**Testimony of**

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

Chairwoman Comstock, Ranking Member Lipinski, and other distinguished members of the Subcommittee. My name is Joan Ferrini-Mundy and I am the National Science Foundation's (NSF) Acting Chief Operating Officer. Prior to assuming my current role, I served as the NSF Assistant Director for Education and Human Resources since 2011. Thank you for the opportunity to testify before you today as NSF examines the societal challenges and opportunities for the nation's future, and NSF celebrates nearly 70 years of scientific accomplishment.

Since its establishment in 1950, the mission of NSF has been "to promote the progress of science; to advance the national health, prosperity and welfare; [and] to secure the national defense…" To do so, NSF has provided funding with an eye toward the frontier – in order to identify the most innovative and promising new research and education projects. NSF specifically targets its investments in discovery research at the edge of science and engineering. Here, advances push the boundaries of innovation and lead to progress and productivity. We prioritize such frontiers by maintaining our proven, "bottom-up" philosophy: the best ideas for research will come directly from the science and engineering community.

The cornerstone of NSF is the merit-based, competitive process that fosters the highest standards of excellence and accountability – standards that have been emulated at funding agencies around the world. To evaluate which proposals have the greatest potential to promote the progress of science, reviewers seek to identify two key factors in every proposal: intellectual merit and broader impacts. Evaluating proposals on the basis of these factors assures that the Foundations' activities are in the national interest.

NSF is vital to our nation because we invest in the fundamental research and the talented people who make the discoveries that transform our future. Those discoveries are a primary driver of the U.S. economy, enhance our nation's security, and give the country the competitive edge to remain a global leader.

**NSF: Where Discoveries and Discoverers Begin**

Federal support for research and education has fueled innovation and provided benefits to the American public for decades, and NSF has played a significant role in this success. For nearly 70 years, NSF has been a catalyst for the development of new ideas in science and engineering and supported the people who generate them.

In 1952, using one of NSF's first grants, Caltech professor Max Delbrück invented molecular biology techniques that enabled one of his students, James Watson, along with colleagues Rosalind Franklin, and Francis Crick, to determine the molecular structure of DNA. Since then, an entire biotechnology industry has bloomed and prospered and understanding of DNA has led to fundamental discoveries about genetics and disease. When considered as an industry in itself, biotech and its economic impact rival the mining, utilities, chemical, computing and electronics industries. In the 1960s and 1970s, NSF provided funding that resulted in seminal fundamental mathematical and process innovations for manufacturing that industry considered too risky to fund. These led directly to rapid prototyping, and revolutionized how products are designed and manufactured.

In the 1980s, NSF supported the very first computer science departments in U.S. universities, growing out of mathematics departments, establishing computer science as a mainstream area of scientific and engineering research, and providing a training ground for the first and subsequent generations of computer scientists and entrepreneurs. Today, NSF provides 82 percent of total federal support for research in computer science conducted in the nation's universities and colleges. Jobs related to computer and information technologies are among the most rapidly growing in the nation according to Bureau of Labor Statistics projections. In the 1990s, NSF supported pioneering research in the emerging field of nanotechnology, an early example of convergent research spanning multiple fields of science and engineering. Between 2001 and 2010, 175 start-ups and collaborations with over 1,200 companies came about as a direct result of NSF-supported centers and networks.

And just last year, NSF-funded infrastructure and research provided for the first direct detection of gravitational waves by NSF's Laser Interferometer Gravitational-Wave Observatory (LIGO). This historic discovery is the result of funding by NSF in the 1970s of the infrastructure needed to prove one of the predictions of Einstein's theory of General Relativity. This detection will continue to push the boundaries of science and discovery for decades to come.

Such investments in basic research often yield unexpected benefits. NSF's support of game theory, auction theory, and experimental economics through the Directorate for Social, Behavioral, and Economic Sciences provided the Federal Communications Commission (FCC) with its current system for apportioning the airwaves. Since 1994, FCC "spectrum auctions" have netted over $45 billion in revenue for the federal government and more than $200 billion in worldwide revenue. Although the payoff was unexpected at the time NSF started supporting game-theory research, the payoff is many times greater than the total investment NSF has made in social and behavioral sciences over our Agency's history.

These transformational discoveries often span many disciplinary fields. The breadth and flexibility of NSF's functions as specified in the NSF Organic Act[1] – "to initiate and support basic scientific research and programs to strengthen scientific research potential and science education programs at all levels, in the mathematical, physical, medical, biological, social, and other sciences, and to initiate and support research fundamental to the engineering process and programs to strengthen engineering research potential and engineering education programs at all levels in the various fields of engineering…." – enables the unexpected interdisciplinary connections that are so often critical to scientific advances.

[1] 42 U.S. Code § 1862

NSF is unique among science agencies in that education is fully integrated with the investment in science and engineering research, and has been since NSF's founding in 1950. By engaging the nation's experts in science and engineering in shaping the education of tomorrow's scientists and engineers, NSF's investments are critical in ensuring that the most talented and innovative people are well prepared to do science and engineering. In addition, having a science, technology, engineering, and mathematics (STEM) literate society is also critical to promoting the progress of science. As Vannevar Bush wrote in *Science – The Endless Frontier*, "Basic scientific research is scientific capital…How do we increase this scientific capital? First, we must have plenty of men and women trained in science, for upon them depends both the creation of new knowledge and its application to practical purposes." In the 1950s NSF began its Graduate Research Fellowship Program, providing support for graduate education for our nation's best and brightest. Over the years NSF has supported over 50,000 fellows, 43 of whom have received Nobel Prizes. NSF-funded evidence-based innovations in K-12, undergraduate, and informal education have led to major shifts in the depth and quality of science and mathematics instruction, opportunities for research and direct collaboration with scientists that prepares undergraduates to pursue science and engineering careers, and inspirational out-of-school learning opportunities that draw young people into science.

**Responsiveness to National Needs**

NSF may not be the largest agency that funds science and engineering research, but our size serves to keep us nimble. The NSF portfolio of funded projects is continually evolving as the science and engineering communities identify and pursue new research at the frontiers of knowledge. An essential part of our mission is to constantly allow for the rethinking of established categories and traditional perspectives as needed to promote the progress of science. This ability is more important than ever, as conventional boundaries constantly shift and disappear – boundaries between disciplines, between science and engineering, and between what is fundamental and what is applied. NSF, with its mandate to support all fields of science and engineering, is uniquely positioned to meet the needs of researchers exploring human knowledge at these interfaces, and those who are establishing new interfaces, whether we are supporting interdisciplinary conferences, enabling cyber-sharing of data and information, or encouraging new collaborations and partnerships across disciplines.

NSF's comprehensive and flexible support of meritorious projects with broad societal impacts enables the Foundation to identify and foster both fundamental and transformative discoveries within and among fields of inquiry. NSF is able to support emerging fields, high-risk ideas, interdisciplinary collaborations, and research that pushes, and even transforms, the very frontiers of knowledge. In these ways, NSF's discoveries inspire the American public—and the world.

NSF's organization mirrors the ways that science and engineering are organized and conducted in universities. Our portfolio spans the biological sciences, computer and information science and engineering, engineering, geosciences, mathematical and physical sciences, and social, behavioral, and economic sciences – encompassing both research and education in these areas. NSF also carries out specific national responsibilities for polar programs and US operations in Antarctica; provides cyberinfrastructure, including high performance computing, used by colleagues funded by multiple federal agencies; fosters international science and engineering; operates scientific instruments and facilities used by researchers worldwide; and successfully engages in a range of responsibilities related to the nation's overall capabilities in science and engineering. Key among those is providing statistical resources on the overall U.S. and international research and development enterprise through our statistical agency, the National Center for Science and Engineering Statistics.

The 25-member National Science Board and the NSF Director jointly pursue the goals and function of the NSF, including the duty to "recommend and encourage the pursuit of national policies for the promotion of research and education in science and engineering."

## Priority Setting and Strategic Planning

NSF constantly strives for a portfolio of investments that best meets the needs of the Nation. The planning and development of that portfolio is an ongoing, multifaceted process for the agency. It engages the National Science Board, incorporates Administration guidance, and addresses requirements established in Congressional legislation. It reflects discussions of emerging areas of science and engineering with NSF's Advisory Committees. And, it draws on a wide array of inputs such as studies by the National Academies and decadal surveys that set priorities for our disciplines. And finally, it incorporates the inputs and analyses of NSF scientific staff from the nearly 50,000 proposals received annually at NSF from the research community, which reflect interests and potential new frontier opportunities.

NSF's periodic strategic plans[2], developed in partnership with the National Science Board, are also an important component of setting priorities. The strategic plan is based on NSF's uniqueness as a federal agency, with attention to the wide range of fields within the scope of its mission and its ability to support the broad interdisciplinary collaborations needed to advance discovery. Our plan will encompass investments in projects, people, and infrastructure with a goal of supporting significant discoveries that will help to: stimulate economic growth; improve the quality of life for Americans; and deepen our understanding of the universe around us. In preparation for developing the new plan (2018 – 2022), since August 2016, NSF has been seeking wide input[3]. We anticipate that the final version of NSF's updated strategic plan will be submitted to Congress with the President's FY 2019 budget request.

Discussions among leadership within NSF are structured so that the directorates work together to identify and pursue the most important priorities and greatest challenges -- regardless of discipline. The cooperation among the directorates, especially at the leadership level, is the defining characteristic of the process. This cooperation allows the NSF Director to present a budget on the frontier of science and engineering. It often results in significant interdisciplinary efforts that span several directorates and are possible because of the flexibility afforded to NSF through its funding structure. For instance, such NSF-wide efforts as Innovations at the Nexus of Food, Energy, and Water Systems, which is seeking to "catalyze well-integrated interdisciplinary and convergent research to transform scientific understanding of the FEW nexus (integrating all three components rather than addressing them separately), in order to improve system function and management, address system stress, increase resilience, and ensure sustainability" indicate NSF's ability to prioritize key areas of societal need.

NSF's current process fosters cooperation across disciplines, provides flexibility to pursue emerging interdisciplinary opportunities, and draws fully upon input from the community, best responds to and anticipates the nation's needs and enables the agency to fulfill its responsibilities for strengthening U.S. science and engineering overall, in keeping with the NSF mission.

## The Science of Tomorrow

At NSF, we constantly look toward the frontier in order to identify the most innovative and promising directions for research and education. In *Science – The Endless Frontier*, Vannevar Bush wrote:

> *Basic research leads to new knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn. New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science. Today it is truer than ever that basic research is the pacemaker of technological progress. In the nineteenth century, Yankee*

[2] https://www.nsf.gov/about/performance/strategic_plan.jsp
[3] https://www.nsf.gov/od/oia/strategicplan/feedback.jsp

*mechanical ingenuity, building largely upon the basic discoveries of European scientists, could greatly advance the technical arts. Now the situation is different. A nation which depends upon others for its new basic scientific knowledge will be slow in its industrial progress and weak in its competitive position in world trade, regardless of its mechanical skill.*

As we look ahead to the coming decades, we must envision bold questions that will drive NSF's long-term agenda for research and education investment -- questions that will ensure future U.S. generations continue to reap the benefits of fundamental research in science and engineering. This is the reason NSF developed the "Ten Big Ideas."[4] These ideas capitalize on what NSF does best: catalyze interest and investment in fundamental research, which is the basis for discovery, invention and innovation. They are meant to suggest a set of cutting-edge research agendas and processes that are uniquely suited for NSF's broad portfolio of investments, and will require collaborations with industry, private foundations, other federal agencies, scientific societies, and education partners ranging from K-12 systems, to community colleges, to universities. Funding the research that will advance these ideas, and efforts to develop the talented people who can pursue them, will push forward the frontiers of U.S.-based science and engineering, contribute innovative approaches to solving some of the most pressing problems the world faces, and lead to unimagined discoveries that can change lives.

The work of today's NSF-funded researchers provides previews of the science and engineering of tomorrow. The need for the research to be robust and reliable so that science has the confidence of the public and of policy makers is paramount. And, to enable collaboration, replication, and wider access to science, concepts of open science are developing, being enacted, and advancing rapidly in all fields. Because the complex problems being addressed by scientists and engineers frequently require expertise from multiple disciplines, the science of tomorrow is increasingly interdisciplinary and convergent across multiple fields of science. And finally, tomorrow's science and engineering advances will be accomplished by people who are being educated today – both in our nation's formal education systems ranging from K-12 schools through graduate school, as well as in informal and self-directed learning environments that range from educational television, to museums, to Massive Open Online Courses (MOOCs), to certificate and badging programs. Thus the preparation of the STEM and STEM-capable workforces is essential.

**Interdisciplinarity and Convergence in Science and Engineering**

The National Academies of Sciences defines interdisciplinary, or convergent, research as "a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice."[5]

NSF has long recognized the value of interdisciplinary research in pushing fields forward and accelerating scientific discovery. Important research ideas often transcend the scope of a single discipline or program. NSF also understands that the integration of research and education through interdisciplinary training prepares a workforce that undertakes scientific challenges in innovative ways. Thus, NSF gives high priority to promoting interdisciplinary research and supports it through a number of specific solicitations. NSF also allows unsolicited interdisciplinary proposals for ideas that are in novel or emerging areas extending beyond any particular current NSF program.

Numerous NSF programs are designed explicitly to be interdisciplinary, often involving several NSF directorates. The NSF *Understanding the Brain* Initiative, for instance, involves multiple NSF directorates:

[4] https://www.nsf.gov/about/congress/reports/nsf_big_ideas.pdf
[5] Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond (2014)

the Biological Sciences; the Mathematical and Physical Sciences; the Social, Behavioral, and Economic Sciences; and Computer and Information Science and Engineering. NSF also develops activity portfolios focusing on areas of national interest, often in collaboration with other federal agencies. For example, NSF has considerable investment in *Safe and Trustworthy Computing*, another initiative that spans several directorates including: Computer and Information Science and Engineering; Engineering, Mathematical and Physical Sciences; Social, Behavioral, and Economic Sciences: and Education and Human Resources. In addition other agencies, including the Department of Homeland Security and the Office of Personnel Management are involved, because of the need for workforce development.

Because the challenges that we face as a society are often complex and require an integrative, collaborative approach, these areas are often interdisciplinary and NSF is poised, as a nimble agency with flexibility, to arrange for funding opportunities that address them as they emerge. NSF's Centers and programs are designed to bring together interdisciplinary research teams, and NSF promotes interdisciplinary research through programs that support development of the next generation of researchers, such as the NSF Research Traineeship Program.

**Robust and Reliable Science**

In order for advances in science and engineering to proceed and have impact it is critical that the public and policymakers have confidence in the robustness and reliability of science. It is also critical that scientists be able to rely on the results of others and build on them. Producing and disseminating scientific knowledge are at the heart of the research enterprise and are central to the mission of NSF. To succeed in our mission, the Foundation is constructing and implementing a framework for fostering scientific "reliability" – the term used within NSF to encompass characteristics of published results in which others have confidence and on which they can build. Because different research practices are appropriate and effective in different scientific and engineering domains, any such framework must accommodate the substantial variety of research that NSF funds. While there are common themes such as clear presentation of methods, appropriate and rigorous statistical analyses, and long-term availability of data that contribute to the reliability of all research, constructing a useful framework requires a broad view of research results as more than observations and conclusions but also as data, calculations, analytic methods, and simulations along with the models and software on which they rest.

A number of factors can contribute to lack of reproducibility of scientific results. Several of those factors have to do with the ways in which research is reported. For instance, details about workflows, methodological steps, and statistical analyses employed need to be clearly specified. NSF is directly addressing the problem of irreproducibility with a multi-pronged approach. We have entered an agreement with the National Academy of Sciences, as specified in the American Innovation and Competitiveness Act, where an Academy committee will assess research and data reproducibility and replicability issues in interdisciplinary research, and make recommendations for improving rigor and transparency in scientific research. Each NSF directorate also has taken up deeper looks into the particular issues of robust and reliable science for their own disciplinary domains, where the nature of scientific inquiry varies considerably. For instance, issues of replicability for mathematicians proving theorems are quite different from those of engineers designing tools and devices, or for social scientists conducting ethnographic inquiries. The education of the next generation of researchers is important and will vary by field. Also, standards and expectations in scientific journals, the research community, and professional societies have an important part to play in emphasizing the critical nature of replication and reproducibility in science.

To further inform continued development and implementation of our framework for fostering scientific reliability, the Foundation is engaged in a wide-ranging examination of issues related to scientific reliability both internally and in consultation with our scientific communities. All of the NSF directorates are examining the nuances of reliability relevant to their scientific disciplines, and all have had specific agenda items on the topic during their respective Advisory Committee meetings in recent years. Several directorates have funded pilot reproducibility studies, and sponsored workshops on the topic to hear from a broad range of stakeholders in the research enterprise, including investigators, other federal agencies, business and industry, private foundations, journal editors, and professional societies.

These activities are ongoing and are expected to inform an agenda that deepens our knowledge about factors that compromise scientific reliability and guides our efforts to improve it in NSF-funded work. An internal working group has been tasked with proposing NSF policy and practice changes to improve scientific reliability in NSF-funded work. Possibilities include strengthening the agency's guidelines for data management plans and the reporting requirements for the research we fund. Ensuring reliability of scientific findings rests on efforts from all corners of the research enterprise and therefore NSF will continue to operate in a transparent fashion, inviting input on its activities from staff across the Foundation and the external scientific communities that we serve.

**Opportunities for Open Science and Data Sharing**

Openness and data sharing in science are already leading to acceleration of discovery, efficiency in analyses, more rapid efforts to conduct replication studies, and innovation in approaches to analysis and methodologies. In addition, when open science principles are applied to government-funded science, new levels of access and transparency are available to the public as well as the private sector, generating the potential of wider and more effective use of funded work. NSF has an agency priority goal aimed at public participation in scientific research which builds on the idea of "citizen science", encouraging the public to participate in data collection, as in the bird observations collected through the Cornell Laboratory of Ornithology, and also in finding patterns and events, as is possible with various public data sets from astronomy.

With technological advances that allow for more ubiquitous data collection through sensors and other instrumenting of our environment, the potential for science to advance through open science and data sharing increases. Indeed, one of NSF's "Ten Big Ideas" is Harnessing Data for 21st Century Science and Engineering. And, with this emphasis on open science comes the development of new fields of scientific practice and inquiry, such as data science. NSF is already funding efforts to determine how to best educate the next generation of scientists who can be leaders in data-enabled science and engineering.

NSF is part of the movement toward open science through a variety of approaches. In 2015, NSF developed a plan outlining a framework for activities to increase public access to scientific publications and digital scientific data resulting from research the foundation funds. The plan, entitled "Today's Data, Tomorrow's Discoveries"[6], sets forth the requirement that NSF funded investigators are expected to share with other researchers, at no more than incremental cost and within a reasonable time, the primary data, samples, physical collections and other supporting materials created or gathered in the course of work under NSF grants. Grantees are expected to encourage and facilitate such sharing. NSF also requires that articles derived from NSF-funded research that appear in peer-reviewed scholarly journals and papers in juried conference proceedings or transactions be deposited in a public access-compliant repository and be available for download, reading and analysis within one year of publication. And, since 2011, NSF has required all proposals to provide information about plans for data management and sharing of the products of research. Prospective principal investigators must outline in detail such things as the standards to be used for data and metadata format and content, and policies for access and sharing with attention to issues of privacy, confidentiality, and intellectual property, and plans for archiving.

[6] https://www.nsf.gov/pubs/2015/nsf15052/nsf15052.pdf

**Preparing the STEM Workforce and a STEM-Literate Society**

In our efforts to advance the frontiers of knowledge and spur innovation, and in ensuring the success of the progress of tomorrow's science and engineering, NSF also aims to develop the nation's talent pool and support the creation of a highly skilled workforce that can be engaged in STEM in a variety of ways, at a variety of levels. This has a profound, and lasting, impact. NSF's education and STEM workforce investments, centered in the Directorate for Education and Human Resources (EHR) and spanning the entire agency, fund activities that support students, teachers, researchers, and the public. The EHR investment in fundamental STEM education research helps build the nation's knowledge base for strategically and efficiently improving STEM learning.

NSF-funded research is characterized by its breadth across all fields of science, and by the assumption that we cannot predict which field of science, or which interdisciplinary mix, will give rise to the next most important discovery that could reshape our lives or society. NSF, with its commitment to investing in fundamental research, has long recognized that any science being applied to practical problems, whether it be developing strong encryption for cybersecurity, to training soldiers in visual recognition as they encounter unfamiliar enemies, rests on fundamental results, theory, and principles. Thus our investment in the training of PhD level scientists and engineers, who become expert in the fundamentals of the NSF-supported disciplinary areas as part of their training, are essential in advancing that work to the new levels that can ultimately offer solutions to problems in the national interest.

For America to continue to lead the world in science and technology innovation, it must have the most knowledgeable and skilled STEM workers in the world. NSF prioritizes the integration of its education and science investments. Our programs support learners at all ages, inside and outside of school, with the goals of inspiring them in STEM and helping them gain access to the complex and powerful concepts and tools of the STEM fields. This is not just the smart thing to do – it is the right thing to do for our country. By drawing on the spectrum of talents and backgrounds of America's diverse populace, we can bring new approaches to scientific discovery, new vantage points to engineering design, and new insights to ensure innovation. And, by helping a public have access to the inspiration and wonder of science and engineering, we build the future. This is essential as we strive to remain competitive in the diverse international marketplace.

A long-standing focus of NSF's workforce development portfolio is on broadening the context of what it means to prepare the *entire* STEM workforce. With STEM playing an increasingly important role in the nation's technological innovation and economic growth, it is important that we provide the technical skills and infrastructure required for all workers to contribute to and take full advantage of today's economy. NSF has supported both two-year institutions and students enrolled in associate's degree programs and undergraduate research.

## Conclusion

In today's high-tech economy, the supply of new jobs is inextricably linked to the health of the nation's innovation endeavor. NSF support drives all aspects of innovation; NSF not only funds the discoveries that directly become the innovations of tomorrow, we fund the development of the discoverers.

Industry continues to rely upon government support for the high-risk, high-reward fundamental research that powers their successes. It is no accident that our country's most productive and competitive industries – including computers and communications, semiconductors, biotechnology, advanced manufacturing, health fields, and aerospace – are those that benefited the most from sustained federal investments in research and development.

I believe that America can continue to be on the leading edge of ideas and research. Through strong federal leadership, we can maintain the standing of our businesses and universities. We must not only maintain our position, we must actively seek to increase our strengths: leadership in fundamental discovery, including high-risk, high-reward transformational research; state-of-the-art facilities and scientific research infrastructure; and a world-class science and engineering workforce. With a firm commitment to these fundamental building blocks of our high-tech economy, we can solidify America's role as the world leader in innovation.

I've touched on just a handful of examples from NSF's diverse and vibrant portfolio. NSF's research and education activities support the nation's innovation enterprise. America's present and future strength, prosperity and global preeminence depend directly on fundamental research.

Madam Chairwoman and members of the Subcommittee, I hope my testimony explains NSF's transformative role in building our nation's future prosperity and continued leadership at the frontiers of discovery, innovation and learning. NSF investments in fundamental science and engineering have paid enormous dividends, improving the lives and livelihoods of generations of Americans.

This concludes my testimony. I thank you for your leadership. I will be pleased to answer any questions the Members may have.