American Institute of Physics

LETTER REPORT

PERIL AND PROMISE

Impacts of the COVID-19 Pandemic on the Physical Sciences

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American Institute of Physics
College Park, MD

www.aip.org

American Institute of Physics

The American Institute of Physics is a federation that advances the success of our 10 Member Societies and an institute that operates as a center of excellence supporting the physical sciences enterprise.

Over the last 400 years, the physical sciences have evolved a powerful predictive model of our world, enabling stunning technological achievements and enriching our understanding of the Universe and our place in it. AIP has, for nearly a century, worked to advance, promote, and serve the physical sciences.

AIP provides the means for its Member Societies to pool, coordinate, and leverage their diverse expertise and contributions in the pursuit of the shared goal of advancing the physical sciences in the research enterprise, in the economy, in education, and in society. Through their partnership in AIP, Member Societies broaden their impact and achieve results beyond their individual missions and mandates.

AIP also acts as an independent institute where research in social science, policy, and history advances the discipline of the physical sciences.

Letter Report: Letter Report panels are convened by AIP when the Chair of the AIP Board of Directors, having identified a topic on which an expedited expert opinion is needed, appoints a small panel of scientific leaders to address the topic in the format of a short report to the Chair of the Board. Letter Report panels report out in the time frame of 2-4 months, depending on the depth of information gathering and analysis expected of the panel and required by the topic at hand. Recommendations would not be expected owing to the limited data/information gathering possible in this expedited format.

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One Physics Ellipse, College Park, MD 20740-3843

June 25, 2020

Dr. David Helfand
Chair, AIP Board of Directors
American Institute of Physics
College Park, MD 20740

Dear Dr. Helfand,

Thank you for the opportunity to chair and serve on AIP's *Panel on the COVID-19 Pandemic's Impact on the Physical Sciences Enterprise.*

I was honored to chair the distinguished panel of experts appointed by AIP to conduct an expedited study resulting in the concise report I have the pleasure to convey to you today. The charge to our panel was to map out the potential impacts of the pandemic crisis on the physical sciences research enterprise. This effort was designed to be an early step in envisioning a post-pandemic recovery strategy. The panel is confident our report will inform future recommendations from the physical sciences community by informing future efforts by AIP, AIP's Member Societies, and others.

In our report, *Peril and Promise: Impacts of the COVID-19 Pandemic on the Physical Sciences*, we note that the pandemic-related shutdown of most activities has stalled research, curtailed the operation of major facilities and international travel, and negatively impacted students and early-career scientists—especially those from underrepresented groups. On the positive side, the pandemic has opened up opportunities to convene scientists in new ways, making use of new technologies that shrink distances and enable new forms of interpersonal interaction across the miles.

We note that the physical sciences have long contributed to our nation's prosperity and well-being. But we are concerned that, in light of the pandemic's impacts, the American physical sciences may be at a tipping point. We conclude that if we take swift action to define and defend a vibrant future for science in the United States as we rebuild and renew after the pandemic, we can bring new strength, resiliency, and diversity to the physical sciences community to the benefit of our economy and society for decades. But, if we do not act on this promise of new opportunity, we are in peril of losing the resilient and robust physical sciences enterprise America needs to remain healthy, innovative, and prosperous.

Sincerely yours,

Dr. Julia M. Phillips
Sandia National Laboratories (Retired)

Executive Summary

As with much of America and the world, the conduct of the physical sciences—physics, chemistry, Earth science, astronomy, and related fields—has been severely disrupted by the COVID-19 pandemic. The shutdown of most activities has stalled research, particularly in the laboratory and field sciences, which generally require in-person interactions and logistical support. The operation of major facilities and international travel have been largely curtailed, and universities are being challenged as never before. Perhaps the largest impact has been on students and early-career scientists, especially those from underrepresented groups. On the positive side, the pandemic has opened up opportunities to convene scientists in new ways, making use of new technologies that shrink distances and enable new forms of interpersonal interaction across miles. Social distancing and other pandemic countermeasures, such as virtual meetings, have illuminated the increasing interconnectedness of the sciences, the important roles played by each field of science, as well as the challenges and opportunities associated with new ways of connecting scientists.

The physical sciences have long contributed to the nation's prosperity and well-being through advancements in, and contributions to, fields from biotechnology to quantum science, from aerospace engineering to renewable energy, and from numerical weather prediction to emergency response. Yet as we survey the pandemic's impacts, the American physical sciences may be at a tipping point.

If we take swift action to define and defend a vibrant future for science in the United States as we rebuild and renew after the pandemic, we can bring new strength, resiliency, and diversity to the physical sciences community to the benefit of our economy and society for decades. If we do not act on this promise of new opportunity, we are in peril of losing the resilient and robust physical sciences enterprise America needs to remain healthy, innovative, and prosperous.

The physical scientists and engineers that are helping the nation begin to recover stand ready to contribute further. We can emerge from the crisis stronger than ever before, but we need to recognize the more critical impacts and act now.

Introduction

Since March 2020, the coronavirus pandemic has been wreaking havoc on the American people and their livelihoods, including critical sectors of the scientific enterprise. American prosperity is built on scientific discovery and innovation, so we—the U.S. scientific community—must face the stark reality that our country's future is at risk.

Six months into the pandemic, scientists are feeling its effects across the entire research enterprise. Research programs in universities, national laboratories and agencies, industrial research facilities, and other institutions have been sharply curtailed or suspended. Face-to-face teaching has ceased, and the financial support and career pathways for undergraduates, graduate students, and postdoctoral scholars have been disrupted. At the same time, some significant adjustments in research and education made during the pandemic offer the opportunity for an even more vibrant and productive research enterprise to emerge.

To assist leaders in government, academia, the private sector, and others who depend on the physical sciences as they craft specific recommendations to address the pandemic's impacts, the American Institute of Physics (AIP)[1] convened this panel of experts to forecast the effects on the physical sciences. The panel is composed of nine experts who bring scientific, institutional, experiential, and other dimensions of diversity to this task. Over the course of six weeks, the panel focused on the actual and potential impacts of the crisis on the physical sciences enterprise as a

1 The American Institute of Physics (AIP) is a federation that advances the success of its ten Member Societies and an institute that operates as a center of excellence for supporting the physical sciences enterprise.

first step in envisioning a post-pandemic recovery strategy. This report discusses the pandemic's current and expected impacts on the physical sciences enterprise in three dimensions: workforce, infrastructure, and the conduct of research.

The foundational role of the physical sciences, as well as the interconnections among the physical sciences and to other scientific and engineering disciplines, manifests itself throughout the economy, our communities, and our lives at home. Technologies that have enabled this panel and many of us to work remotely during the pandemic have their roots in physics, materials science, information technology, and engineering.

According to a 2019 report from an AIP Member Society, the American Physical Society (APS), industrial physics contributed about $2.3 trillion to the U.S. economy in 2016 (American Physical Society, 2019). In addition, the APS (2019) report found that

- The total U.S. employment attributable to industrial physics is about 45 million persons, or slightly less than a quarter (23.6 percent) of the U.S. workforce.
- In 2016, U.S. exports by physics-based sectors were about $1.1 trillion.
- From 2010 to 2016, over 340,000 physics-classified patents were granted to U.S. companies.
- In 2015, U.S. physics-based companies invested over $150 billion for research and development.
- Between 1966 and 2016, the GDP value of the physics-based sectors of the U.S. economy grew by a factor of 22, and total GDP grew by a factor of 4, both in 2016 constant dollars.

The physical sciences do not stand alone, since many of today's emerging and potentially most transformative industries—including artificial intelligence, quantum information sciences, advanced communications, and advanced manufacturing (U.S. Office of Science and Technology Policy, 2019)—require interdisciplinary contributions from scientific fields that were once considered distinct. The pandemic's significant and sustained disruptions to the scientific enterprise present a test of our resilience, imagination, and character: The choices we make now will determine both the health of the physical sciences and our nation's future well-being.

WORKFORCE

Pre-Career — Undergraduate and High School

Across the United States and around the world, undergraduate students have faced the sudden closure of campuses and a switch to remote classes. The short-term result has included scheduling challenges and difficulty in fulfilling degree requirements. Longer-term impacts will likely include delays in graduation, a reduction in opportunities for career development, and changes in majors due to the unavailability of required laboratory-based courses. Anecdotal evidence suggests that some students are taking time off from college in the form of a gap semester or year, choosing to experience a traditional residential education instead of an online one. Such a delay may even be essential in some physical science disciplines so that students can fulfill in-person laboratory course requirements.

> **By investing in the next generation of diverse, domestic stem talent, we can unite this country and provide opportunities for our citizens in the future.**
> – Victor McCrary

At the same time, the long-term impacts of the move to online education remain unknown. While the sudden unplanned switch to online education likely resulted in relatively ineffective teaching practices and poor student outcomes, this does not have to be the case going forward. Optimal use of online teaching could dramatically improve access to education in the physical sciences, particularly by offering high-quality instruction to students for whom it has been unavailable for geographic and economic reasons. That kind of change, coupled with readily available infrastructure to distribute and receive these offerings, could help supply the U.S. economy with the physical scientists needed for the future of our nation's economy. It is noteworthy that physics education research has established a better basis for online teaching than many disciplines (National Research Council, 2012). So, notwithstanding the challenge and disruption associated with the shift to remote teaching, we could see the quality and number of physics majors increase if, and only if, physics faculty are progressive in adopting good research-based teaching methods.

In addition to the disruption of their coursework, many undergraduates in the physical sciences are missing opportunities for a summer research internship. These programs strongly influence career aspirations and offer students valuable research experience beyond their classroom studies (Lincoln et al., 2019; O'Neill, 2010). Many government, industry, and academic institutions have cancelled their 2020 summer internships or converted them to virtual ones. Such disruption is likely to have a disproportionate effect on demographic groups not well represented in physics, as they often have fewer opportunities during their formal education.

High school students will suffer similar educational challenges to undergraduates, and those from less advantaged backgrounds and from underrepresented groups will experience a disproportionate share of the impacts. The pandemic may also influence today's high school students as they decide on future careers. Just as the launch of Sputnik and the resulting large investment in K–12 science education it engendered led to an explosion in the number of students studying the physical sciences, the pandemic may cause a significant jump in students interested in studying biology and medicine. A parallel increase in the number interested in the physical sciences could occur if there is high-quality instruction and if the case is made strongly that physical sciences advances are critical to addressing crises of all kinds, including those of a medical nature.

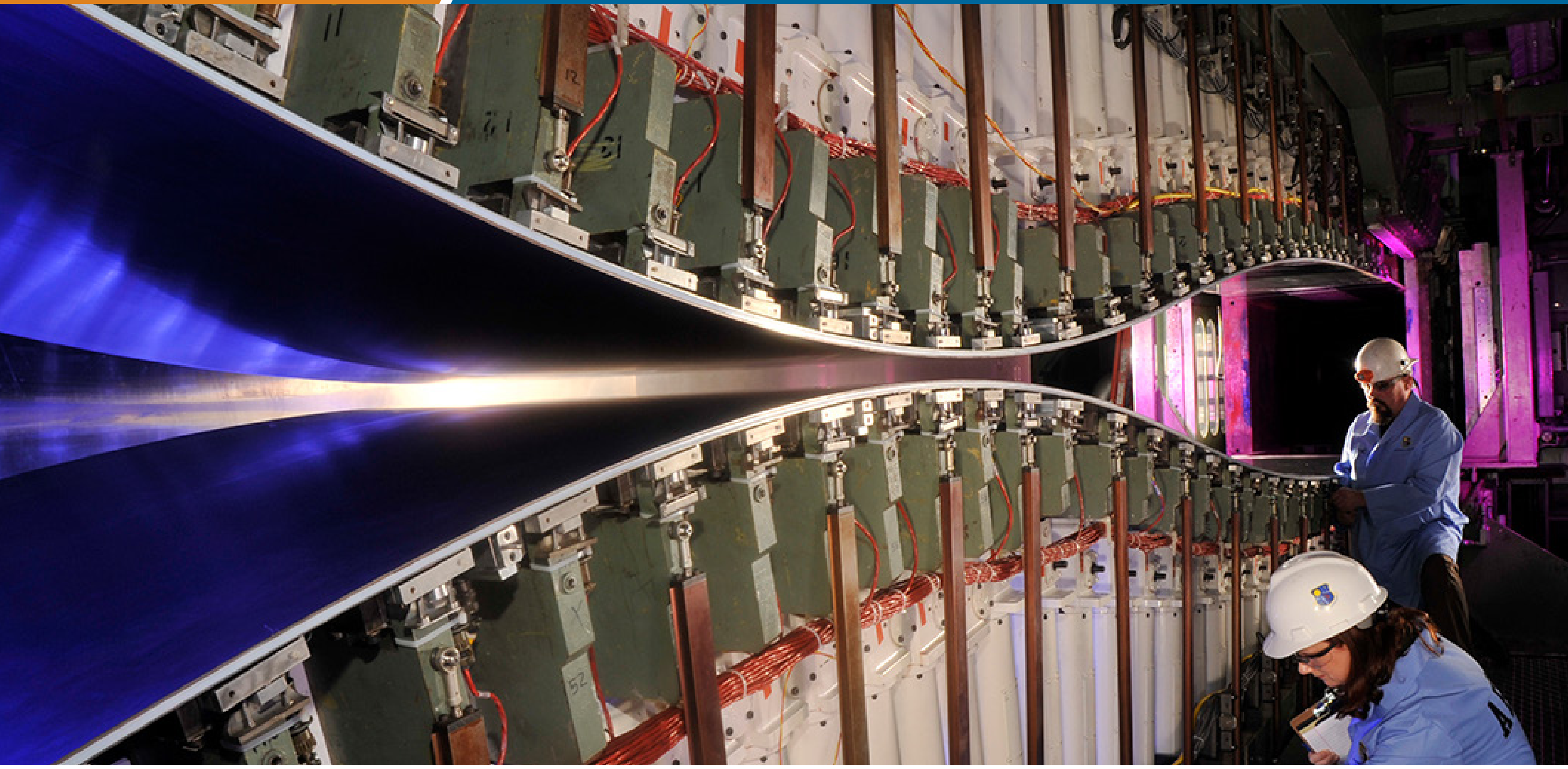
Early Career — Grad Students, Postdocs, and Junior Faculty

Early-career scientists—graduate students, postdocs, and junior faculty—have experienced acute disruptions and face long-lasting impacts that have serious consequences. Postdocs and students, particularly those engaged in experimental investigations and/or field work, are likely to need additional time to complete their research and degrees. Junior faculty may need more time to prepare research and teaching portfolios for tenure decisions, and some may see their positions eliminated because of financial pressures at their universities.

> **With their innovations and insights, young scientists will produce the new science that leads us out of this crisis, so we must give them the tools to do it.**
> – Philip Bucksbaum

Graduate students and postdocs are affected by ongoing disruptions to the operation of laboratories, suspension of field research, closure of user facilities, discontinuities in or loss of data sets, continuing travel restrictions, and expiring visas and other immigration barriers. Separated from their research and scientific cohorts, these young scientists will have difficulty resuming their previous career paths. Students also may experience shortfalls in funding and the truncation of supplemental on-campus and other employment. The pandemic has caused particular challenges for graduate students and postdocs from other countries. In many physical science and engineering disciplines, international students comprise over 50 percent of PhD recipients (National Science Board, National Science Foundation, 2019b), many of whom stay and work in the U.S. after completing their degrees. Restrictions on travel and delays in visa processing resulting from the pandemic are severely impacting their studies, research, and career options.

Impacts on employment have been immediate and will be long lasting. Hiring freezes in academia and private industry have substantially reduced the job prospects for early-career scientists. Many graduates and postdocs who had



academic job offers at the pandemic's start have since had those offers rescinded or delayed. Whereas opportunities in certain areas, including national security, artificial intelligence, healthcare, and data analytics in both the private sector and national laboratories, are likely to remain robust or even grow, the number of academic research positions will likely decrease (Zahneis, 2020).

Diversity, Equity, and Inclusion in the Physical Sciences

If unaddressed, the pandemic will only exacerbate the disadvantages underrepresented minorities (AIP TEAM-UP Task Force, 2020), women (Goodwin & Mitchneck, 2020), and members of the LGBTQ community (Atherton et al., 2016) experience in the physical sciences. College and high school students from underrepresented groups have disproportionately suffered from the disruption in normal teaching and the resulting switch to online teaching. Many of these students have experienced sudden economic loss in their families, which preempts studies because of porous or nonexistent safety nets exacerbated by the fact that Black, Hispanic, and other minority families have considerably less wealth than White families, even among those with similar levels of education (Dettling et al., 2017). Furthermore, these students may live in environments not conducive to study and lack affordable broadband access and other resources needed to succeed in a distance-learning environment. The isolation from university communities also particularly impacts students who lack physical science role models in their home communities.

> **Future American success depends on physical sciences talent that reflects the diversity of the U.S. population and includes the best scientists from every corner of the world.** – Julia Phillips

To help eliminate that systemic societal shortfall, minority technical organizations[2] play a critical role in the recruitment, development, and role modeling for underrepresented groups in the physical sciences. Cancellation or virtualization of conferences associated with these organizations is likely to impact the number of nonmajority students who choose to continue career paths in the physical sciences. On a more optimistic note, virtual conferences and classes can provide opportunities to reach nontraditional populations, which could be a long-term boon to increasing the diversity of physical sciences talent.

The radical and swift change in work environments caused by the pandemic has placed added burdens on faculty due to their lack of preparation for distance teaching, though the changes have not hit all individuals equally. Women, in particular, often have disproportionate responsibilities for the care of dependents, which can significantly hinder their productivity as scientists. Anecdotal evidence based on journal submissions during the pandemic, relative to the same time period in previous years or in the months preceding the pandemic, suggests that some populations have had a noticeable reduction in productivity (Vincent-Lamarre et al., 2020), although the finding did not extend to all journals tracking such information (Wooden, 2020).

The physical sciences community has been making progress identifying and addressing the inequities that have been endemic to it for too long. To better understand one aspect of these inequities, AIP commissioned the AIP TEAM-UP report. The report focused on understanding the lived experience of African American undergraduate students in physics and astronomy, identified several systemic biases, and offered many recommendations for how to create a more inclusive community (AIP TEAM-UP Task Force, 2020). As we now struggle to restart and reinvigorate our research infrastructure in light of both the pandemic and heightened awareness of the broader systemic injustice Black Americans face, we could jeopardize years of progress made toward greater, if imperfect, equity.

Concerted attention will help us better understand the pandemic's impact on diverse populations and their ability to capitalize on the positive developments the pandemic has driven. Lessons learned from the pandemic offer opportunities to improve diversity, equity, and inclusion. This may depend, in no small part, on

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2 NOBCChE: National Organization for the Professional Advancement of Black Chemists & Chemical Engineers; SHPE: Society of Hispanic Professional Engineers; NSBP: National Society of Black Physicists; NSHP: National Society of Hispanic Physicists; SACNAS: Society for Advancement of Chicanos/Hispanics & Native Americans in Science; AISES: American Indian Science & Engineering Society; NSBE: National Society of Black Engineers.

reallocation of digital and financial resources. Developing ways to work effectively in a virtual environment may provide new and better opportunities for individuals previously excluded from full participation in the physical sciences workforce and for those who must continue to practice social distancing after restrictions have been eased.

A characteristic of American success has been the diversity of national origin of our scientists and engineers. Whereas U.S. economic competitiveness demands that we continue to encourage top foreign-born science, technology, engineering, and mathematics (STEM) talent to study and remain in the U.S., we must also develop American-born STEM talent to fully represent the face of our nation in racial, ethnic, gender, and geographic diversity. According to the latest data from the National Science Foundation, 30 percent of workers in science and engineering occupations are foreign born, and the proportion is even greater for higher degree levels (National Science Board, National Science Foundation, 2020). Some 40 percent of doctorate holders in physical sciences occupations are foreign born (National Science Board, National Science Foundation, 2020). Our STEM industrial base depends on all sources of talent, domestic and international. A pre-pandemic report by the National Science Board (2019) fully documented the need to enhance the U.S. skilled technical workforce to ensure our country's position. The challenges associated with increasing the number and diversity of skilled technical workers are exacerbated by the pandemic-induced and other diversity issues just discussed as well as the quarantine aspect of the pandemic, which does not afford the hands-on training many skilled workers require (National Science Board, 2019).

INFRASTRUCTURE

University Teaching and Research

The U.S. system of higher education has long been a role model for the world. It has trained countless physical scientists and is responsible for many transformative research advances. The health of our universities and of the physical sciences are inextricably linked. The Association of American Universities, AAU (2020), reports that although the full extent of the financial impacts of the pandemic are still unknown,

> *The costs of disruption are extraordinarily high and growing while at the same time the loss of revenues will be very significant. Sustaining our nation's research universities and their undergraduate and graduate students, postdocs, faculty, staff, and research personnel is vital during this time of crisis and fundamental to the strength of the longstanding government-university partnership that has been essential to ensuring our public health, national security, and economic growth and competitiveness for decades. (para. 2)*

In response, the AAU has urged Congress and the administration to implement a series of steps, including supplemental appropriations for the major government research agencies.

> **A perfect storm is hitting the economics of higher education.** – Carl Wieman

Answering the cry for help from the universities and colleges facing bankruptcy and cessation of operations is especially critical. Many institutions, particularly state universities, which are the source of a majority of physical science and engineering majors (Nicholson & Mulvey, 2019), have suffered from years of steadily decreasing state support (Marcus, 2019) and rely heavily on revenue from room and board and from international students, sources of income that have been severely cut if not eliminated as a result of the pandemic. Private universities are far from immune, although the magnitude of challenges is uncertain and varies greatly depending on the pre-pandemic financial health of the institution. The drop in endowments and the effects on philanthropy from uncertainty in the financial future may well create major problems for many if not all private universities. Public and private universities with medical centers are experiencing particular stresses due to large losses resulting from the displacement of elective surgeries by COVID-19 patients. The dislocations caused by the pandemic may necessitate development of new hybrid models for education and research that are sustainable in the long term.

Drastic reductions in these revenue sources are particularly disastrous for historically black colleges and universities (HBCUs), exacerbating the severe preexisting financial issues these institutions already face. HBCUs rely on federal, state, and local funding more heavily than predominantly white institutions or other minority-serving institutions and have experienced the steepest, double-digit declines in federal funding per student. Furthermore, their endowments lag behind those of predominantly white institutions by at least 70 percent, further jeopardizing HBCUs' abilities to compensate for reductions in funding from other sources (Williams & Davis, 2019). In the wake of these revenue downturns, HBCUs are asking faculty to assume larger course loads—as much as four courses per semester—leaving little or no time for cutting-edge physical sciences research. These challenges will slow the outsized contributions that HBCUs have made toward creating a more diverse physical sciences community. Since the early 2000s, HBCUs have awarded 24 percent of the bachelor's degrees earned by Black students in science and technology, despite representing only 3 percent of two-year and four-year public and private nonprofit institutions that participate in federal student financial aid programs (Williams & Davis, 2019; National Academies of Sciences, Engineering and Medicine, 2019).

> **Our modern life is made possible by physical scientists in industry who have been turning curiosity- and problem-driven inventions into innovations across many areas including the health, food, transportation, energy, infrastructure, robotics, communications, and entertainment industries.** – Robie I. Samanta Roy

Private Sector Research

Many segments of the private sector have relied upon physical scientists either directly in their workforces, or indirectly in applied research partnerships with government laboratories or academic institutions to transition scientific knowledge ultimately into products and services. The impact of the pandemic has been uneven across this landscape, both by the industry sector and by local effects of the pandemic. Corporate filings for bankruptcy have increased, and unemployment is up (Economist, 2020). While we can discuss observed short-term impacts, longer-term enduring impacts have yet to be fully understood. Furthermore, many pandemic-related impacts on industry are economic, driven by market forces and dynamics as well as international and foreign policy factors that will continue to evolve. This paper makes no pretense of trying to capture those forces; it serves to offer initial "canary in a coal mine" observations of the physical sciences community in the private sector, bearing in mind that some impacts may disappear over time, and others might endure in some form.

Firstly, for industries that rely on a scientific workforce focused more on computational and software-intensive work, the impact has been less compared to those that rely upon physical laboratories and infrastructure that have closed or must operate under health and safety restrictions. The minimal impact on computational and software-intensive work has given more momentum to the increasing digitization of engineering design and development and the associated increased emphasis on fundamental computational modeling, large-scale complex simulations, etc. For example, industries heavily reliant on the application of the latest artificial-intelligence approaches and tools continue to grow applications, and companies focused on cybersecurity, online communications, and cloud computing services are faring better than those that rely on traditional workforce-intensive manufacturing. In fact, elements of high-performance computing, plastics manufacturing, high-technology instrumentation, and other sectors have been repurposed to focus on pandemic-related needs in the pharmaceutical and medical response sectors. Lastly, mission-critical industries, such as in the national security and human security sectors, are not impacted as severely as those that rely solely on the commercial consumer market. Despite these differences, the whole scientific community in industry is impacted by the inability to fully engage professionally, including attending scientific meetings and conferences, as is discussed in the section on the conduct of research.

A second area of impact has been the recruiting talent pipeline. The U.S. federal government has identified “Industries of the Future” (U.S. Office of Science and Technology Policy, 2019)—including artificial intelligence, quantum information sciences, 5G communications, and advanced manufacturing—but the pandemic challenges the development of these vibrant new industries that will require an appropriate talent pipeline to grow and prosper, including physical scientists. As White House strategic plans have emphasized, training needs to begin early, even in elementary school (National Science and Technology Council, 2018). Unfortunately, the pandemic-induced challenges faced by students and teachers at every educational stage (documented earlier in this report) could significantly disrupt the supply of new talent on which those and other industries of the future depend.

That said, students are adapting to the new reality of virtual internships, where available, and are shifting preferred employment pursuits from more volatile start-ups to larger, more stable corporations (Ivy Research Council, 2020). In addition, some sectors, such as national security, are continuing to hire robustly, as the U.S. National Defense Strategy places significant emphasis on advanced technologies such as hypersonics, high-energy lasers, quantum information sciences, and advanced electronics. Lastly, in some areas, such as in hypersonics, the Department of Defense is working to revitalize research in the academic community, and universities across the country have responded positively.

A third area of pandemic-induced impact in the private sector with potential impact on the physical sciences community has been the changing availability of venture capital funding for new start-up companies. Disruptive technologies and future game-changing industries—many driven by advances in the physical sciences—depend in part on creative innovations from small start-up companies and the venture capital funding that finances them. The story is mixed and continues to evolve. There are indicators that the uncertainty in financial markets caused by the pandemic has strained technological start-ups as many venture capital firms have pulled back from new, more uncertain investments and redirected their existing resources to more established portfolios (Haque & Field, 2020). The Economist magazine recently noted, "Options prices imply that over the next two years investors require a far higher expected return in order to accept exposure to vulnerable firms than to more disaster-resilient ones" (Economist, 2020). On the other hand, there are also reports that this is not a universal trend. For example, ARTMS Products, a spin-off from TRIUMF, Canada's national particle accelerator center, to develop new medical isotope production technologies—secured US$19 million in this austere financial landscape (Orton, 2020). Yet the future will depend on financing more than just those companies and centers focused in specialized areas of current interest. The progress of science relies on support for a broad range of scientific fields and a plethora of approaches, some of them high risk.

In summary, the physical science community in the private sector has not escaped the impacts of the pandemic, although the landscape is quite varied, and it will take some time for the longer-term effects to become known with greater clarity.

> **The funding and infrastructure for the physical sciences, which are necessary to assure our country's continuing success, are under increasing threat.** – Eric Isaacs

National Major Research Facilities

The pandemic has been detrimental to the operations and output of national facilities that are crucial for physical sciences research, although the effects vary somewhat for different types of facilities. The burden is particularly severe for research that requires physical experimentation or field observation. Most experimental research centers have closed or have transitioned to virtual operations; some are now beginning to operate at reduced levels required by social distancing. Travel restrictions and differing approaches to the pandemic are particularly challenging for international visitors to domestic facilities and for U.S. scientists visiting and working at major facilities in the U.S. and other countries.

Whereas remote operation may be an option at some facilities—such as telescopes that explore our place in the universe or environmental sensor networks that support public safety—other facilities require intensive on-site personnel for maintenance and operation. Furthermore, the construction and commissioning of major experimental facilities—such as those in nuclear and particle physics, synchrotron and free electron lasers, and the next generation of ground and space telescopes—require hands-on work by large teams of scientists and technicians. Such activities require careful coordination in the best of times, but in the midst of a pandemic they become even more complex and challenging. For example, the launch of NASA's James Webb Space Telescope will be delayed, owing to the impact of the pandemic (Foust, 2020).

> **In some areas of the physical sciences, future U.S. prosperity and safety depend that we be second to none.** – Julia Phillips

Government laboratories and other large research facilities are facing substantial barriers to reopen, such as additional costs, social distancing protocols, travel restrictions, and varying pandemic restrictions in different countries and regions. These impacts are being felt as much in the national security laboratory ecosystem as elsewhere, though in somewhat different form. The mission-critical aspect of many elements of the work of those laboratories in some cases has required them to continue on-site operations, but it has also severely limited the types of work that can be done remotely. Department of Defense and Department of Energy laboratories, federally funded research and development centers, affiliated university research organizations, and research laboratories in industry face common challenges posed by the pandemic. National security imperatives require research in certain fields of the physical sciences be globally preeminent—particularly for research related to the development and maintenance of the nation's nuclear weapons infrastructure, arms control, space situational awareness, and encryption technologies. Thus any loss of U.S. leadership in the science and engineering disciplines underpinning these topics that results from the pandemic poses a significant threat to U.S. national security.

In this time of a pandemic, the value of some facilities with biotechnology application is clear because of their role in the fight against disease. Synchrotron x-ray light sources elucidate the structure of proteins, and both cryo-electron microscopy and neutron beams probe the molecular structure of bacteria and viruses. In other cases, the value is less direct but still critical, as witnessed by the collaboration between laboratories and universities in Canada, Italy, and the U.S. to develop and produce a safe, low-cost, highly capable open-source ventilator to treat COVID-19 patients (Mechanical Ventilator Milano, 2020). But investments in other large instruments for discovery science unrelated to biotechnology may be viewed as expendable in a post-pandemic world of enormous financial pressures, and the consequences for institutions performing the most fundamental science would be particularly concerning.

CONDUCT OF RESEARCH

Pandemic-induced disruptions have impacted field work in multiple disciplines. As an illustrative example, consider Earth system science. The understanding of our planet, its climate, our place on it, and the securing of public safety when faced with natural disasters and extreme weather involves the collection of data over long periods of time and over great distances by a suite of ships, aircraft, networks of sensors, and international collaborative projects. Since early 2020 and owing to the pandemic, researchers have lost or have had diminished access for at least one season to sites that are weather dependent, such as the Arctic and Antarctica. Collection and analysis of sets of data that require months or even years of observations are experiencing a break in continuity. Observations of the atmosphere taken routinely from passenger and cargo planes are transmitted to weather services and used in worldwide weather forecasts as well as atmosphere and climate research. The World Meteorological Organization (2020) recently released a statement expressing increasing concern over the loss of this data stream and the potential for degraded forecast accuracy. Such losses may be compounded by missed network maintenance and upgrades from ocean observational networks that provide important data sets for research, weather forecasting, and climate projections/analyses. Observational astronomy and all field sciences face similar challenges.

> **Although the pandemic has made my world physically smaller because I have been sheltering at home, my world is now mentally larger through the connections I've made to new worlds of thoughts and ideas.** – France Córdova

While research that depends on field work and/or experimental facilities has already suffered during the pandemic, other types of scientific endeavor are poised to blaze new trails as some degree of normalcy returns. The scientific enterprise has been trending toward more inter- and transdisciplinary research over the years. The pandemic may accelerate that trend.

One exciting opportunity is convergence research—a means to catalyze scientific discovery and innovation for solving vexing research problems by intentionally integrating knowledge, methods, and expertise from intellectually diverse researchers and fields of endeavor. To open new avenues of inquiry, convergence research teams must develop sustained relationships and potentially reframe the research questions themselves. Whereas this type of research has been growing rapidly for some time, the pandemic is revealing opportunities for more productive convergent research by means of virtual connectivity and the interactions thereby enabled. One such example, the Folding@home project, conducts simulations of protein dynamics and has been harnessing the computing power of citizen-scientist volunteers to help search for a cure to COVID-19 (Folding@home, 2020).

> **Conferences and webinars, previously reserved for only a few people, are now open to the public. This expands our fields of inquiry to those in other disciplines who might be inspired to collaborate in new ways.** – France Córdova

The pandemic-related increase in the use of virtual connectivity is also having an unexpected fortuitous impact on the growth in conference, symposium, and workshop participation. Professional scientific societies that organize these events pivoted in a matter of weeks to plan online-only scientific conferences and meetings. Going forward, hybrid virtual and physical events in a post-pandemic environment may be deployed. Indeed, virtual interactions offer the possibility of increased participation in the scientific enterprise by groups and individuals that have not historically been included.

Virtualization has also been embraced by some governmental entities to open communication channels to a much broader audience. For example, a U.S. Air Force online workshop held early in the pandemic and targeted at the electric air-mobility community had more than 5,000 participants, resulting in a community outreach far more diverse and inclusive than originally envisioned. AIP Member Societies are among those who have successfully deployed such conferences. For instance, the CLEO conference from The Optical Society reached 20,000 participants from 75 countries in early May 2020, compared with 3,800 registrants for the in-person-only CLEO 2019 conference held in San Jose, CA.

One promising pandemic-related development that could address the long-standing challenge of rapid translation of knowledge from universities to industry concerns technology-licensing processes that are typified by long negotiations over intellectual property ownership, royalties, liabilities, publishing rights, and even export controls. As a result of the urgency of accessing relevant university research to combat the novel coronavirus, a "COVID-19 Technology Access Framework" (2020), initially developed by Stanford University, Harvard University, and MIT, has since been adopted by 20 other universities and institutions in the United States. The goal of this framework is for universities to facilitate "rapidly executable non-exclusive royalty-free licenses … for the purpose of making and distributing products to prevent, diagnose and treat COVID-19 infection during the pandemic and for a short period thereafter" ("COVID-19 Technology Access Framework," 2020, para. 3). One can hope that the demonstration that the transition of knowledge to application can be dramatically accelerated will inspire much broader application of the processes that enabled this important breakthrough in technology transfer.

International Collaboration

Whereas technology deployed widely since the pandemic started has enabled global participation in scientific meetings, and video conferencing has been essential for continued communications among scientists around the globe, collaborations across geographic distances, especially international ones, have been strained. Pre-pandemic, scientists were accustomed to traveling freely to collaborate, exchange ideas, and conduct experiments (Wagner et al., 2015). Before the pandemic, close to one-quarter of all published scientific papers were the result of international collaboration, and these publications have tended to be more highly cited (National Science Board, National Science Foundation, 2019a). But travel restrictions coinciding with the rise of the pandemic have impeded scientific interactions.

> **Scientists are uniting worldwide in pursuit of solutions to this devastating crisis, and our bright hope is that international coordination can be a new template for other scientific challenges.**
> – Philip Bucksbaum

Travel concerns aimed at decreasing the international transmission of the virus are warranted. However, the inappropriate treatment of international students and scholars—especially U.S.-based scientists of Chinese descent—is not. Visa restrictions and the closure of consulates around the globe are likely to have grave consequences for the U.S. scientific enterprise and the technologies that flow from it. The U.S. has a well-earned reputation as a magnet for creative, ambitious, intelligent, and productive scientist-immigrants (National Science Board, National Science Foundation, 2020). However, a recent survey by the American Physical Society showed that, even before the pandemic, physics graduate students perceived that other nations are more welcoming to international students (Johnson, 2018), and recent statistics suggest that the rate at which students are coming to and staying in the U.S. is decreasing (National Science Board, National Science Foundation, 2020). Recent policy decisions to restrict future immigration to the United States will make it even more difficult to attract the top-level foreign-born talent to the United States that we need to fill positions in the physical sciences throughout the research enterprise and the broader economy. Adding to the concern is the fact that many current holders of student and employment visas are facing rescission of their status because the pandemic has made it impossible to meet specific requirements to maintain their status in this country. Whereas this situation may in time lead to the development of a more robust pipeline of domestic scientific talent, the domestic pipeline will take time to fill, and there will almost certainly be a gap when the demand for trained scientific talent outstrips supply. The impact on the U.S. economy as well as leadership in science and technology is likely to be severe.

Scientific Societies

AIP's ten Member Societies represent more than 120,000 scientists, engineers, teachers, practitioners, and students in the physical sciences. The work of their members, published in society journals and highlighted in talks at society conferences, undergirds the success of U.S. discovery and innovation. The social interaction, policy considerations, and knowledge provided by societies serve as "connective tissue" for the science and engineering community.

Scientific societies in the physical sciences have historically derived much of their financial livelihood from large-scale conferences and subscription publications containing peer-reviewed articles, which enables them to provide services and support to their membership communities. Even before the pandemic, the business model of the societies was being challenged by the revolution sweeping the publishing industry. The cancellation of in-person conferences caused by the pandemic has further challenged the viability of these and other scientific organizations. Although there have been many successful transitions to online events with outstanding participation by society members and guests, a new business model that will sustain the organizations and the services they offer has yet to develop. Until then, the entire set of services offered by scientific societies and the critical role they play in the advancement of scientific discovery is at risk.

FUTURE ACTION

Many trends in the science research enterprise, both optimistic and ominous, that the community observed before the pandemic have come into clearer, more urgent focus in these first four months of the global emergency. The impacts the pandemic has had on the workforce, on research infrastructure, on research facilities, and on the conduct of research are outlined in this report. The science and engineering communities will need to work in tandem across government, academia, and the private sector to navigate the current challenges, harness the best coping strategies, and devise new ways of moving the frontiers of science forward.

> **The physical sciences have the potential to emerge from the pandemic with a new and larger mission.**
> – Jonathan Bagger

Our era is analogous in many ways to the world Vannevar Bush faced in the mid-20th century following a ten-year depression and a world war. Seventy-five years after the publication of his report “Science, the Endless Frontier” (Bush, 1945), physical scientists are poised to make critical new contributions to the nation’s scientific and technological enterprise. They continue to make breakthroughs in our understanding of the universe, planet Earth, and life itself. Such discoveries address our need as humans to investigate and understand our world. Equally important, they can lead to transformative technologies that enable us to address global-scale challenges and secure a healthy future.

The COVID-19 pandemic presents our physical sciences community and the broader research enterprise with a clear and present call to action. We can emerge from this crisis stronger than ever before, but we need to recognize threats to the scientific enterprise and act now to mitigate them. We need to draw upon the resiliency and innovation inherent in the physical sciences to make a path forward to a prosperous future.

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AIP Panel on the COVID-19 Pandemic's Impact on the Physical Sciences Enterprise

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TRIUMF

Phil Bucksbaum
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Julia Phillips (Chair) is Director Emerita and Retired Vice President and Chief Technology Officer, Sandia National Laboratories. She is past president of the Materials Research Society, an AIP Affiliated Society. She currently serves on the National Science Board and is the Chair of the Division of Engineering and Physical Sciences of the National Academies of Sciences, Engineering and Medicine.

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Jonathan Bagger is Director of TRIUMF, Canada's particle accelerator center. He has served in that role since 2014. Prior to TRIUMF, he served as Krieger-Eisenhower Professor at the Johns Hopkins University, Chair of the Department of Physics and Astronomy, and Vice Provost for Graduate and Postdoctoral Programs.

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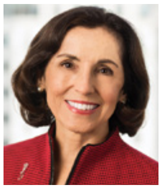

France Córdova served most recently as the 14th Director of the National Science Foundation (NSF), completing her six year term on March 30, 2020. She is president emerita of Purdue University, and chancellor emerita of the University of California, Riverside. Previously, she served as NASA's chief scientist and Chair of the Smithsonian Institution's Board of Regents.

Eric Isaacs is the 11th president of the Carnegie Institution. Before joining Carnegie in July 2018, Isaacs served at the University of Chicago as the Robert A. Millikan Distinguished Service Professor, Department of Physics and the James Franck Institute, as the Executive Vice President for Research, Innovation and National Laboratories and as Provost. Isaacs served as CEO of UChicago Argonne, LLC, Vice-Chairman of the Board of Governors for Argonne National Laboratory and currently chairs the SLAC National Accelerator Laboratory Scientific Programs Committee at Stanford University.

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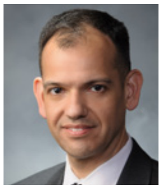

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Carl Wieman holds a joint appointment in the Physics Department and the Graduate School of Education at Stanford University. He is also the DRC Professor in the Stanford University School of Engineering. In 2001, he won the Nobel Prize in Physics, along with Eric Cornell and Wolfgang Ketterle, for fundamental studies of the Bose-Einstein condensate. Wieman was nominated to be The White House's Office of Science and Technology Policy Associate Director of Science in 2010 and served there for two years.