AMERICAN ACADEMY
OF ARTS & SCIENCES

America and the **International Future of Science**

A REPORT FROM THE **CHALLENGES FOR INTERNATIONAL SCIENTIFIC PARTNERSHIPS INITIATIVE**

> "Science is a field which grows continuously with ever expanding frontiers. Further, it is truly international in scope. Any particular advance has been preceded by the contributions of those from many lands who have set firm foundations for further developments. . . . Further, science is a collaborative effort. The combined results of several people working together is often much more effective than could be that of an individual scientist working alone.
>
> *— John Bardeen, speech at Nobel Prize Banquet, December 10, 1972*

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AMERICAN ACADEMY OF ARTS & SCIENCES
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Artistic view of the Brout-Englert-Higgs Field by Daniel Dominguez. © 2013 by CERN.

The views expressed in this report are those held by the contributors and are not necessarily those of the Officers and Members of the American Academy of Arts and Sciences.

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From the President of the American Academy

America and the International Future of Science, a report from the American Academy's multiyear initiative Challenges for International Scientific Partnerships (CISP), arrives during one of the most turbulent times for international scientific engagement in U.S. history. Its lessons are timely and vital for scientific leaders and policy-makers now and in the years to come.

As this report goes to press, a viral pandemic continues to sweep across the globe. COVID-19 has already killed over a million people worldwide, including more than two hundred fifty thousand Americans, and has devastated individual livelihoods and national economies. This crisis has prompted unprecedented levels of international collaboration between U.S. scientists and researchers abroad as they race to discover cures and therapies. Yet it has also been met with a counterproductive government response that has diminished U.S. standing in the international scientific community and reduced our capacity to combat the disease.

At the same time, long-standing political and economic tensions between the United States and China have escalated and threaten to damage bilateral scientific cooperation. China is our largest scientific collaborator; while national security and intellectual property interests warrant safeguards, unnecessarily hampering this scientific relationship through extreme constraints on collaboration directly threatens the success of the American R&D enterprise and, thereby, the nation.

The same is true of efforts to severely curb immigration of people eager to pursue their scientific dreams and make their discoveries in American universities and laboratories or in collaboration with American scientists. Recent announcements of extreme visa restrictions for international students, postdoctoral fellows, and other researchers threaten to deal a devastating blow to American science for years to come.

This project directly addresses timely issues such as these, alongside a longer-term analysis of the challenges and benefits associated with international scientific partnerships. CISP was established in 2017 under the initiative of then Academy President Jonathan F. Fanton. Since then, the project has worked to examine impediments to international collaboration and identify policy changes and best practices to make the United States a better partner in such relationships, especially in large-scale ventures and in collaborations with emerging science partners, topics that will be explored in greater detail in subsequent project reports.

This work was made possible by the dedicated and thoughtful leadership of the CISP initiative. The Academy would like to express deep gratitude to Cochairs **Arthur Bienenstock**, Professor Emeritus of Photon Science, Special Assistant to the President for Federal Research Policy, and Associate Director of the Wallenberg Research Link at Stanford University, and **Peter Michelson**, Luke Blossom Professor in the School of Humanities and Sciences, Professor of Physics, and Senior Associate Dean for the Natural Sciences at Stanford University.

The wisdom and guidance of the CISP Steering Committee and the CISP working groups on Large-Scale Science and Emerging Science Partners were crucial for the development of this report (see Appendix). We are particularly appreciative of the leadership and insight provided by **Shirley Malcom**, Senior Advisor and Director of SEA Change at the American Association for the Advancement of Science, and **Olufunmilayo Olopade**, Walter L. Palmer Distinguished Service Professor in the Biological Sciences Division, Professor of Medicine & Human Genetics, and Associate Dean for Global Health at The University of Chicago, who cochaired the working group on Emerging Science Partners.

We are grateful for the support of many Academy Fellows in the development of this project, especially members of the Academy's Board of Directors, Council, and Trust. We are further appreciative of the Alfred P. Sloan, William and Flora Hewlett, and Gordon and Betty Moore Foundations for their financial support of this initiative.

Thanks as well to the members of the Academy staff who worked to prepare this report: Amanda Vernon, Rebecca Tiernan, Tania Munz, John Randell, Gregory Savageau, Rainer Assé, Erica Kimmerling, Phyllis Bendell, Peter Walton, Heather Struntz, and Scott Raymond.

I join with the contributors to this report to call for its arguments and recommendations to be carefully considered by America's leaders in government, industry, academia, and the nonprofit sector. Our country is strengthened by our engagement with international scientific colleagues, across all disciplines and at all scales, to meet the global challenges that face us.

Sincerely,
David W. Oxtoby
President, American Academy of Arts and Sciences

Project **Takeaways**

Challenges for International Scientific Partnerships (CISP) is an American Academy initiative to identify the benefits of international collaboration and recommend actions to be taken to address the most pressing challenges facing these partnerships. This project has concluded that:

1. The United States should support and expand international scientific collaborations, including with nations with which the United States has strained relations, such as China. Any restrictions on international collaborations involving federally supported research should be well-justified and carefully and narrowly defined.

- Participation in international scientific collaborations is beneficial not only for U.S. science, but for the United States overall.
    - International scientific collaborations complement and contribute to a strong domestic R&D enterprise and strengthen U.S. economic competitiveness and national security.
    - To perform state-of-the-art science and address global challenges effectively, U.S. scientists must continue to engage with the global scientific community.

2. International large-scale scientific endeavors are an important component of our nation's overall science and technology enterprise. The United States must be prepared to participate in international large-scale science partnerships and work to ensure their success, including contributing support for operations outside the United States.[1]

- Some future large-scale science endeavors will be on a global scale and will necessarily involve international cooperation, with some international efforts and facilities sited outside of the United States but requiring U.S. support.
- Large-scale research instrumentation and facilities are essential for scientific advancement across a variety of disciplines and will become increasingly difficult for the United States to fund unilaterally.

3. Emerging science partners around the world are and will continue to be important scientific collaborators. The United States should support and partner with them in scientific research.[2]

- Scientific talent arises across the globe at an increasing rate as many countries invest in building a more robust S&T enterprise.
- Many of the most pressing scientific questions are not defined by national boundaries and require global collaboration for advancement.

Prologue

Challenges for International Scientific Partnerships (CISP) is an American Academy initiative to identify the benefits of international scientific collaboration and recommend actions to be taken to address the most pressing challenges facing these partnerships. Funded by the Alfred P. Sloan, William and Flora Hewlett, and Gordon and Betty Moore Foundations, CISP makes policy recommendations and seeks to identify best practices to mitigate challenges for international science collaborations in all disciplines, including physical facilities, distributed networks, and peer-to-peer partnerships. The project, cochaired by **Arthur Bienenstock** (Stanford University) and **Peter Michelson** (Stanford University), includes three primary components, of which this report is the first.

The Large-Scale Science (LSS) working group approaches international collaborations through the lens of issues particular to large-scale science, and not peer-to-peer or small-scale international work. This group explores how the United States can enhance its role in these partnerships, both in physical facilities (like the European Organization for Nuclear Research) and distributed networks (like the Human Cell Atlas). The group is focusing on recommendations that will bolster U.S. ability to partake in large-scale collaboration efforts as meaningful and engaged partners. The LSS working group is cochaired by **Arthur Bienenstock** and **Peter Michelson**.

The Emerging Science Partners (ESP) working group explores issues particular to U.S. scientific collaborations, at all scales, with countries seeking to boost their scientific capacity, particularly those with limited resources to do so. This working group discusses the importance of these collaborations to the United States and how the United States can be a better partner with emerging science partner countries, including efforts to increase equity in these collaborations. The ESP working group is cochaired by **Olufunmilayo Olopade** (University of Chicago) and **Shirley Malcom** (American Association for the Advancement of Science).

This report, *America and the International Future of Science*, bridges these two working groups to identify and describe the value of international scientific collaboration. Both working groups will publish their own more targeted reports with associated recommendations and examples of best practices in early 2021.

Executive **Summary**

While many U.S. policies and practices related to international scientific cooperation originated in the decades following World War II when U.S. R&D spending eclipsed that of all other nations, that spending now constitutes only about one-quarter of global R&D expenditures. As global R&D investments and international scientific talent have increased, U.S. scientists are increasingly conducting research with international collaborators.

The American Academy of Arts and Sciences undertook the Challenges for International Scientific Partnerships (CISP) initiative to assess both the importance and the challenges of international scientific collaborations to the United States through a series of workshops held between 2018 and 2020 with scientists, science administrators, and policy-makers in the United States and around the world. The CISP project began well before the onset of the COVID-19 pandemic that has swept across the globe and continues to devastate individuals and societies as this report goes to print. The challenge of the pandemic has reinforced the CISP study's principal conclusion that the benefits of international scientific collaboration for the United States and the world are substantial and growing and far outweigh the risks they can present. Those risks, particularly to U.S. national security, must be carefully managed while recognizing there are also benefits from scientific collaboration with potential adversaries and countries with which the United States has strained relations. For this reason, the CISP project recognizes that the topic of U.S. collaboration with China merits special attention.

The CISP initiative identifies six primary factors that underlie the imperative for the United States to continue and to strengthen its investments and participation in international scientific collaboration. These factors are:

1. The Global Nature of Scientific Questions: Advancing Knowledge Often Requires International Engagement

Both fundamental questions and those related to broad societal problems are not defined by national boundaries, and progress often requires data and expertise from more than one country. Addressing complex problems frequently involves people with different capabilities, perspectives, and access to resources. Forming teams with the best skills to address a research challenge increasingly draws on international collaborators. Examples range from imaging a massive black hole at the center of a galaxy to addressing the threats of pandemics and climate change.

2. Leveraging International Talent: Sustaining A Strong STEM Workforce

To maintain leadership in fundamental research, it is essential that the United States continue to have an academic education and research system that is open, strong, and attractive and welcoming to international students, many of whom choose to remain in the United States and become citizens.

3. U.S. Economic Competitiveness: Strengthening America and Boosting Prosperity

The core of the U.S. R&D enterprise is fundamental research. It is a source of discovery and new knowledge, critical to innovation and the development of new technology. Increasingly, fundamental research is performed globally; in 1960, U.S. federal funding represented 45 percent of all global R&D, while today, it accounts for less than 10 percent. The United States, its companies, and its scientists must engage with the broader scientific community if America is to be among the world leaders across all scientific fields and benefit economically from the dividends of scientific research conducted both nationally and internationally.

4. U.S. National Security: Bolstering Security with Knowledgeable Engagement and Science Diplomacy

We are living now in a world in which scientific breakthroughs that lead to technological leadership, military strength, and the ability to face and mitigate destructive natural phenomena are increasingly likely to occur in other countries, some of which are potential adversaries to the United States. In the broad area of fundamental research that is openly publishable, it is vital that the United States maintain a robust scientific and technological community that is both producing many of the breakthroughs and is in a position to learn of, and take advantage of, the advances that occur outside its borders. The United States must work with allies and adversaries alike to counter the global phenomena that threaten all nations. Healthy scientific cooperation, including mutual participation in large international scientific facilities and programs, helps to build trust and should be encouraged. Scientific partnerships can be an important element of foreign policy and international relationships. Problems that impact the world, like environmental degradation, climate change, and pandemics, necessitate such cooperation. The United States has the opportunity to play a global leadership role that will benefit humankind. In doing so, the United States must look not only to those nations that are presently strong, but also to those in the Global South that are emerging as scientific partners.

5. Funding Realities: Requirements for Successful Participation in Large-Scale Science

Large-scale scientific facilities used by American scientists have become increasingly expensive and are most often built by the U.S. federal government and, in some cases, with significant contributions from international partners. International collaboration has been recognized as a major opportunity to sustain U.S. excellence in many fields, effectively leveraging the financial investment in scientific research made by the United States and working with scientific expertise from around the world. Without support and commitment to collaboration from the U.S. government, future U.S. scientists may be excluded from some of the world's leading scientific projects and associated technological advances, especially as multinational funders promote increasingly large international projects. The United States must participate in these advances and be prepared strategically to commit to collaboration

> Now and in the years ahead, we need, more than anything else, the honest and uncompromising common sense of science. Science means a method of thought. That method is characterized by open-mindedness, honesty, perseverance, and, above all, by an unflinching passion for knowledge and truth. When more of the peoples of the world have learned the ways of thought of the scientist, we shall have better reason to expect lasting peace and a fuller life for all.
>
> *— Harry S. Truman, 1948*

on the funding, planning, development, and operation of new large-scale scientific research capabilities at home and abroad.

6. Contributing to Development and Application of Ethical Norms and Scientific Guidelines

The United States must be engaged in the development of global ethical frameworks and guidelines for research. As discoveries and technological capacities increase, ethical questions are becoming more complex, especially when accounting for the range of ethical and cultural norms within the international community and considering shifting societal contexts. Collaborators must also develop norms for the ethical scientific conduct within partnerships, such as protocols for sample and data collection, appropriate attribution and assignment of credit, and ownership of samples and intellectual property. The Asilomar Conference on Recombinant DNA is an important example of how the codevelopment of ethical norms and guidelines promoted international peace and security, as the United States and other countries adopted the safety guidelines and recommendations produced as a way to protect their populations while still furthering the science.

Introduction

In the 1980s, physicists from around the world gathered at the European Organization for Nuclear Research (CERN), a particle physics laboratory in Switzerland, to develop and run experiments using the shared facility's accelerators.[3] However, their scientific progress was impeded by a logistical challenge: how could experimental information be widely shared across the international scientific community? In 1989, Tim Berners-Lee, a software engineer working at CERN, proposed a solution involving three Internet software technologies he had developed—HTML, URL, and HTTP—which, in 1990, would provide the foundation for the World Wide Web.[4]

Scientific fundamental research, technology development, and technological innovation are essential drivers of economic growth and prosperity, both at home and abroad. For the United States to continue to act as a global economic, security, and scientific leader, it must conduct and invest in the most advanced scientific research across many disciplines. To perform such research requires that scientists and engineers be increasingly involved in collaborations: the vast majority of scientific publications have multiple authors.[5]

International scientific collaborations have been an important element of the U.S. research and development (R&D) enterprise for decades, and U.S. scientific research is increasingly conducted with international collaborators. Since 2004, the number of international scientific research collaborations globally has tripled.[6] Now, in an era of strong growth in the global R&D sector and an unavoidable diminishing U.S. share of global R&D expenditures, international scientific engagement across all disciplines and at all scales is essential. This need has been recognized by the researchers themselves.[7] It must also be considered an ongoing strategic national priority and incorporated into U.S. planning and policy.

The fraction of the articles published by U.S. scientists and engineers that are coauthored with scientists from an international institution has increased rapidly since 1996 (Figure 1). This trend reflects the fact that a growing share of global R&D funds is spent outside the United States, thereby rapidly expanding and strengthening the international scientific community. For much of the latter half of the twentieth century, the United States was the world's major R&D funder; today, the U.S. share of global R&D is estimated to have fallen to 28 percent, nearly entirely due to increases in spending in other countries.[8] Today, many countries, including South Korea, Israel, Japan, and Austria, spend a greater percentage of their national GDP on R&D investment than the United States, and China is approaching U.S. overall R&D spending levels when adjusted for purchasing power parity.[9] Manufacturing, chemicals, pharmaceuticals, and information technology sectors are among the top recipients of global R&D

investment, and e-commerce, cloud services, and medical equipment are among the sectors with the highest rates of R&D growth.[10]

As global investments in science have increased, international collaboration has risen as well: from 2000 to 2015, the percent of scientific publications worldwide produced by authors from two or more countries doubled from 10.7 percent to 21.3 percent.[11] Further, this international collaboration strengthens the impact of scientific research; as one marker of this feature, U.S. science publications involving international collaborators rank considerably higher than all other U.S. science publications in field-weighted citation impact (FWCI) analyses, in some cases nearly doubling the average FWCI of publications with only collaborators from the same country.[12]

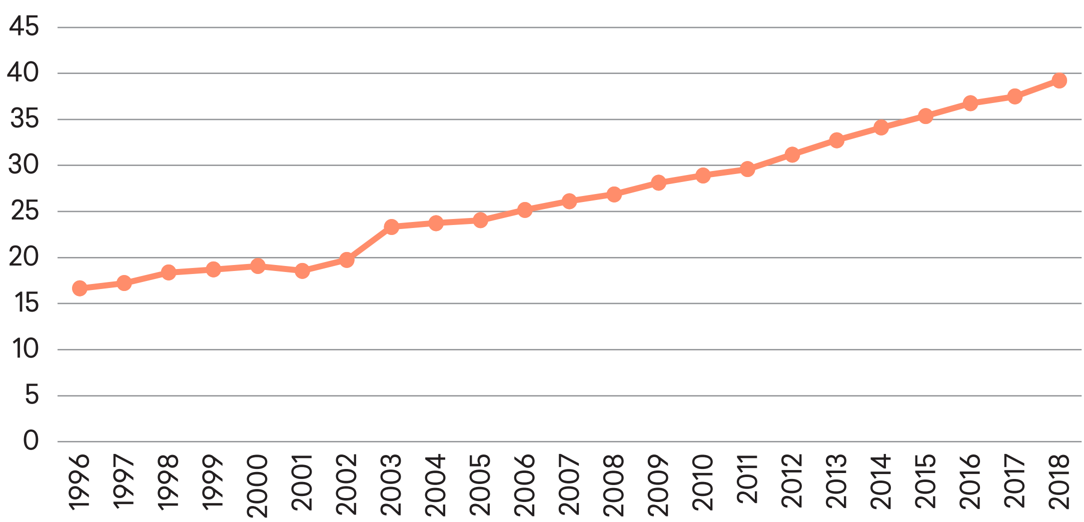
American scientists across disciplines seek the best collaborators for their projects, and those partners are increasingly located in foreign countries. For American scientists to collaborate effectively with scientists around the world and to maximize the benefits of international collaborations for the United States, the U.S. government must be strongly committed to fostering, supporting, and strengthening international scientific partnerships.

Defining International Scientific Partnerships

International scientific partnerships can take many forms. Collaborations take place at all scales, from a peer-to-peer collaboration between scientists in Ames, Iowa, and Nairobi, Kenya, to a large-scale scientific user facility in Switzerland enabling discoveries by thousands

Figure 1

Percent of U.S. Science and Engineering Articles Coauthored with Scientists at International Institutions



Source: National Science Board, *Publications Output: U.S. Trends and International Comparisons* (Alexandria, Va.: National Science Foundation, 2019).

In 2003, then UN Secretary General Kofi Annan sends the first message from a CERN server to students participating in the UN-sponsored World Summit on the Information Society in Geneva. © Jean-Philippe Ksiazek/Getty Images.

of participating U.S. and international scientists. International collaborations also span all scientific disciplines and approaches, such as in fundamental research, technology development, and technological innovation.

Some of these efforts are quantifiable and formal, such as research collaborations that lead to publications with coauthors from institutions in different countries. Others are more informal, such as when two graduate students from separate nations meet at a scientific conference, bond over their common scientific pursuits, and return to their home labs with fresh research ideas. These collaborations can range from very small scale, when an individual researcher deposits data into an internationally supported database, to very large scale, when thousands of researchers in a consortium tackle a major scientific challenge. This report takes a broad view of international scientific partnerships, on all scales and levels of formality, and identifies elements that are integral to successful collaboration.

Imperatives for International Collaborations

The American Academy's initiative on Challenges for International Scientific Partnerships has identified six primary factors that underlie the imperative for the United States to continue and strengthen its investments and participation in international collaboration: 1) the global nature of scientific questions; 2) competition for global talent; 3) U.S. economic competitiveness; 4) U.S. national security; 5) funding realities, particularly for large-scale science projects; and 6) the development and application of international ethical norms and scientific guidelines. The following sections address each of these imperatives in turn.

The Global Nature of Scientific Questions: Advancing Knowledge Often Requires International Engagement

Scientific questions, both fundamental and those related to broad societal problems, are not defined by national boundaries, and progress often requires data and expertise from more than one country.

Large-scale scientific projects and technically complex distributed projects are often required to pursue fundamental questions about the universe. To take one clear-cut recent example, to generate an image of a black hole, astronomers relied on globally distributed telescope facilities (See Einstein's Universe: Exploring Spacetime).[13]

Likewise, the nature of some scientific questions is so complex that expertise across multiple domains and locations is often needed. The study of migratory species often requires knowledge from morphology, data science, environmental field work, and molecular biology, among other areas; it also tends to cross borders and necessitates the cooperation and collaboration of multiple nations. Infectious diseases such as COVID-19, Ebola, and Zika can begin in one country but rapidly spread across national borders, necessitating collaboration between researchers based in different countries (see A Persistent Global Challenge: The Threat of

Einstein's Universe: Exploring Spacetime

The quest to understand our universe and its governing laws is as old as civilization itself. It drives the development of new technologies and in turn enables breakthrough discoveries. And this global pursuit has increasingly required international collaboration.

The Laser Interferometer Gravitational-Wave Observatory (LIGO), for example, was developed in the United States with the support of the U.S. National Science Foundation (NSF) over several decades.[19] LIGO was designed "to open the field of gravitational-wave astrophysics through the direct detection of gravitational waves predicted by Einstein's General Theory of Relativity."[20] In the process, it has led to development opportunities and numerous U.S. patents on technologies that span quantum science, cryogenics, and materials science. Yet LIGO is not merely a U.S. project. The LIGO Scientific Collaboration (LSC) carries out the science of LIGO: detector operations, data analysis, and the development of new techniques and future gravitational wave detectors. The LSC comprises over one thousand collaborators from more than one hundred institutions in eighteen countries.[21]

On September 14, 2015, the LIGO detectors in Louisiana and Washington made the first observation of a burst of gravitational

Pandemics on pages 9–10).[14] And predictions of hurricane trajectories that steer our national preparations incorporate observations and data from as far away as the Ethiopian highlands.[15]

Peer-to-peer collaborations at the scientific grassroots level are also strengthened by global collaboration and vice versa. Dementia affects an estimated fifty million people around the world, and high-impact studies are published worldwide that, in combination, are speeding progress toward preventing and curing this terrible human affliction.[16] As one example of this effort, the National Institutes of Health (NIH), especially through the National Institute on Aging and the Fogarty International Institute, has developed several international initiatives, including worldwide genomic studies and efforts to use big data to treat and prevent Alzheimer's disease.[17]

International peer-to-peer collaborations often result from and rely on the development of different capabilities in different countries. China has established a major program in the development and refinement of advanced materials and can claim leadership in some specialties.[18] The United States has outstanding capabilities for fundamental experimental and theoretical studies of these advanced materials. The frequent collaborations of Chinese materials synthesizers with U.S. materials physicists have advanced both understanding and sophisticated applications like quantum computing and quantum information.

In these and other examples, the United States benefits from international collaboration and global data collected and analyzed in partnership with other countries. To effectively advance scientific knowledge and solve the world's greatest challenges, U.S. scientists must work with their global colleagues, building upon a rich history of U.S. participation in international collaborations and foreign talent coming to the United States (see Preventing Death: Developing a Rotavirus Vaccine on page 8).

waves produced by the coalescence of two black holes; this discovery came nearly one hundred years after Albert Einstein published his general theory of relativity that predicted the existence of both black holes and of gravitational waves: ripples in the fabric of space and time.[22] It took 1.3 billion years for the waves to arrive and be detected at LIGO. The 2017 Nobel Prize in Physics was subsequently awarded to physicists Rainer Weiss, Barry C. Barish, and Kip S. Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves."[23]

This historic event was only the first of many observations of the most violent events in our universe made through this unique window. On August 17, 2017, LIGO and its European counterpart, Virgo, detected a gravitational wave chirp from the collision of two neutron stars: very compact dead stars, each with a mass slightly greater than the Sun but barely twenty kilometers in diameter.[24] Such an event, finally observed, had been anticipated for decades. International coordination and open communication between LIGO and Virgo were key to the determination of the source's direction. This was vital for enabling the rapid follow-up observations by more than seventy radio, optical, and X-ray telescopes. Indeed, just 1.74 seconds after the gravity wave chirp, the NASA-led Fermi Gamma-Ray Space Telescope, itself an international collaboration also supported by the

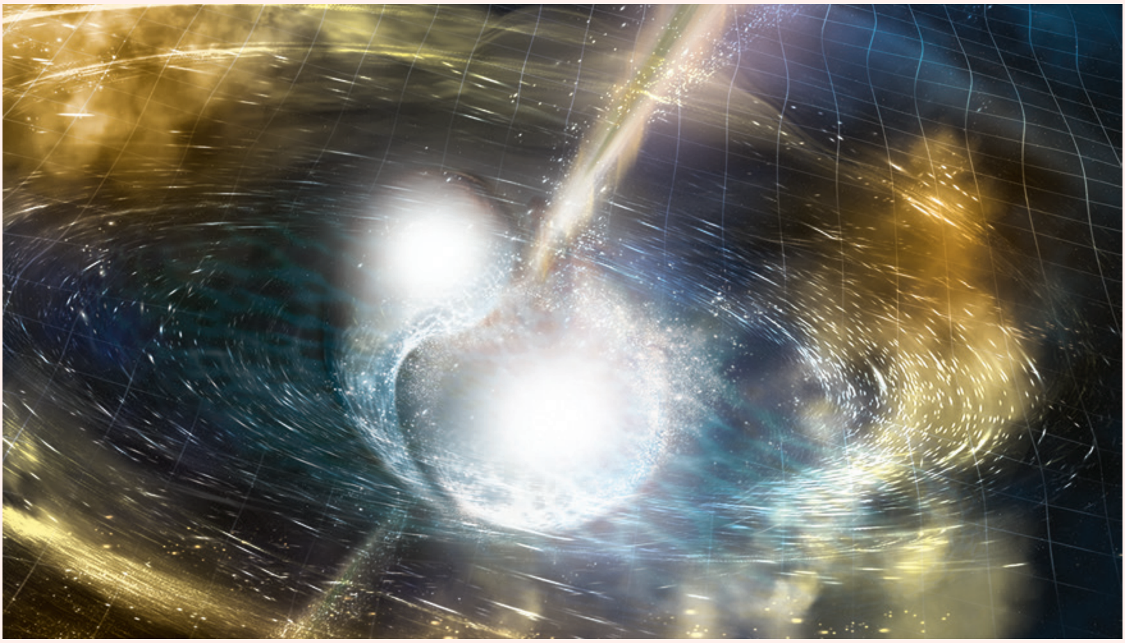
continued on next page

U.S. Department of Energy (DOE), detected a gamma-ray burst from the same direction.[25] The pulse of gamma-rays was likely radiated by a powerful jet of very energetic particles that emerged from the coalescence event as a black hole formed.

What was learned? Not only did the observations of this event solve a decades-old mystery about the origin of very short duration gamma-ray bursts, the optical telescope observations of the afterglow spectrum revealed that the merger event also produced heavy elements, notably gold and platinum. The amount of gold produced in that one merger was about equal to the mass of Earth. This confirmed a long-standing, but unproven, theoretical speculation that neutron-star mergers are the main source of heavy elements in the universe. The results were published in a series of papers, with over three thousand authors from thirty-five countries on every continent except Antarctica.[26]

On a related front, a U.S.-led international collaboration of radio astronomers and computer scientists accomplished what was once thought to be impossible: imaging the event horizon of a black hole or, more precisely, imaging the hot gas from the surrounding region as it falls into the black hole, and capturing, for the first time, the silhouette of the actual black hole.[27] Working for more than a decade, the team developed the Event

Gravitational Waves Erupt from Two Colliding Neutron Stars



Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Illustration by Aurore Simonnet. Image courtesy of National Science Foundation, Laser Interferometer Gravitational-Wave Observatory, and Sonoma State University.

First Image of a Black Hole at the Center of Galaxy M87

The Event Horizon Telescope utilized radio telescopes positioned across continents to capture the first image of a black hole, a supermassive black hole at the center of Galaxy M87. Image courtesy of the Event Horizon Telescope Collaboration.

Horizon Telescope (EHT) by extending a technique known as Very Long Baseline Interferometry (VLBI) to an intercontinental scale. The EHT utilizes an array of radio telescopes on several continents that are precisely synchronized using the Global Positioning System to create an aperture comparable to the size of Earth. Thirteen partner institutions worked together to create the EHT, using both pre-existing infrastructure and support from a variety of agencies. Key funding was provided by the U.S. National Science Foundation (NSF), the European Research Council (ERC), and several funding agencies in East Asia.[28] European facilities played a crucial role in this worldwide effort, with the participation of advanced European telescopes.[29] In addition to $1 billion in funding for foundational investigators, teams, and U.S. research facilities that are part of the network of the EHT, the NSF awarded $28 million over nineteen years to the EHT directly.[30]

On April 10, 2019, the EHT collaboration, with more than two hundred members from fifty-nine institutes in twenty countries, released the first image of the black hole at the center of Galaxy M87.[31] Using EHT observations, the collaboration determined the black hole's mass to be equal to 6.5 billion Suns. This finding also made the M87 black hole an important test case for other methods of estimating the masses of supermassive black holes.[32]

An important lesson learned from these scientific breakthroughs is that they were only possible because of sustained international collaborations. Future discoveries and enhanced capabilities will likewise depend on such collaboration. In this regard, it is notable that the Kamioka Gravitational Wave Detector (KAGRA), Japan's gravitational wave observatory and the newest addition to the worldwide gravitational wave network, became operational on March 3, 2020.

Preventing Death: Developing a Rotavirus Vaccine

Rotavirus is a universal childhood infection that, prior to the introduction of a safe and effective vaccine in 2006, resulted in the hospitalization of 55,000 to 70,000 children in the United States annually. As the most common cause of diarrhea in infants and children worldwide, the rotavirus remains responsible for more than 215,000 infant and child deaths every year.[33] Today, a range of vaccines is available for prevention of rotavirus-induced diarrhea; one of these is currently widely used in India, where nearly one-third of all babies in the world are born. This vaccine was developed from a collaboration between Indian scientists and researchers at the NIH.

Following World War II, India owed the United States for a series of loans made during the war. One mechanism for repayment was to fund grants to U.S. scientists collaborating with Indian scientists, who were supported by the Government of India. Two of these grants were awarded to Maharaj Kishan Bhan, an Indian gastroenterologist and researcher at the All India Institute of Medical Sciences who formed a collaboration with Roger Glass at the NIH, and to Durga Rao, a researcher at the Indian Institute of Science in Bangalore who collaborated with Harry Greenberg at Stanford University, to develop a vaccine for rotavirus.[34] Their research, which ultimately selected the candidate studied by Bhan and Glass, led to the development of a Phase I rotavirus vaccine, which was safety-tested in the United States before wider Phase II and III trials in India. Rao and Greenberg continued to work in collaboration with Bhan and Glass and a new Indian company, Bharat Biotech, as they moved from the basics of virology to real-world development.

Given the high poverty rates in India, it was important to manufacture a vaccine that was readily accessible to the Indian population. The Bill & Melinda Gates Foundation was essential in bringing in funding to launch this Indian initiative.[35] A major challenge undertaken in this collaboration was to create capacity at Bharat Biotech to manufacture the rotavirus vaccine for broad deployment in India.

Bhan was able to bring in the support of the Indian government, while Glass represented the Centers for Disease Control and Prevention (CDC). Eventually, the Bill & Melinda Gates Foundation negotiated a price of one dollar per dose, and the vaccine developed from this collaboration has since become the default treatment for India's poor. It has prevented the deaths of tens of thousands of babies.

Due to this collaboration, capacity and expertise in virus manufacturing grew substantially at Bharat Biotech, which has since expanded to develop Typhoid fever, rabies, and hepatitis vaccines, and is currently working to develop a COVID-19 vaccine. Today, most measles vaccines in the world are manufactured in India thanks to expanding scientific capacity.

A Persistent Global Challenge: The Threat of Pandemics

In December 2019, doctors in Hubei Province, China, documented the emergence of a new respiratory disease, now termed COVID-19. The virus soon made its way across the globe, with the World Health Organization (WHO) declaring a public health emergency of international concern on January 30, 2020, and a pandemic on March 11, 2020.[36] COVID-19 is forcing shelter-in-place orders across nations, dismantling societal norms, shaking global economies, and prompting economic contraction and job loss not seen in the United States since the Great Depression.[37]

Scientists often collaborate with international colleagues to face challenges to global health, including the threat of pandemics. To successfully fight the SARS epidemic in China in 2003, an international response coordinated by the WHO developed a network of thirteen laboratories in ten countries, including the United States, that worked together to characterize the SARS agent and develop a diagnostic test.[38] The resulting infrastructure was instrumental in implementing a rapid response in China to COVID-19.[39]

Ebola, a highly contagious zoonotic disease spread through person-to-person contact that emerged in West Africa, was difficult to contain due to a lack of infrastructure, limited medical capacity, and high levels of poverty and mistrust.[40] Scientists and medical professionals around the world worked together to increase testing capacity, and contributions from African diaspora populations in the United States, the United Kingdom, and elsewhere were instrumental in securing further institutional support for providing expertise and assisting communities in confronting the disease.[41] Nigeria, Senegal, and Mali received strong praise from the WHO for their vigorous response and success in containing the outbreak in 2014.[42] The lasting infrastructure and capacity for pandemic preparedness, while challenging to maintain, has been essential for facing new health threats, including COVID-19; the international community can learn from their successes.[43]

Infectious diseases like COVID-19, SARS, and Ebola are not constrained by national borders, and pose a threat to all people.[44] As the COVID-19 pandemic ravages the planet, scientists around the globe are collaborating at unprecedented levels with their international colleagues to better understand the virus, SARS-CoV-2, and the disease it causes and to develop treatments and vaccines (Figure 2).[45] These efforts have allowed natural and social science communities to rapidly gain information about the virus to widen our understanding of its transmission and possible treatments and vaccines.

U.S. scientists' enthusiasm for international collaboration stood in contrast to the U.S. federal government response, which, among other actions, announced an intention to formally withdraw funding and terminate its relationship with the WHO as of July 6, 2021.[46] Despite this disengagement, U.S. collaboration with both well-established scientific powerhouses and emerging scientific partners continues to be critical for developing mitigation and treatment strategies for COVID-19.[47]

COVID-19 has impacted international scientific partnerships beyond scientists working directly to fight the pandemic. Some disruptions, such as increased use of virtual platforms, have presented opportunities for collaborators that expand accessibility

continued on next page

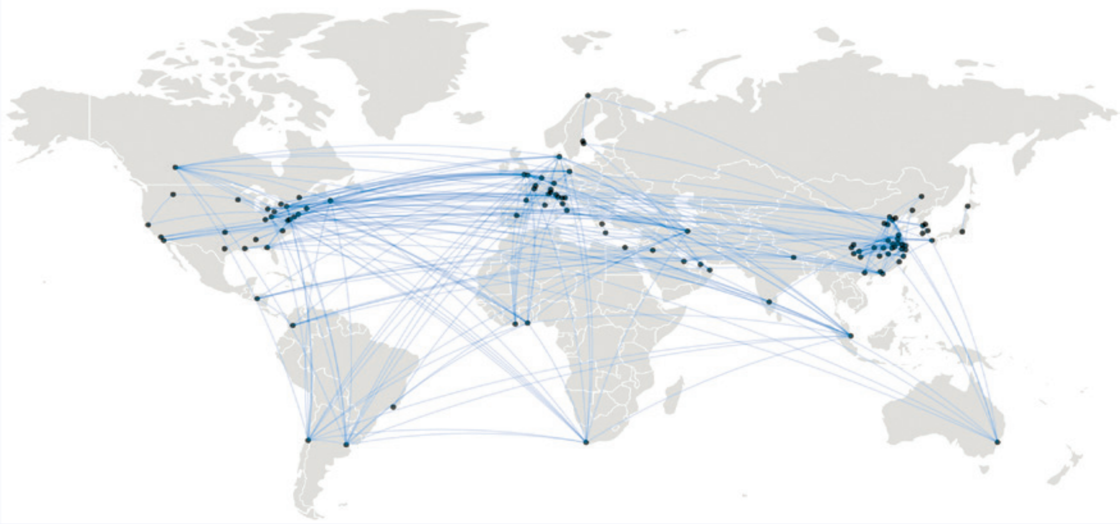
across time zones and continents. Other aspects have been major obstacles for scientific collaboration. The pandemic has disrupted travel, supply chains, scientific conferences, and daily scientific operations as researchers work to adapt their projects to this new context. In the medium to long term, economic downturns may pose a major threat to funding for international scientific projects.

COVID-19 has also brought the debate regarding the need for openness and transparency in science to the surface. China was criticized for its delay in releasing information about virus emergence, though it was also praised for quickly publishing the viral genome to an open access forum.[48] Researchers from around the world have made use of shared genomic information, learning more about the virus and developing new treatments and vaccines.[49] However, despite an increase in data sharing, "vaccine nationalism" is gaining traction, increasing tensions between the United States and China.[50] This nationalism could inhibit efforts by Gavi, the Vaccine Alliance, and the WHO to coordinate an equitable global vaccine campaign as governments, including the United States, Russia, and China, refuse to take part.[51] To address a global problem like COVID-19 rapidly and in a coordinated manner, nations must commit to science, transparency, and cooperation.[52]

As the global pandemic unfolds, with disproportionate effects across nations and populations, it is difficult to predict long-term effects on international scientific collaboration. Policy-makers must ensure that partnerships are supported as the global crisis evolves, and future collaborations should be designed with resiliency in mind for when the next pandemic arises.

Figure 2

Map of International Collaborations on COVID-19 in Scientific Literature as of April 2020



Map of international scientific collaboration on COVID-19 indexed in Scopus on April 7, 2020.
Source: Marion Maisonobe and Netscity.

Leveraging International Talent:
Sustaining a Strong STEM Workforce

The pool of top scientific talent is increasingly international and mobile. More countries are expanding their educational capacities and investing in their research communities, and talented young scientists are pursuing their education in research institutions around the world.

The United States does not have a monopoly on facilities, talent, or thought leadership, and "bottom-up" research activities are an essential component of U.S. participation in international collaborations. As the entire globe invests in training scientists and developing scientific capacity, it has become imperative for the United States to support its scientists who participate in international collaborations, just as it is valuable for researchers at any one U.S. institution to collaborate with talented researchers at other U.S. sites.[53]

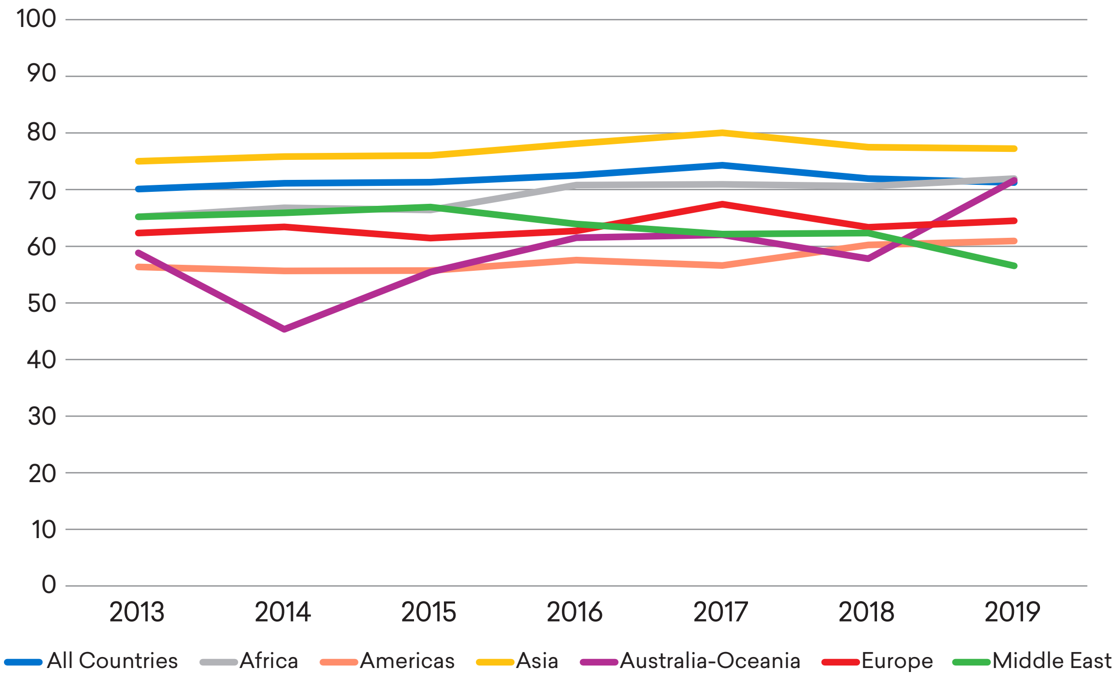
Supporting diverse entry points into international collaborations, including participation in international research conferences and connections between organizations such as the InterAcademy Partnership and the Global Young Academy, is important for building a strong and inclusive scientific collaboration ecosystem.[54] The Human Cell Atlas, a grassroots collaboration of networks of scientists interested in cellular functions, is an important example of the wealth of the world's scientific talent working in collaboration (see Human Cell Atlas: Making a Map of the Building Blocks of Life on pages 13–14).

For a variety of reasons, the number of U.S. citizens and permanent residents who participate in the nation's STEM workforce is insufficient to meet the nation's needs.[55] While an overall boost in participation is needed, particular efforts must be made to support the participation of groups who are notably underrepresented and have significant potential to contribute to the U.S. science and engineering (S&E) workforce. In 2017, women accounted for just 29 percent of all S&E employment, though their representation varies widely across fields. Underrepresented minorities, including individuals who are Black, Hispanic, or American Indian and Alaskan Native, make up 28.1 percent of the U.S. population, but only 13.3 percent of the S&E workforce.[56] While the myriad factors contributing to this underrepresentation are now more widely recognized and addressed, such as through the National Academies of Sciences, Engineering, and Medicine reports on sexual harassment in 2018 and minority serving institutions in 2019,[57] significant work must still be done to overcome the barriers preventing so many in the United States from participating in the S&E workforce.

Unless the nation addresses the many barriers to that participation successfully, we are likely to continue to be strongly dependent on international talent. At the same time, welcoming international students, researchers, engineers, and entrepreneurs to the United States has long been an essential mechanism for the United States to maintain its scientific leadership, and

Figure 3

Percent of International Doctorate Recipients Who Intended to Stay in the United States after Completion of their Degree, 2013–2019



Data include doctorates in science and engineering as well as the humanities and education. The numbers of humanities and education doctorates awarded to temporary visa holders are typically less than 10 percent of the total. **Source:** National Center for Science and Engineering Statistics, Survey of Earned Doctorates, https://ncses.nsf.gov/pubs/nsf21308/data-tables.

this strategy has been very successful in allowing the United States to gain access to global talent. In 2017, 42 percent of U.S. S&E faculty were foreign born.[58] Since 2000, 38 percent of the American awardees of the Nobel Prize in Physics, Medicine, or Chemistry were immigrants.[59] Fifty-five percent of U.S. startup companies valued over $1 billion in 2018 were founded by immigrants, many of whom first came to the United States as science and engineering students.[60] An openness to accepting immigrants and welcoming them into U.S. society has been a major reason for the success of the U.S. S&E enterprise, both in academia and industry. Increasing foreign graduate student admissions, for example, has been linked to increases in U.S. patent applications and patent grants earned by universities and commercial firms alike.[61] It is essential that the United States continue to have an academic education and research system that is open, strong, and attractive and welcoming to international students, many of whom choose to remain in the United States and become citizens. As of 2019, 71.2 percent of all temporary visa-holding doctoral students intended to stay in the United States following the receipt of their doctorate (Figure 3).[62]

Human Cell Atlas:
Making a Map of the Building Blocks of Life

The human body contains an estimated thirty-seven trillion human cells whose properties give rise to all human tissues and organs.[63] Over the past ten years, cellular biology and sequencing technology advances have unlocked a new world of scientific exploration of individual cells and the ways their functions affect human health, including the discovery of new cell types that may reveal the secrets of diseases (see New Human Cell Type below).[64] Cellular biologists are working to capitalize on fundamental research to develop precision medicines, especially for treatment of cancers.[65]

The Human Cell Atlas (HCA) works to generate a comprehensive map of the types and properties of all human cells, building a unified platform for global scientific participation. By working at large scales with

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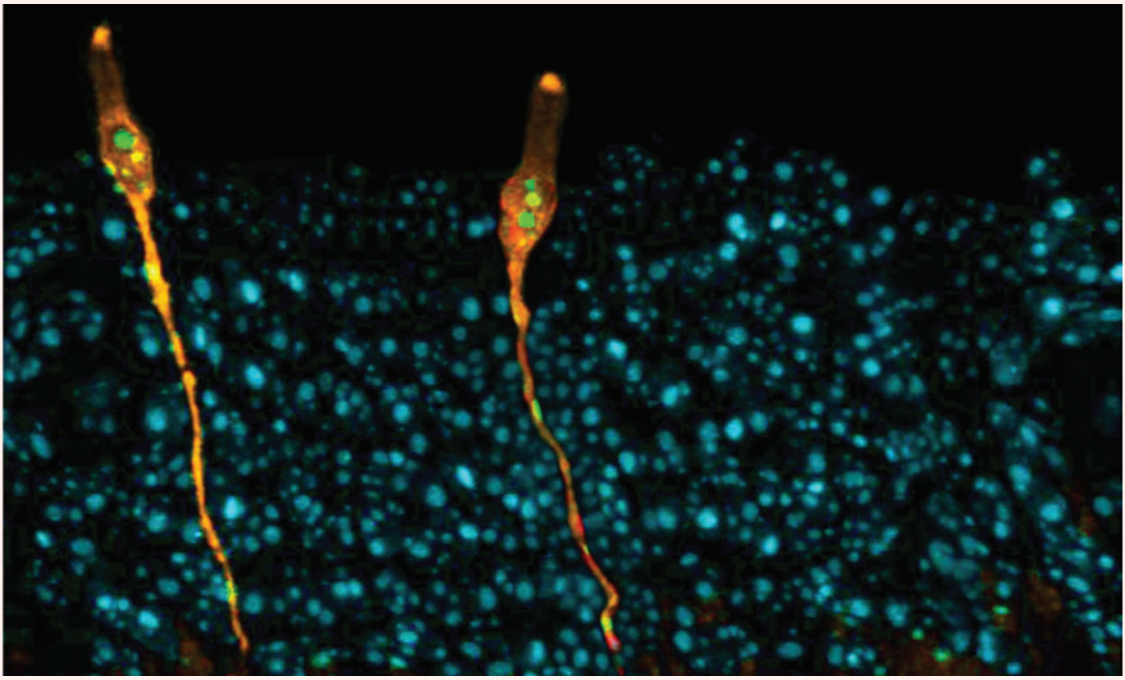
New Human Cell Type Identified in Respiratory Tract

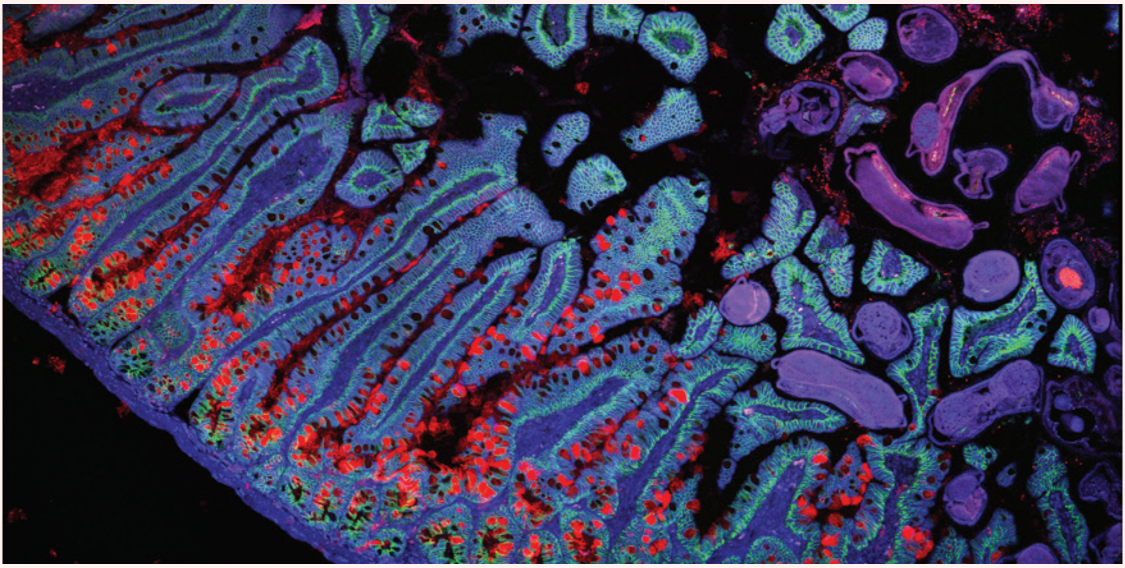


Human Cell Atlas scientists identified an exceedingly rare cell type in the lining of the respiratory tract that had been previously overlooked. Current evidence suggests that this shy cell type may be key to understanding remaining mysteries in cystic fibrosis disease pathology, and is an intriguing target for new therapeutic development. Image by Daniel T. Montoro; image adjustment by Anna Hupalowska. See Daniel T. Montoro, Adam L. Haber, Moshe Biton, et al., "A Revised Airway Epithelial Hierarchy Includes CFTR-Expressing Ionocytes," *Nature* 560 (7718) (2018): 319–324. © Montoro et al./*Nature*/Broad Institute.

hundreds of scientists, the collaboration can achieve major research milestones, including mapping over one million immune cells from human white blood cells, bone marrow, and umbilical cord blood.[66]

Any researcher in the world can become an HCA member by joining the HCA member registry and agreeing to abide by the HCA white paper principles, including a commitment to transparency and data sharing, to open collaboration, and to diversity, equity, and inclusion.[67] Related scientific projects throughout the globe can be listed in the HCA project registry, enabling consistent information release and standards among researchers working in varied international contexts. To date, the project has over two thousand members in over one thousand institutes across more than seventy countries, and it works to incorporate studies from scientists in both well-established and emerging scientific partnerships.[68]

The HCA was started by Aviv Regev and Sarah Teichmann, individual scientists in the field working across national boundaries who developed and agreed upon project goals. Since then, it has grown considerably and attracted significant funding, including a recent $68 million award from the Chan Zuckerberg Initiative, a £6.7 million investment from the United Kingdom Research and Innovation's Medical Research Council, and €4.9 million in grant awards from the European Union's Community Research and Development Information Service.[69] The initiative's bottom-up approach has allowed for a variety of funding and talent sources across the world to contribute to the project as it grew into the established effort it is today. As support for the HCA from entities in the United States and around the world builds, so too does its potential to yield life-saving health discoveries.



Scientists affiliated with the Human Cell Atlas are working to understand the human small intestine—both its healthy functions and in disease states such as Crohn's Disease. © Grace Burgin, Noga Rogel, and Moshe Biton, Klarman Cell Observatory, Broad Institute. Dr. Moshe Biton is now affiliated with the Weizmann Institute of Science, Israel.

U.S. Economic Competitiveness:

Strengthening America and Boosting Prosperity

Economists generally agree that advancements in knowledge, largely based on scientific and technological innovation, are responsible for approximately half of advanced economies' long-term economic growth, a consensus that has historically led to long-standing bipartisan support for U.S. federal funding of fundamental scientific research.[70] Economic growth results from investments in R&D along many paths and across several key sectors.

Scientific research can grow American prosperity by raising the quality of life. Fundamental research and development have resulted in dramatically improved public health, generating many vaccines and new treatments for cancer and heart disease. American life expectancy grew from forty-five to seventy-two years between 1870 and 1970 due in part to medical advances such as these, albeit with unequal distribution of the benefits.[71] American farmers and the American people alike have benefited from a massive increase in agricultural output from farm equipment technologies and bioengineering approaches, although the use of newly developed chemical fertilizers and pesticides have also had negative impacts on the environment and human health.[72] In the past century, international collaborations on agricultural and food sciences have saved millions of people around the world from starvation; with food security as a major global threat in the decades to come, continuing research in these areas is important for supporting both American and global well-being and prosperity (see International Rice Research Institute: Agricultural Research for Global Food Security on pages 16–17). Science has fostered innovations such as modern electronics, cancer radiation therapies, and the Internet. The scientific advancements that improve Americans' quality of life, many of which have been developed by or in collaboration with international researchers, can be produced with greater benefits if the United States commits to supporting scientific endeavors, including those that strengthen international scientific collaborations.

Private industry directly capitalizes on scientific research, generating wealth as small businesses and large companies alike develop and sell technologies that emerge from cutting-edge science. The global biotechnology market, to name one example, is projected to grow at a compound annual growth rate of 9.9 percent and be worth more than $775 billion by 2024 as biotechnology companies continue to develop clinical and other research programs (see Spinal Muscular Atrophy: Developing Treatments for Childhood Disease on page 18).[73]

Companies that perform R&D, including multinational companies based in the United States, have widely recognized the advantages of operating internationally. These multinational companies are an essential component of the private U.S. R&D enterprise. An NSF analysis found that U.S.-based multinational companies performed $197 billion, or 71 percent, of all U.S.-located business R&D in 2010, employing an estimated 788,000 Americans representing over half of the U.S. business R&D workforce.[74] Foreign multinational companies employed an additional 155,000 U.S. R&D workers and conducted 14 percent of U.S. R&D.[75] Global operations, despite potential vulnerabilities to global supply chain disruptions and other challenges, are a key part of these job-generating companies' strategies.

Fundamental research is a major source of discovery and new knowledge, critical to the

International Rice Research Institute: Agricultural Research for Global Food Security

In the 1950s, following World War II, much of Asia was on the brink of famine as rice yields remained stagnant and insufficient to meet the population's needs. For many people in Asia, rice was, and continues to be, vital to survival, constituting up to 80 percent of caloric intake.

The Rockefeller and Ford Foundations joined forces to establish the International Rice Research Institute (IRRI) in 1960 housed on the University of the Philippines campus with support from the government of the Philippines.[77] The Institute assembled an international team of scientists to develop high-yielding rice crop varieties. After years of experimentation, IRRI announced in November 1966 the official release of IR8, a genetic cross between two strains of rice from Indonesia and China (see photo). [78] IR8 was planted on a farm in India in 1967 with tremendous success and quickly made its way to farms across the region and the world. More than fifty years later, IR8 continues to be celebrated for saving millions of lives from starvation, promoting economic prosperity for millions of farmers, and launching the first Green Revolution.[79] Today, IRRI continues its work as a member of CGIAR, a massive global partnership that uses scientific research to address challenges in the world's food system and promote well-being, health, and food security for people around the world.[80]

As the world's population continues to increase, food security will be a growing challenge to national and economic security that the United States will face.[81] The U.S. Department of Agriculture's Economic Research Service's 2020 *International Food Security Assessment* estimated 844,300,000 people across seventy-six low- and middle-income countries (LMICs), mostly in Africa, are food-insecure, an 11 percent increase from 2019 that can largely be attributed to the shock of COVID-19.[82] The *2020 Global Report on Food Crises* reported that 135,000,000 people were living in crisis or worse, with many living in war-torn or conflict-driven areas.[83] In the United States, 16.5 percent of households with children, the majority Black and Hispanic, reported being food insecure in June 2020; while these numbers are exacerbated by the COVID-19 pandemic, 11.1 percent of U.S. households reported experiencing food insecurity in 2018.[84]

To overcome these challenges, continued support of agricultural research endeavors is essential. Global efforts like CGIAR's development of new technology. Fundamental research is crucially dependent on U.S. government support of research at American universities, both for generating new knowledge and for training a robust STEM workforce. Increasingly, fundamental research is performed globally: in 1960, U.S. federal funding represented 45 percent of all global R&D; by 2016, that percentage had fallen to less than 10 percent.[76] In this context, the United States, its companies, and its scientists must engage with the broader scientific community if America is to be among the world leaders across all scientific fields and benefit economically from the dividends of scientific research conducted both nationally and internationally.

Genebank Platform, which houses more than seven hundred thousand genetic samples of plants and crops, provide opportunities for developing new types of resilient and high-yielding crops as environments change and biodiversity is lost.[85] Though in some cases controversial, researchers can also use genetic engineering to address nutritional deficits, such as through the cultivation of the genetically modified Golden Rice, which is biofortified with proVitamin A to reduce Vitamin A deficiency (VAD), a leading cause of preventable childhood blindness and increased risk of infection for over 190 million children worldwide.[86] Researchers can also use agricultural science to identify methods of growing crops more efficiently; for example, the international collaboration Realizing Increased Photosynthetic Efficiency (RIPE), based at the University of Illinois at Urbana-Champaign, seeks to increase crop production by improving the process of photosynthesis.[87]

Food security will continue to be a major global challenge amid many rising threats in the decades ahead, including increasing extreme weather events, desertification, sea level rise, biodiversity loss, and ecological disruption; increasing numbers of displaced peoples due to war, violent conflict, and those seeking environmental refuge; and the future pandemics to come.[88] International research efforts and collaborations hold significant potential for improving food quality and yield and for expanding food access in the face of these challenges.

IR8, a genetic cross between two strains of rice from Indonesia and China, was the first high-yielding rice variety successfully developed by IRRI after the collaboration's establishment in the 1960s. © IRRI/International Rice Research Institute.

Spinal Muscular Atrophy: Developing Treatments for Childhood Disease

Approximately one in fifty people, or six million Americans, are carriers of a defective gene that leads to spinal muscular atrophy (SMA).[89] This disease, which affects 1 in 6,000–10,000 infants and children, is a result of insufficient SMN protein and is marked by muscle weakness and loss of motor function; the most severe form, which is also the most common form, has an age of onset of younger than six months and is associated with a life expectancy of less than two years.[90] SMA is one of the most common of the so-called "rare" diseases and is the leading genetic cause of infant death.[91] It is estimated to affect 10,000–25,000 children per year in the United States alone.[92]

In late 2016, Spinraza, the first approved SMA drug, which directs the gene SMN2 to make a more functional form of the SMN protein, was released.[93] The story of its development is one of intensive collaboration among researchers worldwide, led by Adrian Krainer of Cold Spring Harbor Laboratory in New York.

Krainer was born in Uruguay and first came to the United States on a full scholarship to Columbia University as an undergraduate studying biochemistry.[94] He remained in the United States to complete his Ph.D. studies at Harvard University, where he first became interested in the topic of messenger RNA splicing, which underlies the mechanism of Spinraza.[95] He subsequently established a lab that studies splicing at Cold Spring Harbor Laboratory in New York, a U.S. research institute with a campus for scientific meetings that also offers courses in China.[96] Krainer recruited a diverse set of lab members, including Yimin Hua, a postdoctoral fellow who had received his Ph.D. from Sun Yat-sen University in China and worked on the topic of SMA at the Tufts Medical Center and University of Massachusetts Medical School. Hua's research ultimately made him the coinventor of Spinraza.[97]

Since its establishment over thirty years ago, Krainer's laboratory has collaborated broadly, both domestically and internationally, to advance the field's understanding of RNA splicing, SMA, and other topics. International collaborators have included scientists in Japan, Denmark, Spain, and Canada, among other countries.[98] In the mid-2000s, this body of work led to a close collaboration between Krainer and Ionis Pharmaceuticals, based in California, that ultimately led to the development and release of Spinraza.[99] Since its release, Spinraza has treated more than three thousand Americans and more than ten thousand patients worldwide, ranging in age from three days to eighty years.[100]

The success of Spinraza has also benefited the American private biotechnology sector. As one indicator of its financial value, Biogen, based in Cambridge, Massachusetts, paid Ionis $1 billion in 2018 to expand their industry collaboration and gain rights to license and sell therapies for neurological diseases, primarily due to the development of Spinraza. Global sales of Spinraza exceeded $2 billion in 2019.[101]

U.S. National Security:

Bolstering Security with Knowledgeable Engagement and Science Diplomacy

A robust scientific enterprise is essential if the United States is to enjoy technological leadership in the future. This leadership, coupled with a supportive, strong economy, has made it the most capable military power and provider of foreign assistance in the world.

Science contributes both to new technological capabilities and to innovations that fuel the economy generally. Science is the foundation, as well, of efforts to combat the two natural phenomena that most threaten the nation's security: global pandemics and global climate change.[102] The nation's position of strength is, however, threatened by a number of factors that include the rising scientific capabilities of other nations whose aggregate R&D expenditures presently dwarf those of the United States and the rising economic power of other nations increasing their ability to mount comparable military capabilities. The threat is compounded by the diminishing commitments of the U.S. federal government to R&D expenditures and diminishing state expenditures for public higher education of the S&T workforce, both of which are weakening, and will continue to weaken, our future scientific leadership.[103]

The adjustment to circumstances that are so different from those that prevailed following World War II, when the United States dominated science, trained outstanding scientists, engineers, and technicians, while also attracting superb talent from around the world, requires thoughtful policies and leadership. It is a world in which scientific breakthroughs that lead to technological leadership, military strength, and the ability to face and mitigate destructive natural phenomena are likely to occur in other countries, some of which are potential adversaries.[104] It is a world in which other countries will produce some of, and compete vigorously for, the best scientific and technological talent. What's more, the experiences of the last half-century, in which previously impoverished nations rose to scientific and technological prominence, have led us to expect that presently less-advanced nations will rise markedly in scientific stature and produce some of the future's most talented researchers.[105]

Under such circumstances, it is vital that the United States carefully define those S&T research areas in which classified national security information must be protected, even with the recognition that the lack of openness and broad cooperation is likely to slow progress.[106] Both where the research is performed and who performs it should be vetted. Most universities are not appropriate venues for such research. International collaboration should be controlled thoughtfully.

In the broad area of fundamental research that is openly publishable—the subject of this report—it is vital that the nation maintain a robust scientific and technological community that is producing many of the breakthroughs and is in a position to learn of, and take advantage of, the advances that occur outside its borders.[107] The United States must work with allies and adversaries alike to counter the global phenomena that threaten all nations. Finally, the United States must take strong measures to continue to attract talent from around the globe. It is in these endeavors that international scientific cooperation on fundamental research contributes to national security. As discussed in this report, collaboration tends to produce higher quality research. It helps to attract the best minds to the United States. It is vital that the government nurture, rather than inhibit, such collaboration. In doing so, the United States must look not only to those nations that are presently strong, but also to those in the Global South that are emerging as scientific partners.

A central component of national security policy in this new world is the necessity to maintain sufficiently good relations with potential adversaries so that mutually destructive military action never occurs. Healthy scientific cooperation with researchers in those countries, including mutual participation in large international scientific facilities and programs, helps to build trust and should be encouraged. Common problems like environmental degradation, climate change, and pandemics necessitate such cooperation. They offer the United States the opportunity to provide global leadership that will benefit humankind if our country decides to engage in such international efforts.[108]

In these troubled pandemic times, the thoughts shared by President Harry S. Truman in his address to the 1948 Centennial Anniversary Annual Meeting of the American Association for the Advancement of Science ring true:

> Now and in the years ahead, we need, more than anything else, the honest and uncompromising common sense of science. Science means a method of thought. That method is characterized by open-mindedness, honesty, perseverance, and, above all, by an unflinching passion for knowledge and truth. When more of the peoples of the world have learned the ways of thought of the scientist, we shall have better reason to expect lasting peace and a fuller life for all.[109]

Shared scientific values and a history of partnership can contribute to diplomatic efforts in many different regions of the world. As an example, Synchrotron-light for Experimental Science and Applications in the Middle East (SESAME) serves as one beacon of hope for scientific collaboration promoting peace in the region (see SESAME: Bringing Middle East Countries Together Through Science).

SESAME: Bringing Middle East Countries Together Through Science

Synchrotron-light for Experimental Science and Applications in the Middle East (SESAME) is a major regional international research laboratory based in Allan, Jordan. It provides a third-generation synchrotron light source and is intended to foster Middle East scientific excellence and build bridges across societies that are not political allies, hopefully contributing to a culture of peace through scientific collaboration.[110] The first synchrotron light source was officially inaugurated in 2017, with its first users hosted in 2018.[111]

SESAME was established in 2002 under the auspices of the United Nations Educational, Scientific and Cultural Organization (UNESCO) and counts Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, Palestine, and Turkey as its member states.[112] Its advisory committees include experts from synchrotron light sources in Canada, France, Italy, Japan, Spain, Sweden, Switzerland, the United Kingdom, and the United States. The International Atomic Energy Agency (IAEA) is also an observer on the SESAME council.[113]

SESAME has used the CERN Convention and other CERN protocols as a template for its development. Capital costs posed a major

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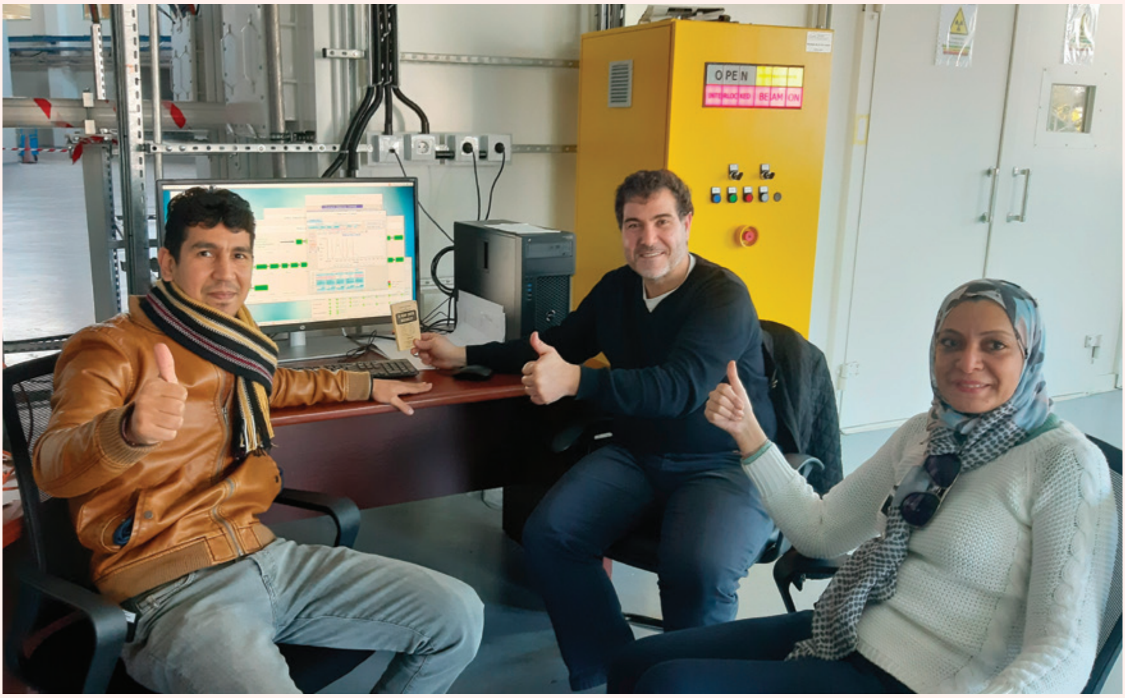
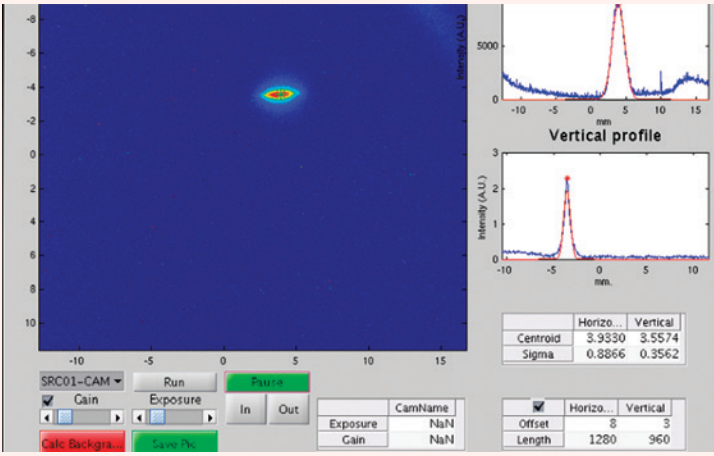
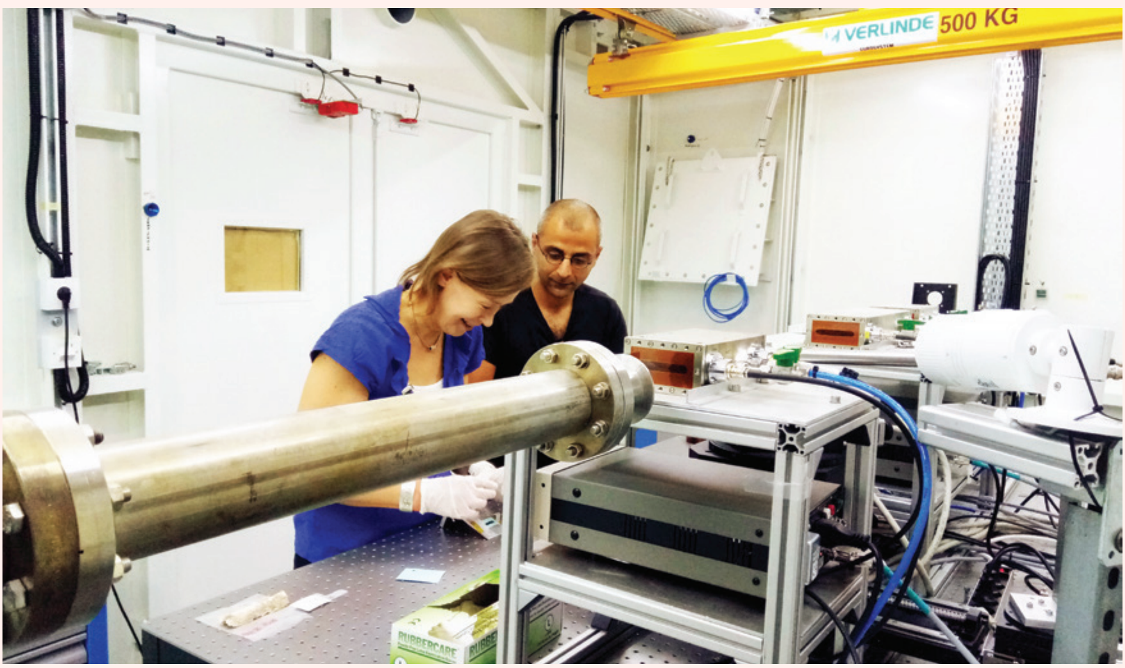


SESAME scientists just after obtaining the first monochromatic X-ray fluorescence signal on December 23, 2019 (from left to right: Mahmoud Abdellatief, MS beamline scientist, Messaoud Harfouche, XAFS/XRF beamline scientist, and Gihan Kamel, IR beamline scientist).
© 2019 by SESAME.

challenge early in its development until Israel, Jordan, and Turkey pledged $5 million each in 2012, followed by €5 million from CERN and €3.35 million from Italy.[114] Concerns about ongoing electrical power costs led to Jordan allocating the necessary $7 million from funds provided by the EU for a solar power plant to support the deployment of clean energy sources. In February 2019, the solar power plant made SESAME the first major research facility in the world to be powered by renewable energy.[115]



The bright red spot on this display shows the first electron beam circulating in a storage ring on January 12, 2017. © 2017 by SESAME.



Researchers from the Cyprus Institute (Kirsi Lorenz, left, and Iosif Hafez, right) performing XAFS and XRF measurements of archaeological human remains from Iran, the first to use dedicated beam-time at SESAME, on July 17, 2018. © 2018 by SESAME.

Funding Realities:

Requirements for Successful Participation in Large-Scale Science

Many fields of research—such as those seeking to fundamentally understand the universe, generate new forms of energy, or unlock the secrets of subatomic particles—require large, technologically advanced instruments and facilities that necessitate decades of planning and billions of dollars of support. In other fields, such as environmental and climate sciences, advanced sensory devices must be deployed and maintained in all corners of the world, requiring not only massive data storage and analysis capabilities, but also cooperation and coordination across countries and international waters. These megaprojects also often advance the frontiers of technology and expertise that can be applied to other fields, but they typically require both more funding than the United States is willing or able to provide alone and commitments of support over many years.

In the early 1900s, philanthropies and private institutions were key players in supporting major investments in the U.S. scientific enterprise. The Carnegie Institution and the Rockefeller Foundation provided support for the construction and operation of U.S. telescopes, including those at the Mount Wilson and Mount Palomar Observatories built in Southern California in 1904 and 1928, respectively.[116] The Rockefeller Foundation, along with academic institutions such as Tulane, Yale, and Johns Hopkins, contributed significantly to the establishment of the field of public health research as we know it today by funding medical and infectious disease research and establishing the International Health Division in 1913, a precursor to the World Health Organization.[117]

A policy framework for significant federal support of research across a wide range of scientific and technical disciplines began in 1945 when Vannevar Bush published *Science—The Endless Frontier*, which argued that scientific progress was in the national interest and merited federal funding, an argument that directly contributed to the establishment of the National Science Foundation in 1950.[118] Increasingly, government funding of science has become essential for the U.S. research enterprise.[119] The Atacama Large Millimeter/submillimeter Array (ALMA), which served as a critical part of the global array of telescopes that captured the first image of a black hole in 2019, cost $1.4 billion, $499 million of which came from the National Science Foundation.[120] The X-ray free electron laser at the SLAC National Accelerator Laboratory, which generates X-ray pulses a billion times brighter than previously available at synchrotrons, required the support of the U.S. government to achieve success. The first construction, completed in 2010, is estimated to cost $460 million, and the second upgrade, approved in 2016, is to cost $1 billion.[121] Since their construction, both megaprojects have been essential in their respective fields.

Today, large-scale scientific facilities used by American scientists have become increasingly expensive and are most often built by the U.S. federal government and, in some cases, with significant contributions from international partners and philanthropies.[122] In the realm of high-energy and nuclear physics, capital costs have risen. For the construction of the SLAC National Accelerator Laboratory, the costs were $115 million in the 1960s (approximately $950 million in 2020 USD). For

CERN: Seeking Answers to Fundamental Questions about Our Universe

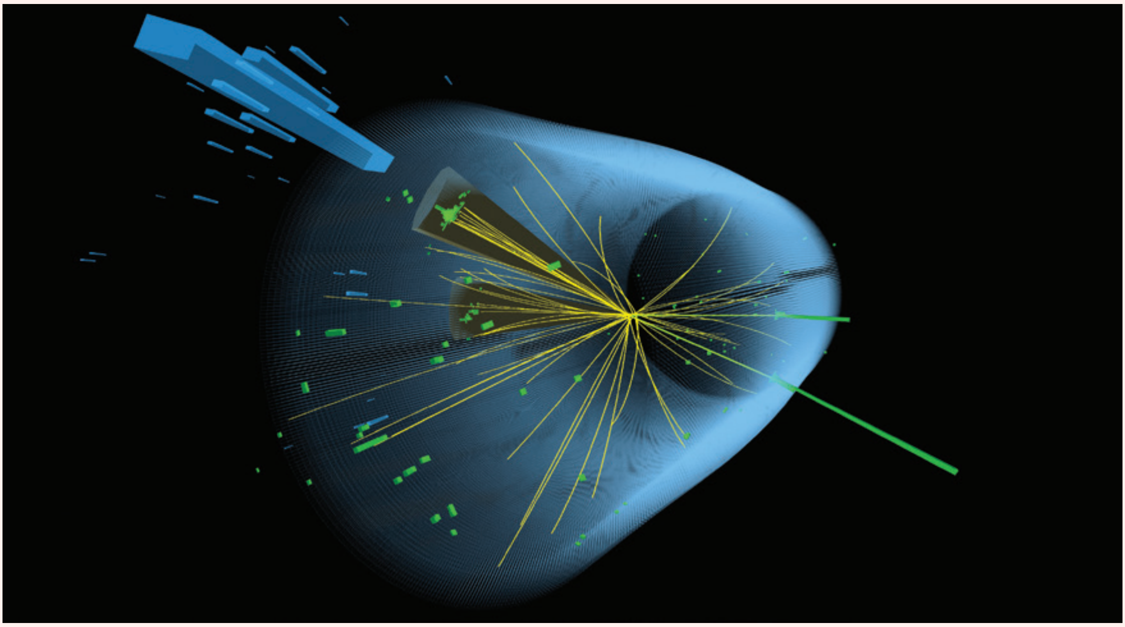
On July 4, 2012, the world learned of the first detection of the Higgs boson, the long-sought particle predicted by Peter Higgs in the 1960s and of central importance to the Standard Model on elementary particles. This discovery was among many made at CERN, based near Geneva, Switzerland, and home to the world's largest high-energy physics particle collider, the Large Hadron Collider. CERN is a collaboration of twenty-three European nations and Israel. The facility provides a platform for over twenty international

Scientists gathered at CERN to celebrate twenty-five years of collaboration on the CMS detector. The CMS Collaboration has members from more than forty countries. © 2017 by the European Organization for Nuclear Research, for the benefit of the CMS Collaboration.

the construction of the Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator, the costs were $4.75 billion in 2008 (approximately $6.7 billion in 2020 USD).[123] The LHC construction was undertaken by the European Organization for Nuclear Research (Conseil Européen pour la Recherche Nucléaire, or CERN), a research organization that sponsors and operates large particle physics instruments. To fund this major undertaking, CERN extended its funding partners to include non-European members, negotiating contributions from other nations including the United States (see CERN: Seeking Answers to Fundamental Questions about Our Universe). The United States was unlikely

experimental programs primarily through its two massive detectors, ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid), sited on the Large Hadron Collider, which circulates proton beams to facilitate research about elementary particles, the most fundamental constituents of matter.

While the United States is not a CERN member, it has made major contributions to the construction, operation, and upgrading of both ATLAS and CMS. Thirty-one U.S. institutions and universities with more than 2,100 users conduct research at CERN, which makes the United States the largest user community.[124] CERN is an excellent example of a facility in which partnership, not leadership, has benefited the United States and U.S. scientists.



Collision event at the Large Hadron Collider that produced jets of particles that very likely resulted from the decay of a Higgs Boson particle. © 2018 by the European Organization for Nuclear Research, for the benefit of the CMS Collaboration.

to have independently funded the construction ($4.75 billion) or the operating costs ($1 billion annually) of such a complex, high-energy instrument; in fact, the United States shut down its domestic Superconducting Super Collider project at 20 percent completion, with $2 billion already spent by the Department of Energy and the State of Texas, as management challenges emerged and estimated costs grew from $4.4 billion to $11 billion ($20 billion in 2020 USD).[125]

The next generation of large-scale facilities required to advance scientific discovery and enable development of cutting-edge technologies, such as space-based observatories, ground-based accelerators and ground-based telescopes, advanced light sources, and deep-ocean research, will cost more than any single country is likely to provide without direct ties to economic or national security interests. Given these costs, international collaborative funding appears to be the most likely path forward. However, it is unlikely that the United States would play a leadership role in all such endeavors. With the growth of international science, any of these projects may be championed and led by scientists and governments in other countries. The United States is currently participating in many collaborations that seek to push the frontiers of science, including the development of an interferometer in India to accompany the U.S., Italian, and Japanese detectors LIGO, Virgo, and KAGRA, respectively, to observe gravitational waves from four operational detectors at one time; and the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) initiative to unlock the mysteries and develop fundamental knowledge about the human brain. The CISP initiative's second report on international large-scale science discusses the future potential and importance of investing in such large-scale international scientific collaborations.[126]

International collaboration has been recognized as a major opportunity to sustain U.S. excellence in many fields, effectively leveraging the financial investment in scientific research made by the United States and working with scientific expertise from around the world. Without support and commitment to collaboration from the U.S. government, future U.S. scientists may be excluded from some of the world's leading scientific projects and associated technological advances, especially as multinational funders, including the EU and the International Science Council Global Forum of Funders, promote increasingly large international projects.[127]

The United States must participate in these advances and be prepared strategically to commit to collaboration on the funding, planning, development, and operation of new large-scale scientific research capabilities at home and abroad.

Contributing to Development and Application of Ethical Norms and Scientific Guidelines

Scientific research has often raised ethical questions and carries ethical obligations. Norms and guidelines, when developed for a global science effort, can have widespread implications. For the perspectives of U.S. scientists to be represented in the development of global ethical frameworks, it is important for the United States to actively participate in and promote international forums engaged in developing ethical guidelines for research.

The ethical questions that confront scientists are becoming increasingly complicated as technology advances. Developments and tools that have raised questions about ethical guidelines include rapid genetic sequencing and editing capabilities, the establishment of large biobanks, the use of comprehensive data sets that threaten personal anonymity, biases in machine learning technologies including facial recognition and predictive analytics, emerging neurotechnologies such as brain implants, and fast-moving cyber security research.[128] Ensuring ethical care of human subjects and biological samples such as human cells and tissue has proven especially difficult with the development of new technologies.

As discoveries and technological capacities increase, ethical questions are becoming more complex, especially when accounting for the range of ethical and cultural norms within the international community and considering shifting societal contexts, such as a history of colonialism or xenophobia. Collaborators must also develop norms for the ethical scientific conduct within partnerships, such as protocols for sample and data collection, appropriate attribution and assignment of credit, and ownership of samples and intellectual property.

The international community of scientists has an opportunity and a responsibility, in concert with individual nations' interests and guidelines, to develop and apply ethical norms as a globally connected community.[129] This approach has found some success in the past, for example through the Asilomar Conference on Recombinant DNA, which developed guidelines for ethical research in DNA manipulation (see Asilomar Conference on Recombinant DNA: Promoting Ethical and Safe Research on page 28).[130] The Asilomar Conference is also an important example of how the codevelopment of ethical norms and guidelines promoted international peace and security, as the United States and other countries adopted the safety guidelines and recommendations produced as a way to protect their populations while still furthering the science. Nascent efforts for international governance of emerging technologies like AI hope to achieve a similar goal.[131]

Asilomar Conference on Recombinant DNA: Promoting Ethical and Safe Research

The 1975 International Congress on Recombinant DNA Molecules, commonly referred to as the Asilomar Conference on Recombinant DNA after its host location, gathered molecular biologists from around the world to discuss potential risks of research that involved manipulation of DNA. It is an important example of U.S. leadership in the establishment of ethical guidelines for biological research.

In 1974, a group of U.S. scientists had called for a worldwide voluntary moratorium on some recombinant DNA experiments, fearing potential hazards to researchers, the public generally, and the environment.[132] Guidelines released by the NIH were subsequently voluntarily adopted worldwide in advance of the planned international conference to more carefully assess risks and appropriate experimental guidelines.[133] The Asilomar Conference welcomed scientists, government officials, journalists, and lawyers, and numbered approximately one hundred and forty participants engaged in heated debate over whether or not to lift the voluntary moratorium.[134]

The attendees worked to assess risks from minimal to high and match them to appropriate biohazard containment levels. Containment was discussed both in the form of biological barriers, such as those engineered into bacteria to prevent their broad transmissibility, as well as physical barriers, such as negative pressure laboratories.[135] Nobel Prize-winner Paul Berg, one of the Asilomar Conference conveners, found this conference helpful not only in determining safety protocols but also in gaining public trust in molecular biologists working with recombinant DNA.[136]

Similar models may continue to prove essential in establishing international ethical norms in biological research. In early 2019, an international group of scientists called for a global moratorium on using technologies such as CRISPR for clinical editing of human germlines and the creation of an international framework for future experiments.[137] To date, two international summits on the topic—organized by the National Academy of Sciences and National Academy of Medicine, the Chinese Academy of Sciences, and the Royal Society of the United Kingdom—have been held to contribute guidelines for future research, and the WHO has established an advisory committee on "developing global standards for governance and oversight of human genome editing."[138]

Maxine Singer, Norton Zinder, Sydney Brenner, and Paul Berg (left to right) at the Asilomar Conference on Recombinant DNA, 1975. Image courtesy of the National Library of Medicine.

Challenges of International Scientific Partnerships

Although the benefits of international partnerships are numerous and significant, they can also be accompanied by additional costs, both fiscal and intangible. Further, certain categories of research, especially classified and dual-use research with direct application to military use, should not be performed as open science and should require scientists to be American citizens due to national security concerns.[139]

Challenges for international research partnerships can include the difficulty of reconciling two or more incommensurate planning or funding mechanisms; the necessity of satisfying multiple funders and government oversight bodies; complications of sharing decision-making, management, and control; ethical concerns; cultural differences; concerns of equality and fairness, especially along racial and gender lines; reduced flexibility and agility; balancing political and scientific interests; public awareness, participation, and education; increased complexity of ownership and data rights, including genetic resources and sequences; a growing need for secure research platforms that allow for distributed research; and requirements of export control regimes. These challenges need to be recognized and addressed up front and the time spent in managing these complications needs to be justified by the enhanced scientific return enabled by the international partnership. The challenges posed by the COVID-19 pandemic only serve to underscore this need (see What Happens After COVID-19? on page 30).

More detailed discussion of the challenges of international scientific collaborations are presented in the forthcoming CISP reports on international large-scale science and collaborations with emerging science partners.

Scientific collaboration can, and should, continue between citizens of countries whose governments have strained diplomatic relations for the benefits of international collaboration already described. However, in circumstances of political strain, special care may be needed to protect the interests of the United States as well as research integrity (See Mitigating the Effects of Strained Diplomatic Relations on Scientific Partnerships on pages 31–35).

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What Happens After COVID-19?

The Challenges for International Scientific Partnerships project started its work well before the COVID-19 pandemic swept across nearly every nation on Earth. As this report goes to print, the pandemic is accelerating and, indeed, the infection rate is rapidly rising in the United States and elsewhere. While there are numerous promising efforts underway to develop effective vaccines, none is yet available, and their effectiveness is not yet known. Health scientists are continuing to learn about the virus, how it mutates, how it can be transmitted, the symptoms and consequences of infection, and effective treatments.

Lessons continue to be learned as this report is finalized. One lesson that is very clear to all the participants in this study is that, in the post-COVID era, international scientific collaboration will be more challenging but also more important than ever before.

Another lesson is that science is most valuable if it is open. Open collaboration can advance scientific knowledge rapidly, and that knowledge can benefit many. Scientific expertise should be at the table when policy that must be informed by science is developed and implemented by government leaders. Strongly connected international communities of scientists are important. A connected international scientific community is one of the most effective means of ensuring that scientific evidence and reasoning are not ignored or covered up, leading to a crisis like the COVID-19 pandemic.

The world needs science more than ever. Not only is the advancement of science beneficial, the consequences of ignoring science can be catastrophic. Understanding and effectively dealing with a global pandemic and avoiding the dire consequences of a future outbreak requires an effective global organization, informed by science, whose primary objective is the public good. That is the role of the World Health Organization, and while it is not perfect, it is the best we have. Its shortcomings should be understood and addressed for the good of all, as is the hope of an independent review effort launched by the WHO to assess the organization and the world's handling of the COVID-19 outbreak.[140] The United States should not walk away from the WHO and its global efforts to improve public health with science-based evidence.

As many nations may turn increasingly inward to address the consequences of the pandemic for their societies, the United States should plan strategically for both the immediate aftermath of the crises and the longer-term effects.[141] It is an opportune time to plan for increased and sustained scientific engagement, particularly with emerging science partners, to assure that the United States has a leadership role in the global community for decades to come.

Special Section

Mitigating the Effects of Strained Diplomatic Relations on Scientific Partnerships

U.S. Collaboration with China

The topic of U.S. collaboration with China, a country that is approaching U.S. overall R&D funding levels when adjusted for purchasing power parity, merits special attention.[142] China has fully recognized the importance of science and technology to its economic and national security and is vigorously acting on it.[143] In part because of China's extensive R&D investments and increased capabilities, more U.S. science and engineering articles are now coauthored with Chinese researchers than with researchers from any other country. In 2018, approximately 10 percent of all U.S. S&E articles had Chinese coauthors, and coauthorship rates have risen dramatically over the past twenty-five years (Figure 4).[144] Much of the coauthoring is a consequence of Chinese researchers having performed their doctoral studies and/or postdoctoral research in the United States. Such collaborations are especially vital for approaching global problems like infectious diseases, climate change, and air and water pollution.

As China's research enterprise continues to grow stronger—increasing its scientific capabilities and making major advances—it is critical that the United States be engaged with this partner and competitor. To conduct the best, world-leading fundamental research that is openly published, U.S. scientists will frequently need to collaborate with Chinese scientists. To understand the global scientific community, the United States must be aware of China's growing role in this community and be sensitive to fast-moving advances. The United States cannot afford to ignore China's emergence as a leading investor with an impressive national research enterprise. It is vital that the United States not be caught by surprise by a major advance made in China. If the United States puts up curtains, China will as well.

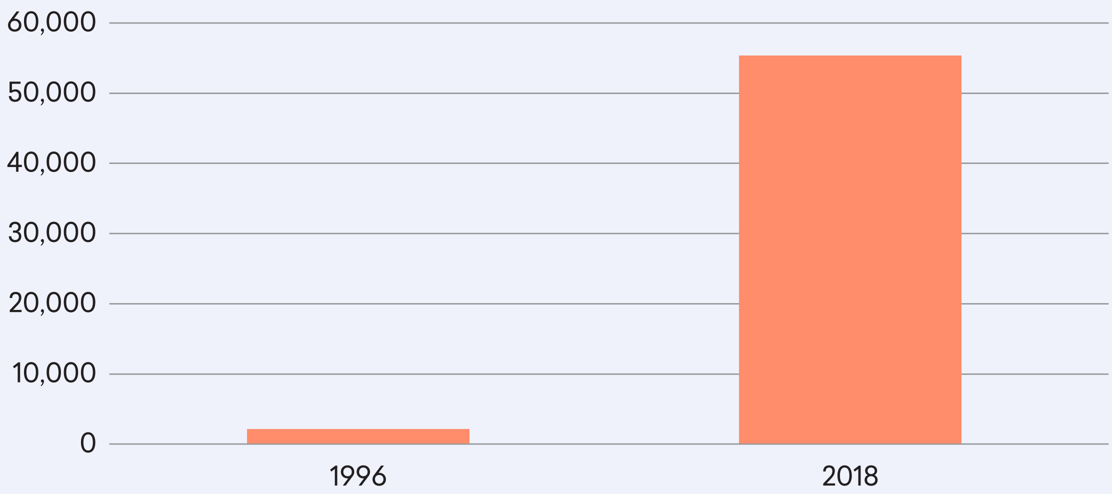
The U.S. intelligence community has indicated, however, that China is using some of its collaborations and nationals studying in the United States to gain access to U.S. intellectual property and ideas in illegal and unethical ways.[145] In addition, some U.S. scientists have failed to provide the required reports to U.S. government funding agencies of collaborations with Chinese nationals and participation in Chinese talent-recruitment programs.[146] For example, NIH has reported finding nine instances of peer review confidentiality violations among 154 total violation findings, of which the remainder were failures to make required disclosures.[147] While any breach of confidentiality could cause serious national security concerns, it is important to put these numbers in context. We estimate that there are fifty thousand doctorate scientists and engineers who came from China living in the United States presently. Of these, the number of biomedical doctorate holders is of the order of ten thousand.

Some in Congress and the executive branch have proposed severe limits on collaborations between U.S. and Chinese scientists and engineers in "strategic" research fields, as well as restrictions on the education of Chinese nationals by U.S. higher education institutions. For example, in a December 2018 memorandum, the deputy secretary of energy announced that the DOE would be developing a Science and Technology Risk Matrix to provide "clear guidance on areas where research collaboration with specific sensitive countries," including China, is prohibited.[148] DOE National Laboratories would be prohibited from conducting international research collaborations in specific areas identified by the S&T Risk Matrix. DOE grant, fellowship, and center recipients would be prohibited from using U.S. tax dollars to conduct international research collaborations or support sensitive-country foreign nationals in those areas. Up to this point, the DOE is showing caution in implementing this approach.[149]

There is at this moment significant tension in the overall U.S.-Chinese relationship. On May 29, 2020, the U.S. government issued the Proclamation on the Suspension of Entry as Nonimmigrants of Certain Students

Figure 4

Number of Publications Coauthored by U.S. and Chinese Researchers



Source: National Science Board, *Publications Output: U.S. Trends and International Comparisons* (Alexandria, Va.: National Science Foundation, 2019).

and Researchers from the People's Republic of China.[150] That proclamation contains the statement,

> The entry into the United States as a nonimmigrant of any national of the PRC seeking to enter the United States pursuant to an F or J visa to study or conduct research in the United States, except for a student seeking to pursue undergraduate study, and who either receives funding from or who currently is employed by, studies at, or conducts research at or on behalf of, or has been employed by, studied at, or conducted research at or on behalf of, an entity in the PRC that implements or supports the PRC's "military-civil fusion strategy" is hereby suspended and limited subject to section 2 of this proclamation. For the purposes of this proclamation, the term "military-civil fusion strategy" means actions by or at the behest of the PRC to acquire and divert foreign technologies, specifically critical and emerging technologies, to incorporate into and advance the PRC's military capabilities.

At the time of this writing, no entity list has been published, and it is not clear how this proclamation will be implemented.

The DOE memorandum and the proclamation have the potential to cause considerable harm to the nation's scientific research, economy, and national security. Students from China constitute a considerable fraction of those performing graduate studies in engineering, physics, and information technology in U.S. universities. Between 2000 and 2017, for example, they received 32 percent of all the doctorates awarded in science and engineering, 34 percent in engineering, 38 percent in physical sciences, and 36 percent in computer science.[151] If they could not participate in university research in strategic research fields, U.S. research in those fields considered most important—including 5G, artificial intelligence, biotechnology, and materials science—would be slowed down considerably. The impact would be felt for years to come, as most Chinese students currently remain in the United States, where they form an important part of the permanent American S&T workforce (Figures 5A and 5B), frequently founding major companies and providing jobs.[152] Prevention of collaborations with Chinese colleagues in these fields is also likely to slow down U.S. research, as is the case in materials science, where some of the high-quality advanced materials required are not available domestically.[153]

The United States is thus faced with a dilemma. Collaboration with Chinese scientists and the education of Chinese students further U.S. science and technology significantly. Approximately 20 percent of those students earning doctorates in the United States return to China and contribute significantly to that country's economic and military development.[154] The approximately 80 percent choosing to remain in the United States constituted about one-quarter of the U.S. doctorate recipients between 2000 and 2017. These students contribute important benefits to the U.S. research enterprise, which ultimately contributes to our economy, the health of our people, and our national security. On balance, it seems wisest to continue educating graduate students from China while remaining vigilant regarding direct linkages to China's military sector. In addition, it is essential that the U.S. science community remain engaged with the Chinese science community as it continues to expand and grow in strength.

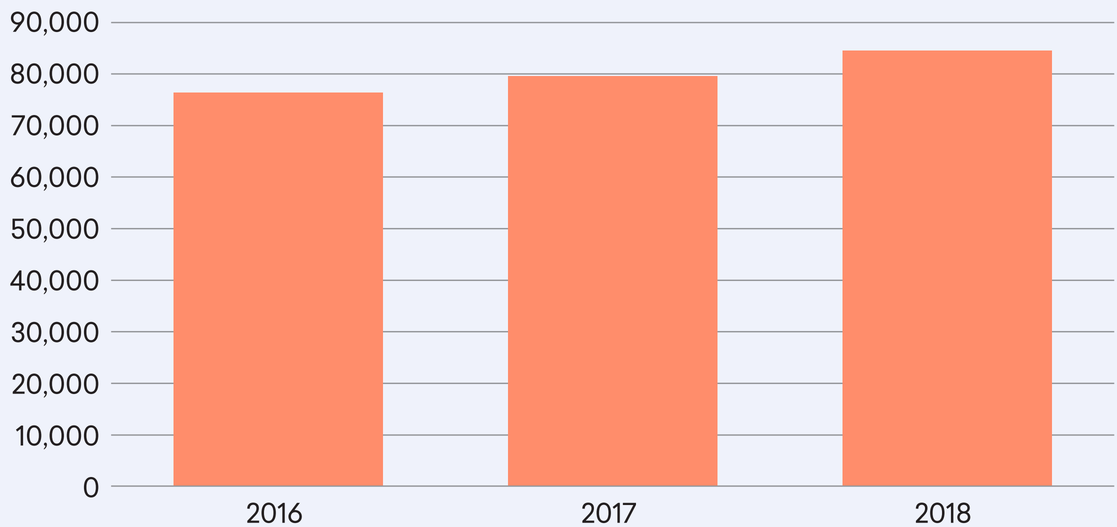
Yet the relatively infrequent instances of inappropriate behavior in collaborative research endeavors do endanger control of U.S. intellectual property and raise research ethics and national security concerns.

The United States must wisely balance and manage both collaboration and competition with China. Here, we offer recommendations for national policy as well as institutional actions to deal with the situation faced by academia and some other institutions performing fundamental, openly publishable research.[155] These recommendations apply to the current U.S.-Chinese tensions, but they can also be extrapolated to apply to international collaborations more generally.

1. National Security Decision Directive (NSDD) 189, promulgated by President Reagan and reaffirmed by Secretary of State Condoleezza Rice, is U.S. policy regarding classification of research and should be adhered to strictly.[156] NSDD 189 indicates that there should be no restrictions on fundamental research. If restrictions need be applied, the research should be classified. NSDD 189 provides the benefits of openness to fundamental research while also ensuring that other research is protected by well-established security procedures. Characterizations such as "sensitive but unclassified" should not be used for government-funded university research. (Note: Specific institutional and principal investigator controls apply to dual-use research of concern in the life sciences.)[157]

Figure 5A

Chinese Science and Engineering Graduate Students Enrolled in the United States



Source: National Science Board, *Higher Education in Science and Engineering* (Alexandria, Va.: National Science Foundation, 2019).

2. Classification should be reserved for research directly linked to national security.

3. Collaboration should be particularly encouraged in compelling areas that promote global health and well-being, such as infectious diseases, climate change, and air and water pollution.

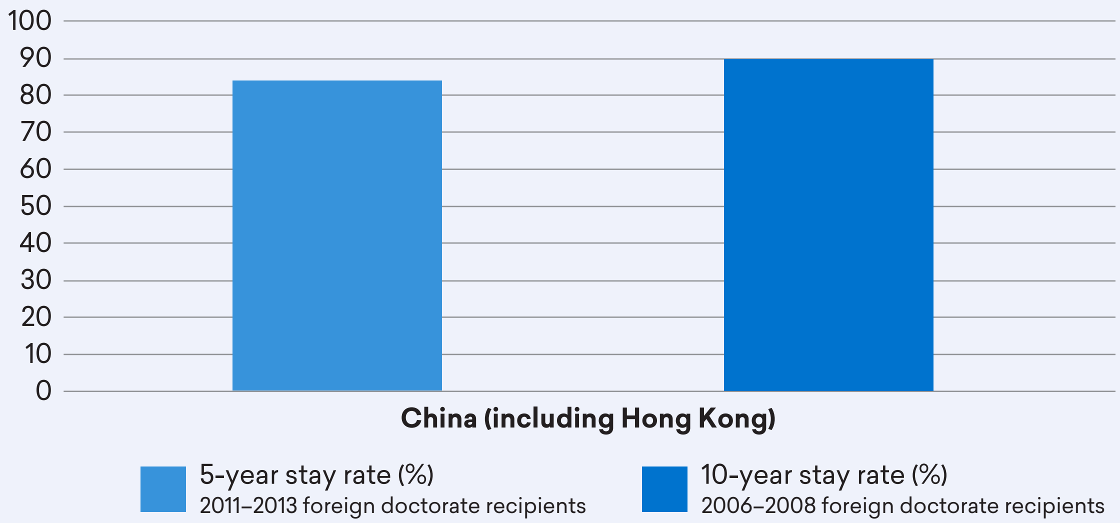
4. U.S. visa policies and practices should encourage Chinese nationals and other foreign citizens both to study in the United States and to continue to reside in the United States following their studies, as this strengthens the U.S. research enterprise. Yet the visa process is the appropriate barrier for those whose entry and education here are determined to be an unacceptable risk to national security.

5. American universities should ensure strict adherence to their conflict of interest, conflict of commitment, and required reporting policies. These institutions should ensure that their policies are clear so that faculty understand them. The same is true for government policies.

6. The leaders of the U.S. scientific community in various fields, including professional societies, should engage their Chinese colleagues to discuss universally agreed norms, ethical obligations, and standard practices that should guide the conduct of scientific collaborations in fundamental research between scientists from the United States and China.[158]

Figure 5B

Rate of Chinese Science and Engineering Doctorate Recipients Who Stay in the United States



Source: National Science Board, *Science and Engineering Labor Force* (Alexandria, Va.: National Science Foundation, 2019).

Conclusions

1. *The United States should expand and support international scientific collaborations, including with nations with which the United States has strained relations, such as China. Any restrictions on international collaborations involving federally supported research should be well-justified and carefully and narrowly defined.*

U.S. participation in international scientific partnerships goes hand-in-hand with building a strong, diverse, and inclusive domestic STEM enterprise, including development of domestic talent from women and minority groups. Access to international sources of talent is not a substitute for developing a domestic base of researchers that includes underrepresented groups.

International scientific engagement advances economic prosperity, improves individual health and well-being, and maintains national security. It allows U.S. scientists to work toward solving global challenges, provides U.S. scientists with access to key collaborators wherever they reside, introduces talented international students and postdoctoral researchers to the U.S. R&D enterprise, pools funding resources transnationally, advances U.S. diplomatic interests, and gives American scientists a key role at international decision-making tables regarding ethical norms and best practices. Although international collaboration provides unique challenges that require careful consideration to address and overcome, the benefits of doing so often far outweigh the costs.

2. *The United States should be prepared to participate in international large-scale science partnerships and ensure their success, including contributing support for operations outside the United States.*

Looking to the future, there are several large-scale scientific endeavors that will necessarily involve international cooperation. Some of them will be sited outside of the United States. The case studies in this report dramatically illustrate the value of large-scale facilities for scientific advancement across disciplines. Funding for these facilities will become increasingly difficult for the United States to consider alone. A deeper study of considerations for large-scale facilities and best practices in approaching megascience collaborations is presented in CISP's second report, *Bold Ambition: International Large-Scale Science.*

3. *Emerging science partners around the world are and will continue to be important scientific collaborators. The United States should support and join with them in scientific research.*

As emphasized in this report, scientific talent is increasingly global, and many of the world's most pressing questions are not defined within national boundaries. Scientific researchers in all countries, including emerging science partner countries investing in their S&T enterprises, are important collaborators for U.S. scientists. These partnerships can also make critical contributions to U.S. diplomacy. Further discussion of the important role of emerging science partners for the U.S. scientific community is presented in CISP's third report, *Global Connections: Emerging Science Partners*.

International scientific partnerships, despite their associated challenges, are essential for the U.S. scientific enterprise today and in the future. Where collaborations are appropriate, the United States should work to build and support them at every level and at all stages.

Appendix

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Endnotes

1. See American Academy of Arts and Sciences, *Bold Ambition: International Large-Scale Science* and *Global Connections: Emerging Science Partners* (Cambridge, Mass.: American Academy of Arts and Science, forthcoming 2021).

2. Ibid.

3. Here and throughout the report, *facility* is used to describe large, sited scientific infrastructure that provides scientific research functionality to researchers.

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This report will explore how the United States can enhance its role in international large-scale partnerships, both in physical facilities (like the European Organization for Nuclear Research, or CERN) and distributed networks (like the Human Cell Atlas). The report will offer recommendations that will bolster U.S. ability to partake in large-scale collaboration efforts as meaningful and engaged partners.

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