Office of Science and Technology Policy
Executive Office of the President

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Introduction

The White House Office of Science and Technology Policy (OSTP)[1] has a broad mandate to: provide the President and the President's senior staff with accurate, relevant, and timely advice on the scientific and technological aspects of all issues before them; ensure the policies and programs developed across the Executive Branch are informed by sound science; and ensure that Federal investments in science and technology (S&T) are making the greatest possible contribution to economic prosperity, public health, environmental quality, and national security.

Technology has become increasingly important to policy, to the delivery of government services, and to the Nation as a whole. President Obama fulfilled a campaign pledge to appoint within OSTP the first-ever U.S. Chief Technology Officer (CTO), with the rank of Assistant to the President. The mission of the Office of the U.S. CTO within OSTP is to advise the President and the President's senior staff on how to harness the power of data, technology, and innovation on behalf of the American people—in so doing, the Office of the U.S. CTO continuously catalyzes and supports the Federal Government to better serve the American people.

In this memorandum, we: (1) highlight the profound impact President Obama's leadership has had in "reaffirming and strengthening America's role as the world's engine of scientific discovery and technological innovation,"[2] as he set out to do at the start of his Administration; (2) offer an overview of frontiers that the American S&T enterprise will advance in the coming decades; and (3) call for actions needed in the years ahead to include all Americans in driving continued innovation and progress across those frontiers.

OSTP continues to be optimistic about America's ongoing leadership in science and technology because of two exceptional characteristics of Americans. Americans continue to lead the world in our curiosity and desire to understand the world around us, which helps us innovate and improve the world around us. And, Americans are exceptionally diverse and can bring a wide range of experiences and backgrounds to solving the hardest problems. Our country's diversity continues to be the greatest source of its strength.

President Obama has repeatedly shown his commitment to inclusion, noting that, "research has shown that diverse groups are more effective at problem solving than homogeneous groups. Policies that promote diversity and inclusion will enhance our ability to draw from the broadest possible pool of talent, solve our toughest challenges, maximize employee engagement and innovation, and lead by example by setting a high standard for providing access to opportunity to all segments of our society."[3] Taking on the S&T frontiers that we describe in this memorandum requires including all Americans in leading innovation across industry, academia, and government.

[1] The Office of Science and Technology Policy was established in 1976 by Public Law 94-282.
[2] From remarks by President Obama on November 23, 2009 at the launch of his "Educate to Innovate" campaign for excellence in science, technology, engineering, and math education.
[3] Presidential Memorandum on *Promoting Diversity and Inclusion in the National Security Workforce* (October 5, 2016)

Record of Progress on Science, Technology, and Innovation

On January 20, 2009, President Obama issued a simple and powerful pledge: to restore science to its rightful place. Coming into office, the President was committed to reinvigorating the American scientific enterprise through a strong commitment to basic and applied research, innovation, and education; to ensuring integrity in science policy; and most importantly, to making decisions on the basis of evidence, rather than ideology. In a speech at the National Academy of Sciences in April 2009, the President called for expanded investments in research and development (R&D) and a renewed focus on science, technology, engineering, and math (STEM) education. He noted that science, technology, and innovation are essential to sustaining economic growth, enabling Americans to lead longer and healthier lives, limiting the harm from climate change, and providing U.S. armed forces and homeland defenders with the tools they need to succeed in every contingency.

In the nearly 8 years since, the full scope of the President's science, technology, and innovation agenda has been sweeping, and is already setting the stage for new industries and continued innovation in the years ahead. For example, President Obama and his Administration:

(1) **Increased science, technology, and innovation talent in the Executive Branch** by creating and empowering new technology leadership positions at the White House and in Federal agencies; reinvigorating the President's Council of Advisors on Science and Technology (PCAST); and recruiting, retaining, and empowering people with information, digital, collaboration, communication, data, and related technical backgrounds to improve government services and inject modern technology expertise into public policymaking.

(2) **Strengthened scientific integrity** by issuing and implementing a policy to ensure the public is able to "trust the science and scientific process informing public-policy decisions," by recruiting and retaining the highest-caliber scientists, by ensuring policy decisions are based on sound science, and by putting in place strong whistleblower protections.

(3) **Enacted a historic increase in research and development**—with $18.3 billion in R&D funding, the American Recovery and Reinvestment Act of February 2009 was part of the largest annual increase in R&D funding in America's history—and maintained R&D funding as a priority despite tight fiscal constraints.

(4) **Prioritized and encouraged broad participation in STEM education and the technology sector,** with the Nation now on track to meet the President's goal to train 100,000 additional excellent STEM teachers by 2021, with 100,000 engineers graduating yearly from American colleges and universities for the first time ever, with organizations around the country responding to the President's call to provide all U.S. students with access to rigorous computer-science education, and with over 1,500 employers hiring from new short-course training programs such as coding boot camps.

(5) **Supported American manufacturing innovation** through a national network of Manufacturing USA Institutes supported by over $600 million in Federal investment and matched by more than $1.3 billion in non-Federal investment, with more institutes on the way, and increased opportunities for Americans to make, design, create, and invent using new hardware and software tools and skills.

(6) **Expanded entrepreneurship across the Nation,** with venture-capital firms committing to advance entrepreneurship opportunities for women and underrepresented minorities, with nearly 80 companies committing to take action to broaden participation and make the technology workforce at each of their companies representative of the American people as soon as possible, with investors pledging to create more inclusiveness in their funding practices, with nearly 200,000 datasets now available to the public on Data.gov, and with more than 4 million full-text scientific journal articles now free and accessible to researchers, entrepreneurs, and the public.

(7) **Launched major new science initiatives to advance health care** through precision medicine, understanding the brain, accelerating progress in treating and preventing cancer, and combating antibiotic resistance.

(8) **Took unprecedented action to address climate change** through the successful December 2015 Paris Agreement; a comprehensive Climate Action Plan to cut carbon pollution, enhance resilience, and lead internationally; and the development of tools, services, and partnerships to make science and information about on climate change actionable for decision-makers across the Nation.

(9) **Expanded broadband access,** adding or improving more than 114,000 miles of broadband infrastructure and making high-speed connections available to more than 25,000 community institutions and fast 4G/LTE mobile broadband available to more than 98 percent of Americans.

(10) **Fostered a burgeoning private space sector and increased capabilities for our journey to Mars,** with the extension of the lifetime of the International Space Station's (ISS) until at least 2024 through the Administration's leadership, with American companies and NASA collaborating to deliver cargo to ISS, and with those companies on track to start ferrying astronauts to ISS within the next 2 years.

20 Science and Technology Frontiers

In October 2016, at the White House Frontiers Conference, President Obama encouraged Americans to imagine our Nation and the world in 50 years and beyond, and to explore America's potential to reach the frontiers that will make the world healthier, more prosperous, more equitable, and more secure.

In answer to the President's challenge, below we highlight 20 S&T frontiers where future investment and cross-sector collaboration will drive American innovation in the decades ahead, including:

- **Personal frontiers** in health care innovation and precision medicine;
- **Local frontiers** in building smart, inclusive communities that serve all residents;
- **National frontiers** in harnessing the potential of artificial intelligence, data science, machine learning, automation, robotics, and advanced computing to engage and benefit all Americans;
- **Global frontiers** in accelerating the clean-energy revolution and developing advanced climate information, tools, services, and collaborations; and
- **Interplanetary** frontiers in space exploration, including our journey to Mars.

Personal Frontiers

Science, technology, and innovation supported and encouraged by the Federal Government have made major contributions to helping Americans live longer, healthier lives. We have vaccines to protect us from devastating diseases such as cervical cancer, flu, and meningitis. We have developed an artificial retina and have achieved promising initial results on brain control of robotic prosthetic arms. Just as the

seeds for these breakthroughs were planted decades ago, President Obama's visionary investments in biomedical research, medicine, health, and the life sciences have set the stage for the cures, treatments, and innovations of the future. Frontiers in biomedicine include:

(1) **Developing precision medicine.** The next great revolution in medicine will emerge from an ability to use genomic, lifestyle, behavioral, environmental, imaging, and clinical data to understand health and disease, and to use those insights to develop tailored prevention approaches and medical treatments. To revolutionize how we improve health and treat disease, President Obama launched the Precision Medicine Initiative with these goals: (a) build a large research program that includes participants who volunteer their biomedical samples and health data, leveraging the diversity of the United States; (b) increase access to data so that researchers can better conduct science to enable groundbreaking new discoveries; (c) create a nimble framework for ensuring the accuracy of genomic-sequencing tests to support public safety; and (d) optimize the deployment of these technologies and research discoveries to medical practitioners.

(2) **Investing in neuroscience and neurotechnology.** Advances in neuroscience and neurotechnology offer promise for developing a comprehensive understanding of the brain in action and uncovering the mysteries that hold the key to future scientific breakthroughs in areas such as Alzheimer's and Parkinson's diseases, depression, and traumatic brain injury. Since April 2013, President Obama's BRAIN Initiative®—Brain Research through Advancing Innovative Neurotechnologies—has catalyzed more than $1.5 billion in public and private funds for novel neurotechnologies aimed at revolutionizing understanding of the human brain. BRAIN Initiative researchers and public-private collaborating organizations are pursuing an ambitious 10-year research agenda.

(3) **Combating antibiotic resistance.** The Centers for Disease Control and Prevention (CDC) estimate that drug-resistant bacteria cause 2 million illnesses and about 23,000 deaths each year in the United States alone. The Obama Administration issued a national strategy and a national action plan—both responsive to the recommendations of a PCAST report—for domestic and international efforts to prevent, detect, and control illness and death related to infections caused by antibiotic-resistant bacteria. OSTP and the Presidential Advisory Council on Combating Antibiotic Resistant Bacteria have noted the opportunity for the next Administration to pilot innovative economic models to encourage investment in antibiotic-drug development, to strengthen antibiotic-resistance surveillance in agricultural settings, and to develop a "one health" approach to combating antibiotic-resistant bacteria, encompassing human, animal, and environmental components.

(4) **Advancing biotechnology and global health security.** Advances in biotechnology have dramatically improved capabilities such as DNA sequencing, gene editing, gene synthesis, and high-throughput manipulation of biomolecules. These advances have reduced the cost and time required to develop biotechnology products and perform novel research. The Obama Administration released the National Bioeconomy Blueprint, led an effort to modernize the regulatory system for biotechnology products, and led biosafety and biosecurity improvements. The next Administration and the scientific community should consider continuing to track the ethical, legal, economic, security, safety, and social implications of biotechnology developments and participate in international discussions around appropriate oversight of biotechnology research and products. In addition, the United States has committed to assist at least 31 countries to achieve common, measurable targets of the Global Health Security Agenda for prevention, detection, and response to infectious disease outbreaks. Opportunities abound for the next Administration to advance S&T against infectious disease threats—especially for mosquito-vector control and through social and behavioral science and biotechnology—and to predict infectious-disease outbreaks through rapid data-sharing and "one health" approaches.

Local Frontiers

Many complex social challenges—from developing transportation systems that fuel equitable growth, to improving community-police relationships, to connecting small towns, tribal communities, and rural areas—will require cities and communities of all sizes to be hubs for innovation. The rapid pace of social innovation and technological change, including the rise of data science, machine learning, artificial intelligence, the sharing economy, social networks, ubiquitous sensor networks, and autonomous vehicles holds significant promise for addressing important challenges communities face throughout the country. Local S&T frontiers include:

(5) **Building smart communities and the Internet of Things.** "Smart Cities" are communities leveraging the "Internet of Things" (IoT) and information-technology tools, including data analytics and urban sensors, to improve the lives of all of their citizens. Federal research investments—with a continued focus needed on cybersecurity—and multisector technology partnerships can help local communities tackle key challenges such as reducing traffic congestion, fighting crime, fostering economic growth, managing the effects of a changing climate, and improving the delivery of city services. The White House Smart Cities Initiative has invested nearly $350 million from multiple Federal agencies in research and technology deployment in communities, with over 70 participating communities. The Opportunity Project has catalyzed the creation of over 40 new digital tools that use Federal and local data to increase access to opportunity in communities around the country by solving challenges such as helping families find affordable housing near jobs and transportation, matching unemployed Americans with jobs that meet their skills, and enabling local leaders to use data to better target investments.

(6) **Using innovation and data to improve policing and the criminal justice system.** As part of President Obama's commitment to ensuring that the power of data and technology are used to address the biggest challenges this country faces, the Police Data and Data Driven Justice Initiatives cultivate local advances in the use of data and technology in policing and the criminal-justice system. The Police Data Initiative supports local police department efforts in leveraging data to increase transparency and accountability and build trust with their communities. The Data-Driven Justice Initiative assists city, county, and State governments in using data-driven strategies to divert low-level offenders with mental illness out of the criminal justice system and to change approaches to pre-trial incarceration so that low-risk offenders no longer stay in jail simply because they cannot afford bond. These complementary initiatives each now support more than 100 jurisdictions—communities, counties, and states—and collectively reach over 95 million Americans.

(7) **Harnessing the ingenuity of citizen solvers and citizen scientists.** The Obama Administration has harnessed American ingenuity, driven local innovation, and engaged citizen solvers in communities across the Nation by increasing the use of open-innovation approaches including crowdsourcing, citizen science, and incentive prizes. Following guidance and legislation in 2010, over 700 incentive prize competitions have been featured on Challenge.gov from over 100 Federal agencies, with steady growth every year. Federal agencies and non-governmental organizations have used citizen science, crowdsourcing, and other innovative approaches to mobilize millions of people—including youth—to accomplish scientific work and improve their communities, from improving predictive models for coastal change and vulnerability to extreme storms, to tagging millions of archival records for the National Archives. Since 2014, OSTP has taken an active role in encouraging the increased use of these approaches to address scientific questions, issuing guidance to agency heads in 2015, and working with General Services Administration to launch CitizenScience.gov in early 2016. The next Administration should consider continuing to increase Federal Government efficiency and effectiveness through these open-innovation approaches.

(8) **Connecting Americans through broadband deployment and spectrum for wireless Internet access.** Recognizing the importance of broadband connectivity for American innovation, collaboration, economic growth, and well-being, the Administration—through initiatives including ConnectED, ConnectHOME, ConnectAll, the Global Connect Initiative, and increased USDA funding of broadband access for tribal communities—has expanded affordable high-speed broadband access, improved adoption, increased speeds, lowered costs, and narrowed the digital divide in the United States. The Administration has advanced international connectivity to bridge the global digital divide and promoted U.S. Internet governance priorities. And, the Administration has taken steps to ensure that there is sufficient spectrum, governed by sound policies to support fast, affordable, and reliable wireless Internet access and other longstanding and emerging technologies, including being on track to meet the President's goal of making available an additional 500MHz of spectrum for exclusive private and shared commercial use by 2020. Going forward, the next Administration should consider continued attention to these goals and to increasing the network-engineering expertise in the Federal Government to accelerate national and international deployment of Internet access and to maximize the benefits of our connected world.

National Frontiers

Emerging technologies carry both potential and risk, present policy challenges, and have economic, safety, security, and regulatory implications for the Nation, including for increasing access to opportunity for all Americans. National technology frontiers include:

(9) **Understanding the potential of AI, machine learning, and big data.** The Administration published a public report on AI, *Preparing for the Future of Artificial Intelligence*, accompanied by a *National Artificial Intelligence Research and Development Strategic Plan*. These documents detail how the Federal Government can take future steps to: use AI to advance social good and improve the operation of government; adapt regulations in a way that encourages innovation while protecting the public; ensure that applications of AI, including those that are not regulated, are fair, safe, and governable; develop the most skilled and diverse AI workforce, including addressing the current limited diversity in the technical-leadership ranks; and address the use of AI in weapons. This work built on earlier Obama Administration work on big data, including three Administration "Big Data" reports covering privacy, values, and fairness in algorithmic systems, ethics, and civil rights, and also PCAST and National Information Technology R&D Program (NITRD) reports on big data.

(10) **Developing robotics and intelligent systems.** Robotics and intelligent systems are technologies that seek to advance physical computational agents that complement, augment, enhance, or emulate human physical capabilities or human intelligence, and have the capacity to improve lives and advance the Nation's economy. OSTP has focused on: R&D investments, including through the National Robotics Initiative; capacity-building in the Federal Government; and providing technical input to the development of smart regulations governing the public and commercial use of such technologies. The Administration has also worked to improve regulatory frameworks for some applications, including the Federal Aviation Administration's integration of unmanned aircraft systems (UAS) into the National Airspace System and the Department of Transportation's work on developing a Federal Automated Vehicles policy. Future work is needed to formulate a Federal strategy for UAS privacy authority and responsibilities.

(11) **Investing in strategic computing.** The National Strategic Computing Initiative (NSCI) was created in July 2015, at President Obama's request, to ensure continued U.S. leadership in high-performance computing (HPC) and to maximize the benefits of HPC for the economy, scientific discovery, and national security. The initiative calls for the creation of a coordinated research, development, and

deployment strategy that draws on the strengths of Federal departments and agencies to accelerate progress on a range of critical applications—from predicting severe weather, to modeling the safety of the nation's nuclear weapons stockpile, to developing new drugs that are tailored to the needs of individual patients. Federal agencies have identified five strategic objectives: (a) accelerate the successful deployment and application of capable exascale computing; (b) ensure that new technologies support advances in data analytics as well as simulation and modeling; (c) explore and accelerate new paths for future computing architectures beyond the limits of today's silicon-based semiconductors; (d) promote a vibrant HPC ecosystem, including the workforce needed to design and use HPC; and (e) establish enduring cross-sector collaboration.

(12) **Supporting advanced manufacturing and a Nation of Makers.** To spur innovation in manufacturing, the Administration has created a growing network of advanced-manufacturing R&D hubs, known as Manufacturing USA. In addition, the Administration has increased support for advanced-manufacturing R&D by 40 percent since FY 2011, and has encouraged multi-agency collaboration in areas such as continuous manufacturing of pharmaceuticals, engineering biology for biomanufacturing, and biomanufacturing for regenerative medicine. Delivering on this vision will require: (a) spurring innovation through next-generation technologies; (b) making the United States more cost-competitive for production; (c) strengthening skills, communities, and supply chains to attract investment; and (d) leveling the playing field for international trade, opening access to foreign markets, and promoting investment in the United States. In addition, people's ability to design, create, and invent is being amplified by hardware and software tools such as computer-aided design software, laser cutters, accessible design tools, and 3D printers. The President's Nation of Makers Initiative is engaging innovators, private-sector leaders, and educators to increase the number of Americans that have the opportunity to participate in making, with a particular emphasis on K-12 education, workforce development, and manufacturing entrepreneurship.

Global Frontiers

Under President Obama, the United States has led global progress in addressing the challenge of climate change—including through the historic Paris Climate Agreement—and has advanced climate science, technology, and innovation to inform decisions and enable breakthroughs. Global frontiers include:

(13) **Advancing climate science, information, tools, and services.** Understanding and addressing the current and future impacts of global climate change requires sustained investments in climate science and services. It is essential that governments, businesses, researchers, and individual citizens have access to science-based information, tools, and services that can inform decision making. The Obama Administration launched the Climate Data Initiative, Climate Resilience Toolkit, and Partnership for Resilience and Preparedness to improve access to the Federal Government's climate data and tools. Thanks to this effort, more than 600 datasets and 200 tools have been made available. The Administration also released the Third National Climate Assessment, the most comprehensive assessment of climate impacts to date, through a user-friendly online interface, and created a sustained assessment process. In addition, the U.S. Government joined with private-sector partners to launch the Resilience Dialogues and Climate Services for Resilient Development, to connect climate information to on-the-ground decision making. Enhanced observations—particularly in areas such as the polar regions and much of the world's oceans that are inadequately monitored today—will be required to advance a more comprehensive understanding of global change.

(14) **Growing a clean-energy economy.** The Obama Administration has made the largest investments in cleaner and more efficient energy systems in the Nation's history, starting with over $90 billion in

the American Recovery and Reinvestment Act in 2009. As a result, the United States has seen dramatic increases in the proportions of energy and electricity coming from low- and no-carbon energy sources. Under President Obama's leadership, the United States has steadily expanded the reach and magnitude of its bilateral and multilateral cooperation with other countries in clean and efficient energy. The "Mission Innovation" initiative, launched by President Obama and other world leaders at the December 2015 climate conference in Paris, brings together 22 countries and the European Union that have pledged to double their governments' investments in clean-energy R&D over a period of 5 years. To complement this effort, the "Breakthrough Energy Coalition" of leading investors has pledged to support the commercialization of the discoveries that result from increased R&D funding. These initiatives will require continued attention and encouragement—including doubling U.S. clean energy R&D by 2021—from the U.S. Government.

(15) **Addressing climate change and national security.** The Obama Administration—through the February 2015 U.S. National Security Strategy and a September 2016 report from the National Intelligence Council—has recognized that global climate change is posing growing challenges to U.S. national security. Sea-level rise threatens operations and infrastructure at important naval bases, including this country's largest (in Norfolk, VA); extreme heat impairs the efficiency of troops and certain military equipment; military forces may be increasingly diverted to humanitarian missions following climate-related extreme events; chronic stresses from climate-change-accentuated phenomena such as droughts and crop failures can lead to civil unrest; and, eventually, flows of refugees from regions rendered less hospitable or even uninhabitable by climate change may produce political instability in areas critical to U.S. interests. President Obama directed Federal agencies in a September 2016 Presidential Memorandum to ensure that climate change is fully considered in national security doctrine, policies, and plans.

(16) **Increasing ocean resilience.** The health and productivity of the world's oceans are imperiled by a number of threats, including climate-change related warming and acidification, overfishing and destructive fishing practices, dead zones, and marine debris and pollution. The Obama Administration has pioneered ocean stewardship through the development of the first ever U.S. National Ocean Policy, as well as through the creation and expansion of Marine Protected Areas and National Monuments, which provide refuges of reduced stress for species. This science-based management and smart conservation will help to enhance ocean resilience to climate change.

Interplanetary Frontiers

At the beginning of his Administration, President Obama set out a new vision for space exploration. In 2010, the Administration restructured the U.S. civil space program to look forward to bold new goals; to collaborate with, rather than compete with, American entrepreneurs; and to broaden participation and take advantage of new technologies being created at NASA and in America's laboratories. These policies have fostered a burgeoning commercial-space sector that is creating new jobs and attracting venture capital. Looking ahead, frontiers in space exploration and space science include:

(17) **Supporting our Journey to Mars and a robust U.S. commercial-space market.** In April 2010, President Obama challenged the country to send American astronauts on a Journey to Mars in the 2030s. Continued development of advanced space technologies—including better life-support systems and efficient solar-powered electric propulsion systems—will be crucial to achieving President Obama's vision for space exploration. NASA already has started collaborating with industry to build the space modules or "habitats" in which U.S. astronauts will live and travel to Mars and other deep-space destinations. And in the coming years, the work NASA will do—in collaboration with private and international partners—to develop these deep-space habitats will

help reduce the barriers to private companies that envision building their own space stations in Earth orbit or beyond. NASA will soon provide companies the opportunity to add their own modules and other capabilities to the International Space Station. As NASA shifts the focus of its human exploration program to deep space, America's businesses will take a larger role in supporting space activities in Earth orbit.

(18) **Driving advancements in space science.** OSTP works with NASA, the National Science Foundation (NSF), and the Department of Energy (DOE) to ensure that Federally funded space-science activities comprise a robust portfolio of space-based missions, ground-based facilities, and research funding for astronomy, planetary science, and heliophysics. The Kepler Space Observatory, which was launched in March 2009, has discovered more than 2,330 extrasolar planets and more than 2,400 additional planet candidates to-date. Curiosity, the Mars Science Laboratory, has been exploring Gale Crater on Mars since it landed in 2011, discovering evidence of an ancient streambed, organic carbon in powdered rock samples, and methane in the Martian atmosphere. Construction of the Atacama Large Millimeter Array (ALMA)—funded by the United States through NSF with other international partners—was completed in 2011 with full science observations beginning in 2013. In July 2015, the New Horizons spacecraft flew by Pluto obtaining the first up-close images of the dwarf planet, and a year later, Juno arrived at Jupiter to begin collecting scientific data to understand the planet's structure and formation. Looking ahead, progress on the James Webb Space Telescope—designed to be the premier space-based observatory of the next decade, serving thousands of astronomers worldwide—is on track and on budget to meet a 2018 launch date. NSF and DOE, in collaboration with other partners, are supporting the development of the ground-based Large Synoptic Survey Telescope, which expects to see first light in 2019.

(19) **Enhancing prediction of and preparedness for space hazards.** OSTP and Federal agencies are identifying actions to extend and enhance prediction and preparedness for potentially hazardous near-Earth objects (NEOs) and define an approach for establishing reference NEO Earth-impact missions that can help the United States and its international partners detect, track, and respond to the threat of collision by a NEO. OSTP also worked with NASA to develop NASA's Asteroid Grand Challenge, an effort focused on finding all asteroid threats to human populations and knowing what to do about them. NASA's Asteroid Redirect Mission will, among other benefits, be used to demonstrate a promising asteroid-deflection technique called a gravity tractor. Also, in an effort to better plan for space weather hazards, OSTP led the development of the October 2015 National Space Weather Strategy and National Action Plan, and subsequently, President Obama signed an Executive Order in October 2016 to minimize the harm that space-weather events can cause across our Nation, save lives, and enhance national security. The called-for actions include identifying mitigation technologies, creating nationwide response and recovery plans and procedures, and improving prediction of space-weather events and their effects.

(20) **Harnessing the small satellite revolution.** A critical area for space-technology development is advancing the capability of small satellites ("smallsats") and constellations of smallsats to support important commercial, civilian, and national-security applications. Potential applications include capturing continuously updated imagery of the entire planet and providing high-speed Internet connectivity to remote rural communities. Traditional large satellites typically cost hundreds of millions of dollars per satellite and often take years to build and launch. Smallsats sometimes can be delivered at a fraction of the cost and time of legacy satellite systems. Scientists and engineers can quickly test smallsat systems on orbit, allowing them to shorten the innovation cycle to devise new, better systems. The next Administration should consider working with OSTP, NASA, the

Department of Defense, the Department of Commerce, and other Federal agencies to foster innovation in the development and use of smallsats.

10 Actions Needed to Foster Continued Innovation across the Frontiers

Below we offer 10 actions that are needed if the United States is to succeed in broadening participation in and delivering on the potential of science, technology, and innovation to drive prosperity for all Americans and to address challenges across science and technology frontiers in the coming decades.

ACTION 1: Invest in Fundamental Research

Federal Government funding for R&D is essential to address societal needs in areas in which the private sector does not have sufficient economic incentive to make the required investments. Key among these is basic research—the fundamental, curiosity-driven inquiry that is a hallmark of the American research enterprise and a powerful driver of new technology and innovation in the medium and long terms. Of all the challenges involved in protecting and expanding Federal R&D budgets in the face of overall fiscal constraints, the challenge of supporting basic research (and the infrastructure that enables it) deserves particular attention in the years to come. The Federal Government must bear proportionally the largest burden for basic research because high risk and high uncertainty about timing and magnitude of returns limit the private sector's incentive to contribute. Simply supporting research is not sufficient, however; Federal agencies should ensure that research results are made available to other scientists, the public, and innovators who can translate them into the businesses and products that will improve our lives.

ACTION 2: Recruit, Retain, and Empower Top S&T Talent in the Federal Government

A core component of President Obama's innovation agenda has been an effort to attract individuals who can help build a more effective, efficient, and innovative government. This included recruiting high-caliber leaders for traditional S&T leadership positions in the Executive Office of the President and across Federal departments and agencies, and creating a new set of modern science, technology, and innovation positions—e.g., the U.S. Chief Technology Officer (CTO), U.S. Chief Information Officer (CIO), and Chief Data Scientist, as well as the White House Office of Digital Strategy, the Director of White House IT, and department and agency CTOs, CIOs, and Chief Data Officers. These technical leaders are bringing new best practices working in deep collaboration with others in government to leverage all tools of government to address our hardest challenges. This work includes the President's efforts to expand technical-talent integration for tech transformation that significantly improves the service delivery of IT services through the U.S. Digital Service, GSA's Tech Transformation Service, and the Presidential Innovation Fellows program, which the Office of the U.S. CTO played a key role in creating. Strategies to make public service more attractive include time-limited "tours of duty"; short "sprint team" engagements to bring new perspective on entrenched problems; a focus on making hiring processes as efficient as possible; and proactive outreach to the technology and scientific communities.

It also means empowering that top technical talent to change the way the Federal Government delivers services and makes policy. For example, within the EOP, the Tech Policy Task Force (TPTF) draws membership from tech components and other policy councils to ensure tech expertise can advise other policy councils and drive its own policy. TPTF has been used to initiate and create tech-related policy, such as the Federal Source Code Policy and the White House's Artificial Intelligence Initiative and Report; to advise on or co-lead agency efforts, such as international connectivity with the State Department; and to answer questions raised by other policy councils, such as considerations regarding

encryption policy and cybersecurity. To maintain this progress in the future, the next Administration should consider including groups such as TPTF in the processes of core policymaking bodies, such as the National Security Council, and continuing to increase the scientific, technical, and innovation understanding at senior levels of agency policymaking.

ACTION 3: Identify and Pursue Grand Challenges

President Obama has called for companies, research universities, foundations, and philanthropists to join him in identifying and pursuing grand challenges as a key component of his innovation strategy. Grand challenges are ambitious yet achievable goals that harness S&T and that have the potential to capture the public's imagination. OSTP has encouraged Federal agencies to pursue grand challenges, including the BRAIN Initiative, NASA's Asteroid Grand Challenge, an Administration effort to eliminate the waiting list for organ transplantation, and a nanotechnology-inspired Grand Challenge in brain-inspired computing. Other agencies that have been particularly active include the Department of Energy (with grand challenges on solar energy and electric vehicles), U.S. Agency for International Development (USAID, with numerous grand challenges related to global development, such as Saving Lives at Birth), and DARPA (with grand challenges related to cybersecurity, robotics, and self-driving cars). President Obama's call to action on Grand Challenges has also encouraged universities to embrace ambitious goals and to make commitments to expand opportunities for undergraduate engineers and create other opportunities for students to learn about and pursue grand challenges.

ACTION 4: Increase Access to High-Quality STEM Education and Drive Innovation for Education

Increasing access to and participation in STEM fields is critical to developing the human capital needed to fuel American innovation; tackling economic inequality and the gender pay gap by allowing more Americans to succeed in high-wage STEM fields; and supporting informed citizenship. The Obama Administration made an unprecedented commitment to improving access to and quality of STEM education for all students and to meeting the need for one million additional STEM graduates in the workforce by 2022 by: (1) setting ambitious goals and rallying public and private action through an "all-hands-on-deck" approach that has led to more than $1 billion in philanthropic support for the President's Educate to Innovate campaign; (2) elevating the profile of STEM education through efforts including the launch of the annual White House Science Fair; and (3) improving the impact of Federal STEM education programs by executing on the first-ever Federal STEM Education 5-Year Strategic Plan. The Administration's STEM for All goals are supported by President Obama's proposed FY 2017 budget and call for increased efforts to improve STEM teaching; support active learning; expand access to rigorous STEM courses; address bias where it exists; and expand opportunities for underrepresented students in STEM. In response to a pressing need to fill high-paying tech jobs,[4] President Obama launched the Computer Science for All initiative to give all U.S. students access to computer-science education, which requires increased Federal funding and, building on actions taken by 14 states, additional collaboration to prepare teachers and expand access to high-quality instructional materials.

Science, technology, and innovation can be leveraged to improve educational outcomes through new models of grant-making; open licensing of educational resources developed through Federal funding; investments in infrastructure and educational-technology R&D to support next-generation learning; redesign the high school experience to make it more engaging; and multi-sector collaborations to increase the adoption of learning technologies. While significant advances have been made to expand

[4] In 2015, there were more than 600,000 high-paying tech jobs across the United States that were unfilled, and by 2018, 51 percent of all STEM jobs are projected to be in computer-science-related fields.

access to technology for education and close the digital divide, there are opportunities for continued improvement in cognitive science, AI, learning analytics, and learning games.

ACTION 5: Improve Diversity, Equity, and Inclusion and Mitigate the Impacts of Bias

America's role as a global leader in science and innovation is fortified by tapping into one of America's foundational strengths—the unparalleled diversity of the American people and the diversity of ideas that they generate. Obama Administration reports, such as on big data and on artificial intelligence, have noted that government policies can help America harness the potential of emerging technologies by designing, deploying, and regulating those technologies in ways that preserve American values, avoid and mitigate bias and discriminatory outcomes, and promote fairness and opportunity. In addition, research shows that diversity on teams leads to better outcomes. Systemic barriers, such as implicit and explicit bias, present challenges to efforts to draw upon a diverse community in building a STEM workforce for the 21st century. In November 2016, OSTP and the Office of Personnel Management (OPM) released a report, *Reducing the Impact of Bias in the STEM Workforce: Strengthening Excellence and Innovation*, which recommended that: (1) each Federal agency exercise leadership at all levels to reduce the impact of bias where it exists in their internal operations; (2) each Federal agency incorporate bias-mitigation strategies into its proposal-review process and offer technical assistance to grantee institutions to implement bias-mitigation strategies; and (3) OSTP, OPM, and the Department of Justice, as appropriate, exercise leadership to reduce the impact of bias where it exists in the Federal STEM workforce and Federally-funded institutions of higher education.

Also in November 2016, OSTP released an Action Grid as a resource for those striving to create diverse, equitable, and inclusive S&T teams and workforces. This set of potential actions—including leadership engagement, retention and advancement, hiring, and ecosystem support—can provide ideas and a jumping-off point for organizations around the country to increase workforce diversity. In addition, research demonstrates that popular entertainment media can influence the public's perceptions of STEM fields and careers. By highlighting the importance of depiction of STEM, as has been led through OSTP's Image of STEM effort, the Federal Government can support inclusion of diverse and compelling STEM images, stories, and positive messages—including improvement of historic accuracy—in mainstream entertainment media to encourage greater diversity in the future STEM workforce.

ACTION 6: Support Innovative Entrepreneurs

America's entrepreneurial economy is the envy of the world. Young companies account for almost 30 percent of new jobs, and as we have fought back from the worst economic crisis of our lifetimes, startups have helped our private sector create 15.5 million jobs since early 2010—the longest streak of private-sector job creation on record. To ensure that every American entrepreneur has a straight shot at success, we need all hands on deck. Since the launch of the White House Startup America initiative in 2011, President Obama has issued a consistent public call to action to companies, nonprofits, universities, investors, and others to accelerate high-growth entrepreneurship and broaden participation. Breaking down barriers for all entrepreneurs is not the task of just one Administration. Studies suggest that the share of venture-funded startups with women founders has nearly doubled in 5 years—but it is still only 18 percent. Continuing to reverse America's 40-year decline in startup activity will require building on President Obama's record of addressing income inequality, promoting competitive markets, reducing unduly restrictive occupational licensing, and scaling up rapid skills training. The next Administration should consider additional steps to ensure early-stage entrepreneurs from all backgrounds have access to startup capital, and to expand access to entrepreneurial networks and resources across all communities, so we field the entire American team of potential entrepreneurs.

ACTION 7: Maximize Economic and Social Return from Federal Government Data and the Results of Federally Funded R&D

The Obama Administration has leveraged open data and data science to inform and support Federal agencies and programs, including engaging data-innovation stakeholders to support agency missions. President Obama ordered the default state of Federal Government information resources to be open and machine readable, followed by an Open Data Policy issued by OMB. In February 2015, the President established the role of the Chief Data Scientist under the U.S. CTO within OSTP to: maximize social and economic return from Federal Government data; create Federal data policies that enable shared services, data engagement, and forward-leaning data practices; and recruit and retain the best minds in data science for public service. Federal agencies should be empowered with the people, processes, and practices necessary to build their data capacity. As of October 2016, nearly 40 Federal agencies have added Chief Data Officers (CDOs) and Chief Data Scientists to ensure data-driven decisions are made in support of mission priorities. OSTP established a Data Cabinet to serve as the principal community of practice for Federal data professionals to share case studies and best practices for scaling data-talent capacity through recruitment, training, and hiring and to ensure data is responsibly gathered, processed, leveraged, and made discoverable, accessible, and reusable in a timely fashion.

The Federal Government invests approximately $140 billion per year in R&D, which results in hundreds of thousands of peer-reviewed scholarly publications and growing volumes of digital research data every year. In February 2013, the Director of OSTP issued a memorandum directing all Federal departments and agencies with R&D expenditures of more than $100 million per year to develop plans for increasing access to the scholarly publications and digital data resulting from Federally funded research. More than 20 Federal agencies responsible for more than 99 percent of Federal R&D have completed and are implementing their public-access plans. Going forward, agencies should identify additional steps to make scientific knowledge freely and readily available to accelerate innovation and drive advances in health, energy, environmental protection, agriculture, national security, and other areas of national and international importance. Agencies are also working to improve the management and accessibility of scientific collections that support research and agency missions. These efforts complement the Obama Administration's Lab-to-Market initiative, which aims to accelerate and improve the transfer of new technologies from the laboratory to the commercial marketplace.

ACTION 8: Increase Federal Agency Capacity for Innovation

As outlined President Obama's *Strategy for American Innovation*, agency S&T innovation capacity is a strategic priority because with the right combination of talent, innovative thinking, and technological tools, government can deliver better results. Federal agencies have pioneered new approaches—and applied approaches piloted by other sectors—that can deliver better results at lower cost for the American people. Widespread adoption of these approaches can significantly improve government effectiveness. OSTP and Federal agencies are developing an Innovation Toolkit to facilitate the broader adoption and awareness of a core set of innovative approaches, including: (1) "pay for performance" incentive prizes; (2) citizen science and crowdsourcing; (3) applying behavioral science insights to improve Federal programs and policies; (4) Grand Challenges; (5) flexible approaches to procurement that allow the government to interact with startups and commercial firms; (6) human-centered design; (7) "market shaping" approaches such as milestone payments and Advance Market Commitments; (8) flexible hiring authorities such as those that allow for "tours of duty" by experts; and (9) "scout and

scale" approaches that find and share existing solutions.

To increase Federal capacity for innovation, the Administration has supported the development of Innovation Labs at Federal agencies that provide resources and support for employees and members of the public to develop, test, and scale new approaches to meeting agency goals, resulting in significant improvements to the effectiveness and efficiency of the Federal Government. Agency innovation capacity also is facilitated by upgrading digital collaboration tools, allowing for real-time shared documents, instant messaging, video conferencing, access to social media and wiki-based sites for team projects, data and content management, and open innovation, which empower communities of practice to work at rapid pace. Incorporating people with diverse skill sets into those communities of practice has led to innovative practices being shared and adopted faster.

ACTION 9: Promote Open Government through Transparency, Participation, and Collaboration

Teams across the Federal Government have been making progress to promote transparency, empower citizens, and transform how the Federal Government engages with the American people. These initiatives have led to cost savings, fueled American businesses, improved civic services, informed policy, catalyzed research and scientific discoveries, driven transparency and accountability, expanded and broadened collaboration, and increased public participation in the democratic dialogue. In addition, the United States co-founded and remains a leader in the Open Government Partnership (OGP), composed of 70 countries working with hundreds of civil-society organizations and civic-tech leaders collaborating internationally and pushing each other to increase public integrity, enhance public access to information, improve management of public resources, reduce costs, and give the public a more active voice in government processes. Each member of the OGP creates bi-annual Open Government National Action Plans (NAPs). More than 20 agencies also are leading continued implementation of the 48 commitments in the third U.S. NAP, including efforts to modernize Freedom of Information Act processes, improve transparency of privacy programs, streamline declassification, and increase public participation in policymaking. Work remains to implement agency-level 2016 Open Government Plans.

ACTION 10: Continue International S&T Cooperation and Engagement

OSTP works to strengthen international science, technology, and innovation cooperation among the United States and international partners through bilateral and multilateral engagements, and to support the President's foreign-policy agenda through international science, technology, and innovation activities. OSTP, in coordination with the State Department, represents the United States in bilateral and multilateral meetings with foreign nations, and works closely with government science agencies, independent research and scientific institutions, and non-governmental organizations to promote international S&T initiatives and strengthen global science cooperation. The OSTP Director co-chairs for the United States all six of the ongoing bilateral, ministerial-level Joint Commissions on Science and Technology Cooperation that exist under S&T cooperation agreements with Brazil, China, India, Japan, Korea, and Russia. In his 2009 Cairo speech, President Obama announced S&T related initiatives for Muslim-majority countries, including his intention to appoint science envoys, U.S. scientists who travel abroad as science ambassadors and inform the White House, U.S. Department of State, and the U.S. scientific community about the insights and opportunities for scientific engagement they find abroad. To date, there have been 5 cohorts of 3-5 Envoys each who have traveled to over 25 countries. The State Department has committed to supporting the Envoy program through 2017.

Conclusion

We have been honored to serve President Obama—our Science, Technology, and Innovation President. He has relentlessly focused on building American talent and capacity in S&T; making the long-term investments that will continue to power American innovation; and setting ambitious goals that inspire and harness the ingenuity and creativity of diverse whole of the American people. We thank the science and technology communities inside and outside government for their continued innovation and collaboration. We are especially appreciative of their shared passion for broadening participation, especially among our youth, to field the whole American team in pursuing the frontiers that will increase prosperity, opportunity, justice, health, and security for all. Driving further progress across the aforementioned frontiers will require focus by the next Administration and the next Congress on: sustained investment in research, development, and innovation; the importance of diverse, cross-sector, and multi-disciplinary collaboration for solving difficult challenges; education innovation to develop skills for Americans at all levels; job creation and workforce-skills development across these sectors; and equity, to ensure all Americans help create these innovations and have access to and benefit from advances in these frontiers.