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"National Science Foundation Part II: Future Opportunities and Challenges for Science"

Introduction

In July 1945, Vannevar Bush, the head of the Office of Scientific Research and Development during World War II and one of my predecessors at MIT, sent the White House a landmark report titled, *Science - the Endless Frontier*. In that report, Bush outlined a vision for national investment in fundamental scientific research and the next generation of scientists. As Bush wrote in his letter of transmittal, "Science offers a largely unexplored hinterland for the pioneer who has the tools for his tasks. The rewards of such exploration both for the Nation and the individual are great. Scientific progress is one essential key to our security as a Nation, to our better health, to more jobs, to a higher standard of living, and to our cultural progress."

Bush's observations about the value of fundamental research to the Nation came from direct experience. He and his colleagues had witnessed how insights from fundamental physics research conducted over the previous 20 years earlier had unexpectedly found application in the atomic bomb and other tools of the U.S. victory in World War II. Bush also saw firsthand the contributions of academic scientists. He led the Radiation Laboratory on MIT's campus during the war years, driving improvements in radar that changed the course of history.

Bush also realized that had it not been for the specific circumstances of the war, other nations might have reaped the fruit of fundamental research that had been conducted largely in Europe. Peacetime federal investment in research and scientists, Bush realized, would not only allow the United States to surpass European nations as a source of basic research, but it would, if sustained, release the United States from its dependence on other nations for the basic scientific knowledge foundational to our security and prosperity.

The result of Bush's vision was the National Science Foundation (NSF). For nearly 70 years, NSF has catalyzed pioneering basic research in *all* fields of science and engineering (S&E). This research has opened new windows on our universe, made possible new industries, and given all Americans life-changing and life-saving technologies. Last year, NSF researchers—through the LIGO experiment (the Laser Interferometer Gravitational-Wave Observatory)—observed gravitational waves. These ripples in the fabric of the universe confirmed a key prediction of Einstein's theory of general relativity and opened a new approach to studying fundamental questions about the universe. LIGO is but one of NSF's many successes. NSF-funded research led to the invention of core routing protocols of the Internet, the original algorithms for the Google Search engine, and the lithium ion batteries and touch screen technologies of the iPhone. These and other developments have put hundreds of thousands if not millions of Americans to work and improved our Nation's prosperity and security.

Thanks to nearly 70 years of sustained federal investment in basic research, today's hinterlands of science differ from those of 1945. However, Bush's conviction about the importance of fundamental research to the United States' future economy, security, and prosperity remains every bit as relevant. As the second decade of this new century draws to a close, we find ourselves in an increasingly competitive global landscape with challenges that only the insights of science and technology and the ingenuity of the American workforce can help us address.

Meeting challenges and seizing the opportunities of today and tomorrow requires NSF, Congress, the Administration, and the research community to continue to work together to support U.S. S&E leadership. The past 70 years has provided us with a blueprint: sustained, predictable federal investment in curiosity-driven research across all fields of S&E, preparing a STEM-capable U.S. workforce, and maintaining the faith and confidence of the American public. Only by working together will our Nation realize the promise of the future.

Basic Research – The Bedrock

Fundamental, curiosity-driven research supported by NSF forms the basis of the U.S. science and technology ecosystem. As the largest source of federal support for non-medical, basic S&E research at U.S. colleges and universities, NSF drives the earliest stage of research. By building deep domain knowledge across all fields of S&E and laying the groundwork for commercialization through our Innovation Corps, Small Business Innovation Research, and Small Business Technology Transfer programs, NSF creates the foundation for the mission-oriented science pursued at other agencies and technological innovations that industry develops and brings to market.

Building the foundation for the science and technology enterprise is a critical task, not the least because science and technology have been responsible for over half of the growth in the U.S. economy since World War II. For its part, NSF fuels this enterprise by supporting a robust portfolio that includes a mix of core and directed research in all fields of S&E. Priorities for this portfolio are set using a mixed bottom-up and top-down approach that incorporates extensive input from the research community, NSF senior leadership, National Science Board (NSB; Board), the Administration, Congress, and industry. To ensure that every proposal NSF funds represents the best science in the national interest we use NSF's internationally-acclaimed merit review system.

Unsolicited core research allows researchers to follow the science and deepen fundamental knowledge in all fields. Rather than picking winners and losers *a priori*, this core research takes advantage of the creativity and ingenuity of the best minds America has to offer to drive science progress—often in unanticipated, groundbreaking directions. This crowd-sourced, grass-roots approach to finding ideas and research opportunities is the bedrock of NSF's success. It has created a stock of knowledge, tools, and methodologies that can be drawn on by industry, inventors and entrepreneurs, other scientists and engineers, and even the public for generations. Core research also lays the foundation of knowledge critical for pathbreaking work at the intersection of fields—what is often called interdisciplinary or convergent research.

NSF couples unsolicited core research with initiatives that encourage research germane to timely concerns and/or opportunities for U.S. scientific leadership. Directed initiatives help to break down disciplinary silos, accelerate progress on particularly challenging matters, and move science in directions that provide opportunities for strengthening U.S. global leadership. At the Board's urging, this year NSF identified 10 Big Ideas to help drive NSF's long-term research agenda. These ideas, which NSF has generated in concert with us and the community, provide a blueprint for today's scientific hinterlands that are ripe for exploration. The Big Ideas, which range from data science and the quantum leap to the human/technology frontier and the new Arctic, would enable NSF and the United States to push the boundaries of science, seize new opportunities, and ensure U.S. leadership on topics that are of national interest and global competition.

Scientific discoveries advance in concert with tools and technology, as the recent LIGO detection underscores. NSF's major facilities, including research vessels, supercomputers, telescopes, laboratories, and more, span the United States and the globe. These assets are vital to new discoveries and to sustaining the Nation's S&E enterprise. As we evaluate our facilities portfolio, NSF must balance continued operations and maintenance of our existing highly productive research infrastructure with the development of new, cutting-edge facilities. In addition, funding for facilities must be balanced against funding for research.

Workforce of the Future

Ensuring the long-term strength of the Nation's scientific workforce has always been a core component of NSF's mission. Our workforce has been—and continues to be—the essence of American innovation, economic competitiveness, and national security. In 1950, Vannevar Bush wrote that "the responsibility for the creation of new scientific knowledge - and for most of its application - rests on that small body of men and women who understand the fundamental laws of nature and are skilled in the techniques of scientific research." At that time, and for the next several decades, this meant scientists and engineers engaged in research and development (R&D) in government, academic, or industry laboratories.

How we think about this workforce has evolved—and expanded—since NSF's founding. While the education and training of scientists and engineers who perform fundamental research—our Nation's "Discoverers"—remains at the heart of NSF's mission, we now recognize that STEM capabilities are important to the *entire* U.S. workforce. As we look towards the next 70 years, the NSB believes that for our Nation to continue to thrive and lead in a globally competitive knowledge- and technology-intensive economy we must do more than create a "STEM workforce"; Congress, the Administration, business leaders, educators, and other decision-makers must work together to create a STEM-capable **U.S. workforce**.

Why is this so important to our Nation's future? Scientific and technological advances have transformed the workplace, especially in traditionally middle-class, blue-collar jobs such as manufacturing. These and many other jobs now demand higher levels of STEM knowledge and skill. In 2013, about 13.3 million U.S. workers were employed in a STEM job. Yet in a survey of individuals with at least a four-year degree, including many working in sales, marketing, and management, an estimated 17.7 million reported that their job required at least a bachelor's degree level of STEM expertise. And the number of non-STEM jobs requiring these skills is growing. Fostering a STEM-capable U.S. workforce ensures that all Americans are prepared to meet evolving workplace demands. Likewise, it ensures that existing and new American businesses have the talent necessary to compete and win in a global economy.

Creating a STEM-capable U.S. workforce requires a more expansive vision for STEM. This vision includes students and workers at all education levels, working on the farm, the factory floor, the laboratory, and everywhere in between using STEM capabilities to learn, adapt, install, debug, train, and maintain new processes or technologies. This vision includes women, traditionally underrepresented groups, and blue-collar workers who were hard hit by transformations in the domestic and global economy. This vision of a STEM-capable U.S. workforce does not replace what Vannevar Bush originally envisioned. It builds on that foundation to more fully mobilize what he called the vigorous "pioneer spirit" within our Nation and all of its people.

Turning this vision into a reality requires the public, private, and nonprofit sectors working together to ensure that all Americans have access to high-quality, affordable education and training. NSF is at the forefront of training the next generation of scientists and engineers, weaving education and training throughout our research grants in addition to dedicated Education and Human Resources (EHR) programs. I will focus on a few specific examples of how NSF contributes to achieving this vision.

NSF's **Graduate Research Fellowship Program** is the country's oldest fellowship program that directly supports graduate students in all STEM fields. Since 1952, NSF has funded over 50,000 Graduate Research Fellowships. NSF Fellows represent our future leaders and experts who can contribute significantly to research, teaching, and innovations in STEM. Currently, 42 Fellows have gone on to become Nobel laureates, and more than 450 have become members of the National Academy of Sciences.

Individuals with advanced degrees in STEM not only generate new knowledge through R&D activities that fuel innovation, but they also add value throughout our economy in STEM and non-STEM jobs alike. The **NSF Research Traineeship** (NRT) program ensures that graduate students develop the skills, knowledge, and competencies to pursue a range of STEM careers, especially in areas of national need, such as cybersecurity and data science, brain research, and the food-energy-water nexus. NRT emphasizes institutional capacity building and encourages partnerships with the private sector, non-governmental organizations, government agencies, national labs, and other relevant groups.

In addition to the fellowships and traineeships aimed at graduate students, NSF contributes to the education and training of the next generation of STEM-capable workers in other critical ways. The **Research Experiences for Undergraduates** (REU) program supports active research participation by undergraduate students in the areas of research funded by NSF. **EHR Core Research** (ECR) supports fundamental research into STEM learning and learning contexts, both formal and informal, from childhood through adulthood, for all groups, and from the earliest developmental stages of life through participation in the workforce. ECR provides a coherent foundation of research evidence to guide and improve STEM learning, STEM workforce development, and Federal STEM investment strategies.

Deeply embedded in the vision of a STEM-capable U.S. workforce is the imperative that all Americans be afforded the opportunity to participate in and reap the benefits of our Nation's great scientific endeavor. NSF supports this goal through its numerous investments aimed at tapping into populations historically underrepresented in STEM. For example, **NSF INCLUDES** ("Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science") is a national initiative designed to ensure that all Americans have access to educational and career opportunities enabled by STEM. Multiple NSF programs focus on elucidating how students can better understand and employ skills in computer science and computational thinking. The **Advanced Technological Education** (ATE) program is focused on two-year colleges and supports the education of technical workers who form the backbone of our S&E enterprise.

This vision for the future workforce can be realized only through the bipartisan efforts of Congress and the Administration. Recently, the President signed into law two bipartisan bills that exemplify this. The *Promoting Women in Entrepreneurship Act* mandates that NSF should "encourage its entrepreneurial programs to recruit and support women to extend their focus beyond the laboratory and into the commercial world." The *Inspiring the Next Space Pioneers, Innovators, Researchers, and Explorers (INSPIRE) Women Act* directs NASA to "encourage women and girls to study science, technology, engineering, and mathematics, pursue careers in aerospace, and further advance the Nation's space science and exploration efforts."

The bipartisan *American Innovation and Competitive Act* recognizes NSF's critical contributions to the development of a skilled, diverse, and globally competitive STEM-capable U.S. workforce. The NSB believes that NSF is poised to lead this development through its unique integration of basic research in all scientific fields with the education and training of a STEM-capable workforce. If we do not take advantage of this opportunity, U.S. businesses could look elsewhere to find the STEM-capable workers they need to compete. With the support of Congress, NSF will continue to make investments that ensure our Nation takes full advantage of the creativity, ingenuity, and hard work of all Americans.

Reproducibility, Transparency, and Confidence in Science

As scientists and engineers, we must be champions of transparency. It's not enough for the scientific community to point to our many accomplishments and expect public support. Our process, our institutions, and the conduct of research itself need to be unassailable. For the Foundation and Board this means ensuring the integrity of merit review and making sure that our grants and priorities fund the best ideas from the community and serve the national interest. It also means doing all of this in a way that can be understood and appreciated by taxpayers. NSF also needs to continue to work in partnership with research institutions to make sure that they comply with fiduciary requirements with the lowest possible administrative burden.

Scientists must work together to stamp out fraud, be honest about the limits of our knowledge, and generally hold ourselves to our highest ideals. Indeed, the reason we publish is to present our data and describe our methods openly to our colleagues and to the world. We want to help others to independently verify our conclusions, by reproducing our experiments where possible, and by designing and executing complementary experiments to test our conclusions. This openness is critical to maintaining credibility among our scientific peers and with the public. This requires not just the traditional sharing of experimental techniques and measurements, but also openness into underlying data, algorithms, and software.

Public support for civilian science has served our Nation well over the past 70 years. This support has been made possible in large part due to the trust and confidence of the American people. In 2014, 90% of Americans expressed "a great deal" or "some" confidence in the leaders of the scientific community—second only to the military.[1] But we must not be complacent, and reports over the last few years of irreproducible results should concern all scientists. They certainly concern the Board.

Science is an ongoing process of hypothesizing, observation, experimentation, and testing. The scientific theories that are derived from this process are the product of many repetitions of this cycle. By its very nature, reproducibility and repeatability are essential to science. However, the process of science is not simply one of direct duplication of results—repeating the same experiment using the same data and identical protocols. Not every study is exactly repeatable—for example, studies that use data from one-time events such as natural disasters or observations of astronomical phenomena. Instead, the process involves doing multiple experiments or making multiple observations of the same or similar objects or phenomena (often by independent investigators), perhaps with different data sets, perhaps with a variety of techniques, that together lead to a recognition and verification of the underlying processes that can explain the observed results. These constitute the built-in mechanisms for reproducibility and self-correction—mechanisms that depend on transparency.

Of course, science is a human endeavor, and, as such, is replete with frailties and imperfections. Scientists need to recognize that and vigorously embrace our self-correcting norm, addressing the reported rise in irreproducible findings and retractions with sunlight and experiments designed to cross-check published results. As the sociologist of science Robert Merton put it more than half a century ago "the activities of scientists are subject to rigorous policing, to a degree perhaps unparalleled in any other field of activity." Instances when scientists detect and address flaws in work constitute evidence of success, not failure, because they demonstrate the underlying protective mechanisms of science at work. In fact, it is not always the case that the inability to reproduce a result indicates unreliable data, protocols, or analysis. Sometimes, the lack of reproducibility is the sign of a fundamental discovery.

We also recognize that scientists currently have few incentives to reproduce the work of others. In academia, researchers encounter institutional pressure to focus on work that will lead to publications, in order to land a job in an extremely competitive academic market, to progress in their careers, and to obtain grants to continue to pursue their research. It is challenging to publish studies focused on reproducibility in high-impact, high prestige scientific journals where emphasis is placed on novel, positive results. The incentives and outlets for publishing negative findings or null results are limited. Recognizing this issue, there are now a few journals devoted to publishing reproducibility studies. However, these journals are still new and relatively low-impact. This presents both a challenge and an opportunity. As we strive to raise our standards of scientific excellence ever higher, we must evolve the incentive structure in academia to reward quality over quantity, and to value the vital work of enhancing scientific credibility through independent corroboration of published results.

[1] National Science Board (2016). *Science and Engineering Indicators 2016*. Chapter 7: "Science and Technology: Public Attitudes and Understanding."

Open access to data also presents a major opportunity and a challenge for science. We live in a data-rich age. “Big data” is already revolutionizing every area of science, allowing researchers to tackle previously elusive problems, including questions in the social, behavioral, and economic sciences that are among the hardest to crack. To harness the vast potential of these data streams, and to use the built-in mechanisms of science to ensure the integrity of published results, requires that the community have access to the underlying data. In addition, it is important that the protocols, experimental design, and techniques used to analyze the data be made available to the scientific community.

NSF’s commitment to data sharing, and to clear and open communication of research findings, is long-standing. However, the issues surrounding open data are complex. For example, much biomedical research relies on medical and clinical data for which there are strong legal and institutional protections to preserve privacy. These protections often prohibit data-sharing with other researchers or with the public. Likewise, industrial data may be proprietary. Another factor to be considered is the sheer volume of data—terabytes or even petabytes per day—that are generated by many modern experiments such as LIGO, particle physics experiments, and major astronomical surveys. The infrastructure required to make all data output from these facilities fully open access may have significant budgetary and personnel impacts for academic institutions and scientific laboratories. These factors, which will only grow in prominence in the future, should all be considered when developing "open access" policies, keeping in mind that a “one-size-fits-all” approach may prove problematic.

To increase public access to scientific publications and the data resulting from research funded by the Foundation, NSF has already implemented a plan consistent with the objectives set forth by the Office of Science and Technology Policy in February 2013. For all awards resulting from proposals submitted since January 25, 2016, NSF requires that either the version of record or the final accepted manuscript be deposited in a public access compliant repository; be available for download, reading, and analysis free of charge no later than 12 months after initial publication; have a minimum of two machine-readable metadata elements available free of charge upon initial publication; and be managed to ensure long-term preservation.

Protecting the integrity of science is the responsibility of everyone in our community. All researchers need to recognize that the best science is produced when they persistently search for flaws in their arguments. Industry as well as academia should publish its failed efforts to reproduce scientific findings. Grant funding agencies and professional scientific societies should continue to educate their communities about ways to communicate key scientific findings more effectively to the public. Journals should continue to ask for higher standards of transparency and reproducibility.

To protect the hard-earned confidence society has in the scientific enterprise, to preserve the role of science and innovation as drivers of our economy, and to sustain the dynamic progress that has brought such benefits to our society and our world, we scientists must hold ourselves to the highest standards. Just as preserving a system of government requires unceasing dedication and vigilance, so too does preserving the integrity of science.

As this Committee has recognized throughout its history, science and technology are essential elements to America’s future. We look forward to working with you toward a reauthorization of NSF that empowers scientists to ask fearless questions about ourselves, our world, and our universe and which supports exploration of those endless frontiers and hinterlands that represent the next steps in humanity’s collective search for truth and understanding.