicators, August 2018 | AAAS

Risers

- Korea
- Singapore
- Estonia
- Russia
- Denmark
- Norway

Stagnators

- Finland
- Sweden
- Taiwan
- Germany
- Japan
- Canada

Decliners

- Netherlands
- United Kingdom
- France
- United States
- Iceland
- Israel

International R&D Investment Targets and Strategies

Korea: Following the establishment of multiple government research institutes and the Ministry of Science and Technology in the 1960s, and the introduction of R&D tax credits in the 1970s, Korea has become an international R&D powerhouse. Last summer, the Korean government reached an agreement to double funding for basic science by 2022.

Germany: Last year, Germany pledged to increase the country's research intensity from 2.9 percent to 3.5 percent – which would rank the country third in the world. Some German officials have also considered establishing an R&D tax credit for the first time.

United Kingdom: After years of high scientific achievement but surprisingly low investment in R&D, the UK's latest industrial strategy, released in late 2017, aims to increase total investment from 1.7 percent of GDP to 2.4 percent by 2027, which would put the UK on par with other major economies and begin to approach current U.S. research intensity.

China: China's most recent five-year-plan for science and technology, issued in 2016 and extending through 2020, pledges continued spending growth and establishes a research intensity target of 2.5 percent of GDP by 2020. This target came on the heels of China's much-noted Made in China 2025 strategy issued in 2015, which seeks to establish Chinese dominance in high-tech manufacturing areas such as robotics, aerospace, and energy-saving vehicles.

Knowledge Creation & New Ideas Benchmarks

2

RESEARCH PUBLICATIONS

Along with R&D funding, research publications are an important measure for comparing countries' scientific outputs and innovation capabilities. Not all publications are equal, but they are a useful metric on innovation overall. Fundamental discoveries and breakthroughs are published in scientific journals and are expanded upon by other scientists over time. Continuous and high-quality publications are essential qualifications for university researchers in an increasingly competitive environment.

U.S. publication output is declining. The U.S. global share of research publications fell from 27 percent in 2003 to 18 percent in 2016 (see **GRAPH 2.5**). The European Union has experienced less of a decline than the U.S., while Japan's world share shrunk by half over the 2003-2016 period. Meanwhile, China's share surged from 7 percent to 19 percent, overtaking the U.S. as of 2016. In absolute terms, China is now the single largest contributor of research publications (see **GRAPH 2.6**). India is also emerging as a producer of research publications.

> "We may not want to admit it yet, but the rise of China to the top ranks of global scientific achievement is now a historical fact."
>
> Peter Orszag, former director of the White House Office of Management and Budget[11]

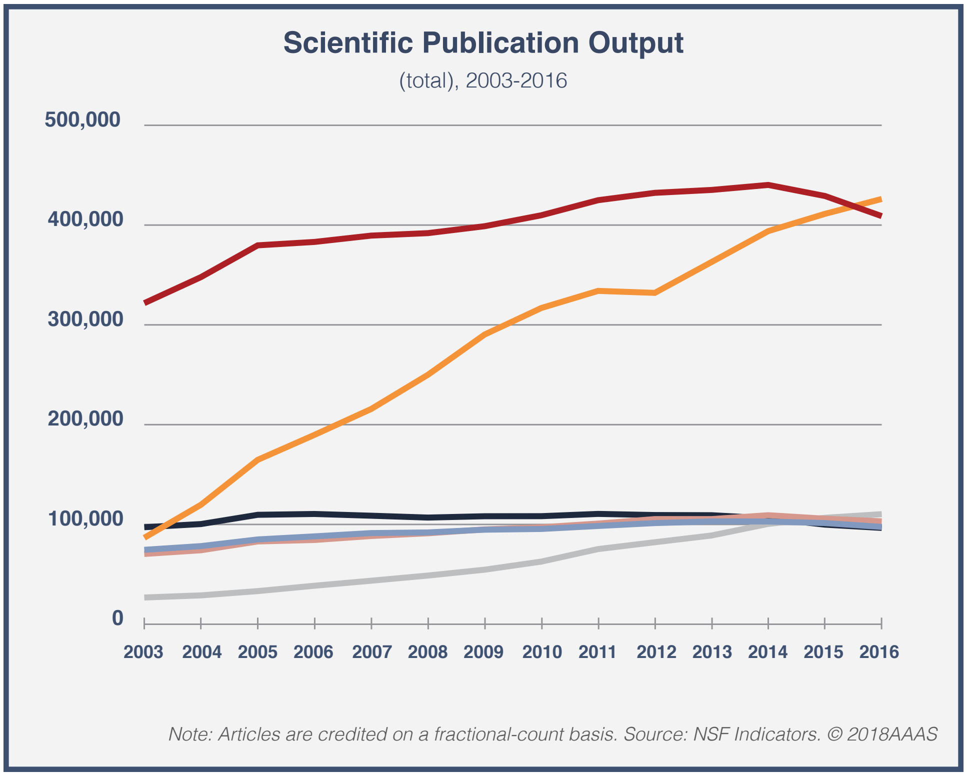
U.S. research quality is stagnating. The U.S. continues to publish some of the most cited research but is losing ground on the international stage (see **GRAPH 2.7**). Countries that have recently surpassed the U.S. in the top 1 percent of cited publications include the U.K., Australia, and Canada, all of which have implemented national research 'excellence' programs.[12] Saudi Arabia, meanwhile, has aggressively reformed its peer review policies as part of the country's transition to a knowledge-based economy. China, now the world's largest research producer, has more than doubled its share of the top 1 percent of cited publications amid ongoing restructuring of the country's national research evaluation system. A recent analysis by Elsevier – the world's largest scientific publishing company – predicts that China could overtake the U.S. in research productivity by the mid-2020's.[13]

GRAPH 2.5

Scientific Publication Output

(total), 2003-2016

- USA
- China
- UK
- Germany
- Japan
- India

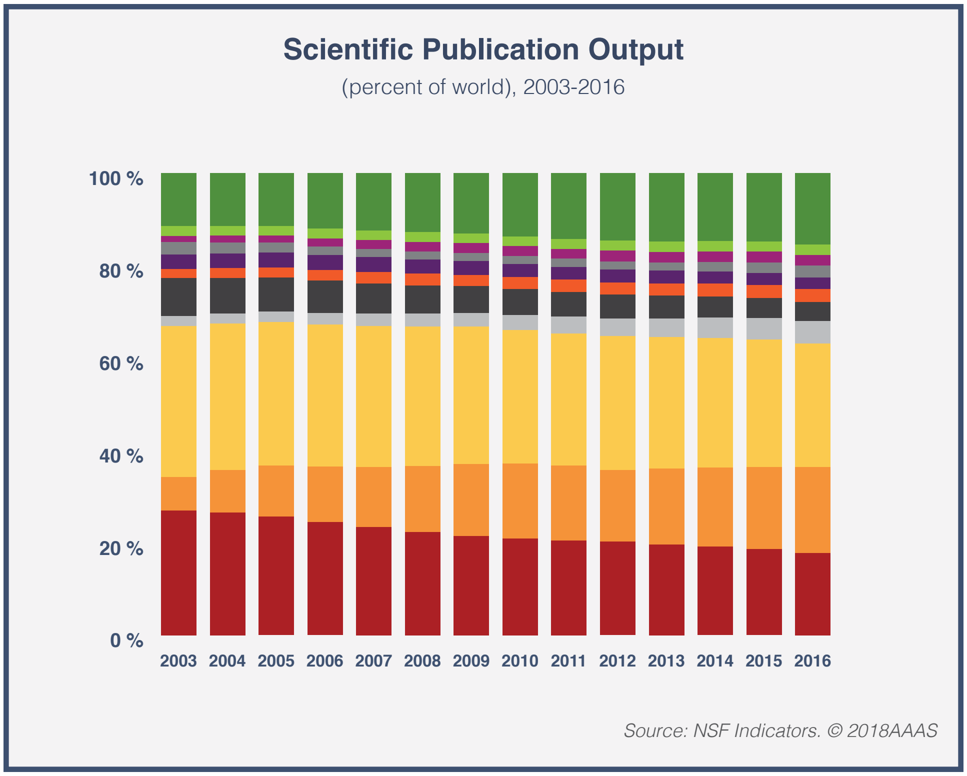


GRAPH 2.6

Scientific Publication Output

(percent of world), 2003-2016

- Rest of World
- Australia
- Brazil
- Russia
- Canada
- Korea
- Japan
- India
- EU-28
- China
- USA

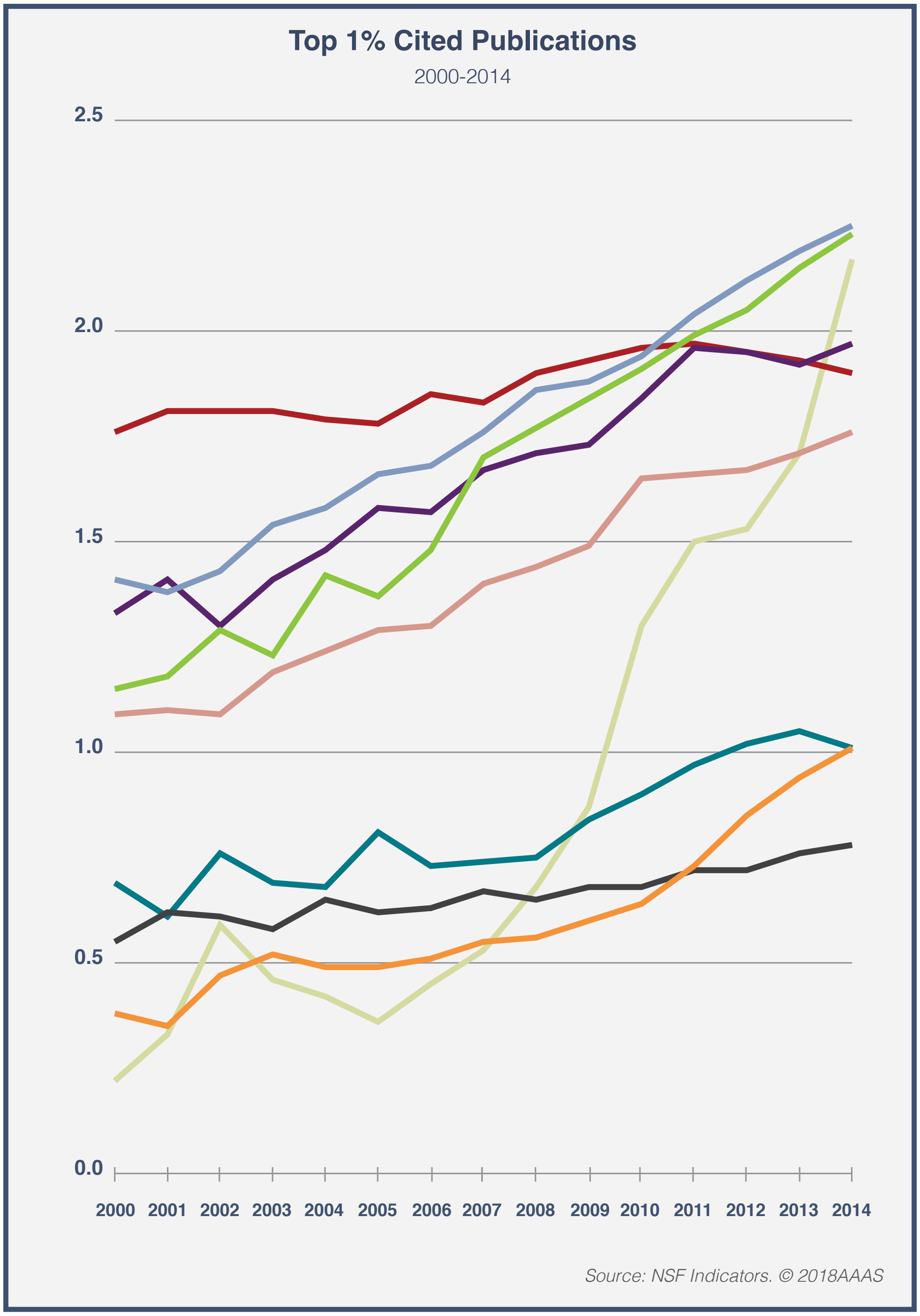


GRAPH 2.7

Top 1% Cited Publications

2000-2014

- UK
- Australia
- Canada
- USA
- Germany
- China
- Japan
- South Korea
- Saudi Arabia



Global competition has exacerbated imbalances in the U.S. research portfolio. Measured globally, U.S. publication output remains heavily geared towards medical and life sciences, while engineering, physics, mathematics, and computer science are lagging. Federal/public investments in these areas are essential for the U.S. to remain a global innovation leader (see **GRAPHS 2.8, 2.9, & 2.10**).

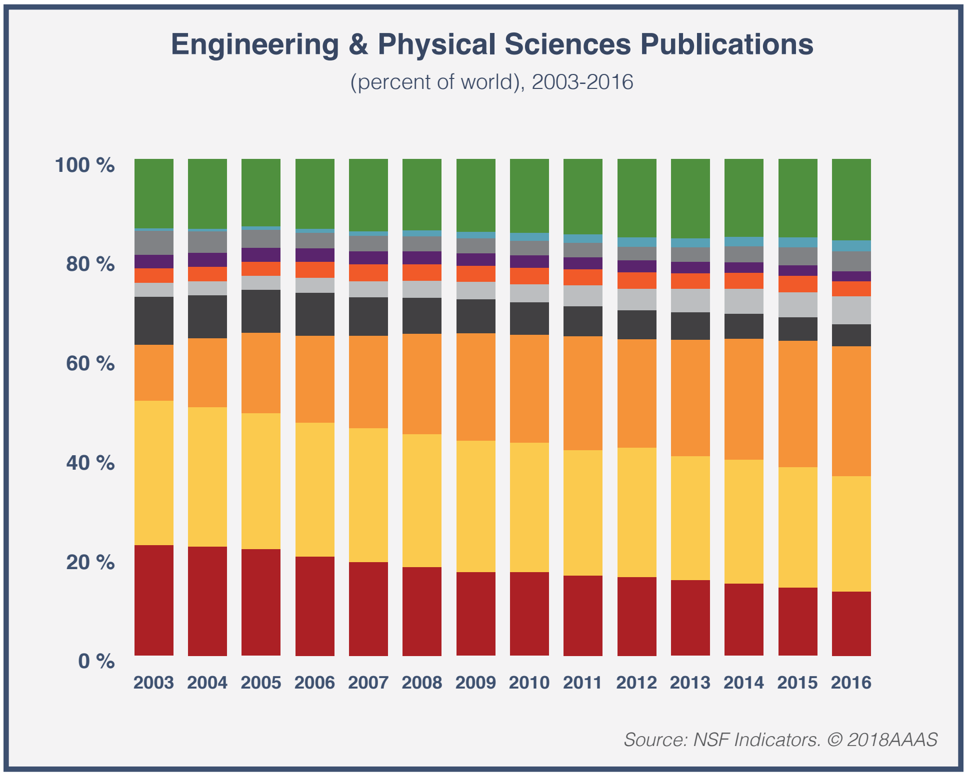
In engineering alone, the U.S. share of article production decreased from 23 percent to 12 percent during the 2003-2016 period. This dramatic shift can be attributed to changing U.S. domestic priorities – namely an increased emphasis on health research since the end of the Cold War – alongside rising global competition, particularly from China. In just over a decade, China has eclipsed U.S. publication shares in key research areas including engineering, physics, chemistry, geosciences, and mathematics. Meanwhile, the European Union has collectively fared better than the U.S. This is particularly evident in the field of computer sciences, with U.S. publication shares halved between 2003 and 2016, versus much smaller gradual declines in the E.U.

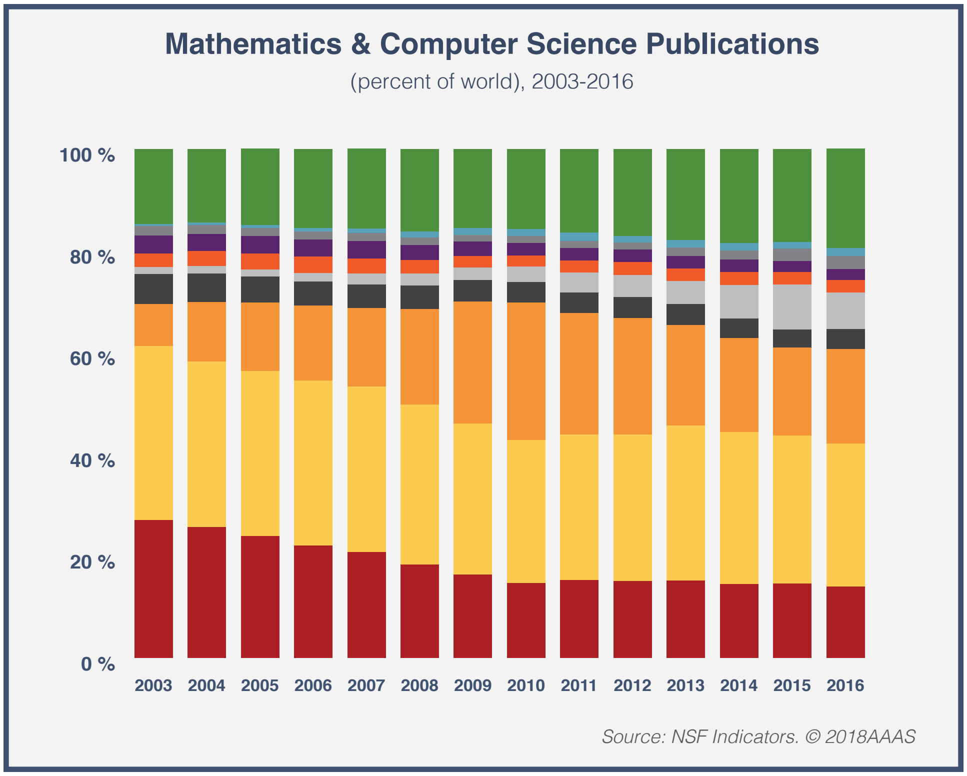
GRAPH 2.8

Engineering & Physical Sciences Publications

(percent of world), 2003-2016

- Rest of World
- Iran
- Russia
- Canada
- Korea
- India
- Japan
- China
- EU-28
- USA



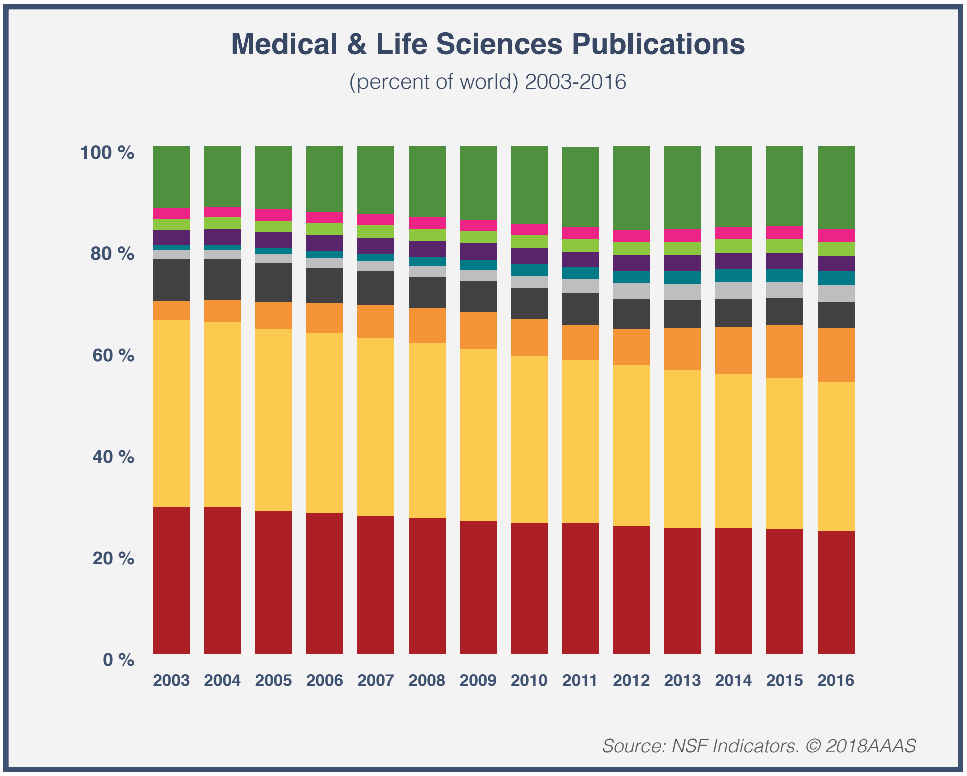


GRAPH 2.9

Mathematics & Computer Science Publications

(percent of world), 2003-2016

- Rest of World
- Iran
- Russia
- Canada
- Korea
- India
- Japan
- China
- EU-28
- USA



GRAPH 2.10

Medical & Life Sciences Publications

(percent of world) 2003-2016

- Rest of World
- Turkey
- Australia
- Canada
- Korea
- India
- Japan
- China
- EU-28
- USA

Addressing the U.S. Research Imbalance

A new white paper[14] published by The Center for Innovation Policy at Duke Law highlights a growing imbalance in the federal government's research portfolio – namely a shift away from the physical sciences and engineering (PS&E) and toward the life sciences.

In 1980 PS&E research represented 41 percent of the federal science budget. Thirty-five years later its share had fallen to 28 percent. The life sciences had picked up the entire difference.

The author also points out that other non-governmental sources of research support – businesses, nonprofit, and philanthropic organizations, and universities' own funds – are even more heavily focused on biomedical research than federal agencies.

The report discusses past failed attempts to rebalance the nation's research investments towards PS&E fields. For example, funding for the 2007 America COMPETES Act – which sought to double the research budgets at the NSF, NIST, and the DOE's Office of Science – repeatedly fell short of the doubling target. This stands in contrast to the remarkably successful effort by Congress to double the NIH budget between 1998 and 2003 and increased investments in recent years as authorized by the 21st Century Cures Act.

The solution is not to simply shift resources from the life sciences to the physical sciences and engineering, according to the author, but to treat all major fields of science and technology as a national priority. This begins with addressing the current sequestration caps on both domestic and defense discretionary spending. Sustained research funding should be the goal – not rapid infusions of funds. The report also recommends expanding the scope and capacity of key science advising bodies, including the Office of Science and Technology Policy (OSTP) and the National Science and Technology Council (NSTC).

PATENTS

Like publications, patents are a useful – if imperfect – measure of scientific productivity. Patented inventions are an important source of the innovations that ultimately materialize in the marketplace. Patents and the pace of their emergence can help signal the health of national innovation systems.

The U.S. Share of International Patents is Declining. In 1990, U.S. innovators claimed over 11,000 "triadic patent" families, or patents for the same invention or set of inventions, filed in the United States, Europe, and Japan. Because holders of triadic patents have gone through the cost and effort of filing in multiple patent offices around the world, triadic patent families are generally seen as representing higher quality and greater value.

What is a "Triadic Patent"?

"The triadic patent families are defined at the OECD as a set of patents taken at the European Patent Office, Japan Patent Office, and the United States Patent and Trademark Office that share one or more priorities… Counting triadic patent families provides indicators of improved quality and international comparability for measuring innovation performance of countries." - OECD, "Triadic Patent Families Methodology" working paper.[61]

Triadic patenting rates in East Asian economies – which here include Japan (by far the largest), South Korea, Taiwan, China, Hong Kong, and Singapore – began to take off in 1998. East Asia, the E.U., and the U.S. all reached roughly 15,000 triadic families in 1998. Then the Asian economies began to surge ahead and collectively surpassed 20,000 triadic families in 2003; they have widened the gap since then. While the U.S. increased its annual triadic patent count by 21.7 percent between 1990 and 2012, the East Asian group more than doubled its patent output over that time to 23,000. The biggest driver is a near-doubling of Japanese triadic patents, though South Korea and China have also exhibited dramatic gains over this period: both have risen from fewer than 100 patent families a year to over 2,000.

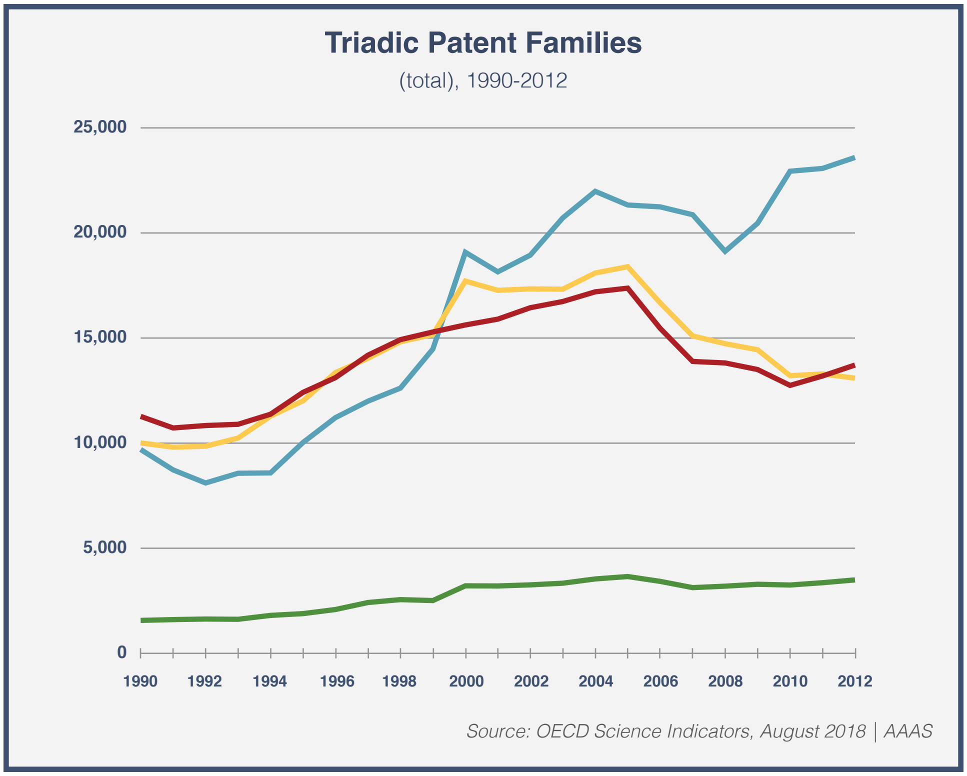
GRAPH 2.11

Triadic Patent Families

(total), 1990-2012

- USA
- EU-28
- East Asia*
- Rest of World

**Japan, Korea, China, Singapore, Taiwan, Hong Kong*

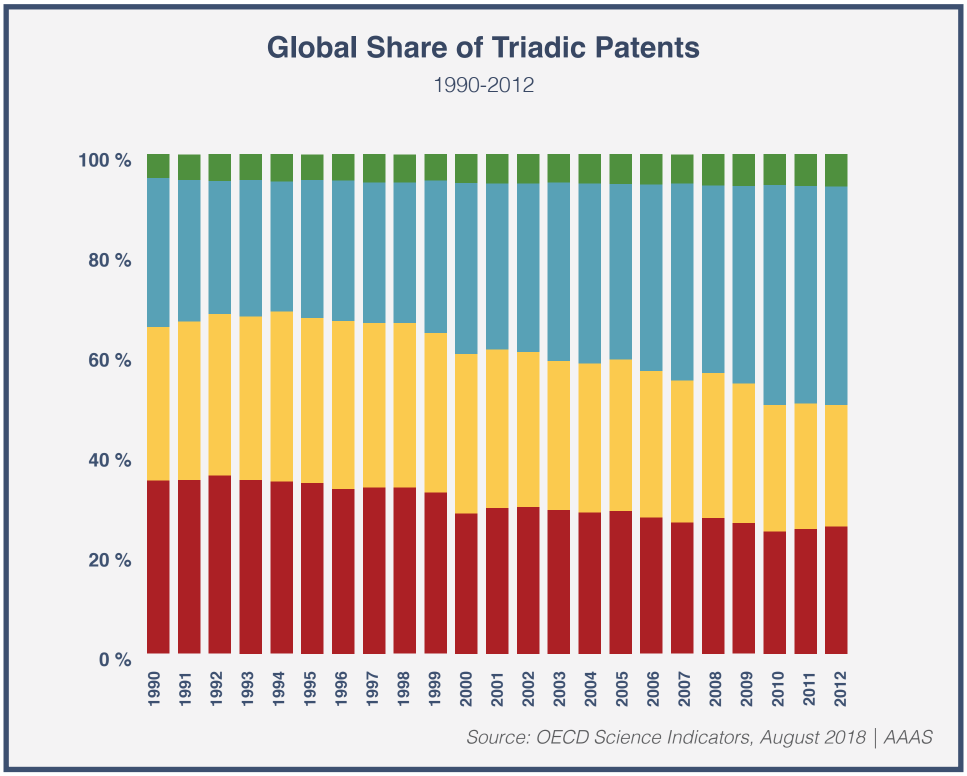


GRAPH 2.12

Global Share of Triadic Patents

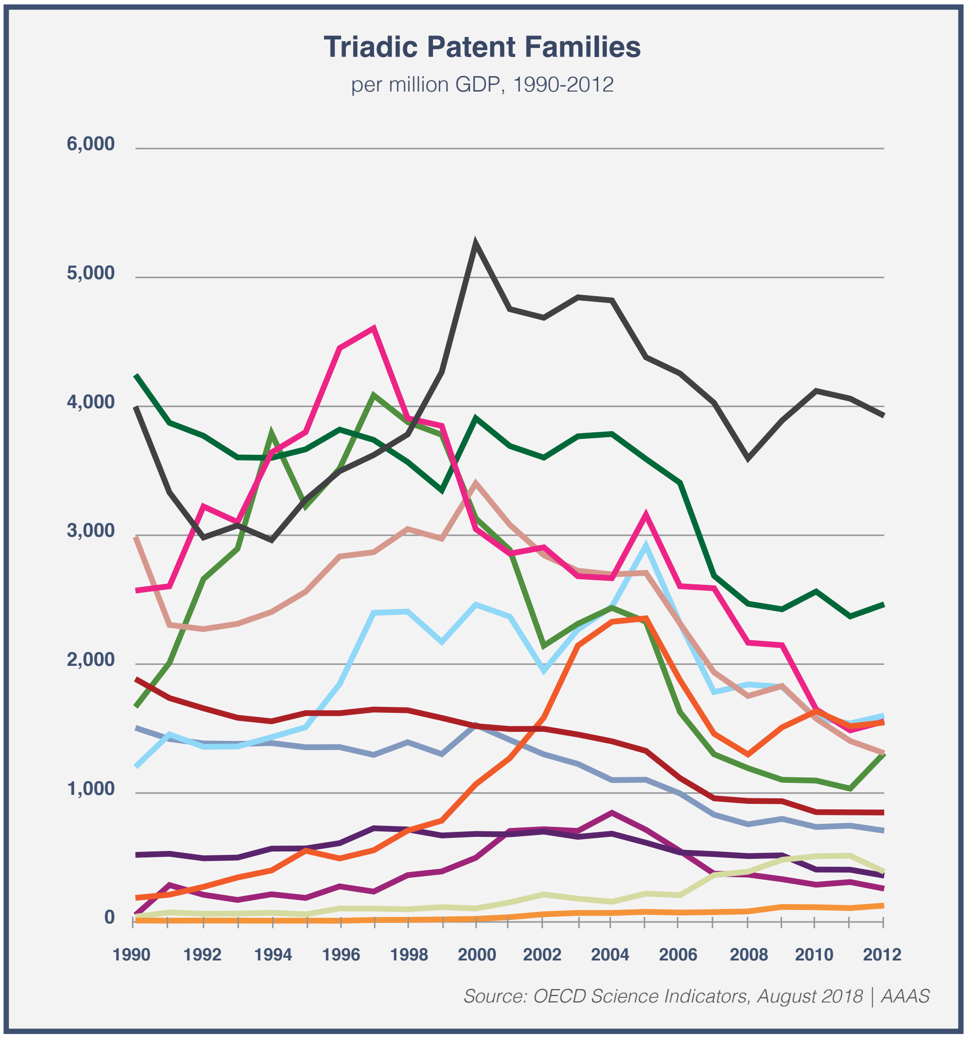
1990-2012

- Rest of World
- East Asia*
- EU-28
- USA



While Asia has experienced this acceleration, U.S. patenting rates have slowed. The U.S. share of the triadic total has declined by roughly a third since 1990 (see **GRAPH 2.11 and 2.12**).

U.S. Patenting Intensity Has Declined. While in the aggregate the U.S. boasts more triadic patent families than any other single country, much of this is due simply to the size of our economy. When adjusting to account for different levels of GDP, U.S. triadic patenting rates are actually middle of the pack and have slowed. In 1990, U.S. innovators claimed over 1,800 triadic patent families for every million dollars of GDP. By 2012, this rate had fallen to fewer than 900 per million dollars of GDP. Even in a period in which patent productivity seems to have declined globally, the U.S.'s decline is somewhat larger than average. By comparison, the economies of Japan, Sweden, and Switzerland remained much more productive in 2012, while triadic patent productivity in Finland, Israel, and Korea have all surpassed the U.S. since 1990 (see **GRAPH 2.13**).



GRAPH 2.13

Triadic Patent Families

per million GDP, 1990-2012

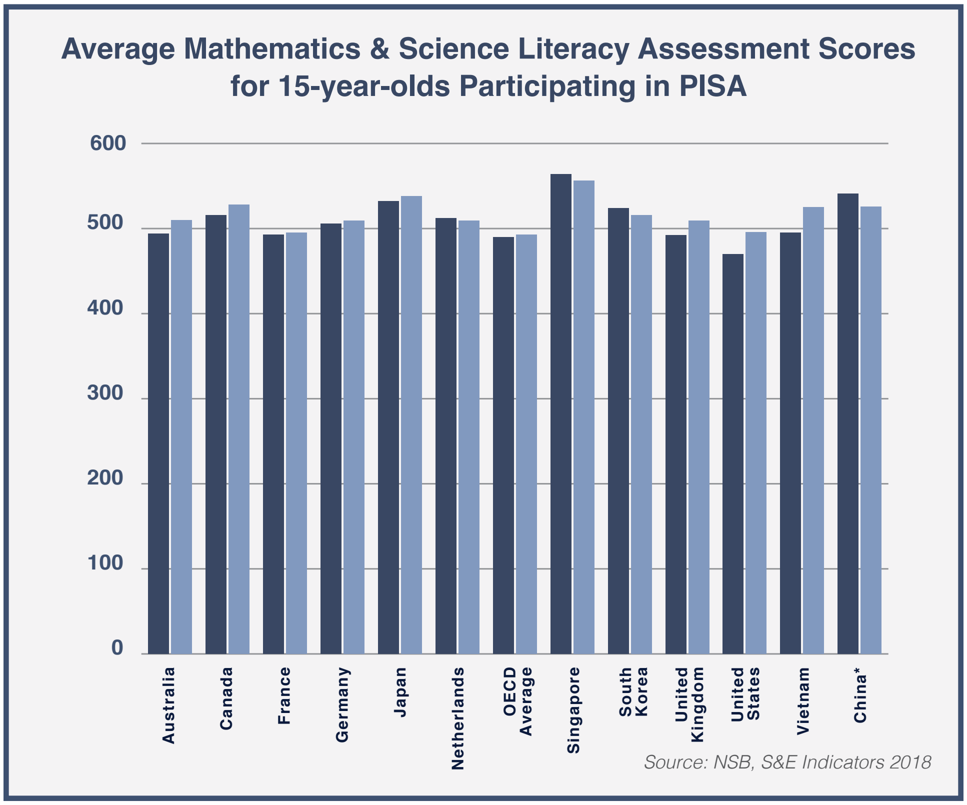
- USA
- Japan
- China
- Korea
- Taiwan
- Sweden
- Canada
- Germany
- Switzerland
- Finland
- Israel

Education Benchmarks

3

Education is an integral measure for comparing countries' innovation and knowledge creation capabilities. A strong foundation in math and science at the K-12 level helps develop thinking and skills that are essential in STEM disciplines. Higher education provides the advanced knowledge and expertise necessary to excel in discovery and application and is paramount to the creation, recruitment, retention, and training of a diverse and highly-skilled STEM workforce.

Students in the U.S. fall behind those in China, Europe, and Canada in math and science. A global comparison of Program for International Student Assessment (PISA) scores from 2015 shows the average score for the U.S. was lower than that of many other countries for both math and science. While the average science literacy score of 496 was somewhat better than the average score of 470 for the PISA Math assessment, the overall U.S. scores were well below those of top performers like Singapore, Japan, and China* (see **GRAPH 3.14**). With the scientists and engineers of tomorrow currently in school, the U.S. needs to strengthen its education system to support the development of domestic science and engineering talent.



GRAPH 3.14
Average Mathematics & Science Literacy Assessment Scores for 15-year-olds Participating in PISA
by Education System, 2015

■ Math Literacy Assessment Score
■ Science Literacy Assessment Score

* *"China's average PISA Score is an average of the scores from Taiwan, Macau, Hong Kong, Beijing, Shanghai, Jiangsu, and Guangdong."*

Both U.S. scientists and the public are critical of the quality of the country's K-12 STEM education.

"Only 16 percent of AAAS [American Association for the Advancement of Science] scientists and 29 percent of the general public rank U.S. STEM education for grades K-12 as above average or the best in the world. 46 percent of AAAS scientists and 29 percent of the public rank K-12 STEM as 'below average.'"[15]

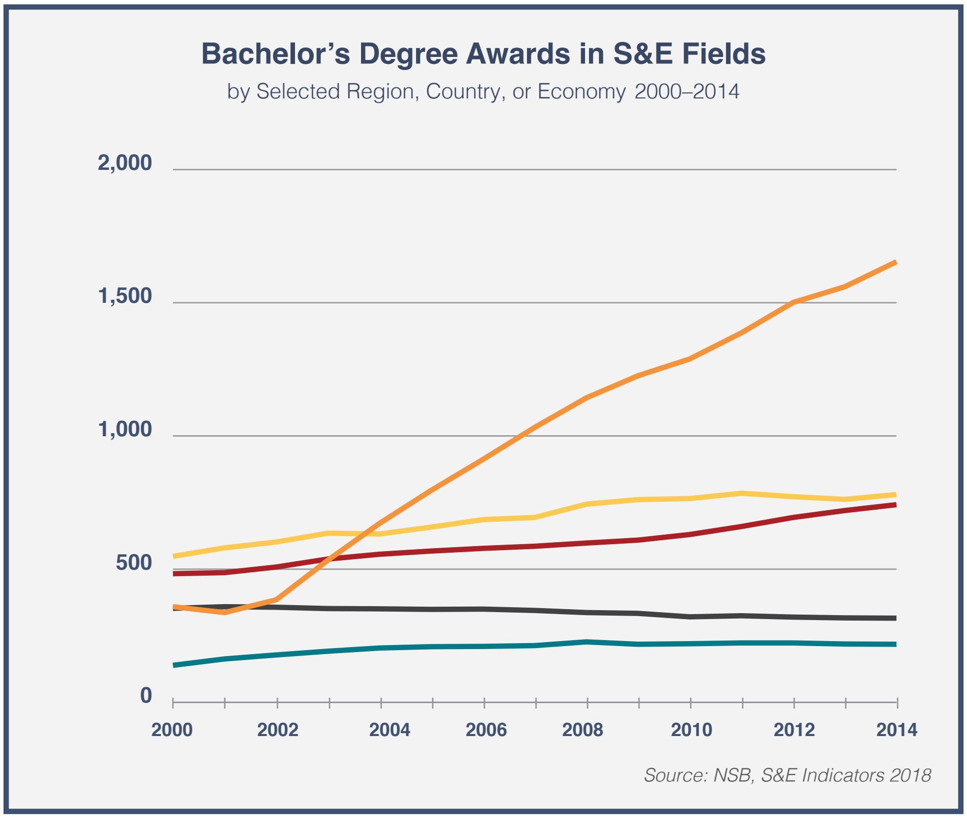
The United States is lagging in the output of bachelor's degrees in science and engineering fields. The U.S. continues to trail the top eight countries in the E.U., as measured by the total number of bachelor's degrees in science and engineering (S&E) awarded since 2000, and has also been eclipsed by China. China's output of S&E bachelor's degrees has increased by over 360 percent since 2000. In 2014, the European Union (12 percent) and the United States (10 percent) accounted for less than a quarter of the bachelor's degrees awarded in S&E fields globally, while China accounted for 22 percent of the global share (see **GRAPH 3.15**).[16]

GRAPH 3.15

Bachelor's Degree Awards in S&E Fields

by Selected Region, Country, or Economy 2000–2014

- China
- EU - Top 8*
- Japan
- South Korea and Taiwan
- USA



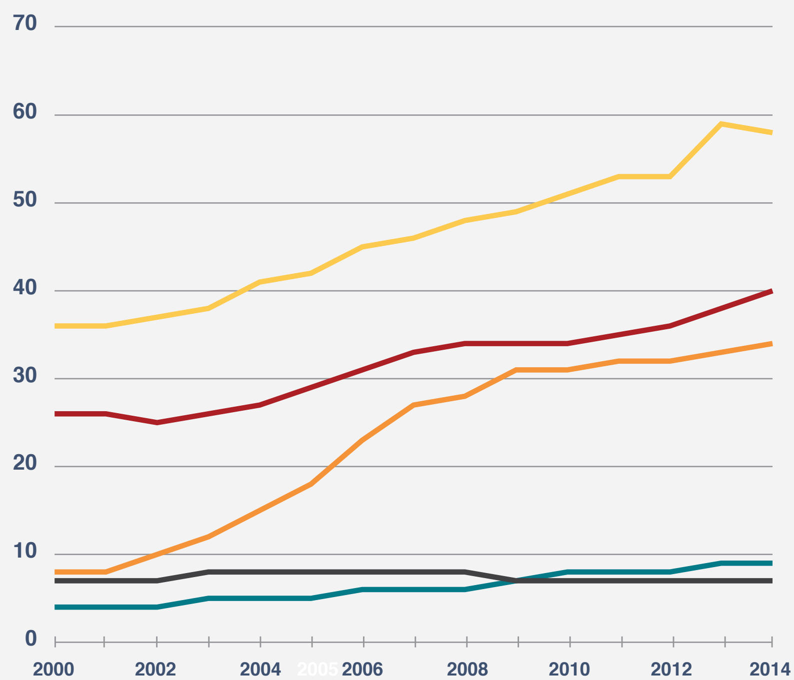
** United Kingdom, Germany, France, Poland, Italy, Spain, Romania, and the Netherlands*

> "S&E fields account for a larger proportion of all bachelor's degrees in China than in the United States. In 2014, these fields accounted for 48 percent of all bachelor's degrees in China, compared with 39 percent of all bachelor's degrees in the United States."[17]

The U.S. trails the European Union in doctoral degrees awarded in science and engineering and faces intense competition from China. China now awards nearly as many S&E doctorates as the U.S. In the 15-year period between 2000 and 2014, China increased their doctoral degree output in science and engineering by over 53 percent (see **GRAPH 3.16**).

Doctoral Degree Awards in S&E Fields

by Selected Region, Country, or Economy 2000–2014



Source: NSB, S&E Indicators 2018

GRAPH 3.16

Doctoral Degree Awards in S&E Fields

by Selected Region, Country, or Economy 2000–2014

- China
- EU - Top 8
- Japan
- South Korea and Taiwan
- USA

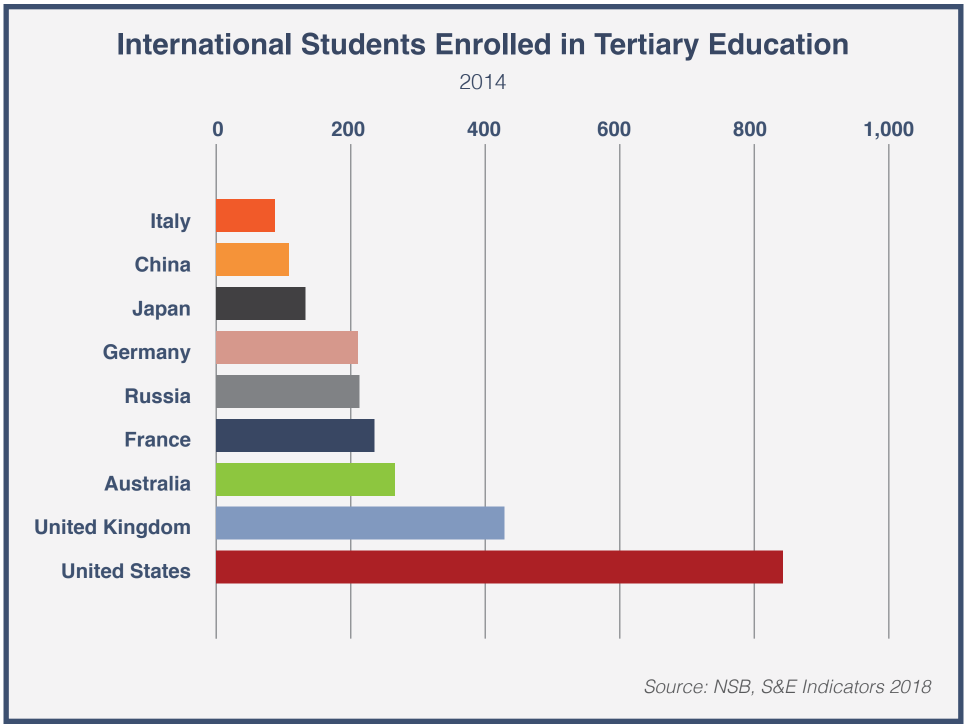
While the U.S. remains a leader in attracting international students (see GRAPH 3.17), **reports indicate a decline in new international student enrollment since 2016.** The Institute of International Education's (IIE) 2018 Open Door Report reported a decline in new international student enrollment by a total 6.6 percent in Fall 2017 when compared to the previous year.[18]

GRAPH 3.17

International Students Enrolled in Tertiary Education

2014

- Italy
- China
- Japan
- Germany
- Russia
- France
- Australia
- United Kingdom
- USA



The exclusion of foreign talent at universities negatively impacts U.S. industry.

"Survey respondents list visa application process issues or visa delays/denials as the top reason for Fall 2017 drops in new enrollment. The percentage of institutions citing this issue grew from 33.8 percent in Fall 2016 to 68.4 percent in Fall 2017 (+35 percentage points)." – IIE's Fall 2017 Hot Topics Survey [19]

A downward trend in new student enrollment poses a problem for maintaining the U.S.'s competitive edge in the race for talent, especially as other countries build initiatives to strengthen programs and attract top foreign scholars.

What are other countries doing to attract and retain the best and brightest researchers from around the world?

There is intensifying global competition to recruit top science and engineering researchers; countries have instituted incentive programs to attract foreign students and faculty, improve the quality of their universities, conduct research in their respective countries, and become acclaimed research destinations.

Canada: The Canada Excellence Research Chairs (CERC) Program is a foreign-talent recruitment effort that works to attract research leaders to come and work at Canadian universities by awarding up to 10 million Canadian dollars (over 7.5 million USD) over seven years to support the establishment of high-caliber research programs at Canadian universities.[20]

Germany: The Excellence Initiative, passed by the German government, seeks to make Germany more internationally competitive and an attractive research location by funding awards to promote top-level research and to improve the quality of its major universities.[21] The initiative has attracted over 4,000 foreign scientists to Germany.[22]

China: The Thousand Talents Program is a Chinese government incentive program with the goal of recruiting science, technology and entrepreneurship experts from across the globe. The program offers benefits including a competitive salary, lump-sum bonus, and research subsidies up to 5 million yuan (about 719,600 USD), whose amount vary depending on the type, level, and quality of the program.[23]

United States: The U.S. currently lacks an overarching talent development program with the goal of attracting and retaining science and engineering researchers. However, some focused talent development programs exist within the federal government. The National Defense Science and Engineering Graduate (NDSEG) Fellowship Program has awarded nearly 3,600 fellowships since 1989. These fellowships support U.S. citizens and nationals pursuing doctoral studies in one of fifteen disciplines, with the goal of increasing the number of science and engineering researchers trained in areas of military importance. This program is sponsored by the Air Force Office of Scientific Research (AFOSR), the Army Research Office (ARO), and the Office of Naval Research (ONR) through the Office of the Assistant Secretary of Defense (OSD) for Research and Engineering. Other graduate student research fellowships are offered through NSF, NASA, and the Department of Energy. Without a concerted strategy and accompanying investment, the U.S. will continue to lose ground to other nations in developing world-class domestic talent.

4

Workforce Benchmarks

As the research enterprise continues to grow, the professional workforce within the U.S. must meet the demands of the market to remain competitive. Investing in human capital is one area where government and industry can work together to ensure that enough STEM talent is trained through formal education, apprenticeship programs, and retraining programs.

U.S. Labor Force

Women and underrepresented minorities[24] are less represented in science and engineering occupations. In 2015, women accounted for less than one-third of the population employed in science and engineering occupations (see **GRAPH 4.18**) while underrepresented minorities accounted for 11 percent of S&E employment.[25] There is a tremendous opportunity to cultivate "Lost Einsteins" and add to the numbers of STEM workers and innovators.[26] Tapping into our domestic talent by increasing the number of women and underrepresented minorities in the STEM workforce will help increase the talent pool and bring a broader range of perspectives and talent to the workforce.

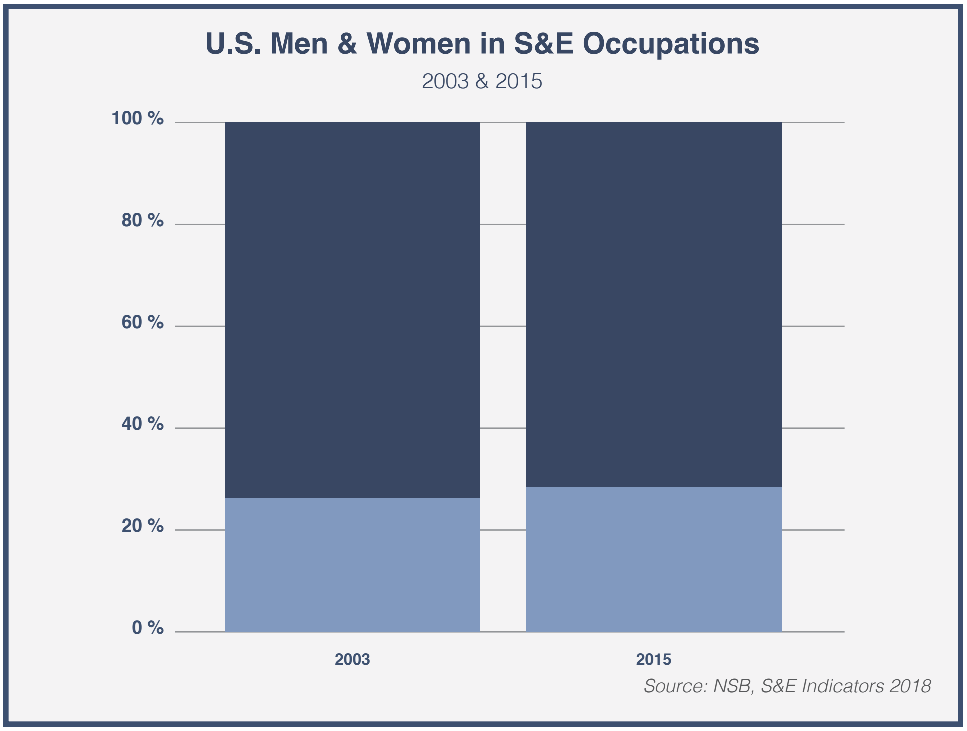
GRAPH 4.18

U.S. Men & Women in S&E Occupations

2003 & 2015

■ Men

■ Women



In addition to the professional workforce involved in the U.S. research enterprise, the skilled technical workforce is critical to innovation in health care, infrastructure, and other fields that generate high economic growth. In 2014, 11.9 percent of the total workforce in the U.S. was in skilled technical professions including occupations like construction; maintenance, installation, and repair; healthcare practitioner and technical occupations; and computer and mathematical occupations (see **TABLE 4.1**). For example, "the Nobel-Prize winning discovery of gravitational waves at NSF's Laser Interferometer Gravitational-Wave Observatory (LIGO) would not have been possible without the invaluable expertise of the people who assemble and maintain the facility's large and complex heating, ventilation, vacuum, air conditioning, and electronic systems."[27]

TABLE 4.1

Number & Percentage of Skilled Technical Workers by Occupational Group, 2014[28]

Number & Percentage of Skilled Technical Workers by Occupational Group, 2014

Major Occupational Group	Skilled Technical Workers	Skilled Technical Workers as Share of Total Occupation
Installation, Maintenance, and Repair Occupations	4,418,880	84%
Construction and Extraction Occupations	2,825,350	53%
Healthcare Practitioners and Technical Occupations	3,343,020	43%
Production Occupations	2,576,660	29%
Architecture and Engineering Occupations	653,650	27%
Computer and Mathematical Occupations	824,640	22%
Arts, Design, Entertainment, Sports and Media Occupations	213,330	12%
Protective Service Occupations	308,790	9%
Farming, Fishing, and Forestry Occupations	31,370	7%
Life, Physical, and Social Science Occupations	79,780	7%
Legal Occupations	63,450	6%
Business and Financial Operations Occupations	237,420	3%
Transportation and Material Moving Occupations	231,790	3%
Food Preparation and Serving Related Occupations	118,130	1%
Office and Administrative Support Occupations	137,900	1%
Personal Care and Service Occupations	25,160	1%
Management Occupations	17,930	0%
Sales and Related Occupations	0	0%
Education, Training, and Library Occupations	0	0%
Building and Grounds Cleaning and Maintenance Occupations	0	0%
Healthcare Support Occupations	0	0%
Community and Social Service Occupations	0	0%
Total skilled technical workforce	**16,107,249**	**12%**

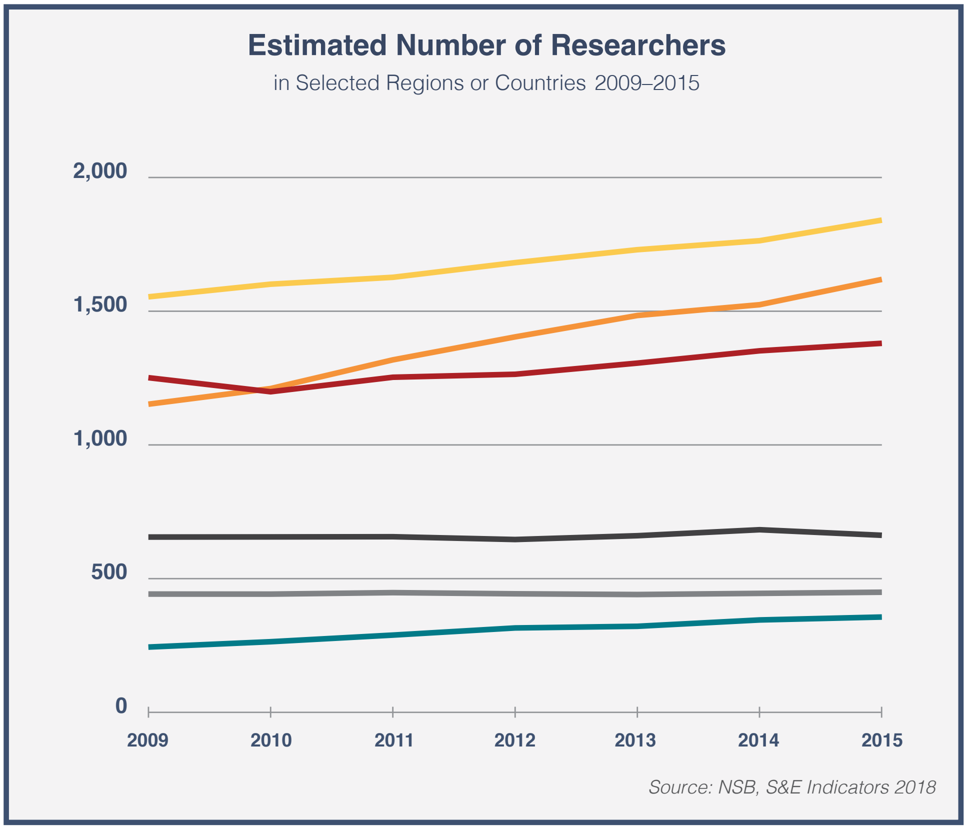
Foreign talent – particularly Asian-born researchers – contribute significantly to the U.S. science and engineering workforce. Immigration has a significant impact on the U.S.'s science and engineering (S&E) workforce. Foreign-born scientists accounted for almost 41 percent of the master's degree holders and nearly 37 percent of doctorate holders working in S&E occupations in 2015. Many of these foreign-born individuals are from Asia. In 2013, it was found that foreign-born individuals accounted for 18 percent of the U.S. S&E workforce, with 57 percent of foreign-born scientists and engineers within the United States originating from Asia and 16 percent originating from Europe.[29]

International Workforce

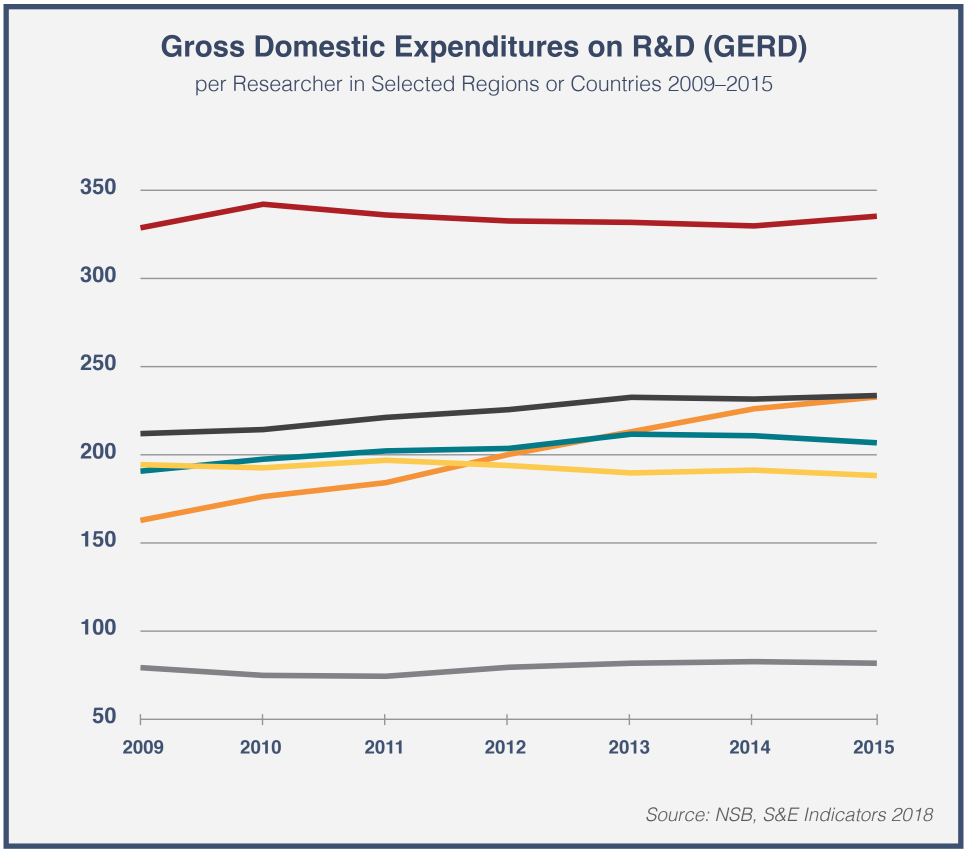
There are more researchers in the European Union and in China than in the United States. Since 2010, China has surpassed the number of researchers in the U.S. In 2015, the estimated number of total researchers in China was more than 1.6 million compared to 1.3 million in the United States (see **GRAPH 4.19**).

GRAPH 4.19
Estimated Number of Researchers
in Selected Regions or Countries 2009–2015

- USA
- EU
- South Korea
- China
- Russia
- Japan



China is increasing its expenditures per researcher faster than other countries. The U.S. leads in the amount of funds spent per researcher but faces competition from countries like China (see **GRAPH 4.20**), who continue to increase both their number of researchers and their R&D expenditures. Between 2009 and 2015, China reported an increase of almost 43 percent for its gross domestic expenditures on R&D (GERD) per researcher (in constant prices and purchasing power parity). Over the past seven years, Japan, South Korea, and the U.S. have more GERD per researcher; however, compared to China, their growth rates are stagnant. Unlike China's extraordinary percentage growth, Japan only increased by 10 percent and South Korea by 8 percent. Meanwhile, the U.S. pales in comparison with only a 3 percent increase over the past seven years.



GRAPH 4.20

Gross Domestic Expenditures on R&D (GERD)

per Researcher in Selected Regions or Countries 2009–2015

- USA
- EU
- South Korea
- China
- Russia
- Japan

5 High-Tech Sectors Benchmarks

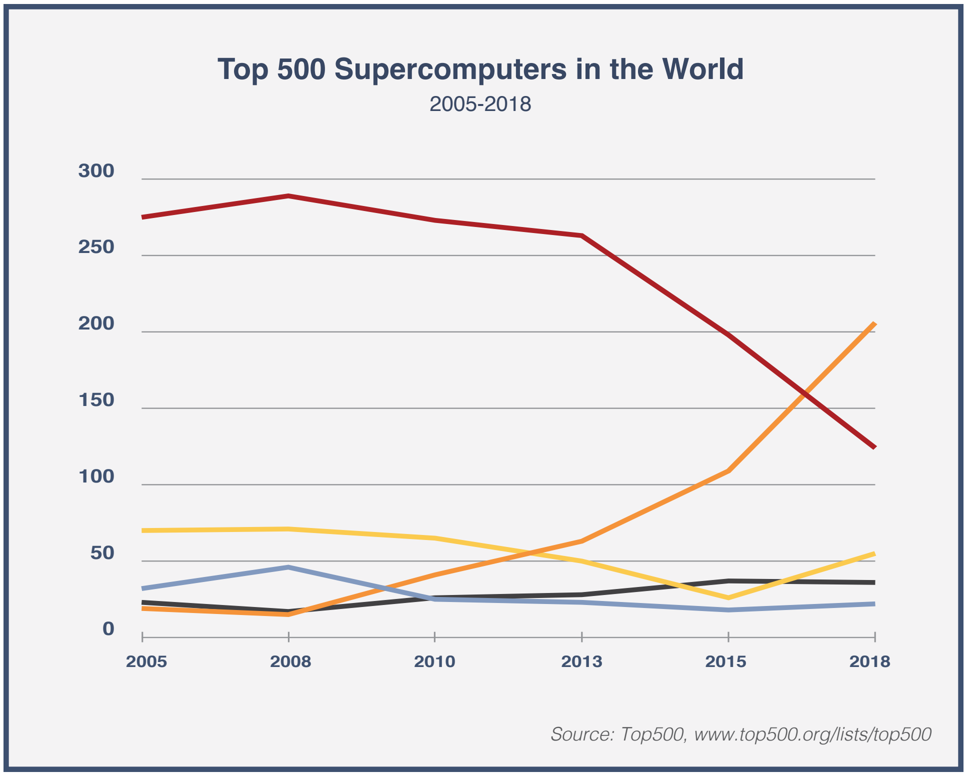
Across many sectors of the economy, signs of trouble for the U.S. are emerging in areas important to national security, economic competitiveness, technological leadership, and industrial capacity. These warning signs show the ripple effects of lapses in support for research and education. Below are a few examples of high-tech sectors which demonstrate this trend.

Supercomputing

Supercomputing is the processing of large and complex, or data-laden problems, using the concentrated computer resources of multiple computer systems working in parallel. These systems work at the maximum potential performance of any computer. Supercomputing enables problem-solving and data analysis that would be impossible, too time-consuming, or more costly to perform with standard computers. Applications include weather forecasting and modeling; oil and gas exploration; molecular structure modeling; and airplane and spacecraft aerodynamics design, to name a few.

The U.S. invested heavily in both the physical infrastructure of supercomputers and the related research field of supercomputing in the 1980s and 1990s. The U.S. has reaped the benefits of this investment by being the world leader in computing fields and introducing several new products, including the internet. However, this supremacy is being challenged.

- Since TFAI's 2005 Benchmarks Report, the U.S. has surrendered its commanding lead in the world's top supercomputers. On the Top 500 list of the world's fastest supercomputers (see **GRAPH 5.21**), the U.S. in 2005 controlled almost half the world's top supercomputers; it now controls less than a quarter, with China now controlling the largest number of the fastest supercomputers.[30]
- Changing the benchmark to the top 100 supercomputers (see **GRAPH 5.22**), U.S. leadership is on a downward trajectory. The U.S.'s lack of investment over the past two decades is best demonstrated by China gaining the top spot on the list in 2010[31] and the U.S. did not recapture that spot until 2018.

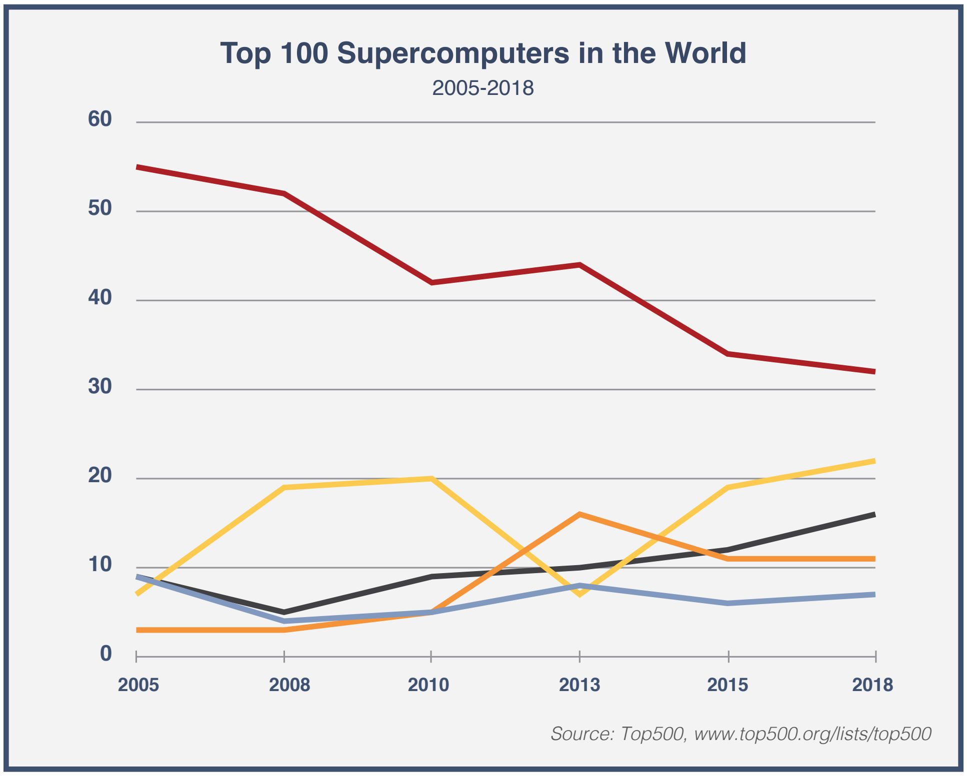


GRAPH 5.21

Top 500 Supercomputers in the World

2005-2018

- USA
- UK
- China
- EU
- Japan



GRAPH 5.22

Top 100 Supercomputers in the World

2005-2018

- USA
- UK
- China
- EU
- Japan

- There are efforts at addressing this trend in quantum and exascale computing research. These include the National Quantum Initiative Act (Public Law No: 115-368), signed into law at the end of 2018, which directs the president to implement a national initiative to establish goals and priorities for a 10-year plan to accelerate the development of quantum information science and technology applications. Additionally, the Trump administration directed DOE to field the world's first operational exascale capable computer system by 2021, which would be a major breakthrough in computer processing power.[32]

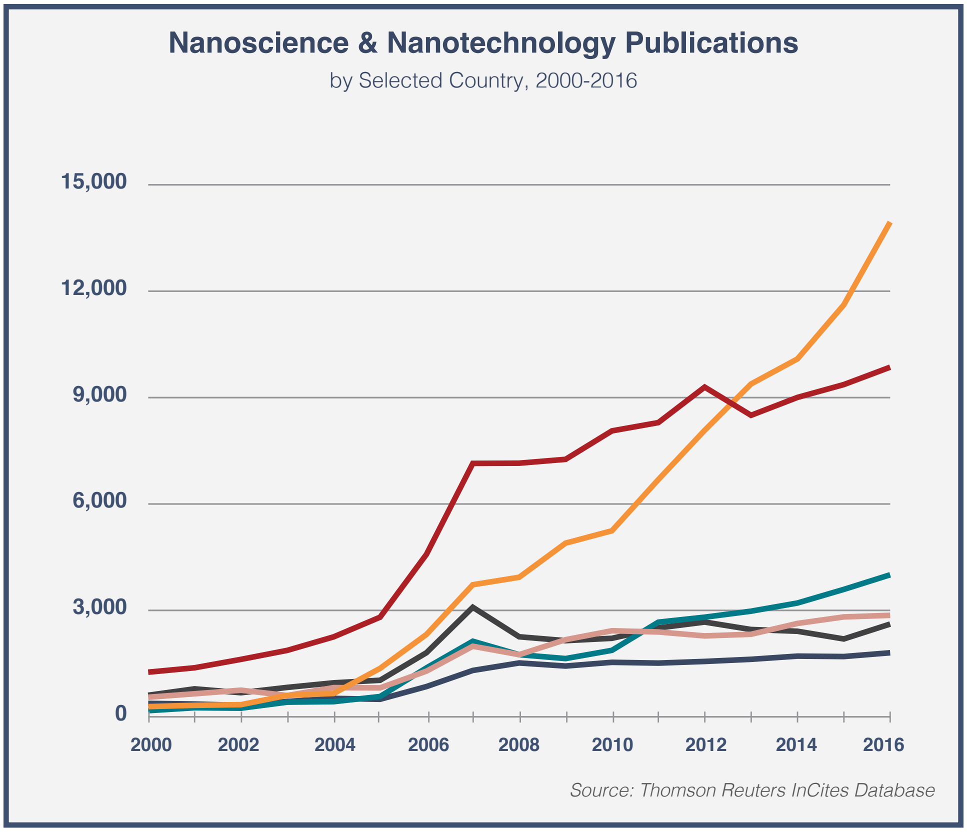
> **"To out compete is to out compute."**
>
> Trademark quote of the Council on Competitiveness.

- The U.S. under-investment in supercomputing is alarming, given former House Science, Space, and Technology Committee Chairman Lamar Smith's assertion that, "high performance computing can lead to scientific discoveries, economic growth, and will maintain America's leadership in science and technology."[33]

Nanotechnology

Nanoscience and nanotechnology are the study and application of matter at the atomic and molecular levels – the basic building blocks of all natural and man-made things. Improvements in our ability to study matter at the nanoscale could reshape many industries, such as manufacturing, electronics, and medicine. Potential applications include new vaccines, longer lasting batteries, and improved food packaging.

- While the U.S. took the global lead by establishing the National Nanotechnology Initiative (NNI) in 2000, funding for NNI has declined in recent years. Since reaching a peak in 2010, the total NNI budget has dropped by 28 percent, according to AAAS historical analysis.
- Meanwhile, the U.S. nanotechnology enterprise is being challenged by global competitors, notably China. Nano-related publication output from China is growing exponentially, having recently surpassed the U.S. (see **GRAPH 5.23**).
- China has also eclipsed the U.S. in the total number of nano-related patents, amid China's growing emphasis on translating research into practical applications and societal impacts.[34]



GRAPH 5.23
Nanoscience & Nanotechnology Publications
by Selected Country, 2000-2016

- USA
- China
- Germany
- South Korea
- Japan
- France

Aerospace

Since World War II, America's aerospace industry has been an important part of the country's national and economic security. In 2017, the U.S. aerospace and defense industry generated $865 billion in economic output and supported 2.4 million domestic jobs. Additionally, the industry generated $143 billion in exports, with a positive trade balance of $86 billion.[35] It is one of the few industry sectors in which the U.S. currently has a commanding lead, with a 53 percent share of the global aircraft and spacecraft industry (the E.U. is second with a 22 percent share and China is third with a 6 percent share).[36] However, there is pressure that could chip away at this lead:

- An example of that pressure: the first large Chinese-made jetliner, the C919, successfully completing its maiden test flight in 2017. This is, "a key step in China's plan to...become a global competitor in advanced technologies."[37] While, "the plane relies on foreign-made technology for critical systems, including its engines," the fact that more than 200 Chinese companies and 36 universities have been involved in the research and development of the jetliner demonstrates that China is making a concerted effort to develop expertise in this field.

- In his April 26, 2018 testimony to the Senate Armed Services Committee, former Secretary of Defense James Mattis pointed to hypersonic weapons as one of a number of research areas that the U.S. Defense Department needs to focus its R&D resources to, "ensure we will be able to fight and win wars of the future."[38]

> "I'm sorry for everybody out there who champion some other high priority...but there has to be a first, and hypersonics is my first."
>
> Michael Griffin, Undersecretary of Defense for Research and Engineering.

- Hypersonic weapons are a significant research and engineering challenge; operating aircraft at speeds of Mach 5 or higher requires expertise in multiple fields. Reports suggest China recently developed and tested a hypersonic weapon, and Russia has made claims of developing similar weapons; the U.S. military does not have a comparable capability.[39 40]

Artificial Intelligence

Artificial intelligence (AI) is a general term for computer systems, or algorithms, which can perform tasks and decisions that would normally require human intelligence. AI encompasses a constellation of subfields, such as robotics, machine learning, computer vision, and natural language processing, to name a few. The field is positioned to become a major driver of economic development and scientific discovery in the near future; it has the potential to add around $13 trillion in global economic activity by 2030, a cumulative GDP gain of 16 percent compared with today.[41]

Areas that AI could impact could be as diverse as city infrastructure management and transportation planning; public health and infectious disease monitoring; education policy; crime detection and monitoring; and military capabilities.

- China is positioning itself to become a global leader in AI by 2030, with a target to develop a $150 billion domestic AI industry. "The major developed countries in the world regard the development of artificial intelligence as a major strategy to enhance national competitiveness and safeguard national security." This is a translation from the introduction of, "A New Generation of Artificial Intelligence Development Planning," a document issued by the central government of the People's Republic of China in July 2017.

- While Europe publishes the most scientific papers on AI, China saw a sharp increase (150 percent) in its production on the topic between 2007 and 2017. The U.S. lags behind in third.[42]
- In 2017, "48 percent of total equity funding of AI startups globally came from China, compared to 38 percent funded by the U.S., and 13 percent by the rest of the world."[43]
- AI has also been identified by the U.S. Department of Defense as an area of special attention for the department's research efforts by former Secretary of Defense James Mattis.[44]

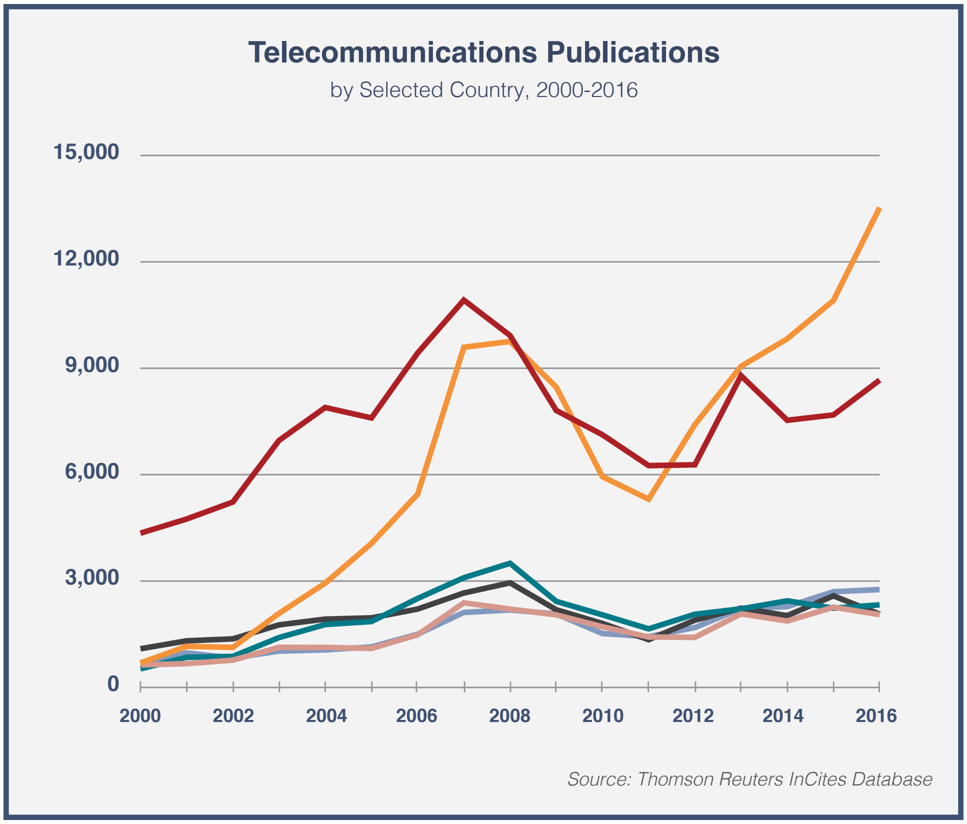
> **"Corporate and government leaders agree that China's rapid application of AI to business and military problems should be a "Sputnik moment" to propel change in America. As a top-down command economy, China is directing money and its best brains to develop the smart systems that will operate cars, planes, offices, and information — along with the transformation of warfare."[45]**

Telecommunications

The term “5G” refers to “fifth-generation cellular wireless,” or the next generation of telecommunications networks.[46] 5G yields three major improvements to the existing 4G network: greater speed (to move more data, faster), lower latency (to increase responsiveness), and the ability to connect a high quantity of devices to the network all at once (to enable an increasing number of sensors and smart devices).[47] 5G technologies are crucial to the fruition of future projects in areas such as AI, robotics, automation, the Internet of Things (IoT), smart cities, and even precision medicine. Tom Wheeler, the former Chairman of the Federal Communications Commission (FCC), writes that, “there is no doubt that 5G is an important step forward for wireless technology that will benefit consumers and drive economic growth.”[48]

> “Our government overall needs to encourage the kind of innovation that will make 5G networks pop - such as artificial intelligence and quantum computing.”
>
> FCC Chairman Ajit Pai [49]

CITA, the leading trade association for the wireless industry, has warned that the U.S. is in third place – behind China and South Korea – when it comes to the advancement of 5G technology and facilitation of successful network deployment.[50] In particular, China is positioned to invest an outsize amount of resources into 5G networks and technologies, as these are slated to become the backbone of the country’s digital economy.[51] China’s three state-owned telecommunications companies are planning to invest approximately $180 billion to create 5G infrastructure over a seven-year period, and Chinese firm Huawei is spending more than two and a half times as much on research and development as its two major rivals, Nokia of Finland and Ericsson of Sweden.[52] A “5G-ready China” has the potential to assume global leadership in areas such as product delivery, technical patents, usability testing, and industry certifications.[53] Furthermore, China has overtaken the U.S. in telecommunications publications over the past 10 years (see **GRAPH 5.24**).



GRAPH 5.24

Telecommunications Publications
by Selected Country, 2000-2016

- USA
- China
- Germany
- South Korea
- Japan
- UK

There is a need for the U.S. to increase government and industry investment in advanced communications networks, including 5G, to sustain an increasingly-connected society. U.S. officials have also stated that winning the 5G "race" is critical to both the economy and national security.[54] The FY 2020 Administration Research and Development Budget Priorities document, authored by Mick Mulvaney, Director of the U.S. Office of Management and Budget, and Michael Kratsios, Deputy Assistant to the President, Office of Science and Technology Policy, directs federal agencies to support the development and deployment of 5G wireless networks, including by "prioritizing R&D to manage spectrum, secure networks, and increase access to high-speed internet."[55] In addition, current FCC Chairman Ajit Pai shared the "Facilitate America's Superiority in 5G Technology," or 5G FAST Plan at the White House 5G Summit on September 28, 2018. This comprehensive strategy seeks to push more spectrum into the marketplace, update infrastructure policy and encourage private sector investment in 5G networks, and modernize outdated regulations, with the goal of fully realizing the potential of 5G technologies and ensuring continued U.S. competitiveness.[56]

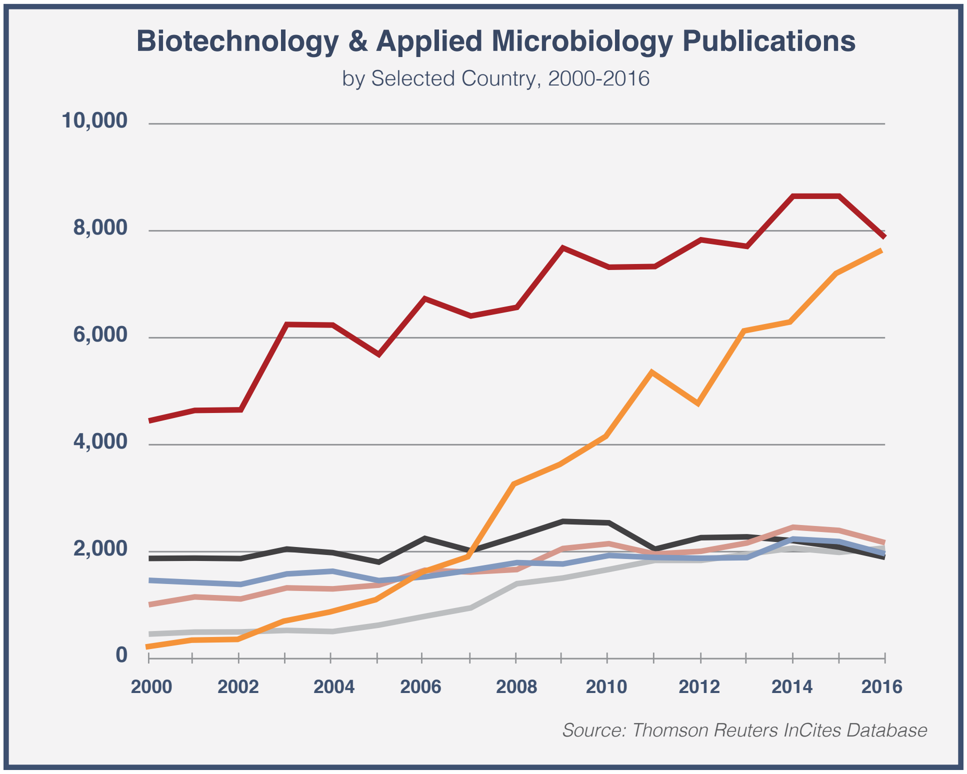
Biotechnology

Biotechnology harnesses cellular and biomolecular processes to develop innovative products, largely in medicine (e.g. new vaccines, improved diagnostics, and artificial organs) and agriculture (e.g. pest-resistant plants, high-yield crops, and vitamin-rich foods). The emerging 'bioeconomy' could provide major societal and economic benefits, including new manufacturing jobs while contributing to industries essential to U.S. national security.

- The U.S. must grapple with a maturing biotech ecosystem in Asia, where government and industry investments have intensified. Biotech venture rounds in Asia now rival those of counterparts in the U.S. and Europe, according to Ernst & Young.[57]
- The Chinese government is channeling significant resources into developing an innovative edge in biotechnology and genomic sequencing. China's embrace of new gene-editing technology such as CRISPR may help them become more competitive in agricultural research, warns the U.S.-China Economic and Security Review Commission.[58]
- Notably, China has caught up to the U.S. in total number of biotechnology and applied microbiology research publications (see **GRAPH 5.25**). China is also aggressively recruiting overseas scientists and entrepreneurs, particularly in the biotech sector, through its so-called 'Thousand Talents Plan.'[59]

GRAPH 5.25
Biotechnology & Applied Microbiology Publications
by Selected Country, 2000-2016

- USA
- China
- UK
- Germany
- Japan
- India



Source: Thomson Reuters InCites Database

U.S. Industrial Base Faces Critical Challenges

A DOD report [60], recently commissioned by Executive Order No. 13806, finds that the U.S. manufacturing and defense industrial base is facing unprecedented risks and vulnerabilities. This includes dependence on competitor nations, workforce issues, and offshoring. Compounding the problem is budget sequestration and uncertainty of U.S. government funding, exacerbated by the decade-long reliance on congressional continuing resolutions. Other factors include the decline of domestic manufacturing capabilities and supply chain weaknesses; deleterious government procurement practices; aggressive industrial policies of other countries; and diminishing U.S. STEM skills.

“All facets of the manufacturing and defense industrial base are currently under threat, at a time when strategic competitors and revisionist powers appear to be growing in strength and capability.”

China poses a significant and growing risk to U.S. economic and national security, according to the report. Of utmost concern is China’s dominance in the supply of rare earth metals and a number of critical materials used in munitions and missiles. China’s R&D spending has nearly caught up with the U.S., with Chinese investments targeted at emerging areas such as artificial intelligence, robotics, and gene editing.

The report recommends the creation of a National Advanced Manufacturing Strategy by the White House Office of Science and Technology Policy. Additionally, the report urges greater workforce development efforts to grow domestic STEM and critical trade skills. And importantly, increased near-term DOD budget stability, building on recent bipartisan budget deals.

Conclusion

The benchmarks in this report illustrate that while the U.S. continues to lead the world in constant dollars invested in overall R&D, other countries, such as China, are on a pace to catch up and soon surpass us (see **GRAPH 1.2** on page 10). And by numerous other measures, America's leadership among its global competitors in research and technology is not being sustained. Given that federal investments have a direct impact on future economic growth, prosperity, and national security, increasing the current level of investment in the U.S. research enterprise is critical to ensuring that our nation remains the global innovation leader.

Our nation's technological dominance is at stake as China and other countries are greatly accelerating their investments in R&D, thereby accelerating innovation. With stagnant and declining federal investment in scientific research, the U.S. risks losing its footing as the leader in critical research fields, including AI, aerospace, advanced manufacturing, and telecommunications. Given that scientific research produces critical knowledge that spurs innovation, drives economic growth, enhances national security and increases global influence, the United States' declining investments relative to the rest of the developed world creates openings for other countries to set standards and to dominate future global technological markets. Being the first to make scientific discoveries empowers the U.S. to be the first to innovate and bring new technologies to market. This is how America has been - and how it can continue to be - the leader in global innovation and continue to enjoy the economic and national security benefits that come with such preeminence.

Countries around the world are investing in innovation and building their STEM workforce. This focus on education is an additional threat to the U.S. research enterprise, as foreign countries continue to improve the quality of their universities and as competition for attracting international talent is rapidly increasing.

The strength of our distinctive partnership among the federal government, universities, and the private sector has allowed the U.S. to outpace the world in discovery and innovation, attract top talent, and spark sustained growth in an economy increasingly dependent upon the generation of new knowledge and ideas. This report, however, indicates that American leadership in science, technology and innovation is now being challenged. It is time to redouble our commitment to science and technology, and to strengthen and reinvigorate the unique partnership that has made the U.S. a global innovation powerhouse.

References

1 Bell, Alex; Chetty, Raj; Jaravel, Xavier; Petkova, Neviana; Van Reenen, John, "Who Becomes an Inventor in America? The Importance of Exposure to Innovation," The Equality of Opportunity Project, Harvard University (November 2018). Available at www.equality-of-opportunity.org/assets/documents/inventors_paper.pdf

2 "Glossary of Statistical Terms - Researchers," *OECD,* last modified June 11, 2013. Available at stats.oecd.org/glossary/detail.asp?ID=2318.

3 Rothwell, Jonathan, "Defining Skilled Technical Work," *National Academies Board on Science, Technology, and Economic Policy* (2015). Available at sites.nationalacademies.org/cs/groups/pgasite/documents/webpage/pga_167744.pdf.

4 National Security Strategy of the United States of America, December 2017. Available at www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf

5 National Security Strategy of the United States of America, December 2017. Available at www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf

6 Reif, Rafael, "China's Challenge is America's Opportunity." New York Times. Aug 8, 2018. Available at www.nytimes.com/2018/08/08/opinion/china-technology-trade-united-states.html

7 Hourihan, Matt. "If Government Scales Back Technology Research, Should We Expect Industry to Step In?" *American Association for the Advancement of Science*, October 16, 2017. Available at www.aaas.org/news/new-brief-could-industry-fill-gaps-following-federal-rd-cuts

8 Toole, Andrew A. "Does Public Scientific Research Complement Private Investment in Research and Development in the Pharmaceutical Industry?" *The Journal of Law and Economics*, 50, no. 1 (2007); Li, Azoulay, and Sampat."The applied value of public investments in biomedical research," *Science*, 356 (2017).

9 National Science Foundation, National Center for Science and Engineering Statistics, "National Patterns of R&D Resources: 2015–16 Data Update." Available at www.nsf.gov/statistics/2018/nsf18309/.

10 Russell J. Funk and Jason Owen-Smith, "A Dynamic Network Measure of Technological Change," *Management Science* 63, no. 3 (2017). Available at doi.org/10.1287/mnsc.2015.2366

11 Orszag, Peter R. "China is Overtaking the U.S. in Scientific Research," Bloomberg, September 12, 2018. Available at www.bloomberg.com/opinion/articles/2018-09-12/chinese-researchers-are-outperforming-americans-in-science.

12 This includes the 'UK Research Excellence Framework,' 'Excellence in Research for Australia,' and Canada's 'Networks of Centres of Excellence.'

13 Baker, Simon. "China on the Rise," *Inside Higher Ed*, July 11, 2018. Available at www.insidehighered.com/news/2018/07/19/china-may-overtake-us-research-impact-scholars-analysis-finds.

14 Source: Merrill, Stephen A. "Righting the Research Imbalance," The Center for Innovation Policy at Duke Law, 2018. Available at law.duke.edu/sites/default/files/centers/cip/CIP-White-Paper_Righting-the-Research-Imbalance.pdf.

15 Cary Funk and Lee Raine, "Public and Scientists' Views on Science and Society" January 29, 2015. Available at www.pewinternet.org/2015/01/29/public-and-scientists-views-on-science-and-society/

16 National Science Board. 2018. *Science and Engineering Indicators 2018 One Pager: Rise of China in Science and Engineering*. NSB-2018-2. Alexandria, VA: National Science Foundation. Available at nsf.gov/nsb/sei/one-pagers/China-2018.pdf

17 National Science Board. 2018. *Science and Engineering Indicators 2018, Chapter 2: Higher Education in Science and Engineering.* NSB-2018-2. Alexandria, VA: National Science Foundation. Available at www.nsf.gov/statistics/2018/nsb20181/report/sections/higher-education-in-science-and-engineering/undergraduate-education-enrollment-and-degrees-in-the-united-states

18 "2018 'Fast Facts'," IIE, November 2018. Available at www.iie.org/-/media/Files/Corporate/Open-Doors/Fast-Facts/Fast-Facts-2018.ashx?la=en&hash=E87E077CE69F84A65A9AA0B0960C2691E922835A.

19 Julie Baer, "Fall 2017 International Student Enrollment Hot Topics Survey," IIE, November 2017. Available at www.iie.org/-/media/Files/Corporate/Open-Doors/Special-Reports/Fall-2017-Hot-Topics-Report.ashx?la=en&hash=9C21EEDC2F4EA4F2BB11F3B14E30106BCF87253C.

20 Canada Excellence Research Chairs, last modified November 29, 2012. Available at www.cerc.gc.ca/home-accueil-eng.aspx.

21 "Excellence Initiative (2005-2017)." *DFG - German Research Foundation*, last modified January 9, 2018. Available at www.dfg.de/en/research_funding/programmes/excellence_initiative/index.html.

22 Schiermeier, Quirin. "Academic Excellence: Golden Germany." *Nature,* no. 549, September 07, 2017: 119-121. Available at www.nature.com/nature/journal/v549/n7670/full/nj7670-119a.html.

23 "The Thousand Talents Plan," Available at www.1000plan.org/en/foreign.html.

24 Underrepresented minorities include blacks, Hispanics, and American Indians and Alaska Natives.

25 National Science Board. 2018. Science and Engineering Indicators 2018 Digest. NSB-2018-2. Alexandria, VA: National Science Foundation. Available at www.nsf.gov/statistics/2018/nsb20181/digest/sections/u-s-s-e-workforce-trends-and-composition

26 David Leonhardt, "Lost Einsteins: The Innovations We're Missing," *The New York Times,* Dec. 3, 2017. Available at www.nytimes.com/2017/12/03/opinion/lost-einsteins-innovation-inequality.html.

27 National Science Board. 2018. *Science and Engineering Indicators 2018 One Pager: Our Nation's Future Competitiveness relies on building a STEM - capable U.S. Workforce*. NSB-2018-7. Alexandria, VA: National Science Foundation. Available at www.nsf.gov/nsb/sei/companion-brief/NSB-2018-7.pdf

28 Rothwell, Jonathan, "Defined Skilled Technical Work." Sept 2015. National Academies Board on Science, Technology, and Economic Policy, Project on "The Supply Chain for Middle-Skilled Jobs: Education. Training and Certification Pathways." Available at sites.nationalacademies.org/cs/groups/pgasite/documents/webpage/pga_167744.pdf.

29 National Science Foundation, National Center for Science and Engineering Statistics. Sept 2015. "Immigrants' Growing Presence in the U.S. Science and Engineering Workforce: Education and Employment Characteristics in 2013." Available at www.nsf.gov/statistics/2015/nsf15328/nsf15328.pdf

30 "Top 500 List, 26th Edition, 32nd Edition, 36th Edition, 42nd Edition, 46th Edition, and 52nd Edition." Top 500. Nov 2005, Nov 2008, Nov 2010, 2013, 2015, 2018. Available at www.top500.org/lists/.

31 "Top 500 List, 36th Edition." Top500. November 2010. Available at www.top500.org/lists/2010/11/

32 Perry, James Richard. "The Future Is in Supercomputers." WhiteHouse.gov, May 3, 2018. Available at www.whitehouse.gov/articles/the-future-is-in-supercomputers/.

33 United States. Cong. House. Committee on Science, Space, and Technology. Hearing on Supercomputing and American Technology Leadership. Jan. 28, 2015. 114th Cong. 1st sess. Washington. (Statement of Lamar Smith, Representative of Texas).

34 Gerstner, Ed, Minghua Liu, Xiangyang Huang, Yingying Zhou, Zhiyong Tang, Zhiyong Tang, Shuxian Wu, et al. “Small Science in Big China: An Overview of the State of Chinese Nanoscience and Technology,” *Springer Nature*. Available at *media.springernature.com/full/springer-cms/rest/v1/content/15302926/data/v3.*

35 “2018 Facts & Figures: U.S. Aerospace & Defense,” Aerospace Industries Association, available at www.aia-aerospace.org/report/2018-facts-figures/

36 National Science Board. 2018. Science and Engineering Indicators 2018. NSB-2018-1. Alexandria, VA: National Science Foundation. Graph available at www.nsf.gov/statistics/2018/nsb20181/figures/fig06-13

37 National Science Board. 2018. Science and Engineering Indicators 2018. Chapter 6, “Global Trends in High-Technology Manufacturing Industries” NSB-2018-1. Alexandria, VA: National Science Foundation. www.nsf.gov/statistics/2018/nsb20181/report/sections/industry-technology-and-the-global-marketplace/patterns-and-trends-of-knowledge--and-technology-intensive-industries#global-trends-in-high-technology-manufacturing-industries

38 United States. Cong. Senate. Committee on Armed Services. Hearing on Department of Defense Budget Posture April 26, 2018. 115th Cong. 2nd sess. (Statement of James Mattis, Secretary of Defense). Available at www.armed-services.senate.gov/imo/media/doc/Mattis_04-26-18.pdf

39 Lei, Zhao. “Superfast aircraft test a ‘success’.” China Daily, August 6, 2018. Available at usa.chinadaily.com.cn/a/201808/06/WS5b6787b4a3100d951b8c8ae6.html

40 Trevithick, Joseph. “Russia Releases Videos Offering An Unprecedented Look At Its Six New Super Weapons.” The Drive, Time Inc., July 19, 2018. Available at www.thedrive.com/the-war-zone/22270/russia-releases-videos-offering-an-unprecedented-look-at-its-six-new-super-weapons

41 “Notes from the AI frontier: Modeling the impact of AI on the world economy,” McKinsey Global Institute, September 2018. Available at www.mckinsey.com/featured-insights/artificial-intelligence/notes-from-the-ai-frontier-modeling-the-impact-of-ai-on-the-world-economy

42 Yoav Shoham, Raymond Perrault, Erik Brynjolfsson, Jack Clark, James Manyika, Juan Carlos Niebles, Terah Lyons, John Etchemendy, Barbara Grosz and Zoe Bauer, “The AI Index 2018 Annual Report”, AI Index Steering Committee, Human-Centered AI Initiative, Stanford University, Stanford, CA, December 2018. Available at cdn.aiindex.org/2018/AI%20Index%202018%20Annual%20Report.pdf

43 Robles, Pablo. “China plans to be a world leader in Artificial Intelligence by 2030.” South China Morning Post, Oct 1, 2018. Available at multimedia.scmp.com/news/china/article/2166148/china-2025-artificial-intelligence/index.html

44 United States. Cong. Senate. Committee on Armed Services. Hearing on Department of Defense Budget Posture April 26, 2018. 115th Cong. 2nd sess. (Statement of James Mattis, Secretary of Defense). Available at www.armed-services.senate.gov/imo/media/doc/Mattis_04-26-18.pdf

45 Ignatius, David, “China’s application of AI should be a Sputnik moment for the U.S. But will it be?” Washington Post. November 6, 2018. Available at www.washingtonpost.com/opinions/chinas-application-of-ai-should-be-a-sputnik-moment-for-the-us-but-will-it-be/2018/11/06/69132de4-e204-11e8-b759-3d88a5ce9e19_story.html?utm_term=.6e085cc947d1

46 Segan, Sascha. “What is 5G?” PC Magazine. Dec 14 2018. Available at www.pcmag.com/article/345387/what-is-5g

47 Segan, Sascha. “What is 5G?” PC Magazine. Dec 14 2018. Available at www.pcmag.com/article/345387/what-is-5g

48 Tom Wheeler, “The real 5G ‘race’ is to serve all Americans.” Brookings Institution. Available at www.brookings.edu/blog/techtank/2018/09/25/the-real-5g-race-is-to-serve-all-americans/

49 Pai, Ajit. “5G is in reach. But only if we set the right policies.” The Washington Post. September 26, 2018. Available at www.washingtonpost.com/opinions/5g-is-in-reach-but-only-if-we-set-the-right-policies/2018/09/26/9d5c322e-c1c7-11e8-8f06-009b39c3f6dd_story.html?utm_term=.3202903de6eb

50 Abecassis, David, Nickerson, Chris, and Stewart, Janette. “Global Race to 5G – Spectrum and Infrastructure Plans and Priorities.” April 2018. Available at api.ctia.org/wp-content/uploads/2018/04/Analysys-Mason-Global-Race-To-5G_2018.pdf

51 Morris, Iain. “Huawei Dwarfs Ericsson, Nokia on R&D Spend in 2017.” Light Reading. April 3 2018. Available at www.lightreading.com/artificial-intelligence-machine-learning/huawei-dwarfs-ericsson-nokia-on-randd-spend-in-2017/d/d-id/741944

52 Morris, Iain. “Huawei Dwarfs Ericsson, Nokia on R&D Spend in 2017.” Light Reading. April 3 2018. Available at www.lightreading.com/artificial-intelligence-machine-learning/huawei-dwarfs-ericsson-nokia-on-randd-spend-in-2017/d/d-id/741944

53 Nicol Turner Lee, “Will the US be 5G ready?” Brookings Institution. Available at www.brookings.edu/blog/techtank/2018/07/13/will-the-us-be-5g-ready/

54 Woo, Stu. “Why Being First in 5G Matters.” The Wall Street Journal. September 12, 2018. Available at www.wsj.com/articles/why-being-first-in-5g-matters-1536804360

55 FY 2020 Administration Research and Development Budget Priorities. July 31, 2018. Available at www.whitehouse.gov/wp-content/uploads/2018/07/M-18-22.pdf

56 The FCC’s 5G FAST Plan. Available at docs.fcc.gov/public/attachments/DOC-354326A1.pdf

57 Ernst & Young, LLP. “Beyond Borders: Biotechnology Report 2017.” Available at www.ey.com/Publication/vwLUAssets/ey-biotechnology-report-2017-beyond-borders-staying-the-course/$FILE/ey-biotechnology-report-2017-beyond-borders-staying-the-course.pdf.

58 United States. U.S.-China Economic and Security Review Commission. USCC 2018 Annual Report. Washington: U.S. G.P.O., 2018. Available at www.uscc.gov/Annual_Reports/2018-annual-report.

59 Ellis, Shannon, “Biotech Booms in China,” Nature, January 17, 2018. Available at www.nature.com/articles/d41586-018-00542-3.

60 Source: United States. Department of Defense. Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States. September 2018. Available at media.defense.gov/2018/Oct/05/2002048904/-1/-1/1/ASSESSING-AND-STRENGTHENING-THE-MANUFACTURING-AND%20DEFENSE-INDUSTRIAL-BASE-AND-SUPPLY-CHAIN-RESILIENCY.PDF.

61 Hélène Dernis and Mosahid Khan, «Triadic Patent Families Methodology», OECD Science, Technology and Industry Working Papers, No. 2004/02 (2004). Available at doi.org/10.1787/443844125004.

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CGS COUNCIL OF GRADUATE SCHOOLS

CRA Computing Research Association

Crop Science SOCIETY OF AMERICA

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IEEE USA

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