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"Reimagining our Innovation Future"

Chairwoman Johnson, Ranking Member Lucas, and Members of the Committee, I am grateful for the opportunity to testify today. My name is Farnam Jahanian, and I currently serve as president of Carnegie Mellon University (CMU) and had the honor of previously serving as Assistant Director for Computer and Information Science and Engineering at the National Science Foundation.

My testimony will underscore the foundational role that science and engineering continues to play in our nation's prosperity for the past seven decades. It also speaks to the urgency of the current moment. Today, as unprecedented advances drive societal and economic transformation, the United States must double down on our national investments in research and innovation to secure our global competitiveness and address complex societal challenges. While we need the power of large, intentional, and sustained investments in emerging technologies such as artificial intelligence (AI), advanced manufacturing, and quantum computing, we also require investment across the continuum of innovation – from curiosity-driven discovery and use-inspired research, to our national scientific infrastructure and workforce development efforts, and a robust ecosystem for technology transfer.

I. A Nation Dedicated to New Frontiers in Science, Technology, and Innovation

Throughout our nation's history, and especially in the post-World War II era, a thriving research and development (R&D) ecosystem has served as the foundation for broad economic prosperity, national security, and individual and collective well-being. Advancements in science and technology have sparked new businesses and markets, modernized our system of health care, improved life expectancy and quality of life, and created more interconnected society. They created the modern world and placed the United States at the forefront of innovation. This took significant investment and risk-taking to achieve, with the U.S. taxpayer serving as the most important investor in catalyzing our nation's discovery and innovation.

The process of innovation has often been marked by long, unpredictable incubation periods between initial scientific discovery and societal and economic impact, requiring sustained investment at every step of the way. We have seen this in a broad range of technologies and industries, including the Internet, semiconductors, clean energy, advanced materials, biotechnologies, and genomics, to name a few. While the initial investment is often made by the federal government, the private sector plays a critical role in the R&D continuum to turn federally funded research into commercial impact, with broad economic and societal benefits. For example, consider the rise of autonomous vehicle (AV) technology, which illustrates the powerful impact of curiosity-driven research combined with intentional investment in key technologies.

In tracing the history of AV technology, many choose to start the narrative on March 13, 2004. On that day, 15 vehicles competed to make history in the first-ever Defense Advanced Research Projects Agency (DARPA) Grand Challenge, which was focused on fostering the development of self-driving ground vehicles. The immediate goal: autonomously navigate a 142-mile course that ran across the Mojave Desert, with a longer-term aim to accelerate development of the technological foundations for autonomous vehicles that could ultimately substitute for men and women in hazardous military operations.

That first competition – and subsequent Grand Challenges in this field – incentivized a community of innovators, engineers, programmers and students to try and solve a complex technical problem. But when one considers the knowledge and insight they brought to those early challenges, the rich history of federally-funded foundational research during the previous decades emerges – research that enabled all subsequent innovation in this area. For approximately a quarter of a century – from 1980 to 2003 – university research centers, often funded by or in partnership with federal agencies, undertook fundamental studies into the technologies that underpin autonomous transportation, including early-stage locomotion capabilities, obstacle detection and avoidance, light detection and ranging (LIDAR), radar and computer vision, AI, image processing, omni-directional cameras, and other sensing technologies. These innovations were initially forged by years of investment in curiosity-driven programs across eight different federal agencies including the National Science Foundation (NSF), the Department of Energy (DoE), the National Aeronautics and Space Administration (NASA), the Department of Transportation (DoT), and the Department of Defense (DoD). And those early pioneers were *themselves* building on a national computing infrastructure that had its origins in federal investment, including significant support from NSF and DARPA for computer science departments and university computing centers in the 1960s, 1970s, and 1980s.

The rise in AV technology has had broad national and economic impact, and its growth in the next few decades is expected to soar. A recent joint report from Intel and the research company Strategy Analytics estimates that autonomous car technology could add $2 trillion to the U.S. economy by 2050 and make a global market of $7 trillion accessible to U.S. innovators.[1] The symbiotic relationship between the public and private sectors has contributed to a stunning rise of the autonomous vehicle and robotics industry in Pittsburgh, where major AV companies have attracted billions of dollars of investment in new engineering centers that dot Pittsburgh's Robotics Row as well as test facilities across rural Southwestern Pennsylvania. More than 80 robotics companies are now located in Pittsburgh – many directly spinning out of CMU – and they employ more than 3,000 people.[2] Many of these jobs are located in Pittsburgh neighborhoods that are adjacent to CMU's National Robotics Engineering Center (NREC), our center for use-inspired and translational robotics research. These concentrated geographies – sometimes called innovation districts – have helped to transform the city

[1] "Accelerating the Future: The Economic Impact of the Emerging Passenger Economy," Strategy Analytics report prepared for Intel, June 2017. https://newsroom.intel.com/newsroom/wp-content/uploads/sites/11/2017/05/passenger-economy.pdf
[2] Economic Analysis from Fourth Economy

from one whose economy was driven by steel and mining, to one at the forefront of the modern, global economy.

Time and time again, smart, strategic, early and sustained investment by the federal government has helped to catalyze discovery and innovation that leads to broad societal benefit. This vibrant ecosystem for science and research is precisely what Vannevar Bush, Director of the Office of Scientific Research and Development after World War II, envisioned. He recognized that the interactions of research ideas often multiply their impact and seed new ideas with the potential to lead to unanticipated advances and broad economic impact. In his July 1945 report entitled *The Endless Frontier*, he noted that "[n]ew 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."[3] His belief in science as a national priority led directly to the formation of the NSF, and ultimately led the United States to further expand its science policy through agencies like DARPA, the National Institutes of Health (NIH) and NASA. It also underpins our response to the current moment.

II. An Inflection Point for the Nation

More than three quarters of a century after the publication of the *Endless Frontier* report, the United States science and engineering enterprise is at an inflection point. Our nation is poised at a remarkable confluence of opportunities and challenges. In particular, three realities are making this moment in time distinctly consequential: (1) a historic acceleration in the pace and scale of technological advances; (2) intense global competition by motivated challengers; and 3) a widening economic opportunity gap that is leaving far too many Americans behind.

Unprecedented Pace and Scale of Discovery and Innovation

We are in the midst of a profound societal and economic transformation that is being catalyzed by rapid advances in digital technologies, by access to unprecedented amounts of data, and by a powerful convergence of cross-disciplinary knowledge, methods and expertise.

The scale, scope and pace of these advances are truly unprecedented in human history. We are not dealing with a singular technology, but rather a set of interrelated breakthroughs that is expanding capabilities on a colossal scale. This dynamic necessitates an approach that fosters cross-disciplinary education and research, and close interaction between technologists and domain experts. The scope of impact is also remarkable, with near ubiquitous deployment that is reaching every sector of our economy and a wide range of occupations. Finally, the pace of innovation is dramatically accelerating, requiring new strategies for integrating foundational research and use-inspired research with more flexible approaches to technology transfer and workforce development. These advances are underpinning our economic prosperity, our national security and are accelerating the pace of discovery in nearly all fields of inquiry.

These cascading advances have re-shaped the culture and conduct of scientific research, with computation and data at the forefront of discovery in ways that were barely imagined twenty-five years ago. Data has become a particularly transformative currency for science, engineering, and education, with practitioners quickly

[3] *Science: The Endless Frontier, A Report to the President* by Vannevar Bush, Director of the Office of Scientific Research and Development, July 1945 (United States Government Printing Office, Washington: 1945)

extracting powerful insights from massive data sets and creating new approaches to drive discovery and decision-making. Combined with the deep integration of the cyber and physical worlds, wireless connectivity at broadband speeds, and seamless access to resources in the cloud, this explosion of data has catalyzed discovery and innovation.

The growing impact of data has also amplified the power of artificial intelligence and machine learning – which collectively represents one of most significant intellectual developments of our time. While the deployment of AI has ethical, policy and privacy implications that humanity must consider, AI and other computational technologies can powerfully augment our cognitive and even physical capabilities – in speech recognition and language translation, computer vision, assistive technologies, Internet search engines, and educational outcomes. Stemming from a strong legacy of federal investments in both basic and applied research, the total economic and societal impact of artificial intelligence is vast and on the edge of exponential growth. It is estimated that, by 2030, the global market size for AI will have grown to nearly $1.4 trillion.[3] AI and machine learning are also combining with other emerging fields to advance new frontiers in healthcare, smart transportation, advanced manufacturing, climate, clean energy, agriculture, and education, among others.

A convergence of knowledge, methods, and expertise from different disciplines continues to catalyze discovery and innovation and help solve complex societal problems facing humanity. For example, the successful development of novel messenger RNA-based (mRNA-based) vaccines – now available for the SARS-CoV-2 virus – was only possible due to convergent developments in basic research over the past decade, much of it funded by the NIH, combined with the ability to engineer proteins that mitigate the virus. More recently, an NSF-funded team of multidisciplinary researchers used a "computational microscope," linking high-performance computing with artificial intelligence, to develop the first full-scale model of the coronavirus spike protein itself. They later simulated 305 million atoms showing the fine details of how the spike protein moves, opens and contacts a healthy human cell. Their work has paved the way for drug and vaccine development.[4]

In an increasingly knowledge-based global economy, scientific discoveries and technological innovations must lie at the core of our response to national priorities and societal challenges – not just in medicine and healthcare but in sustainability, access to clean air and water, food security, transportation, clean energy, public health and safety, cybersecurity, and national defense.

Global Competition

The U.S. R&D engine had been the envy of the world for the last half century, and we should not be surprised that our global partners and competitors are replicating our extraordinarily successful model of an innovation-based economy.

In 1960, the United States dominated research and development (R&D), accounting for a 69 percent share of global R&D investment.[4] Our investments put us squarely in the driver's seat when it came to scientific discovery and technological innovation. In more recent years, with the democratization of knowledge and

[3] HR&A projections based on data from Allied Market Research, Grand View Research, Fortune Business Insights, and Tractica.
[4] First ACM Gordon Bell Special Prize for High Performance Computing-Based COVID-19 Research Awarded, November 19, 2020. https://www.acm.org/media-center/2020/november/gordon-bell-special-prize-covid-research-2020
[4] Competing in the Next Economy: The New Age of Innovation, Council on Competitiveness, pg. 13-14

broadening access to emerging technologies, other nations have increased their R&D investments, while the U.S. global share of R&D investments has dropped to just 29 percent in 2020.[5]

A nation's R&D intensity, expressed as R&D expenditures as a percentage of GDP, provides another gauge of national R&D performance. In this particular measure, the U.S. position globally again has lagged. The United States' R&D investment as a percent of GDP now ranks 10th in the world, behind major global competitors such as Taiwan, Japan, Germany, and South Korea, which rank at the top in this metric.[6] With the nation's *federal* spending as a percent of GDP dropping from more than 2 percent at the end of the 1960s to just slightly less than 0.7 percent currently, we have ceded considerable ground in the race to discover, innovate and create the fair, equitable and productive economies of the future.

Of all our global competitors, China is particularly focused on investing at scale to replicate the U.S. model of science- and technology-based growth and is rapidly closing in on the United States in measures such as gross R&D spending, funding for basic research, patents granted, and scientists and engineers employed. China now awards more bachelor's degrees in science and engineering than the United States, the European Union and Japan combined.[7] In recent years, R&D investment has soared by an average of 18 percent annually in China, whereas even with growing bipartisan support, U.S. federal spending rose by just over 4 percent each year.[8]

The United States became a world power due to our fervent belief in the power of American ingenuity. Now, we must double down on what we do best: leading the world in innovation, creativity and finding solutions to society's most pressing challenges. For decades, our research enterprise has been successful because we have competed globally not in the hope that others will lose, but in the belief that when we win, the world wins.

As we navigate the delicate balance between open research and national security, the nation must remain clear-eyed and alert to the threat of foreign influence in the form of intellectual property theft, cyber-attacks, espionage and other broad-scale, state-sponsored efforts. These are direct threats to our national security and economic prosperity, and the U.S. must be diligent in taking action in such cases but must not go so far as to retreat from global engagement or change the way research is conducted. We must not cripple the engine that has delivered fruitful economic and societal benefits. In this most disruptive age, we will win by out-investing and out-innovating.

A Widening Opportunity Gap

As we consider this inflection point for our nation, we must also acknowledge recent evidence that large segments of our population in both rural and urban communities are being left behind in this new economy. A recent study by Brookings found that 90 percent of technology related job growth has taken place in just five coastal metro regions.[9] Economic inequality is on the rise, not only because of digital transformation and globalization, but also due to persistent structural barriers to access and opportunity. The COVID-19 pandemic

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[5] A Snapshot of U.S. R&D Competitiveness: 2020 Update, Report from the American Association for the Advancement of Science (AAAS), October 22, 2020. https://www.aaas.org/news/snapshot-us-rd-competitiveness-2020-update
[6] A Snapshot of U.S. R&D Competitiveness: 2020 Update, Report from the American Association for the Advancement of Science (AAAS), October 22, 2020. https://www.aaas.org/news/snapshot-us-rd-competitiveness-2020-update
[7] National Science Board, Science and Engineering Indicators 2018, NSB-2018-1 (National Science Foundation), 2-47–2-60.
[8] "The Rise of China in Science and Engineering," National Science Board, Science and Engineering Indicators 2018 (National Science Foundation). https://www.nsf.gov/nsb/sei/one-pagers/China-2018.pdf
[9] Robert D. Atkinson, Mark Muro, and Jacob Whiton, "The case for growth centers: How to spread tech innovation across America," Brookings Institution, December 9, 2019. https://www.brookings.edu/research/growth-centers-how-to-spread-tech-innovation-across-america.

and the subsequent economic downturn have only amplified these inequalities, and made the issues surrounding access and opportunity more urgent.

Although the current gaps in opportunity and access are tied to a variety of factors, it is undeniable that the rapid pace of technological change has contributed to a profound re-shaping of the workforce. As technologies enhance and, in some cases, outpace, human capabilities, entire industries are expanding and contracting, and the skills needed to keep up in almost any job are increasingly churning at a faster rate.

As the president of a research university, I believe innovations in education will be key to staying ahead of the fast-moving current. Our system of education must deliver continuous training in the uniquely human skills that will only increase in relevance as automation matures – such as communication, problem-solving, collaboration, and critical and ethical thinking – but we must also create a national initiative to increase STEM education. We are seeing an undeniable and growing reliance on science and technology as drivers of new jobs. In fact, the Department of Labor estimates that science, technology, engineering, and mathematics (STEM) occupations are projected to grow more than two times faster than the total for all occupations in the next decade. But, according to the Smithsonian Science Education Center, about 2.4 million STEM jobs went unfilled in the U.S in 2018, and it is feared that we are not equipped to provide the base of talent to meet this rising need.[10] Developing human capital is especially important in areas that are identified as critical, emerging technologies. The demand for AI talent, for example, has grown by 74 percent annually in the past four years, and we will need to retrain or upskill up to an estimated 11 million workers in the next three years.[11]

Winning the race for talent demands more aggressive strategies to bring greater diversity to our STEM talent base and address long-standing barriers to broadening participation. The Smithsonian Science Education Center report also found that just 2.2 percent of Latinos, 2.7 percent of African Americans, and 3.3 percent of Native Americans and Alaska Natives have earned a university degree in STEM fields[12]. If not addressed, lack of sustained pathways will hamper U.S. efforts to develop the strong and diverse domestic STEM workforce that is so critical to the growth of our innovation-based economy.

Given the rapid pace of change, learning must be a lifelong endeavor, with continuing education serving as a tool for people of all ages and backgrounds. It is increasingly important for higher education to work closely with partners in the public and private sector on workforce development, including apprenticeships and re-skilling. Without significant public and private investments in workforce development and re-skilling initiatives, the nation may inadvertently disenfranchise parts of our population from gaining access to opportunity. We must be very intentional in building an innovation economy that engages everyone and that works for everyone – the nation's rural and suburban communities as well as its cities. If we succeed, the United States will fully realize the power of science and technology as a force for shared prosperity.

III. An Agenda for Action

These economic and societal transformations demand that we think and act anew. Bold steps are needed to ensure that the United States remains a leader in scientific discovery and to activate America's defining entrepreneurial spirit in translating discoveries into solutions, products and services that benefit society.

[10] Smithsonian Science Education Center STEM initiative, https://ssec.si.edu/stem-imperative
[11] The Perils of Complacency: America at a Tipping Point in Science & Engineering, American Academy of Arts and Science, September 2020, pg. 16
[12] Smithsonian Science Education Center STEM initiative, https://ssec.si.edu/stem-imperative

The pandemic has demonstrated how the power of science can mobilize rapidly to meet urgent societal needs. In many respects, it was an illustration of American science and innovation at its best. Yet the pandemic has also shined a light on the need for our science and innovation ecosystem, and the policies that support it, to be much more intentional in generating economic opportunities and promoting a high quality of life in all communities in our nation. The reality of the nation's growing economic divide, as much as increased international competition, should define a "Sputnik" moment for our times.

The nation must now come together around a shared national vision for science and innovation: a vision that mobilizes to meet new challenges while renewing and reinvigorating the promise of discovery and innovation to expand economic and social mobility. I believe this call-to-action should rest on four thrusts: (1) Investing in Research at the Pace of Discovery and Innovation; (2) Winning the Global Race for Talent; (3) Committing to a Robust Research and Innovation Infrastructure; and (4) Expanding the Geography of U.S. Innovation. The ideas outlined below are offered as potential building blocks of such a vision.

1. Invest in Research at the Pace of Discovery and Innovation

America's total national (public and private) investment in research and development as a fraction of our GDP has remained stagnant at between 2.4 and 2.7 percent for nearly half a century.[13] And as noted earlier in this testimony, if you look at the overall federal investment in research and development, it actually declined steadily during that period – to around 0.7 percent of our GDP, well below previous levels. Furthermore, federal funding specific to research – both basic and applied – has remained flat, hovering around 0.4 percent of our GDP for about half a century. The nation must urgently increase federal investments in research to double the current levels over the next several years; this increase is needed to invest in the "big bets" that will drive our global leadership and enable the science and technology breakthroughs needed to address urgent societal challenges. Increased investment is also needed at this time to address the impact research disruptions stemming from the pandemic.[14]

Yet, we cannot merely spend our way to improved competitiveness. The accelerating pace of innovation also necessitates a fundamental re-imagining of the American research enterprise. To some, the current moment creates an imperative to choose between increased support for curiosity-driven research and strategic, mission-driven initiatives in emerging technologies. This is a false choice. Scientific exploration occurs along a dynamic continuum — from foundational discovery to use-inspired research. A historic strength of the American innovation ecosystem has been the role of the federal government in de-risking investment at both ends of this continuum. In areas ranging from nanotechnology, battery storage and the internet to genomic medicine and drug discovery, fostering interaction between fundamental research and use-focused applications has transformed industries, created new ones and helped address previously intractable societal challenges. The failure of public investment to keep pace with the growing role of innovation in catalyzing economic growth is a threat to our future.

The United States must invest in, and re-energize, the environment for foundational research across all disciplines. This requires investments to pursue bold ideas that may seem, at first, to have little immediate

[13] The Perils of Complacency: America at a Tipping Point in Science & Engineering, American Academy of Arts and Science, September 2020, pg. 13
[14] See the Research Investment to Spark the Economy (RISE) Act. https://www.congress.gov/bill/117th-congress/house-bill/869

application to products or specific industries, yet hold long-term potential for transformational breakthroughs. Such investments should include funding for early career awards as well as support for multi-disciplinary and multi-investigator research.

Revitalizing our approach also requires a commitment to use-inspired research that is motivated by complex societal challenges, including realizing clean air and water, advancing public safety, addressing inequality and creating a more resilient and opportunity-rich economy. Specifically, to create innovative solutions that meet our national priorities, the nation must urgently invest in emerging technologies that have become near ubiquitous in their impact over the past decade, including AI, autonomy and robotics, advanced manufacturing, materials science, biotechnology, quantum computing and next-generation wireless. Breakthroughs in these high-impact research areas are critical to addressing societal challenges and hold enormous potential to create new industries and transform existing sectors – from agriculture and manufacturing, to healthcare and transportation, and beyond.

To extract the most value from these technologies over the long run, especially given the accelerating pace of innovation, it is vital that our investments in these areas include research across the continuum – including both foundational as well as use-inspired – and that we also embed a focus on ethics, privacy and workforce impacts at all levels of science education and research.

As recognized by Congress and the administration, this interplay between foundational discovery and use-inspired research to meet major societal challenges and enhance our global competitiveness demands the creation of a new directorate within the NSF. Working synergistically across the foundation, this directorate would serve as the hub for mission-driven innovations and solutions that may be enabled by powerful, emerging technologies. The foundation should be given flexibility to structure this directorate in a way that would leverage NSF's strengths and its relationships with other agencies and the private sector, and allow it to adapt to evolving national priorities and technologies of the future.

The directorate must have the capability to support research at scale across the continuum – from breakthrough discovery to use-inspired development, prototyping and deployment. This will require investments in center-scale initiatives and new models for public-private and multi-institutional collaborations capable of engaging the best researchers across the nation with the frontline end users of technology. To accelerate technology transition, the directorate should also support work to align education and re-skilling initiatives with research efforts. The directorate should also align its technology transfer initiatives with a goal of expanding the geography of innovation.

Finally, to pull together our collective efforts to increase research funding and restructure key science programs, the nation should also commit to establish a National Grand-Challenges Initiative. One of the historic strengths of American science has been its capacity to spark the national imagination and mobilize an all-of-nation commitment toward bold goals. These kinds of "grand challenges" go beyond targeted research questions; they speak to ultimate, high-stakes goals that are transformative in their impact, scale and ability to seed major breakthroughs. While grounded in technical pursuits, Grand Challenges energize individuals and entrepreneurs from all walks of life, and from both public and private sector organizations. Grand Challenges can also accelerate the transition to commercial development, lead to next-generation training programs and help to expand the geography of innovation to encompass communities across the nation.

2. Win the Global Race for Talent

The potential economic and societal impact of discovery and innovation will not fully be realized without also winning the global race for talent. Attracting the world's top talent is crucial to capitalizing on the investments we make in research to achieve scientific discoveries and technological innovations.

The nation must match its commitment to re-energizing the research enterprise with bold new initiatives in STEM education across preK-12, college, graduate and post-graduate education as well as in workforce training and re-skilling. A central focus of this effort must be increasing the diversity of the American science and technology workforce, simultaneously ensuring that no region of the nation is without high-quality STEM education for its children and young people. This investment must be an essential component of a national strategy to increase the nation's STEM workforce, broaden pathways to careers and create more opportunities to participate fully in today's innovation economy.

As digital innovation is transforming every sector of our economy and facet of our society, it is essential that every child has access to high-quality programs aimed at building digital competency and encouraging computational thinking. (NSF's CSforALL program, which supports rigorous K-12 computer science education across the nation, is a promising model upon which to build.) The United States must redouble its commitment to a public-private partnership aimed at making computer science education available to every middle and high school student in America. Creative community-based initiatives can leverage this investment to expand adult retraining and re-skilling initiatives as well.

Building on these initiatives in STEM, we should also commit to doubling the number of graduate students and post-doctoral researchers in science and engineering. Such an effort should not only focus on an expansion of the number of fellowships; it should also re-envision graduate education to ensure that the public or private sector leaders of tomorrow are prepared for the ever-accelerating pace of innovation and the societal and economic challenges they will be summoned to address. Special attention should also be paid to pathways for the industry and government workforce, with fellowships available so they can return to school for advanced degrees.

A new National Scholarships for Service Initiative can inspire a much closer connection between Americans and our national science mission and embody an all-of-nation commitment to advancing innovation. Such an initiative could have two components – one would provide training for those not headed to traditional college through apprenticeships or "stackable" micro-credit/nano-degree vocational programs, while another would extend financial support to those individuals headed to a four-year college to study high-demand disciplines. In exchange for training or aid, participants in the program would contribute to the nation through local, state or national service in an occupation related to the learned skill, with private sector employment in rural or underserved areas also qualifying as service. In order for this public-private partnership to be successful, the federal government should expand its engagement with vocational colleges, industry and local communities to incentivize re-skilling and capacity building, and drive talent into high-demand fields. Such a program could ignite new models of collaboration across the educational continuum and support economic development initiatives in regions across the country. The NSF's Scholarship For Service (SFS) program, which is focused on developing a superior cybersecurity workforce, is an example of a successful model. The SFS program recruits and trains the next generation of information technology professionals to meet the needs of the cybersecurity mission across federal, state and local governments.

Each of these measures to build new pathways to the innovation economy would be strengthened by securing America's standing as a magnet for global talent – and recruiting the world's top minds. One-third of U.S. Ph.D. STEM graduates are not U.S. citizens or permanent residents, and 28 percent of U.S. STEM faculty were born overseas, as were over half of U.S.-trained science and education postdoctoral workers.[15] The ability to attract the best and brightest to innovate and work alongside Americans has been vital to American innovation since Thomas Edison started his lab in Menlo Park and Major General Groves assembled talent for the Manhattan Project. That proud tradition continues today, and as a president of a major research university, I have witnessed firsthand the contributions that international students make to our research community. Many of these scholars go on to become remarkable innovators; for example, nearly half of U.S. Fortune 500 companies were founded by immigrants or children of immigrants.[16] Considering that 80 percent of international students who come to the U.S. to study in critical fields wish to stay in America,[17] I believe facilitating the ability of foreign students who earn advanced degrees to remain in the United States would be a powerful contribution to America's talent development and innovation capacity.

3. Commit to a Robust Research and Innovation Infrastructure

Accelerating research and building a vibrant science and technical workforce also depends on a robust national research infrastructure.

Research infrastructure investments are essential to fostering multi-disciplinary collaborations and early-stage partnerships with industry. Such infrastructure does not just include hardware and physical equipment; it encompasses software, services, tool development and operational support.

While facilities and instrumentation such as highly powerful telescopes, photonic light sources and particle accelerators have always been vital to our progress in basic scientific investigation, a 21st-century environment must also support research and discovery across the spectrum of digital innovation. This includes targeted investments in the digital research infrastructure capabilities needed to support advances in AI, data analytics, robotics, edge computing and microelectronics. Vast research cloud computing assets, sensor networks and testbeds that facilitate big data and system modeling and simulation, and living laboratories that allow for piloting research-based solutions in practical settings are *all* essential for demonstrating technologies and experimenting on solutions *at scale*.

Given that large-scale digital innovation is increasingly dependent upon the ability to capture, process and manage large amounts of information, a National Data Initiative is a key linchpin in a competitive national research infrastructure strategy. Such an initiative would provide science, engineering and education with a comprehensive data infrastructure to enable the capture, management, curation, analysis, interpretation, archiving and sharing of data at unprecedented scale, parallelism and complexity in a manner that will stimulate discovery in nearly all areas of inquiry.

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[15]National Science Board, Science and Engineering Indicators 2018, 2-61–2-85. https://nsf.gov/statistics/2018/nsb20181/report/sections/higher-education-in-science-and-engineering/graduate-education-enrollment-and-degrees-in-the-united-states.
[16] Ian Hathaway, "Almost Half of Fortune 500 Companies Were Founded by American Immigrants or Their Children," The Avenue, December 4, 2017, Brookings Institution.
[17] Remco Zwetsloot, Roxanne Heston, and Zachary Arnold, "Strengthening the U.S. AI Workforce: A Policy and Research Agenda," Center for Security and Emerging Technology at iii, Sept. 2019. https://cset.georgetown.edu/wp-content/uploads/CSET_U.S._AI_Workforce.pdf.

Finally, this national infrastructure investment must be aligned with accelerated research and deployment of next-generation broadband capability. Innovations in a broad range of applications and industries – ranging from transportation, energy and smart cities to environmental sciences and health care – all depend upon convergence with advances in connectivity. High-speed broadband and access to advanced computing and data infrastructure are vital to bridging the divide between discovery and deployment for a host of innovations and in closing the "geography gap" that prevents the entire country from contributing to our national prosperity and competitiveness.

Expanding the nation's research infrastructure will diversify and democratize American science as research infrastructure "hubs" can play a critical role in supporting STEM programs and providing a gateway to thriving regional innovation ecosystems.

This committee has long recognized the power of investments in infrastructure to support discovery and innovation. It is now time to build upon this leadership and significantly expand our investment in research infrastructure initiatives.

4. Expand the Geography of U.S. Innovation

To compete in an increasingly global marketplace and expand the power of science and innovation to address major societal challenges, the U.S. needs new, bolder strategies for transitioning discoveries from the lab to the market, with a focus on expanding the geography of U.S. innovation. The nation must facilitate the development and deployment of innovations emerging from our universities and national labs faster and at a much greater scale than we are currently realizing.

Policies that nurture a re-energized national R&D environment and foster a culture supportive of technology transfer constitute a pivotal starting point. We can think of this national environment as consisting of a set of fundamental building blocks that come together to catalyze innovation. These building blocks include:

- Government investments in research and education;
- A vibrant and diverse base of scientists and engineers in a flexible talent-rich labor market;
- A private sector catalyzed by the American entrepreneurial spirit;
- Public-private partnerships that spur productive entrepreneurship and enhance both skill development and innovative supply chains; and
- A strategic alignment of education, economic and community development and infrastructure initiatives with innovation strategies.

Federal agencies have a unique role in cultivating these building blocks and nurturing an environment conducive to the rapid transition of technology from lab to market. This can include funding that can enable promising research projects to more easily move to a prototype development stage and testbeds to model the early-stage deployment of technologies. The nation also has the opportunity to scale its existing suite of programs focused on technology transfer.[18] These and other measures can incentivize earlier engagement with both industry and regional innovation ecosystems, accelerating the path from research to discovery.

[18] These existing programs include ones led or initiated by the National Science Foundation, including Innovation Corps (I-Corps), the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, as well as the Partnerships for Innovation (PFI) program.

Furthermore, the nation must commit to expand significantly the U.S. geography of innovation, anchored by our universities and national labs. U.S. academic institutions and research labs have an extraordinary concentration of intellectual capital and capacity to generate ideas, discoveries and innovations that can catalyze economic growth and job creation. For example, there are more than 200 institutions, distributed across rural, urban and suburban America, with significant research capabilities – each with at least $50 million in R&D expenditures annually.[19] The strengths of these institutions may vary, but each institution can offer scientific and engineering assets to help its surrounding region become part of the innovation economy. There is tremendous potential to launch programs that prompt colleges and universities to intentionally partner with their surrounding communities for regional economic development, to motivate research-based solutions to societal challenges, and to enhance the engagement in science and research by a broader cross section of our country. To broaden access to the innovation economy, this collaboration should consider participation by community-based partners, including labor organizations. Furthermore, closer collaboration among universities and colleges within regions and across the nation, especially greater linkages between diverse urban and rural institutions, is an important consideration as we realize this vision.

To complement university-centered efforts, the nation must also invest in entities "adjacent" to universities in the innovation ecosystem that are capable of facilitating hand-offs and the seamless transfer of technology and skills. This effort may require the development of entirely new models of adjacent, community-based innovation support organizations that are driven by a mission to foster a more inclusive technology economy.

It is important to note that a vibrant ecosystem does not measure its success merely by commercial terms and metrics. The transition of technologies and innovations to reduce food insecurity, reduce transit and mobility deserts or improve prenatal care are all examples of strategic objectives for regional innovation.

While attention is often focused on the more visible elements of local innovation ecosystems such as incubators, an important step is to design flexible policies that create the context and conditions for innovation. For example, faculty leave and tenure and promotion policies that support the flow of talent between the university and industry can help facilitate an environment conducive to innovation. This fusion of people and ideas underpins the productive interplay of federally funded university research, privately funded industrial research and entrepreneurial companies founded by people who often move back and forth between universities and companies. Entrepreneurship training for students, faculty and staff, combined with streamlined and flexible intellectual property licensing approaches, can also help define the conditions for innovation. Each of these key policies can be activated by higher education institutions embracing regional economic development as a core mission. The diversity of American institutions of higher education will spark a wide array of strategies. Many institutions have developed research excellence capable of growing startups and generating new industry clusters in their regions; there are some that are best suited to support existing industry through the transfer of knowledge or technology; and others can accelerate the development of new skills throughout the workforce.

These efforts are limited only by our imagination. Just as universities must continue to consider the societal implications of research, institutions charged with job creation and economic growth must now fully embrace the role of science in shared prosperity. The possibilities for creative, innovation-based economic development

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[19] Higher Education Research and Development (HERD) Report for Fiscal Year 2019, National Science Foundation, January 29, 2021. https://ncses.nsf.gov/pubs/nsf21314

partnerships to support American competitiveness are endless – ranging from pre-competitive, shared, deep bench laboratories to robust and tailored technology entrepreneurship support programming.

IV. Conclusion

Despite the significant challenges before us, it is an inspiring time to be envisioning the future of U.S. leadership in science and technology. The bipartisan proposals emerging in this Congress and from the administration reflect a shared sense of urgency to invest in our nation's competitiveness at a scale and scope not seen since the space race of the 1960s. I wish to acknowledge this committee's bold vison, including the introduction of the National Science Foundation for the Future Act, which would significantly expand funding for the NSF and create a more strategic focus on translational, mission research while also supporting bold initiatives across the entire education and research continuum.

With these investments come significant responsibilities for the science and technology community. Federal agencies, national labs, research universities and our partners must not only continue to be effective stewards of public resources but must also push the envelope in exploring and creating new fields of discovery; forge partnerships across the landscape, including with local communities, private industry and foundations; leverage science and technology to drive competitiveness and job creation; and focus on including people of all backgrounds in these efforts. I know I speak for my colleagues at Carnegie Mellon University and many others across the country when I say our community is determined to rise to the occasion.

Once again, thank you for giving me the opportunity to testify before this committee.

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Farnam Jahanian is the 10th president of Carnegie Mellon University, where he previously served as provost and chief academic officer as well as vice president for research.

A nationally recognized computer scientist, entrepreneur, public servant and higher education leader, Jahanian has extensive leadership and administrative expertise, not only in advancing research and education within and across disciplines, but also in translating research into technologies and practices that benefit society.

Jahanian first joined CMU as vice president for research in 2014, where he was responsible for nurturing excellence in research, scholarship and creative activities. From May 2015 to June 2017, Jahanian served as the university's provost and chief academic officer, with broad responsibility for leading CMU's schools, colleges, institutes and campuses and engaging in long-range institutional and academic planning and implementation.

Jahanian holds faculty appointments in the School of Computer Science, the College of Engineering and the H. John Heinz III College of Information Systems and Public Policy at Carnegie Mellon University.

Prior to coming to CMU, Jahanian led the National Science Foundation Directorate for Computer and Information Science and Engineering (CISE) from 2011 to 2014, where he guided a budget of almost $900 million to advance scientific discovery and engineering innovation through its support of fundamental research. During his tenure at NSF, he also served as co-chair of the Networking and Information Technology Research and Development Subcommittee of the National Science and Technology Council Committee on Technology, facilitating the coordination of networking and information technology research and development efforts across Federal agencies.

Previously, Jahanian spent 21 years at the University of Michigan as the Edward S. Davidson Collegiate Professor. He was director of their Software Systems Laboratory from 1997 to 2000 and served as chair of the university's Computer Science and Engineering department from 2007 to 2011.

Jahanian has been an active advocate for how basic research can be uniquely central to an innovation ecosystem that drives global competitiveness and addresses national priorities. His highly influential research on Internet infrastructure security formed the basis for the Internet security company Arbor Networks, which he co-founded in 2001 and served as chair until its acquisition in 2010.

Jahanian serves as chair of the National Research Council's Computer Science and Telecommunications Board (CSTB), sits on the executive committee of the U.S. Council on Competitiveness, and is a trustee of the Dietrich Foundation. He has also been a board member of the Computing Research Association (CRA), the National Center for Women and Information Technology (NCWIT), and the Allegheny Conference on Community Development, among others.

Jahanian is also active with the World Economic Forum, serving as vice chair of the Global University Leaders Forum (GULF) and as a member of the Global Network Advisory Board for WEF's Centre for the Fourth Industrial Revolution (C4IR). He also serves on C4IR's Internet of Things Council.

Jahanian holds a Ph.D. in computer science from the University of Texas at Austin. He is a fellow of the Association for Computing Machinery, the Institute of Electrical and Electronic Engineers and the American Association for the Advancement of Science.