NETWORKING AND INFORMATION TECHNOLOGY RESEARCH AND DEVELOPMENT PROGRAM REVIEW

A Report to the President of the United States of America and the U.S. Congress

The President's Council of Advisors on
Science and Technology

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About the President's Council of Advisors on Science and Technology

Created by Executive Order in 2019, PCAST advises the President on matters involving science, technology, education, and innovation policy. The Council also provides the President with scientific and technical information that is needed to inform public policy relating to the American economy, the American worker, national and homeland security, and other topics. Members include distinguished individuals from sectors outside of the Federal Government having diverse perspectives and expertise in science, technology, education, and innovation.

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About this Document

As required by statute, PCAST is tasked with periodically reviewing the Networking and Information Technology Research and Development (NITRD) Program, the Nation's primary source of federally funded research and development in advanced information technologies such as computing, networking, and software. This report examines the NITRD Program's progress since the last review was conducted in 2015, explores emerging areas of interest relevant to the NITRD Program, and presents PCAST's findings and recommendations.

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The President
The White House
Washington, DC 20500

Dear Mr. President,

As Chair of the President's Council of Advisors on Science and Technology (PCAST), I am pleased to transmit, on behalf of PCAST, *Networking and Information Technology Research and Development Program Review*.

Current statute requires that periodic evaluations of the Networking and Information Technology Research and Development (NITRD) Program be conducted by an advisory committee, known since 1998 as the President's Innovation and Technology Advisory Committee (PITAC). Executive Order 13895 delegated PCAST to serve as the PITAC and conduct the current NITRD Program review. This report serves as that review.

The NITRD Program was originally authorized by the High-Performance Computing Act of 1991 (P.L. 102-194) "To provide for a coordinated Federal program to ensure continued United States leadership in high-performance computing." The America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act of 2007 (P.L. 110-69) and the American Innovation and Competitiveness Act of 2017 (P.L. 114-329) expanded the Program's goals, with requirements to focus on big data, cyber-physical systems, privacy, and cybersecurity research and to emphasize public–private partnerships and the transition of research to practice.

In the current report, PCAST describes that it has found the NITRD Program to be very effective and a key component of the U.S. networking and information technology (NIT) ecosystem. The NITRD Program priorities described above align well with several NIT priorities that PCAST has identified for the 21st century, in addition to the priorities of NIT education and a NIT-ready workforce, among others. The recommendations PCAST provides in this report offer opportunities to further strengthen the NITRD Program to ensure continued positive returns for the American public and American global leadership for the present and the future.

Sincerely,

Kelvin Droegemeier
PCAST Chair

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Abbreviations and Acronyms

AI Artificial Intelligence

AICA American Innovation and Competitiveness Act

BRD Broadband Research and Development

CHuman Computing-Enabled Human Interaction, Communications, and Augmentation

CMOS Complementary Metal–Oxide–Semiconductor

CNPS Computing-Enabled Networked Physical Systems

COMPETES Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science

CSIA Cybersecurity and Information Assurance

CSP Cyber Security and Privacy

DARPA Defense Advanced Research Projects Agency

DoD Department of Defense

DOE Department of Energy

EdW Education and Workforce

EHCS Enabling Research and Development for High-Capability Computing Systems

FC-STEM Federal Coordination in STEM Education Subcommittee

FTAC Fast Track Action Committee

HCI & IM Human Computer Interaction and Information Management

HCIA High-Capability Computing Infrastructure and Applications

HCSIA High-Capability Computing Systems Infrastructure and Applications

HCSS High Confidence Software and Systems

HEC High End Computing

HEC I&A High End Computing Infrastructure and Applications

HITRD Health Information Technology Research and Development

HPC High-Performance Computing

IotF Industries of the Future

IRAS Intelligent Robotics and Autonomous Systems

IT Information Technology

IWG Interagency Working Group

JET Joint Engineering Team

LSDMA Large Scale Data Management and Analysis

LSN Large Scale Networking

MAGIC	Middleware and Grid Interagency Coordination
ML	Machine Learning
MLAI	Machine Learning and Artificial Intelligence
NASA	National Aeronautics and Space Administration
NCO	National Coordination Office
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NIT	Networking and Information Technology
NITRD	Networking and Information Technology Research and Development
NNCO	National Nanotechnology Coordination Office
NNI	National Nanotechnology Initiative
NQCO	National Quantum Coordination Office
NSET	Nanoscale Science, Engineering, and Technology
NSF	National Science Foundation
NSTC	National Science and Technology Council
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PCA	Program Component Area
PCAST	President's Council of Advisors on Science and Technology
PITAC	President's Innovation and Technology Advisory Committee
QIS	Quantum Information science
R&D	Research and development
RFI	Request for Information
RIS	Robotics and Intelligent Systems
SDP	Software Design and Productivity
SEW	Social, Economic, and Workforce Implications of IT and IT Workforce Development
SoC	System on a chip
SPSQ	Software Productivity, Sustainability, and Quality
STEM	Science, technology, engineering, and mathematics
U.S.	United States
VIA	Video and Image Analytics
WSRD	Wireless Spectrum Research and Development

Executive Summary

From networked smart phones to on-board navigation systems to industrial robotics, networking and information technology (NIT) has become part of the fabric of American daily life and underpins our national economic prosperity and security. Recent NIT trends—including democratization of data and technology, ongoing automation of traditional industrial practices, the Internet of Things, and smart machines that can augment or complement human capabilities—have had profound impacts on commerce, entertainment, workforce development, markets, industries, interpersonal communications, and American culture. The ubiquity of NIT in daily life—and its utility across nearly every sector and occupational field—has elevated the need for technology literacy, education, and training for our Nation's current and future workforce. The critical role of NIT in our society—and the importance of access to the benefits of NIT tools and infrastructure for all Americans—has become even clearer during the COVID-19 pandemic. During this time, technologies such as reliable broadband Internet, cellular phones, videoconferencing platforms, and collaboration software have enabled many to maintain connections to family, friends, and colleagues, and to engage in remote learning and work.

The U.S. innovation ecosystem is a multi-sector enterprise spanning industry, government, academia, and non-profit organizations, with each sector playing an important role in conducting basic research (hereafter referred to as foundational research) to translating discoveries into transformative products and services for deployment and commercialization. While the United States has long been a driver of NIT innovation, the global technology landscape has become increasingly competitive, and changing uses and reliance on technology continue to pose new challenges that require research and development (R&D) from all sectors to understand and solve. Ongoing NIT R&D is necessary to improve the resilience, security, and integrity of our existing NIT systems; to build the networking, hardware, and software capabilities of the future; and to ensure that the United States remains a leader in shaping the global technology landscape.

Nearly 30 years ago, Congress passed the High-Performance Computing Act of 1991 (P.L. 102-194), which established the Networking and Information Technology Research and Development (NITRD) Program "To provide for a coordinated Federal program to ensure continued United States leadership in high-performance computing."[1] The NITRD Subcommittee coordinates NIT R&D policy across the Federal R&D enterprise and ensures consistency with the President's stated goals. The NITRD National Coordinating Office (NCO) supports the NITRD Subcommittee and the activities of the NITRD Subcommittee Interagency Working Groups (IWGs) by providing technical expertise; supporting planning, budgeting, assessment, and coordination; and serving as a central point of contact. The IWGs are the primary means by which agencies coordinate their R&D resources on shared NIT problems. The NITRD NCO tracks spending through Program Component Areas (PCAs), which are NITRD-specific budget areas used to summarize Federal R&D investment in networking and IT.

The current legislation mandates "periodic evaluations of the funding, management, coordination, implementation, and activities of the [NITRD] Program" be conducted by an advisory committee. In 2005, Executive Order 13385, "Continuance of Certain Federal Advisory Committees and Amendments to and Revocation of Other Executive Orders," first delegated the President's Council of Advisors on Science and Technology (PCAST) to serve as the advisory committee to conduct NITRD Program

[1] Public Law 102-194, High-Performance Computing Act of 1991. The program was originally known as the "National High-Performance Computing Program."

reviews, a precedent that has been continued by subsequent administrations.[2] This report serves as that review conducted by PCAST. It begins with a description of changes in the NITRD Program since the 2015 NITRD Review, including discussion of progress made in response to the 2015 report recommendations. The report then shifts to a forward-looking approach with identification and discussion of six emerging trends and areas of national interest relevant to NITRD: 1) Microelectronics; 2) Industries of the Future; 3) Multi-sector partnerships; 4) Translation from research to practice; 5) Coordination with National Science and Technology Council Subcommittees in areas related to NIT; and 6) Emerging approaches to NIT-related workforce and training. The report then concludes with findings and recommendations. For the purposes of this review, only those recommendations in the 2015 report pertaining to the NCO and the NITRD Program as a whole are thoroughly considered, rather than those directed to individual research agencies, which are beyond the NITRD NCO's ability to implement change.

Microelectronics

The Trump Administration has prioritized research on electronics, including microelectronics, as one element of a broader strategy to emphasize domestic manufacturing and supply-chain security for critical industries. Microelectronics—from materials to beyond complementary metal–oxide–semiconductor devices to modern System-on-a-Chip (SoC) designs to multi-chip modules—are fundamental to virtually all aspects of NIT. They underlie the hardware that powers the computing and networking technologies for which the NITRD Program was authorized to coordinate Federal R&D efforts. Security assurance for SoC and multi-chip modules across the hardware and software interface will remain a significant and important challenge requiring new R&D efforts. The cybersecurity vulnerabilities of microelectronics components may require new research foci as well. As of 2020, NITRD IWGs focus on coordinating Federal R&D related to hardware architectures and software but not on the components themselves. PCAST finds that coordinating microelectronics research represents a gap in NITRD's activities. PCAST finds there to be the potential for gaps in research coordination between NITRD and the National Nanotechnology Initiative (NNI) and a need for joint research planning that spans the hardware-software and system architecture boundary in microelectronics research.

Industries of the Future

The Trump Administration has highlighted five fields—collectively known as Industries of the Future (IotF)—with the potential to create high-paying jobs and economic prosperity while improving security and quality of life for all Americans: artificial intelligence (AI), quantum information science (QIS), advanced communications networks, advanced manufacturing, and biotechnology. Three of these industries—AI, QIS, and advanced communications networks—fall squarely within the realm of NIT. R&D in the other two IotF areas relies upon computing technologies and infrastructure, and could be accelerated by developments in AI, QIS, and advanced communications networks. PCAST finds that NITRD's AI activities represent an exemplar for coordination in one of the IotF areas. PCAST finds that the NITRD Program does not have an explicit focus on the other four IotF areas, although aspects of some of them are incorporated into NITRD Program activities.

[2] Executive Order 13539 "President's Council of Advisors on Science and Technology," 2010; Executive Order 13895 "President's Council of Advisors on Science and Technology," 2019.

Multi-sector Partnerships

Multi-sector partnerships—such as collaborations across government, industry, and academia—have been gaining increased attention in the United States and abroad as a mechanism through which to accelerate advances in NIT. For example, China, the European Union, and Japan are each undertaking coordinated NIT R&D efforts. These efforts emphasize multi-sector R&D partnerships and support for small- and medium-sized enterprises. The NITRD Program already includes some convening structures that involve industry and academia. PCAST finds that some IWGs do not report emphases on multi-sector convenings as part of their activities. PCAST also finds that while some IWG strategic plans explicitly include multi-sector partnerships as core elements of their approach, others do not.

Translation from Research to Practice

The 2015 NITRD Review noted the importance of the translation of NIT R&D research results into practice. Although it did not devote a specific section or group of recommendations to the topic, some recommendations, such as the cybersecurity recommendations, included specific suggestions related to translation. Some NITRD IWG strategic plans specifically discuss transition to practice, such as including a section on the importance of multi-sector partnerships among Federal agencies, industry, and academia to accelerate the translation of research into practice. The Federal Cybersecurity Research and Development Strategic Plan includes a section titled “Transition to Practice” that recommended increasing Federal funding for mechanisms intended to support translation, such as research consortia, small business innovation research awards, and system integrator forums; the use of special contracting mechanisms such as other transactions authority was also recommended for use by agencies that are authorized to employ them. PCAST finds that while some NITRD IWG strategic plans address the importance of accelerating the translation of research into practice so that inventions can be deployed to benefit the public and serve agencies’ missions, others do not.

Coordination with National Science and Technology Council (NSTC) Subcommittees in Areas Related to NIT

NIT, especially computing and data analytics, have become critical to progress in science and technology. Accordingly, many NSTC Subcommittees focus on areas that involve substantial use of IT, big data, or other NITRD-related topics. The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee that oversees the NNI overlaps with NITRD interests in the context of microelectronics. R&D towards new materials and designs for computing hardware components will affect the future of NIT and could help to sustain growth in computing performance post-Moore’s Law. The National Nanotechnology Coordination Office (NNCO) contributes to coordination of this work. Similarly, QIS focuses on future information processing and communications capabilities that could help to fill gaps in the post-Moore’s Law landscape—though R&D in this area is still in early stages. The National Quantum Coordination Office (NQCO) contributes to coordination of this work.

PCAST finds there are opportunities for—and would be value in—increased coordination across some of these areas through the network of national coordination offices. Another mechanism for coordination is through participation of agency personnel on multiple NSTC Subcommittees or through IWGs. Some agencies already designate the same expert to sit on multiple subcommittees or IWGs, facilitating the diffusion of information across groups working in related research domains.

Emerging Approaches to NIT-related Workforce and Training

In 2018, the NSTC released *Charting a Course for Success: America's Strategy for STEM Education*, intended to guide Federal investment in STEM education through 2023. Three pathways associated with the strategy are of particular relevance to the NITRD Program: 1) Develop and enrich strategic partnerships; 2) Engage students where disciplines converge; and 3) Build computational literacy. The strategy also identified promoting diversity and inclusion in STEM as one of its primary goals.[3] PCAST finds that the NITRD Program is already engaging in coordination activities in these areas. The PCA on education and workforce tracks investments in how to better develop the next generation of cyber-capable citizens and professionals, and this subject area is already incorporated into many of the priorities of the NITRD IWGs. Given the importance of ensuring the United States continues to stay at the forefront of NIT and the need to train future scientists, PCAST finds that there is a need to expand the number of Americans trained to work in NIT fields at all levels of education, ranging from technician-level trainees to postsecondary degree-level. PCAST also finds that given that U.S. leadership in many areas of science and technology has benefitted greatly from the contributions of international students, scientists, and engineers, it is essential that the United States continue to be the beacon for highly-skilled global talent in NIT and related areas and renew its emphasis on attracting and retaining these highly-skilled individuals.

Recommendations

The review concludes with PCAST's findings and recommendations related to the future of the NITRD Program. PCAST recognizes that implementing these recommendations may warrant additional funding.

<u>Recommendation 1</u>: The current NITRD Program model and its approach to coordinating foundational research in NIT fields across participating agencies should continue as constituted, with the following modifications:

- NITRD groups should continue to review the PCAs regularly using a fast track action committee (FTAC) and adjust as needed (with a frequency of perhaps every 3 years rather than every 5–6 years, as had been recommended in the 2015 NITRD Review). It should also continue to review IWGs periodically, as recommended in the 2015 NITRD Review.
- The NITRD Program should continue to pursue incremental modifications of existing structures (e.g., IWGs, PCAs) rather than engage in wholesale reorganizations at this time.
- When launching wholly new IWGs and PCAs (e.g., such as the AI IWG and AI PCA), the NITRD Program should consider showing clearly in the annual NITRD Supplement to the President's Budget which lines of effort derive from previous structures and which are wholly new programmatic areas and funding lines. This will be especially important should NITRD groups increase the frequency with which they review and modify PCAs.

<u>Recommendation 2</u>: The NITRD Program should examine current structures and operations to identify opportunities for greater multi-sector engagement in its activities. Opportunities include the following:

- Amplify multi-sector outreach and engagement efforts. While the NITRD Program notifies the public about its convening activities, it could augment its outreach.

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[3] Committee on STEM Education. 2018. *Charting a Course for Success: America's Strategy for STEM Education*. Washington, DC: National Science and Technology Council. https://www.whitehouse.gov/wp-content/uploads/2018/12/STEM-Education-Strategic-Plan-2018.pdf.

- Expand the NITRD Program's efforts to track non-U.S. coordinated NIT efforts and collaborate with international efforts where appropriate. This should be done in coordination with the NSTC International S&T Coordination Subcommittee to avoid duplicating efforts.

Recommendation 3: The NITRD Program should examine current structures and operations to identify opportunities for improving coordination in IotF areas related to the program. Opportunities could include:

- AI—continue coordination efforts within the NITRD Program and between NITRD IWGs and the NSTC Select Committee on AI and the Machine Learning and Artificial Intelligence (MLAI) Subcommittee.
- Advanced communications networks—continue coordination efforts within the NITRD Program through the Subcommittee and the LSN and WSRD IWGs.
- QIS—increase coordination with the NQCO and the NSTC QIS Subcommittee, particularly on topics such as post-quantum cryptography R&D and other implications of the development of quantum technologies on the NIT landscape with advances in QIS.
- Biotechnology—coordinate with NSTC bodies working in biosciences-related areas such as the Biodefense R&D (BDRD) Subcommittee and the Biological Sciences Subcommittee (BSSC).
- Advanced manufacturing—coordinate with the NSTC Subcommittee on Advanced Manufacturing and large-scale manufacturing R&D efforts such as the ManufacturingUSA Institutes.

Recommendation 4: The NITRD Program should incorporate microelectronics R&D explicitly into its programmatic activities.

- Could take the form of a separate IWG or incorporating hardware/components R&D into existing IWGs.
- Should be stronger NNI-NITRD coordination to ensure alignment of R&D strategies and programmatic activities.

Recommendation 5: The NITRD Program should further examine ways it can coordinate its participating agencies—such as through an IWG or other multiagency bodies—to ensure they support and emphasize the following:

- STEM education, including PhD fellowships, in NIT.
- Programs at the intersection and convergence of computational science and other fields (CS + X) at 2-year and 4-year educational institutions.
- Retraining and upskilling the non-technical workforce to participate in the cyber-ready workforce.
- A diverse and inclusive NIT workforce across all levels of technical staff, engineers, and scientists.
- Strengthen efforts to attract and retain international students, scientists, and engineers who wish to contribute to NIT R&D in the United States. These efforts should be informed by conducting studies of the role that international talent plays in the U.S. NIT workforce and any factors affecting recent changes in recruitment and retention.

Introduction

Statutory Authority

The Networking and Information Technology Research and Development (NITRD) Program was originally authorized by the High-Performance Computing Act of 1991 (P.L. 102-194), "To provide for a coordinated Federal program to ensure continued United States leadership in high-performance computing."[4] The Act was subsequently amended by the Next Generation Internet Research Act of 1998 (P.L. 105-305),[5] the America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science (COMPETES) Act of 2007 (P.L. 110-69),[6] and the American Innovation and Competitiveness Act (AICA) of 2017 (P.L. 114-329).[7] The Next-Generation Internet Research Act expanded the program's mandate from its initial emphasis on high-performance computing to encompass Internet-related research as well. The COMPETES Act and AICA expanded the program's reporting and evaluation requirements. These two laws also expanded the program's goals, with AICA adding requirements for the NITRD Program to focus on big data, cyber-physical systems, privacy, and cybersecurity research; AICA also required the program to emphasize public-private partnerships and the transition of research to practice.[8]

Current statute requires that "periodic evaluations of the funding, management, coordination, implementation, and activities of the [NITRD] Program" be conducted by an advisory committee, known since 1998 as the President's Innovation and Technology Advisory Committee (PITAC).[9] The program's legislative authorization further states that, "The advisory committee shall report not less frequently than once every 3 fiscal years to the Committee on Science, Space, and Technology of the House of Representatives and the Committee on Commerce, Science, and Transportation of the Senate on its findings and recommendations."[10] In 2005, Executive Order 13385, "Continuance of Certain Federal Advisory Committees and Amendments to and Revocation of Other Executive Orders," first delegated the President's Council of Advisors on Science and Technology (PCAST) to serve as the PITAC and conduct NITRD Program Reviews, a precedent that has been continued by subsequent administrations.[11]

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4 Public Law 102-194, High-Performance Computing Act of 1991. The program was originally known as the "National High-Performance Computing Program."

5 Public Law 105-305, Next Generation Internet Research Act of 1998.

6 Public Law 110-69, America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science (COMPETES) Act of 2007.

7 Public Law 114-329, American Innovation and Competitiveness Act (AICA) of 2017.

8 Public Law 110-69, America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science (COMPETES) Act of 2007, Section 7024; Public Law 114-329, American Innovation and Competitiveness Act (AICA) of 2017, Section 105.

9 In 1998, Executive Order 13092, "President's Information Technology Advisory Committee, Amendments to Executive Order 13035," named the advisory committee first authorized in the High-Performance Computing Act of 1991 the "President's Information Technology Advisory Committee."

10 15 U.S. Code § 5511 (b)(2)

11 Executive Order 13539 "President's Council of Advisors on Science and Technology," 2010; Executive Order 13895 "President's Council of Advisors on Science and Technology," 2019.

Importance of Networking and Information Technology (NIT) Research and Development (R&D)

From networked smart phones to on-board navigation systems to industrial robotics, networking and information technology (NIT) has become an important part of daily life and underpins our national economic prosperity and security. It comprises the tools and infrastructure that support commerce, entertainment, and interpersonal communications. It supports today's unprecedented pace of innovation and is critical for meeting the societal demand for new smart, sustainable, Internet-connected, and trusted devices.

Recent NIT trends—including democratization of data and technology, ongoing automation of traditional industrial practices, the Internet of Things, and smart machines that can augment or complement human capabilities—have had profound impacts on workforce development, markets, industries, and the cultural fabric of society. The ubiquity of NIT in daily life—and its utility across nearly every sector and occupational field—has also elevated the need for technology literacy, education, and training for our Nation's current and future workforce. The information technology sector is a major contributor to the U.S. economy, representing approximately 6% of gross domestic product,[12] and generating goods and services that shape the way we work, learn, and play.

The critical role of NIT in our society—and the importance of access to the benefits of NIT tools and infrastructure for all Americans—has become even clearer during the COVID-19 pandemic. During this time, technologies such as reliable broadband Internet, cell-phones, videoconferencing platforms, and collaboration software have enabled many to maintain connections to family, friends, and colleagues, and to engage in remote learning and work.

The U.S. innovation ecosystem is a multi-sector enterprise, spanning industry, government, non-profit organizations, and academia, with each sector playing an important role in translating discoveries to transformative products and services in a national innovation ecosystem—from foundational and applied research to product development and commercialization. The Federal Government has a unique role as the Nation's leading funder of foundational research—an important precursor to innovation, with discoveries often resulting in transformative new capabilities and products, which lead to significant benefits for the Nation—though how, or on what timescale, are typically not obvious at the time.

For example, foundational NIT research in areas such as digital communications, computer architecture, networking, and computer graphics dating back to the 1960s helped to build major, multitrillion dollar U.S. IT sectors such as broadband and mobile, personal computing, Internet and web, and entertainment and design.[13] Beyond economic impact, NIT plays a major role in support of science and engineering R&D towards solutions to many of today's societal challenges, such as health promotion and disease prevention and treatment. These technologies—from supercomputers to distributed sensors—enable innovation in all other sectors of today's science and engineering enterprise. Continued support for NIT R&D is necessary to ensure advances in these capabilities for future applications.

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[12] Bureau of Economic Analysis. 2020. "Value Added by Industry." December 22, 2020. https://apps.bea.gov/iTable/iTable.cfm?reqid=150&step=2&isuri=1&categories=gdpxind. See "Information" category.

[13] National Research Council. 2012. *Continuing Innovation in Information Technology*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13427.

While the United States has long been a driver of NIT innovation, today's global technology landscape is highly competitive. In addition, our changing uses and reliance on technology continue to pose new challenges that require R&D from all sectors to understand and solve. Ongoing NIT R&D is necessary to improve the resilience, security, and integrity of our existing NIT systems; to build the networking, hardware, and software capabilities of the future; and to ensure that the United States remains a leader in shaping the global technology landscape. Much of this effort is made possible by the Federal funding dedicated to NIT R&D.

Overview of the NITRD Program

The entity charged with overseeing and coordinating Federal support for this critical work is the NITRD Program. The NITRD Program was designed to "provide for long-term basic and applied research" in NIT fields.[14] More specifically, it was established to coordinate and track activities across the Federal Government's primary sources of R&D in these areas.[15] The R&D coordinated by the NITRD Program is funded by individual agencies through their regular appropriations, rather than through a separate, designated set of funding. Thus, agencies determine which of their R&D funding and efforts are part of the NITRD Program.

Collectively, the NITRD Program works to coordinate interagency NIT R&D efforts, provide strategic guidance and management to those Federal efforts, and implement activities (e.g., strategic planning, workshops, and reporting) that advance a whole-of-government approach to NIT R&D. The relationships developed through the NITRD Program promote beneficial information sharing and programmatic coordination across NITRD agencies. The NITRD National Coordination Office (NCO) serves as a single point of contact and coordinator of programmatic efforts. The NITRD Program also tracks funding in NIT R&D topic areas over time, which enables individual agencies and the NITRD Program to identify opportunities for cross-agency synergies and potential gaps or duplication in the Federal NIT R&D portfolio.

Role of the NSTC Subcommittee on NITRD

The National Science and Technology Council (NSTC) works to coordinate Federal research and development projects in the field of science and technology policy for the executive branch.[16] The NSTC Subcommittee on NITRD is composed of senior representatives from 23 Federal agencies and departments that conduct or support R&D in advanced networking and information technologies.[17] It also includes representatives of the White House Office of Science and Technology Policy (OSTP) and the White House Office of Management and Budget (OMB).[18] The Subcommittee coordinates NIT R&D policy across the Federal R&D enterprise and ensures consistency with the President's stated goals. It is co-chaired by the Director of the NITRD NCO (currently Ms. Kamie Roberts) and an OSTP-designated representative from among the NITRD member agencies (currently Dr. Margaret Martonosi, who leads the National Science Foundation's [NSF] Computer and Information Science and Engineering Directorate).

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[14] 15 U.S. Code § 5511 (a)(1)(A)

[15] Ibid.

[16] OSTP. n.d. "National Science and Technology Council." Accessed December 22, 2020. https://www.whitehouse.gov/ostp/nstc.

[17] NITRD. 2020. "About the NITRD Program." August 14, 2020. https://www.nitrd.gov/about/index.aspx.

[18] Ibid.

Structure and Role of the NITRD NCO

The NITRD NCO supports the NITRD Subcommittee and the activities of the NITRD Subcommittee Interagency Working Groups (IWGs) by providing technical expertise; supporting planning, budgeting, assessment, and coordination; and serving as a central point of contact.[19] Another role of the NCO is to coordinate the development of the annual NITRD supplement to the President's budget (the "Budget Supplement"). This document, released annually, describes the funding for initiatives included as part of the NITRD Program and identifies key activities being undertaken by agencies as part of the NITRD Program.[20] The NCO Director is appointed by and reports directly to the Director of OSTP. As of September 2020, the NCO has a staff of 15. The NCO Director is a Federal employee, while the other 14 staff members are government contractors.[21]

Role of IWGs

The IWGs are the primary means by which agencies coordinate their R&D resources on shared NIT problems. The fiscal year (FY) 2021 NITRD Budget Supplement describes the role of IWGs as aligning agency R&D initiatives with the Trump Administration's priorities, coordinating agencies' investments in foundational research, helping agencies to transfer research into practice, coordinating the advancement of Federal IT infrastructure, and fostering multi-sector research partnerships. In the IWGs, representatives exchange information; collaborate on research plans; and organize activities such as testbeds, workshops, and cooperative solicitations. Long-term engagement by IWG representatives builds connections and facilitates informal communication and sharing of tacit knowledge across agencies. In addition to the NSTC Subcommittee member agencies, approximately 50 Federal departments and agencies have designated experts to participate in at least one IWG.[22] As of 2020, there are 11 IWGs, whose names and acronyms are listed in Box 1.

The relationship among the Subcommittee, the NCO, and the IWGs in coordinating the NITRD Program is shown in Figure 1.

Two of the IWGs—AI and LSN—have created structures to advance multi-sector collaboration within their areas of responsibility. The AI IWG supports a Video and Image Analytics (VIA) Team that coordinates Federal R&D while sharing information with stakeholders in academia, industry, and non-profit organizations and fostering public-private research partnerships. The LSN IWG supports three teams: 1) Broadband R&D (BRD) Team; 2) Joint Engineering Team (JET);

> Box 1: NITRD IWGs
>
> - Artificial Intelligence R&D (AI)
> - Big Data
> - Computing-Enabled Networked Physical Systems (CNPS)
> - Cybersecurity & Information Assurance (CSIA)
> - Health Information Technology R&D (HITRD)
> - High End Computing (HEC)
> - Intelligent Robotics and Autonomous Systems (IRAS)
> - Large Scale Networking (LSN)
> - Privacy R&D (Privacy)
> - Software Productivity, Sustainability, and Quality (SPSQ)
> - Wireless Spectrum R&D (WSRD)
>
> List of IWGs as of September 2020, available from nitrd.gov

[19] NITRD. n.d. "National Coordination Office." Accessed December 22, 2020. https://www.nitrd.gov/about/about_nco.aspx.

[20] Subcommittee on Networking and Information Technology Research and Development. 2020. *The Networking & Information Technology Research & Development Program Supplement to the President's FY2021 Budget*. Washington, DC: National Science and Technology Council. https://www.whitehouse.gov/wp-content/uploads/2017/12/FY2021-NITRD-Supplement.pdf.

[21] Personal communication with Kamie Roberts, Director of the NITRD NCO.

[22] *The Networking & Information Technology Research & Development Program Supplement to the President's FY2021 Budget*, *op. cit.*

and 3) the Middleware and Grid Interagency Coordination (MAGIC) Team. All three teams are intended to foster research collaboration with non-Federal stakeholders as well as across Federal agencies, and both the JET and the MAGIC Team explicitly list—as of 2020—non-profit, academic, and industry partners among their participants.[23]

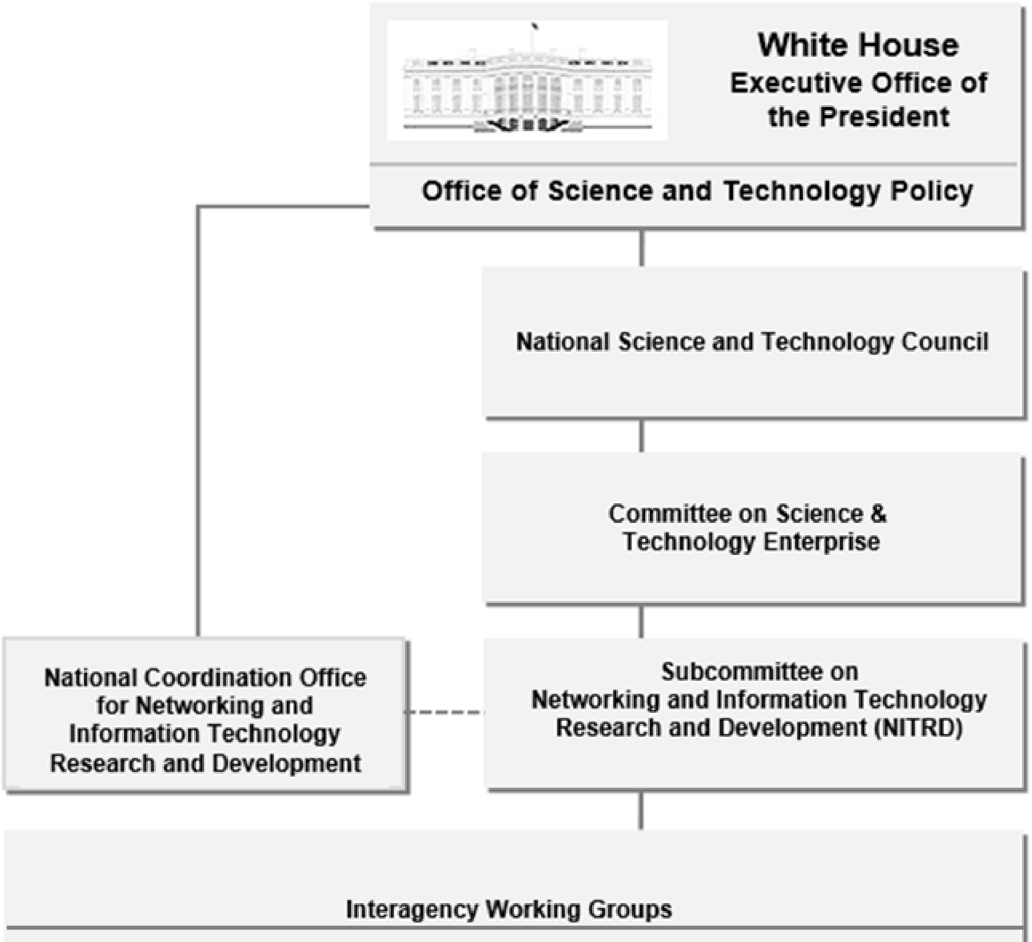

Figure 1. NITRD Program Organizational Chart

Source: https://www.nitrd.gov/about/index.aspx

NITRD Funding by Agency

Agencies' reported budgets for their NITRD activities (which collectively comprise the NITRD Program budget) since 2010 is plotted over time in Figure 2. Throughout this time period, NSF, the Department of Defense (DoD), the National Institutes of Health (NIH), and the Department of Energy (DOE) have been

[23] NITRD. n.d. "Video and Image Analytics Team." Accessed December 22, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=VIA.
NITRD. n.d. "Broadband Research and Development Team." Accessed December 22, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=Broadband.
NITRD. n.d. "Joint Engineering Team (JET)." Accessed December 22, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=JET.
NITRD. n.d. "Middleware and Grid Interagency Coordination (MAGIC)." Accessed December 22, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=MAGIC.

the four agencies whose reported initiatives constitute the largest share of the NITRD Program. Specifically, NSF's reported NIT R&D investment levels have remained steady in absolute terms while declining as a proportion of the total funds reported for the NITRD Program. The absolute amount of funding reported for NIH and DOE activities included in the NITRD Program has increased in absolute terms and as a proportion of the total funding in the NITRD Program. The absolute amount of funding reported for DoD activities included the NITRD Program budget has increased while remaining steady as a proportion of the total funds included in the NITRD Program.

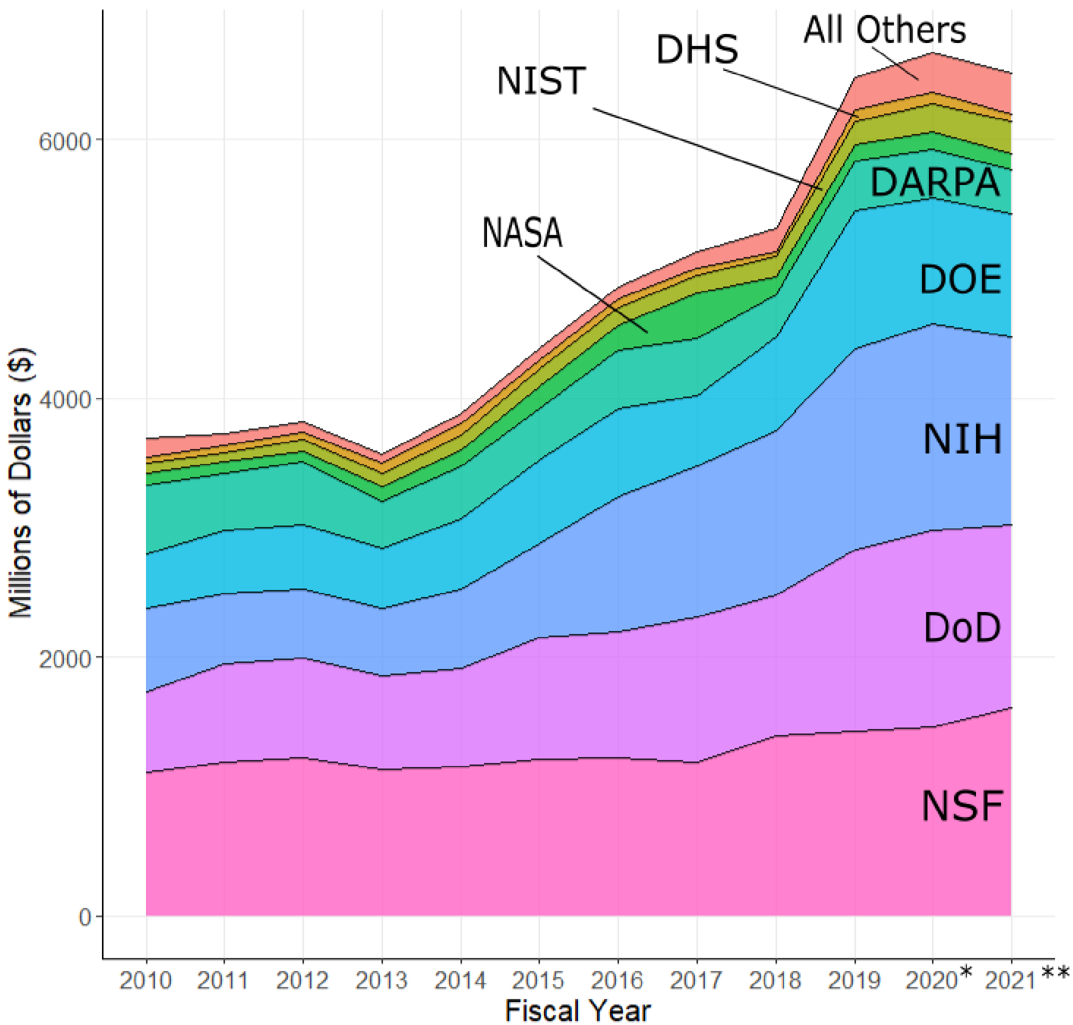

Figure 2. Reporting of Individual Agency Annual Funding for Their Activities that are Included in the NITRD Program, Fiscal Years 2010–2021

Notes: For FY2010–FY2019, actual budgets are shown, which is based on the Networking & Information Technology Research & Development Program Supplements to the President's Budget for FY2012–FY2021, respectively. FY2020 budget estimates and FY2021 budget requests are from the Budget Supplement for FY2021. Dollar figures have not been adjusted for inflation. "All Others" category refers to the agencies contributing less than $50M per year on average. Asterisk (*) denotes that the FY2020 budget is an estimated amount. Asterisks (**) denote that the FY2021 budget is the amount requested by the Trump Administration rather than actual or estimated appropriations.

Spending in NITRD Program Component Areas (PCAs) over Time

PCAs are NITRD-specific budget areas used to categorize and summarize Federal R&D investment in networking and IT. Publishing an annual report of the program's spending has been a part of NITRD's activities since it was established, but as networking and IT have evolved, so too have the PCA categories used to track that spending (see Box 2 for a list of the current PCAs and their acronyms). The PCAs do not have a strict one-to-one correspondence with the IWGs (Figure 3). Their decoupling was recommended in the 2010 NITRD Review to enable the PCAs and IWGs to evolve independently to best serve their distinct purposes: IWGs are a forum for agency coordination of projects and activities, whereas PCAs are a way to track classes of investment to facilitate cross-agency and longitudinal portfolio comparisons.[24] In particular, the CSP and LSN PCAs are each affiliated with two IWGs, which are related to different aspects of their subject areas, and the HEC IWG is related to two PCAs. The Health Information Technology Research and Development (HITRD) IWG is not affiliated with any PCA: its participating agencies make R&D investments in several PCAs. The CHuman and EdW PCAs do not correspond directly to individual coordinating IWGs: as described by the FY2021 Budget Supplement, the agencies that invest in these two subject areas coordinate their activity through multiple relevant IWGs.[25]

Box 2: NITRD PCAs

- Artificial Intelligence (AI)
- Computing-Enabled Human Interaction, Communications, and Augmentation (CHuman)
- Computing-Enabled Networked Physical Systems (CNPS)
- Cyber Security and Privacy (CSP)
- Education and Workforce (EdW)
- Enabling R&D for High-Capability Computing Systems (EHCS)
- High-Capability Computing Infrastructure and Applications (HCIA)
- Intelligent Robotics and Autonomous Systems (IRAS)
- Large Scale Data Management and Analysis (LSDMA)
- Large Scale Networking (LSN)
- Software Productivity, Sustainability, and Quality (SPSQ)

Source: NITRD FY2021 Budget Supplement

[24] PCAST. 2010. *Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology*. https://www.nitrd.gov/pubs/PCAST-NITRD-report-2010.pdf.

[25] *The Networking & Information Technology Research & Development Program Supplement to the President's FY2021 Budget*, *op. cit.*

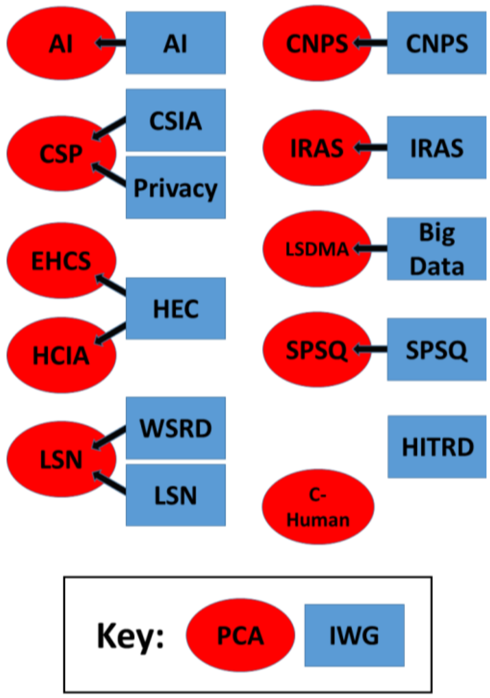

Figure 3. Relationships among the NITRD PCAs and IWGs

Source: Adapted from Supplement to the President's Budget for FY2021, op. cit. Figure 1, page 5.

Prior to 2015, the PCA focal areas had not changed since the establishment of the NITRD Program in the 1990s. Subsequent to PCAST's 2013 and 2015 reviews of NITRD, which recommended updating the PCAs to reflect the contemporary landscape of NIT R&D,[26,27] several out-of-date PCAs were retired or refocused (and accordingly renamed) and some Federal R&D activities were moved from one PCA to another.[28] Figure 4 provides a visualization of this evolution.

Over the past decade, the relative funding levels of the major groupings of PCAs have largely remained stable, with two exceptions: 1) the IRAS, LSDMA, and CHuman group of PCAs, for which funding has grown in absolute terms and as a proportion of overall funding relative to its HCI & IM predecessor; and 2) the new AI PCA's share of funding has grown, which is due partly to an increase in the total NITRD budget and partly to some programs being transferred from the LSDMA PCA to the AI PCA.

[26] PCAST. 2013. *Report to the President and Congress Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology*. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast-nitrd2013.pdf.

[27] PCAST. 2015. *Report to the President and Congress Ensuring Leadership in Federally Funded Research and Development in Information Technology*. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/nitrd_report_aug_2015.pdf

[28] NITRD. n.d. "NITRD Program Component Areas." Accessed December 22, 2020. https://www.nitrd.gov/subcommittee/NITRD-PCAs.aspx.

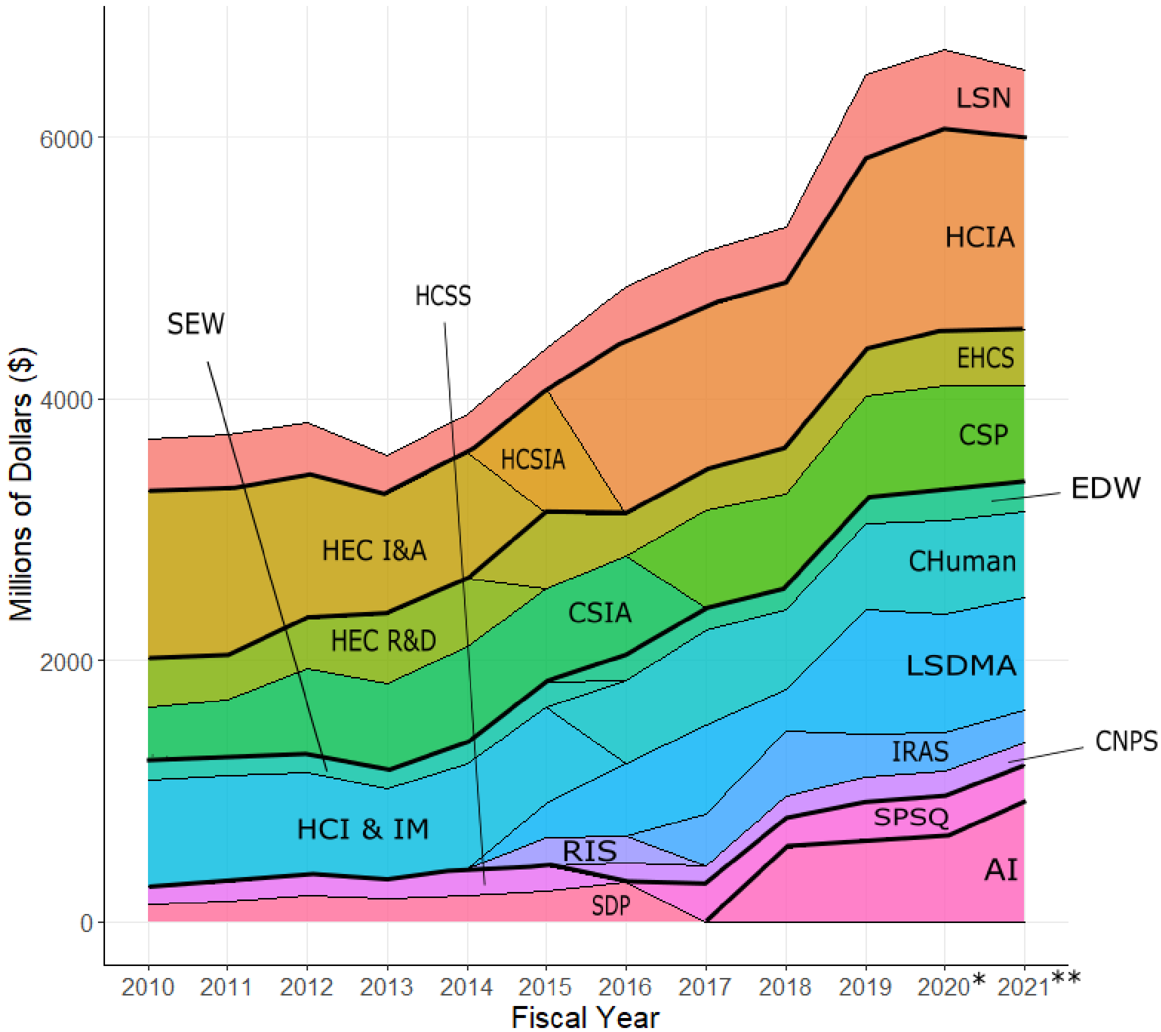

Figure 4. Reporting of Annual Funding from NITRD Program Member Agencies, by PCA, Fiscal Years 2010–2021

Notes: The NITRD PCAs have been reorganized over time. The stable groupings are indicated by black lines; transitions between PCAs are indicated by interdigitating wedges (e.g., the transition from the HEC I&A PCA to the HCSIA and EHCS PCAs). Actuals reported in a particular year are taken from the Budget Supplement from 2 years ahead (e.g., the FY2017 actuals are reported based on the FY2019 Budget Supplement). If PCAs changed during the intervening years, the reporting uses the PCA structure from the year of the Budget Supplement, even if the PCA did not exist during the year where actuals were reported).

For FY2010–FY2019, actual budgets are shown, which is based on the Networking & Information Technology Research & Development Program Supplements to the President's Budget for FY2012–FY2021, respectively. Asterisk (*) denotes that the FY2020 budget is an estimated amount. Asterisks (**) denote that the FY2021 budget is the amount requested by the Trump Administration rather than actual or estimated appropriations. FY2020 budget estimates and FY2021 budget requests are from the Budget Supplement for FY2021. Dollar figures have not been adjusted for inflation.

The following PCAs are have been retired: HCSIA = High-Capability Computing Systems Infrastructure and Applications; HEC I&A = High End Computing Infrastructure and Applications; HEC R&D = High End Computing Research and Development; CSIA = Cyber Security and Information Assurance; SEW = Social, Economic, and Workforce Implications of IT and IT Workforce Development; HCI & IM = Human Computer Interaction and Information Management; RIS = Robotics and Intelligent Systems; HCSS = High Confidence Software and Systems; SDP = Software Design and Productivity.

Purpose of This Report

This report provides a review of NITRD's "funding, management, coordination, implementation, and activities," as required by statute.[29] It includes findings on the changes to the NITRD Program since the 2015 NITRD Review, including progress made in response to the 2015 recommendations.[30] For the purposes of this review, only those recommendations pertaining to the NCO and the NITRD Program as a whole are thoroughly considered, rather than those directed to individual research agencies (which are beyond the NITRD NCO's ability to implement change). New findings and recommendations are made in the context of the evolution of NIT fields and emerging priorities.

Structure and Organization of this Report

Section 2 describes changes in the NITRD Program since the 2015 NITRD Review. Section 3 identifies a set of emerging trends and areas of interest relevant to NITRD. Section 4 presents summary findings and recommendations. Section 5 summarizes this report's conclusions.

[29] 15 U.S. Code § 5511 (b)(2)

[30] PCAST. 2015. *Report to the President and Congress Ensuring Leadership in Federally Funded Research and Development in Information Technology, op. cit.*

NITRD Program Activities since the 2015 NITRD Review

R&D in Information Technology

This section describes NITRD Program activities undertaken in several technical areas identified in the 2015 NITRD Review to be of "major importance" to R&D in NIT at that time.

Cybersecurity

In 2016, the NITRD Subcommittee and the CSIA IWG published *Federal Cybersecurity Research and Development Strategic Plan: Ensuring Prosperity and National Security*, as directed in the Cybersecurity Enhancement Act of 2014.[31] This report identified short-term, mid-term, and long-term research goals, four "defensive elements" (deter, protect, detect, and adapt), and six critical dependencies that the authors found critical to cybersecurity R&D: 1) Scientific foundations; 2) Enhancements in risk management; 3) Human aspects; 4) Transitioning successful research into pervasive use; 5) Workforce development; and 6) Enhancing the infrastructure for research.[32]

The Subcommittee's and the CSIA IWG's 2019 strategic plan update, *Federal Cybersecurity Research and Development Strategic Plan,* modified the defensive elements slightly (i.e., changing "adapt" to "respond") and outlined research objectives in six priority areas: 1) Artificial intelligence (AI); 2) Quantum information science (QIS); 3) Trustworthy distributed digital infrastructure; 4) Privacy; 5) Secure hardware and software; and 6) Education and workforce development. The plan also identified five critical dependencies: 1) Human aspects; 2) Research infrastructure; 3) Risk management; 4) Scientific foundations; and 5) Transition to practice.[33] The CSIA IWG also publishes an annual implementation roadmap describing progress toward the goals of the strategic plan.[34] The FY2021 Budget Supplement described the IWG's activities with respect to the four defensive elements and the six priority areas.[35]

The CSIA IWG also convenes workshops and releases reports describing the proceedings. The most recent was the publication of *Artificial Intelligence and Cybersecurity: Opportunities and Challenges*, a March 2020 report of a June 2019 workshop convened jointly with the NSTC Machine Learning and Artificial Intelligence (MLAI) Subcommittee and the NSTC Special Cybersecurity Operations Research

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31 Public Law 113-274, Cybersecurity Enhancement Act of 2014.

32 Subcommittee on Networking and Information Technology Research and Development and Cybersecurity Research and Development Strategic Plan Working Group. 2016. *Federal Cybersecurity Research and Development Strategic Plan: Ensuring Prosperity and National Security*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/2016-Federal-Cybersecurity-Research-and-Development-Strategic-Plan.pdf.

33 Committee on Science & Technology Enterprise, Subcommittee on Networking & Information Technology Research & Development, and Cyber Security & Information Assurance Interagency Working Group. 2019. *Federal Cybersecurity Research and Development Strategic Plan*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/Federal-Cybersecurity-RD-Strategic-Plan-2019.pdf. Note that these are virtually the same topics as in the 2016 strategic plan, with the exception of workforce, which was included among the priority research areas.

34 Cyber Security & Information Assurance Interagency Working Group of the Networking and Information Technology Research and Development Program. 2020. *FY2021 Federal Cybersecurity R&D Strategic Plan Implementation Roadmap*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/FY2021-Cybersecurity-RD-Roadmap.pdf.

35 FY2021 Budget Supplement, *op. cit.*, pages 18-19.

and Engineering Subcommittee. The convening covered the security of AI, the use of AI to promote cybersecurity, and the needs of the science and engineering community.[36]

IT and Health

The HITRD IWG coordinates Federal R&D for improving medical, functional, and public health outcomes. In 2020, the IWG issued the *Federal Health Information Technology Research & Development Strategic Framework,* intended to assist agencies in coordinating research efforts and to identify technologies that if pursued might enable new research areas. The report identified four cross-cutting areas: 1) Accelerate the research, development, and implementation of next-generation health IT tools and services; 2) Design effective health IT for the full community of users; 3) Promote infrastructure and standards to make health data, devices, and applications accessible, interoperable, and reusable; and 4) Build the health IT workforce of the future. Participating agencies mapped their ongoing R&D efforts to these four categories.[37] The FY2021 Budget Supplement identified four priorities for the IWG's activities: 1) Support R&D of health IT tools and services to reduce administrative burdens, enable a new bio-economy, and serve the full community of users; 2) Leverage the power of data, computing, and AI to promote infrastructure and standards for accessible, interoperable, reusable health data, devices, and related applications; 3) Support the development of robust health IT R&D that focuses on cybersecurity and privacy; and 4) Build and leverage a diverse, highly-skilled American health IT workforce of the future.[38]

The HITRD IWG has also focused efforts specifically on the interoperability of health IT. The IWG coordinated a request for information (RFI) in February 2019 that sought responses from industry, academia, and non-governmental organizations on new approaches to addressing interoperability issues among medical devices, data, and platforms. The IWG then conducted a listening session in July 2019 that convened 76 representatives from the government and from the device, standards, academic, and medical communities. Information gathered through these two efforts were summarized in a 2020 report, *The Interoperability of Medical Devices, Data, and Platforms to Enhance Patient Care: A Summary of the February 2019 Request for Information and July 2019 Listening Session*.[39]

Big Data & Data-Intensive Computing

The Big Data IWG published the *Federal Big Data Research and Development Strategic Plan* in May of 2016 to develop key strategies for improving big data R&D. The report rested on a shared vision among the Big Data IWG and other Federal agency partners to create a big data innovation ecosystem capable

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[36] Networking and Information Technology Research and Development Subcommittee and Machine Learning and Artificial Intelligence Subcommittee. 2020. *Artificial Intelligence and Cybersecurity: Opportunities and Challenges*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/AI-CS-Tech-Summary-2020.pdf.

[37] Health Information Technology Research & Development Interagency Working Group of the Networking and Information Technology Research and Development Program. 2020. *Federal Health Information Technology Research & Development Strategic Framework*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/Federal-Health-IT-Strategic-Framework-2020.pdf.

[38] FY2021 Budget Supplement, *op. cit*., page 32.

[39] Health Information Technology Research & Development Interagency Working Group of the Networking and Information Technology Research and Development Program. 2020. *The Interoperability of Medical Devices, Data, and Platforms to Enhance Patient Care: A Summary of the February 2019 Request for Information and July 2019 Listening Session*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/Medical-Interoperability-2020.pdf.

of extracting and utilizing data to promote innovation and educational practices across the Nation.[40] The FY2021 Budget Supplement described the Big Data IWG's priorities: 1) Maximize use of large-scale data resources through foundational research into innovative tools and methodologies to solve problems of national and societal importance; 2) Establish the trustworthiness of data-driven discovery and decision-making to ensure reliability, accuracy, generalizability, and performance in solutions to drive science and technology and the Industries of the Future (IotF); 3) Enable the interoperability of diverse data types and sources that is scalable and allows for data integration among heterogeneous datasets to support innovative solutions; 4) Support real-time analytics by reducing latency between data ingest, analysis, and decision-making; 5) Develop and retain a data-literate workforce via R&D and training opportunities; and 6) Transition research to practice by translating R&D into operational tools and technologies that enhance U.S. economy, security, and well-being.[41]

In 2018, the Big Data IWG, in collaboration with the High End Computing IWG, published a report on the convergence of high-performance computing (HPC), big data, and machine learning (ML). The publication followed a workshop held by both IWGs wherein community leaders across academia, industry, and the public sector were asked to provide input in HPC, big data, and ML. Key takeaways from the meeting, detailed throughout the report, include: 1) The exponential scale at which data is growing; 2) The increased heterogeneity of technical systems; 3) The rapid pace at which computing ecosystems are changing; and 4) The need for increased collaboration among the HPC, big data, and ML communities to ensure continued progress in the above areas.[42]

Since 2015, the Big Data IWG has held several workshops concerning various aspects of big data. In 2017, the IWG held a workshop on an Open Knowledge Network that discussed the feasibility of creating a non-proprietary information network available to all stakeholders.[43] In 2018, a workshop measuring the impact of digital repositories was hosted by the Big Data IWG that aimed to identify the effectiveness of, and obstacles to, developing digital repositories in driving innovation and producing high-impact R&D.[44] Another 2018 report on data visualization aimed to address the best way to produce high-quality visualizations using big data.[45]

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[40] Big Data Senior Steering Group of the Networking and Information Technology Research and Development Program. 2016. *The Federal Big Data Research and Development Strategic Plan*. Washington, DC: Networking and Information Technology Research and Development Program. https://www.nitrd.gov/pubs/bigdatardstrategicplan.pdf.

[41] FY2021 Budget Supplement, *op. cit*., page 27.

[42] Big Data Interagency Working Group and High End Computing Interagency Working Group of the Networking and Information Technology Research and Development Program and the Committee on Science and Technology Enterprise. *The Convergence of High Performance Computing, Big Data, and Machine Learning*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/Convergence-HPC-BD-ML-JointWSreport-2019.pdf.

[43] Big Data Interagency Working Group of the Networking and Information Technology Research and Development program and the Committee on Science and Technology Enterprise. *Open Knowledge Network*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/Open-Knowledge-Network-Workshop-Report-2018.pdf.

[44] Big Data Interagency Working Group of the Networking and Information Technology Research and Development program and the Committee on Science and Technology Enterprise. *Measuring the Impact of Digital Repositories*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/BD-IWG-Digital-Repository-Workshop-Report-2018.pdf.

[45] Human Computer Interaction and Information Management Task Force and Big Data Interagency Working Group of the Networking and Information Technology Research and Development program and the

IT and the Physical World

In 2018, the NITRD Smart Cities & Communities Task Force promulgated a guide detailing how Federal agencies could promote the deployment of digital technologies to support the development of smart cities and communities. The document, titled *Connecting and Securing Communities*, was intended to inform Federal agencies supporting smart city and community efforts and to facilitate Federal agencies' identification of opportunities to further strengthen private sector partnerships in this regard. The document identified four approaches to developing smart communities: 1) Promote R&D and translate innovation into practice; 2) Facilitate local efforts to build resilient infrastructure for smart communities; 3) Enable smart city advances through data and knowledge sharing and collaboration; and 4) enable evaluation of progress for smart community development.[46]

In 2019, NITRD merged the Cyber-Physical Systems IWG and the High Confidence Software and Systems IWG to form the NITRD Computing-Enabled Networked Physical Systems (CNPS) IWG. The CNPS IWG Internet site describes its work as including, "complex, high-reliability, safety and security-critical, real-time computing, and engineered systems with varying degrees of autonomy and human-system interaction."[47] Recently, the IWG developed and publicized an online *Federal Smart Cities and Communities Programs Resource Guide* that extends the 2018 Task Force effort and describes federally funded smart city R&D programs across the United States.[48] As reported in the FY2021 Budget Supplement, the CNPS IWG has five strategic priorities: 1) Develop core science and engineering for complex CNPS technologies; 2) Support and enable safety- and security-critical and high-dependability applications, especially in applications of assured autonomy and AI technologies; 3) Support advances in smart cities and communities; 4) Facilitate the transition of new CNPS technologies and tools from laboratories and academia to public and private systems; and 5) Promote inclusive education and workforce development by developing new curricula that integrate CNPS theory and methodology.[49]

Privacy

In 2016, NITRD established the Privacy R&D IWG in order to coordinate Federal privacy R&D related to NIT across the Federal Government. In an effort to expand R&D on privacy protection, this IWG has defined six priorities: 1) Understanding privacy desires; 2) Adopting methods that incorporate privacy; 3) Creating information-use techniques favorable to user privacy; 4) Enabling user-driven controls and actions; 5) Minimizing reidentification risks; and 6) Developing solutions for recovery.[50] The Privacy R&D

Committee on Science and Technology Enterprise. *Frontiers of Visualization II: Data Wrangling*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/NITRD-FOVII-Workshop-Report-2018.pdf.

[46] Smart Cities & Communities Task Force of Subcommittee on Networking & Information Technology Research & Development and Committee on Science & Technology Enterprise. *Connecting and Securing Communities*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/nitrd-connecting-securing-communities-federal-guide-2018.pdf.

[47] NITRD. n.d. "Computing-Enabled Networked Physical Systems Interagency Working Group." Accessed December 22, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=CNPS.

[48] NITRD. 2019. "Federal Smart Cities and Communities Programs Resource Guide." November 6, 2019. https://www.nitrd.gov/apps/smartcity/index.aspx.

[49] FY2021 Budget Supplement, *op. cit.*, pages 17-18.

[50] NITRD. n.d. "Privacy R&R Interagency Working Group." Accessed December 23, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=PrivacyRD#Strategic_Priorities.

IWG has also collaborated with other NITRD IWGs such as the CSIA IWG in order to connect privacy to cybersecurity.

The Privacy R&D IWG published the *National Privacy Research Strategy* in June of 2016. The report recognized previous PCAST recommendations from the 2010, 2013, and 2015 NITRD Reviews as well as a 2014 PCAST report entitled *Big Data and Privacy: A Technological Perspective* concerning privacy and worked to create a clear framework for conducting research that allows for protections of personal information and privacy. The document outlines key obstacles to personal privacy in the digital age, before addressing the research priorities the IWG believes should be adopted across government.[51] The FY2021 Budget Supplement described the Privacy IWG's priorities as: 1) Understand privacy desires and impacts; 2) Develop system design methods that incorporate privacy requirements and controls; 3) Develop techniques to assure that information use is consistent with privacy rules; 4) Develop solutions to enable user-driven controls and actions over data collection, use, and deletion; 5) Develop solutions for minimizing reidentification risks while maximizing utility of data analytics; and 6) Develop solutions for recovery from privacy violations.[52]

In the FY2019 NITRD Budget Supplement, the NITRD Cyber Security and Information Assurance PCA expanded to include privacy issues and was renamed the CSP PCA. As part of this change, the Privacy R&D IWG became more directly involved with the CSP PCA.[53]

Cyber-Human Systems

In 2015, given the rapid growth of the cyber-human systems ecosystem that integrates individuals with IT and allows individuals to collaborate and communicate via various online platforms, PCAST recommended further support for R&D to improve understanding of the fundamental interactions between people and computational systems. This included a call to further support interagency coordination and broaden R&D in social computing, human-robot interaction, privacy, and health-related aspects of human-computer systems.[54]

The IRAS IWG was formed in 2017 to expedite interagency coordination and facilitate IRAS R&D across 28 agencies. The IRAS IWG coordinates R&D in various aspects of autonomous robots, including accelerating the development and use of collaborative robots and other intelligent physical systems. The IWG identified four strategic priorities: 1) Promoting safe and efficient human-robot teaming; 2) Advancing intelligent physical systems; 3) Improving validation and verification of robotic and autonomous systems; and 4) Enhancing wearable robotic fabrics and devices.[55] The FY2021 Budget Supplement described the IWG's priorities similarly, as: 1) Promote safe, efficient human-robot teaming, including evaluating human-robotic interaction systems for safe, trustworthy, transparent collaboration to increase quality of work and life; 2) Advance intelligent physical systems to improve

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51 National Science and Technology Council and Networking and Information Technology Research and Development Program. 2016. *National Privacy Research Strategy*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/NationalPrivacyResearchStrategy.pdf.

52 FY2021 Budget Supplement, *op. cit.*, pages 20-21.

53 Subcommittee on Networking & Information Technology Research & Development. 2018. *Supplement to the President's FY2019 Budget*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/FY2019-NITRD-Supplement.pdf.

54 PCAST. 2015. *Report to the President and Congress Ensuring Leadership in Federally Funded Research and Development in Information Technology, op. cit.*, page 4.

55 NITRD. n.d. "Intelligent Robotics and Autonomous Systems Interagency Working Group." Accessed December 22, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title= IRAS.

their abilities to robustly sense, model, act, plan, learn, and behave ethically in complex and uncertain situations; and 3) Improve wearable robotic systems, including exoskeletons and exosuits.[56] Key opportunities for coordination have included developing open-source, interoperable performance metrics; setting standards for vehicles and collaborative robots; and working with industry and other partners to promote best practices and increase workplace safety.[57]

High-Capability Computing for Discovery, Security, and Commerce

In 2019, the NITRD Fast Track Action Committee (FTAC)[58] on Strategic Computing and the NSTC co-authored an update to the *National Strategic Computing Initiative*. The update refocused several objectives in the original initiative to: 1) Pioneer new frontiers of digital and non-digital computing, 2) Advance the Nation's computational infrastructure, and 3) Expand partnerships for the future of computing. The report provided a series of recommendations in the field of advanced computing through conversations with government, academia, and industry.[59] As described earlier, the HEC IWG, in collaboration with the Big Data IWG, published a report on the convergence of HPC, big data, and ML. The FY2021 Budget Supplement described the HEC IWG's research coordination priorities (as distinct from infrastructure-related priorities) as: 1) Research and develop innovative approaches and technologies critical to the delivery of extreme-scale computing systems; 2) Research and develop technologies to make breakthroughs in high-capability computing's most pressing challenges, pioneer new digital and nondigital computing frontiers, and take computing beyond Moore's Law, including advancing quantum computing; 3) Research and develop new approaches and techniques to improve programmability, portability, and usability of high-capability computing to boost the productivity of high-capability computing systems; 4) Conduct crosscutting activities that serve to extend the breadth and impact of high-capability computing; and 5) Develop the future HEC workforce.[60] In August 2020, OSTP and the HEC IWG convened a meeting on, "Pioneering the Future Advanced Computing Ecosystem." This two-day virtual meeting engaged stakeholders from government, industry, academia, and non-profit organizations to discuss the future evolution of advanced computing infrastructure in the United States.[61]

NITRD Education, Training, and Coordination Activities since 2015

In addition to the eight technical areas that PCAST reviewed in 2015, PCAST also assessed the NITRD Program's education and training activities, the NITRD PCAs, and the working groups and other coordinating structures associated with the NITRD Program. In the 2015 review, PCAST said it selected these areas because of its emphasis on both preparing the current and future IT workforce and the value

[56] FY2021 Budget Supplement, *op. cit.*, pages 25-26.

[57] Ibid.

[58] An FTAC is a body formed by the NSTC to perform a specific, short-term task. After that task is completed, the FTAC is dissolved.

[59] Fast Track Action Committee on Strategic Computing of Networking & Information Technology Research & Development Subcommittee and Committee on Science & Technology Enterprise. *National Strategic Computing Initiative Update: Pioneering the Future of Computing*. Washington, DC: National Science and Technology Council. https://www.whitehouse.gov/wp-content/uploads/2019/11/National-Strategic-Computing-Initiative-Update-2019.pdf.

[60] FY2021 Budget Supplement, *op. cit*., pages 22-23.

[61] NITRD. 2020. "OSTP Convening: Pioneering the Future Advanced Computing Ecosystem." August 21, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=Pioneering-the-Future-Advanced-Computing-Ecosystem.

of coordinating Federal IT research as part of the continuation of the United States' global leadership in networking and IT. These priorities remain for the current PCAST review of NITRD.

Education and Training

In 2015, PCAST reaffirmed many of the recommendations offered in the 2013 NITRD Review, namely continuing to develop a spectrum of educational programs that prepare students and workers for careers in IT. The 2015 report identified a growing need for IT expertise and therefore the need to boost education and training at multiple levels. The report specified that efforts should be made beginning in K-12 education in partnership with the private sector to attract a large and diverse pool of young workers to IT. It also encouraged the development of programs that could adapt to technological change in addition to train, retain, and address the needs of workers of all ages, socioeconomic statuses, and cultural backgrounds. Finally, the 2015 NITRD Review recommended furthering research that examines the best ways to enable students to learn IT concepts.

NITRD's investment planning in education and workforce areas is currently being coordinated with the 2018 Federal STEM Education 5-year plan, *Charting a Course for Success: America's Strategy for STEM Education.*[62] Priorities identified by NITRD include promoting coordination between Federal agencies and the business, education, and non-profit sectors to create opportunities for Americans to learn IT and AI skills regardless of educational level. Additionally, NITRD is interested in facilitating the development of life-long NIT learning programs in communities and workplaces to help prepare Americans to participate in the economy and society. The NITRD Subcommittee meeting in July 2020 initiated coordination with the NSTC Committee on STEM Education and its Federal Coordination in STEM Education (FC-STEM) Subcommittee. That meeting included an FC-STEM panel describing activities under the STEM Strategic Plan as well as a NITRD panel describing workforce needs in NIT fields.[63]

NITRD PCAs

The 2015 NITRD Review recommended that OSTP, the NITRD NCO, the NITRD Subcommittee, and OMB collaborate to revise the PCAs continuously to better reflect the current nature of IT, IT advancements, and national priorities. In 2015, PCAST recommended the four entities develop a process to review the PCAs every 5 to 6 years with the intention to implement revisions proposed by PCAST or the PITAC.[64]

In 2016, the NITRD Subcommittee created an FTAC to review and update the NITRD PCA definitions. After consulting with the NITRD Subcommittee and NITRD member agencies, the FTAC defined three new PCAs, left the definitions unchanged for four PCAs, and revised and updated the definitions of the rest of the PCAs. The FTAC was then disbanded. Over the course of the FY2017 and FY2018 Budget Supplements, the number of PCAs increased from 8 to 10.[65] The program added an eleventh PCA related

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[62] Committee on STEM Education. 2018. *Charting a Course for Success: America's Strategy for STEM Education*. Washington, DC: National Science and Technology Council. https://www.whitehouse.gov/wp-content/uploads/2018/12/STEM-Education-Strategic-Plan-2018.pdf.

[63] Personal communication with Kamie Roberts, Director of the NITRD NCO.

[64] PCAST. 2015. *Report to the President and Congress Ensuring Leadership in Federally Funded Research and Development in Information Technology, op. cit.*

[65] Subcommittee on Networking and Information Technology Research and Development. 2017. *The Networking & Information Technology Research & Development Program Supplement to the President's FY2018 Budget*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/2018supplement/FY2018NITRDSupplement.pdf.

to AI in the FY2020 and 2021 Budget Supplements. Figure 4 highlights the recent evolution of NITRD's PCAs. The following are noteworthy changes that contributed to the increase in number of PCAs:[66]

- The Social, Economic, and Workforce Implications of IT and IT Workforce Development (SEW) PCA was renamed the EdW PCA in FY2018. The Social Computing aspects of SEW began being reported in the CHuman PCA beginning in FY2018.
- The FY2017 Human Computer Interaction and Information Management (HCI&IM) PCA was discontinued; starting in FY2018, HCI activities began to be reported under the CHuman PCA, while information management activities began to be reported under LSDMA.
- Robotics aspects of the FY2016 HCI&IM PCA and High Confidence Software and Systems (HCSS PCAs) were moved to the new Robotics and Intelligent Systems (RIS) PCA in FY2017. Later the RIS PCA was renamed as the IRAS PCA for FY2019.
- In the FY2020 Budget Supplement, NITRD established the AI PCA. Activities captured under this PCA include programs that make long-term investment in AI, develop effective methods for human-AI collaboration, and ensure the safety and security of AI systems.

Additionally, in collaboration with the NCO and OSTP, the NITRD Subcommittee conducts annual reviews of the PCA definitions.[67]

NITRD IWGs

The NITRD Subcommittee co-chairs, one of whom is the NCO Director, review the IWGs annually; other staff from the NSF Directorate for Computer & Information Science & Engineering's leadership participate in the review process as well.[68] Between 2015 and 2020, those reviews have led to sunsetting, merging, and creating new IWGs. One example of a sunset IWG was the Social Computing IWG. The co-chairs found that many other IWGs (e.g., CSIA, Privacy) were also integrating the social sciences and human-centered computing aspects of IT into their work, and thus they chose to discontinue the distinct IWG focused on this topic.[69] An example of a merger was the creation of the Computing-Enabled Networked Physical Systems IWG in 2020. That IWG arose from the Cyber Physical Systems and High Confidence Software and Systems IWGs, which were already working together. The new AI IWG was created in 2018 to coordinate Federal AI R&D across more than 30 agencies and to support activities tasked by both the NSTC Select Committee on AI and the MLAI Subcommittee.[70]

Each IWG has published a set of strategic priorities on its Internet site within the overarching NITRD site. Since 2018, four IWGs (AI, CSIA, HEC, WSRD) have published a strategic plan setting out research priorities; in 2020, HITRD published a "strategic framework" that set out cross-cutting health IT needs and target areas for research but did not include specific short-term or long-term recommendations for

[66] NITRD. n.d. "NITRD Program Component Areas (PCAs)." Accessed December 22, 2020. https://www.nitrd.gov/subcommittee/NITRD-PCAs.aspx.

[67] Subcommittee on Networking and Information Technology Research and Development. 2019. *The Networking & Information Technology Research & Development Program Supplement to the President's FY2020 Budget*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/FY2020-NITRD-Supplement.pdf.

[68] Personal communication with Kamie Roberts, Director of the NITRD NCO.

[69] Personal communication with Kamie Roberts, Director of the NITRD NCO.

[70] NITRD. n.d. "Artificial Intelligence Interagency Working Group." Accessed December 22, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=AI.

action.[71,72,73] Three other IWGs (Big Data, CNPS, Privacy) derive their priorities from strategic plans and vision statements published in 2015 and 2016.[74,75,76] Of the other three IWGs, one (LSN) has published workshop reports but not full strategic plans and two (IRAS and SPSQ) do not feature any current strategic planning-type documents on their NITRD IWG web sites.

Other Notable NITRD Activities since 2015

In addition to implementing changes in response to the 2015 NITRD Review, NITRD has also been active in areas that fell outside the topics specifically addressed in that review. These activities are described here and categorized by IWG. We emphasize that these categories have evolved significantly since the last PCAST NITRD review.

Artificial Intelligence Interagency Working Group

Created in 2018, the AI IWG is guided by the strategic priorities put forth in *The National Artificial Intelligence Research and Development Strategic Plan: 2019 Update*. Specifically, the IWG aims to 1) Make and coordinate long-term Federal investments in AI; 2) Promote safe and effective methods for human-AI collaboration; 3) Address the ethical, legal and societal implications of AI; 4) Improve the safety and security of AI systems; 5) Develop the shared public datasets and environments for AI testing and training; 6) Measure and evaluate AI technologies; 7) Expand the AI workforce through education and training; and 8) Facilitate public-private AI partnerships.[77] The progress made across Federal agencies in each of these strategic areas is detailed in the *2016-2019 Progress Report: Advancing Artificial Intelligence R&D.* This report, published jointly by the AI IWG, the NSTC Subcommittees on NITRD and Machine Learning & Artificial Intelligence, and the NSTC Select Committee on AI, details AI advancements made between 2016 and 2019.[78]

Since its formation, the IWG has engaged in a number of activities that work to advance one or more of the strategic priorities listed above. In 2019, the IWG held a workshop on AI and cybersecurity. This workshop, summarized in the 2020 report *Artificial Intelligence and Cybersecurity: A Detailed Technical Workshop Report*, addressed how AI could be used to exploit system vulnerabilities, how AI-enabled

[71] Select Committee on Artificial Intelligence. 2019. *The National Artificial Intelligence Research and Development Strategic Plan: 2019 Update*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/National-AI-RD-Strategy-2019.pdf.

[72] *Federal Cybersecurity Research and Development Strategic Plan 2019*, *op. cit.*

[73] Fast Track Action Committee on Strategic Computing and the Committee on Science and Technology Enterprise. 2019. *National Strategic Computing Initiative Update: Pioneering the Future of Computing*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/National-Strategic-Computing-Initiative-Update-2019.pdf.

[74] *The Federal Big Data Research and Development Strategic Plan*, *op. cit.*

[75] Cyber Physical Systems Interagency Working Group. 2015. *Cyber Physical Systems Vision Statement.* June 3, 2015.https://www.nitrd.gov/nitrdgroups/images/6/6a/Cyber_Physical_Systems_%28CPS%29_Vision_Statement.pdf.

[76] *National Privacy Research Strategy*, *op. cit.*

[77] *The National Artificial Intelligence Research and Development Strategic Plan: 2019 Update*, *op. cit.*

[78] Artificial Intelligence Research and Development Interagency Working Group, Subcommittee on Networking and Information Technology Research and Development, Subcommittee on Machine Learning and Artificial Intelligence, and the Select Committee on Artificial Intelligence. 2019. *2016-2019 Progress Report: Advancing Artificial Intelligence R&D*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/AI-Research-and-Development-Progress-Report-2016-2019.pdf.

systems might be exploited, and how AI could be used to combat threats.[79] Additionally, NITRD has tracked AI R&D investments in support of Executive Order 13859, "Maintaining American Leadership in Artificial Intelligence," which was written in 2019.[80]

The VIA Team, created in 2016, is now a part of the AI IWG. The team aims to advance the ability to convey detailed information through video and image technologies. Recently the team has engaged in developing frameworks for media processing and assembling a repository of image spoofs and fakes.[81]

Large Scale Networking Interagency Working Group

The LSN IWG, formed in 1991, aims to promote long-term research in future networks related to cloud infrastructure, data modeling, and wireless networks across the Nation. The IWG's five strategic priorities are: 1) Promote long-term research in concepts, techniques, architectures, and protocols for future networks; 2) Enable cloud infrastructure enhancements from enterprise to tactical edge including standards and guidance for the adoption of cloud computing; 3) Scale data-intensive workload and management capabilities to meet the requirements of applications such as data modeling and analytics; 4) Achieve new levels of security and resilience for emerging wireless networks and multidomain Internets and to protect core infrastructure; and 5) Advance wireless networks through innovations such as the use of nontraditional waveforms and the deployment of nationwide testbeds.[82] In 2017, LSN held a workshop focusing on software-defined networks (SDN), i.e., a network infrastructure that enables flexibility in programming and operation to account for future advancements in the field. A 2018 report of the workshop titled *Operationalizing Software Defined Networks* summarized the key takeaways from the workshop, noting the requirements for creating interoperable and comprehensive SDNs in the United States.[83]

Recently, LSN has explored interagency collaboration opportunities in broadband connectivity. The BRD Team has developed a Broadband Resource Guide that provides a list of Federal broadband R&D resources and interagency collaboration opportunities.[84] The two other teams reporting to LSN include the JET, which focuses on inter-domain traffic monitoring and performance measurement,[85] and the MAGIC Team, which focuses on the development of computer grids, clouds and middleware.[86] Both of these teams promote information sharing among Federal agencies and with non-Federal participants.

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[79] NITRD. 2020. *Artificial Intelligence and Cybersecurity: A Detailed Technical Workshop Report*. Washington, DC: Networking and Information Technology Research and Development Program. https://www.nitrd.gov/pubs/AI-CS-Detailed-Technical-Workshop-Report-2020.pdf.

[80] NITRD. 2020. "AI R&D Investments." August 14, 2020. https://www.nitrd.gov/apps/itdashboard/AI-RD-Investments.

[81] NITRD. n.d. "Video and Image Analytics Team." Accessed December 23, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=VIA.

[82] NITRD. n.d. "Large Scale Networking Interagency Working Group." Accessed December 23, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=LSN.

[83] Large Scale Networking Interagency Working Group and Committee on Science and Technology Enterprise. 2018. *Operationalizing Software Defined Networks*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/Operationalizing-SDN-Report-2018.pdf.

[84] NITRD. 2019. "Broadband Resource Guide." March 7, 2019. https://www.nitrd.gov/apps/broadband/index.aspx.

[85] NITRD. n.d. "Joint Engineering Team." Accessed December 29, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=JET.

[86] NITRD. n.d. "Middleware and Grid Interagency Coordination." Accessed December 29, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=MAGIC.

Software Productivity, Sustainability, and Quality Interagency Working Group

The Software Productivity, Sustainability, and Quality (SPSQ) IWG, formed in 1991, works to coordinate across agencies to reduce the time and cost associated with developing and sustaining software. Specifically, SPSQ aims to: 1) Advance the development of low defect, low vulnerability software; 2) Enhance critical software quality and productivity; 3) Modernize and improve safety, security and trustworthiness of software systems; and 4) Develop the workforce of the future in SPSQ. In 2020, SPSQ hosted a workshop on software in the era of extreme heterogeneity that centered on examining challenges associated with developing software on incredibly diverse and complicated computational systems.[87] In 2021, SPSQ aims to hold a workshop on Deep Learning and Software Engineering.[88]

Wireless Spectrum Research and Development Interagency Working Group

The Wireless Spectrum Research and Development (WSRD) IWG, established in 2011, was formed to coordinate and make recommendations promoting the use of wireless spectrum through new technologies. The strategic priorities put forth by WSRD are to 1) Increase spectrum efficiency, flexibility and adaptability; 2) Design robust, secure and dependable wireless spectrum systems; 3) Build devices that can monitor their spectrum environment; 4) Expand communications capacity; and 5) Accelerate the development of usable spectrum tools.[89] Additionally, WSRD coordinates research on spectrum sharing technologies across the Federal Government.[90] However, this is not listed as one of the IWG's core priorities.

Since 2015, WSRD coordinated the 2019 *Research and Development Priorities for American Leadership in Wireless Communications*, which promulgated research priorities to advance spectrum access and efficiency and identified research priorities related to spectrum sharing and other research topics.[91] It has also worked closely with the AI IWG to convene the 2019 Artificial Intelligence & Wireless Spectrum: Opportunities and Challenges workshop. The workshop aimed to explore the use of AI in future communications networks. Additionally, in 2018, WSRD held a workshop on security from a wireless spectrum perspective. The workshop addressed security issues in the context of wireless spectrum and discussed ongoing innovations and the new security challenges that could emerge from them. Currently, the IWG includes among its priorities ensuring that the United States reaches its full 5G potential.[92]

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[87] NITRD. n.d. "Software Productivity, Sustainability and Quality Interagency Working Group." Accessed December 23, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=SPSQ.

[88] Ibid.

[89] NITRD. n.d. "Wireless Spectrum R&D Interagency Working Group." Accessed December 23, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=WSRD.

[90] OSTP. 2019. *Research and Development Priorities for American Leadership in Wireless Communications*. Washington, DC: OSTP. https://www.whitehouse.gov/wp-content/uploads/2019/05/Research-and-Development-Priorities-for-American-Leadership-in-Wireless-Communications-Report-May-2019.pdf.

[91] Wireless Spectrum Research and Development Interagency Working Group. 2019. *Research and Development Priorities for American Leadership in Wireless Communications*. Washington, DC: National Science and Technology Council. https://www.whitehouse.gov/wp-content/uploads/2019/05/Research-and-Development-Priorities-for-American-Leadership-in-Wireless-Communications-Report-May-2019.pdf.

[92] NITRD. n.d. "Wireless Spectrum R&D Interagency Working Group." Accessed December 29, 2020. https://www.nitrd.gov/nitrdgroups/index.php?title=WSRD.

Emerging NIT Trends and Areas of National Need

This section highlights six emerging trends and other key areas of national need that PCAST finds important as of 2020: 1) Microelectronics; 2) Industries of the Future; 3) Multi-sector partnerships; 4) Translation from research to practice; 5) Coordination with NSTC Subcommittees in areas related to NIT; and 6) Emerging approaches to NIT-related workforce and training. Several of these areas are related to topics that PCAST discussed in its report issued in June 2020, titled *Recommendations for Strengthening American Leadership in Industries of the Future,* which focused on actions that could be taken to accelerate progress in the areas of AI, QIS, advanced communications networks, advanced manufacturing, and biotechnology.[93]

Microelectronics

Microelectronics, from materials to beyond complementary metal–oxide–semiconductor (CMOS) devices to modern System on a Chip (SoC) designs to multi-chip modules, are fundamental to virtually all aspects of NIT. The United States has historically led in the advancement of CMOS technologies. However, these technologies are approaching physical limits for the number of transistors that can fit on a single chip (the doubling of which every 18 months has been the basis for "Moore's Law" scaling of computing power) and heat dissipation within devices—necessitating new technology paradigms to support sustained growth in performance.[94] In addition, the United States faces supply chain security challenges associated with increased fabrication costs and an increasingly global industry.[95] Even with investment to re-shore critical components in the microelectronics supply chain, the United States will still rely on offshore foundries for access to state-of-the-art technologies and the production volumes needed to satisfy demand. Security assurance for SoC and multi-chip modules across the hardware and software interface, including intellectual property verification and supply chain provenance, will remain a significant and important challenge.[96] Finally, recently discovered vulnerabilities[97,98] in commercial processors have elevated the importance of understanding and accounting for the cybersecurity implications of hardware design among researchers, technologists, and policy makers.[99]

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[93] PCAST. 2020. *Recommendations for Strengthening American Leadership in Industries of the Future*. https://science.osti.gov/-/media/_/pdf/about/pcast/202006/PCAST_June_2020_Report.pdf?la=en&hash=019A4F17C79FDEE5005C51D3D6CAC81FB31E3ABC.

[94] Debenedictis, Erik P. 2017. "It's Time to Redefine Moore's Law Again." *Computer* 50: 72-75.

[95] Mak, Marie A. 2015. *Trusted Defense Microelectronics: Future Access and Capabilities Are Uncertain*. GAO-16-185T. Washington, DC: Government Accountability Office.

[96] Ray, Sandip, Eric Peeters, Mark M. Tehranipoor, and Swarup Bhunia. 2018. "System-on-Chip Platform Security Assurance: Architecture and Validation." *Proceedings of the IEEE* 106 (1): 21-37.

[97] Lipp, Moritz, Michael Schwarz, Daniel Gruss, Thomas Prescher, Werner Haas, Anders Fogh, Jann Horn, Stefan Mangard, Paul Kocher, Daniel Genkin, Yuval Yarom, and Mike Hamburg. 2018. "Meltdown: Reading Kernel Memory from User Space." In *Proceedings of the 27th {USENIX} Security Symposium*, 973-990. Baltimore, MD. https://www.usenix.org/system/files/conference/usenixsecurity18/sec18-lipp.pdf.

[98] Kocher, Paul, Jann Horn, Anders Fogh, Daniel Genkin, Daniel Gruss, Werner Haas, Mike Hamburg, Moritz Lipp, Stefan Mangard, Thomas Prescher, Michael Schwarz, and Yuval Yarom. 2019. "Spectre Attacks: Exploiting Speculative Execution." In *2019 IEEE Symposium on Security and Privacy (SP)*, 1-19. San Francisco, CA. doi: 10.1109/SP.2019.00002.

[99] National Academies of Sciences, Engineering, and Medicine (NASEM). 2019. *Beyond Spectre: Confronting New Technical and Policy Challenges: Proceedings of a Workshop*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25418.

The NSTC Subcommittee on Advanced Manufacturing's 2018 *Strategy for American Leadership in Advanced Manufacturing* identifies "Leadership in Electronics Design and Fabrication" as a key objective. The strategy recommended that the United States prioritize the development of capabilities that will ensure microelectronics are manufactured domestically, including supporting the development of new semiconductor materials and photonic and spintronic technologies.[100] The importance of securing the NIT supply chain was also highlighted in a recent Executive Order.[101] Semiconductors, including microelectronics, were also included in the FY2022 OMB/OSTP R&D priorities memorandum.[102]

Many Federal agencies are engaged in R&D activities related to microelectronics. For example, the PowerAmerica Institute (1 of 14 ManufacturingUSA Institutes supported by the U.S. Departments of Commerce, Defense, and Energy as public-private partnerships intended to boost advanced manufacturing capabilities) is devoted to the demonstration and adoption of wide bandgap semiconductors made of silicon carbide and gallium nitride for improved efficiency.[103] The Defense Advanced Research Projects Agency (DARPA) Microsystems Technology Office funds a variety of programs related to high-performance microsystems that create enabling capabilities for defense uses.[104] NSF is partnering with the Intel Corporation to support microarchitecture research, seeking efficiencies from innovative deployment of existing semiconductor types.[105]

The National Nanotechnology Initiative (NNI) and its NSTC Nanoscale Science, Engineering and Technology (NSET) Subcommittee and the National Nanotechnology Coordination Office (NNCO), which coordinates R&D activities related to nanotechnology across 20 departments and independent agencies, is also engaged in coordinating R&D in next-generation computer hardware. The NNI's Signature Initiative on Nanoelectronics for 2020 and Beyond spans NSF, the National Institute of Standards and Technology (NIST), the National Aeronautics and Space Administration (NASA), DOE, and DoD to coordinate interrelated R&D "to accelerate the discovery and use of novel nanoscale fabrication processes and innovative concepts to produce revolutionary materials, devices, systems, and architectures to advance the field of nanoelectronics.[106] Its six major thrust areas address new models, materials, devices, and infrastructure for computing rooted in nanoscale science. These agencies are also a part of the NITRD Program. Agency representatives participate in both NNI thrust areas and NITRD IWGs, and the NCO and NNCO Directors (and their staffs) interact regularly. NCO and

[100] Subcommittee on Advanced Manufacturing and Committee on Technology. 2018. *Strategy for American Leadership in Advanced Manufacturing*. Washington, DC: National Science and Technology Council. https://www.whitehouse.gov/wp-content/uploads/2018/10/Advanced-Manufacturing-Strategic-Plan-2018.pdf.

[101] Executive Order 13873 "Securing the Information and Communications Technology and Services Supply Chain," 2019.

[102] Vought, Russell T., and Kelvin K. Droegemeier. 2020. "Fiscal Year (FY) 2022 Administration Research and Development Budget Priorities and Cross-cutting Actions." Official Memorandum. Washington, DC: Executive Office of the President. https://www.whitehouse.gov/wp-content/uploads/2020/08/M-20-29.pdf.

[103] See, for example, https://www.manufacturingusa.com/sites/manufacturingusa.com/files/POWERAMERICA_FINAL.pdf.

[104] See, for example, https://www.darpa.mil/about-us/offices/mto.

[105] See, for example, https://www.nsf.gov/pubs/2019/nsf19598/nsf19598.htm.

[106] See, for example, https://www.nano.gov/about-nni/what, https://www.nano.gov/NSINanoelectronics.

NNCO have discussed micro/nanoelectronics and have considered a joint effort in this area, but as of 2020 have not pursued one.[107]

Industries of the Future

As part of its 2020 and 2021 R&D priorities, as detailed in the FY2022 OMB/OSTP R&D priorities memorandum, the Trump Administration has highlighted a group of Industries of the Future (IotF)—AI, QIS, advanced communications networks, advanced manufacturing, and biotechnology—with potential to create high-paying jobs and economic prosperity while improving security and quality of life for all Americans. Prioritizing R&D in these areas is intended to enable future scientific discovery and economic innovation that will strengthen U.S. leadership in science and technology globally. Synergies at the intersections of each of the fields comprising the IotF also have the potential to accelerate the pace of breakthroughs in these and other fields important for the U.S. economy and national security.[108]

Three of these areas—AI, QIS, and advanced communications networks—fall within the realm of NIT.

AI: New applications and breakthroughs in AI have great potential to expand the U.S economy, improve U.S. defense and security capabilities, and enhance American quality of life, as noted in 2019 in Executive Order 13859, "Maintaining American Leadership in Artificial Intelligence." In recent years, significant progress has been made in a range of AI areas such as natural language processing, computer vision, and deep learning, driven in part by the impressive computational power of today's processors and an abundance of data—critical for "training" many AI models. AI R&D is thriving in both academia and the private sector, in particular in the areas of ML, deep learning, and neural networks. Labor market demand for workers with AI-related knowledge and skills and the potential for AI to enable automation of a range of tasks are likely to affect the nature and distribution of work across all sectors in the coming years, with implications for U.S. STEM education and workforce development.[109] AI-based tools already have applications in a range of fields and industries, from transportation to finance to scientific research.[110]

In the area of ML, algorithms "learning" tacit knowledge from real-world data may lack transparency about how or why the algorithm produces a particular result, causing a propagation of error or bias inherent in the input, leading to incorrect conclusions, or causing a system to work other than as intended. As AI technologies are applied in new ways, principles and methods for designing and assessing the trustworthiness of AI systems are becoming critically important, and a key area for R&D. On the security front, AI-based generation of video, audio, or text that cannot be distinguished from genuine artifacts presents the risk that such capabilities could be misused for the purpose of spreading disinformation. AI is also changing the cybersecurity landscape through opportunities to automate both potential offensive (from denial-of-service attacks to social engineering) and defensive (e.g.,

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[107] Personal communications with Kamie Roberts, Director of the NITRD NCO and Lisa Friedersdorf, Director of the NNCO.

[108] *FY2022 Administration Research and Development Budget Priorities and Cross-cutting Actions*, *op. cit*.

[109] NASEM. 2017. *Information Technology and the U.S. Workforce: Where Are We and Where Do We Go from Here?* Washington, DC: The National Academies Press. https://doi.org/10.17226/24649.

[110] Stone, Peter, Rodney Brooks, Erik Brynjolfsson, Ryan Calo, Oren Etzioni, Greg Hager, Julia Hirschberg, Shivaram Kalyanakrishnan, Ece Kamar, Sarit Kraus, Kevin Leyton-Brown, David Parkes, William Press, AnnaLee Saxenian, Julie Shah, Milind Tambe, and Astro Teller. 2016. "Artificial Intelligence and Life in 2030." One Hundred Year Study on Artificial Intelligence: Report of the 2015-2016 Study Panel, Stanford University, Stanford, CA. https://ai100.stanford.edu/2016-report.

automated intrusion detection) operations, and by broadening the cyberattack surface to include vulnerabilities deriving from the use of AI in systems.[111,112,113]

Such areas of AI have been a particular focus of the Trump Administration and the NITRD Program as evidenced by work of the NITRD AI IWG initiated in 2018, the NSTC Select Committee on AI, and the NSTC Subcommittee on AI and Machine Learning (see this report's section on NITRD Program Activities Since the 2015 NITRD Review). The NITRD Program member agencies have also made AI R&D and practice high priorities, for example via NIST's ongoing efforts on trustworthy AI[114] and the DoD Joint AI Center.[115,116]

QIS: R&D in QIS could lead to new communication technologies, novel sensing modalities, and a completely new paradigm in computing and simulation, with the potential to disrupt the current NIT landscape in both beneficial and challenging ways. In particular, quantum computers have been shown to offer exponential speedup over existing computational approaches for certain computational tasks and are often identified as part of the solution for advancing computational capabilities in a post-Moore's Law regime. While the time frame for developing technically mature quantum computers operating entirely coherently is unclear, rapid progress is being made with hybrid devices in which quantum processors operate analogously to co-processors or accelerators and carry out only certain parts of a larger computational process. Quantum computing has many potential applications in science, technology, data analytics, digital security, and financial areas.

On the other hand, quantum computing also poses risks. For example, quantum algorithms have been developed that, if implemented, would be capable of defeating the encryption used to protect today's electronic communications and stored data, posing a major cybersecurity risk.[117,118] NIST is currently working to select the first standard quantum-resistant cryptographic algorithms to serve as the initial

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[111] NITRD. 2020. *Artificial Intelligence and Cybersecurity: A Detailed Technical Workshop Report*. Washington, DC: Networking and Information Technology Research and Development Program. https://www.nitrd.gov/pubs/AI-CS-Detailed-Technical-Workshop-Report-2020.pdf.

[112] Brundage, Miles, Shahar Avin, Jack Clark, Helen Toner, Peter Eckersley, Ben Garfinkel, Allan Dafoe, Paul Scharre, Thomas Zeitzoff, Bobby Filar, Hyrum Anderson, Heather Roff, Gregory Allen, Jacob Steinhardt, Carrick Flynn, Seán hÉigeartaigh, Simon Beard, Haydn Belfield, Sebastian Farquhar, and Dario Amodei. 2018. "The Malicious Use of Artificial Intelligence: Forecasting, Prevention, and Mitigation." https://arxiv.org/ftp/arxiv/papers/1802/1802.07228.pdf.

[113] NASEM. 2019. *Implications of Artificial Intelligence for Cybersecurity: Proceedings of a Workshop*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25488.

[114] See https://www.nist.gov/topics/artificial-intelligence.

[115] See https://dodcio.defense.gov/About-DoD-CIO/Organization/JAIC.

[116] Artificial Intelligence Research and Development Interagency Working Group, Subcommittee on Networking and Information Technology Research and Development, Subcommittee on Machine Learning and Artificial Intelligence, and the Select Committee on Artificial Intelligence. 2019. *2016-2019 Progress Report: Advancing Artificial Intelligence R&D*. Washington, DC: National Science and Technology Council. https://www.nitrd.gov/pubs/AI-Research-and-Development-Progress-Report-2016-2019.pdf.

[117] Defense Science Board. 2019. *Applications of Quantum Technologies: Executive Summary*. Washington, DC: Department of Defense. https://dsb.cto.mil/reports/2010s/DSB_QuantumTechnologies_Executive%20Summary_10.23.2019_SR.pdf.

[118] NASEM. 2019. *Quantum Computing: Progress and Prospects*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25196.

foundation for post-quantum cryptography.[119] As QIS and NIT continue to advance, yielding new computational capabilities and algorithms, post-quantum cryptography will remain a major area of research. Similarly, security implications of quantum communications and networking, including distributed quantum computing and sensing technologies, is an ongoing research area.[120] These topics are relevant to the Cybersecurity and Information Assurance IWG.

Advances in QIS have also raised new questions about what the technologies of today and the near future can do, spurring progress in computing and information theory and practice writ large. Given these issues and the rapidly evolving nature of QIS and associated quantum technologies, the U.S. National Strategic Overview for QIS highlights a science-first approach to this IotF that includes interplay between quantum technological and algorithmic emphases.[121] This includes, for example, research for development of enabling technologies such as quantum memory devices, quantum error mitigation techniques, quantum state transduction mechanisms, quantum repeaters, and quantum device materials and fabrication methods, in addition to research into developing and characterizing the power of new quantum algorithms.

Advanced Communications Networks: The Trump Administration's strategy for leadership in advanced communications networks and for future generations of networking technologies emphasizes research efforts to increase the efficiency of wireless spectrum use, as well as incentives for investment in wireless infrastructure. Advanced communications networks will facilitate the introduction of self-driving cars, expand the use of precision agriculture techniques, and enable telemedicine advances such as remote surgery by providing a real-time, high-speed communications infrastructure.[122]

The transition to 5G wireless telephony requires new allocations of spectrum for commercial use. In 2020, the America's Mid-Band Initiative Team (AMBIT) developed a framework that allowed 100 megahertz of mid-band spectrum that had previously been reserved for national security applications to transition to predominantly commercial use, although the military will retain permanent access to that spectrum in delineated geographic areas as well as temporary access at particular points in time.[123] Although this approach allowed 5G development to move forward, from an R&D perspective it would be useful in the near term—and could become a requirement in the long term—for 5G and beyond to develop ways in which the commercial communication sector can more effectively collaborate on spectrum utilization involving military and personal safety systems. While some Federal agencies have

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[119] NIST. 2020. "NIST's Post-Quantum Cryptography Program Enters 'Selection Round'." July 22, 2020. https://www.nist.gov/news-events/news/2020/07/nists-post-quantum-cryptography-program-enters-selection-round.

[120] See The White House National Quantum Coordination Office. 2020. *A Strategic Vision for America's Quantum Networks*. Washington, DC: The White House. https://www.whitehouse.gov/wp-content/uploads/2017/12/A-Strategic-Vision-for-Americas-Quantum-Networks-Feb-2020.pdf.

[121] Subcommittee on Quantum Information Science. 2018. *National Strategic Overview for Quantum Information Science*. Washington, DC: National Science and Technology Council. https://www.whitehouse.gov/wp-content/uploads/2018/09/National-Strategic-Overview-for-Quantum-Information-Science.pdf.

[122] OSTP. 2019. "Ensuring America Reaches Its 5G Potential." May 30, 2019. https://www.whitehouse.gov/articles/ensuring-america-reaches-its-5g-potential.

[123] Department of Commerce, National Telecommunications and Information Administration. 2020. "Amendment of the Commission's Rules with Regard to Facilitating Shared Use in the 3100-3550 MHz Band (WT Docket No. 19-348)." September 8, 2020. https://www.ntia.doc.gov/files/ntia/publications/ntia-osm_letter_to_fcc-oetwtb_re_3450-3550_mhz_fnprm_9-8-20.pdf.

already been investing in spectrum sharing R&D through initiatives such as DARPA's Spectrum Collaboration Challenge[124] and NSF's Spectrum Innovation Initiative,[125] we expect that analyzing the impact of sharing with various defense systems will become increasingly important. AI will also play an important role in this context, with the growing need for spectrum usage decisions to be mediated at the speed of computing instead of at the speed of human deliberation and rulemaking. There is a cybersecurity aspect as well, since AI decision making for spectrum use could be an attack vector through cyber or physical means.

Other IotF Areas: Although advanced manufacturing and biotechnology do not squarely fall within NIT, R&D in these fields relies upon computing technologies and infrastructure, and could be accelerated by developments in AI, QIS, and advanced communications networks. Building intelligent manufacturing systems is a key objective of the *Strategy for American Leadership in Advanced Manufacturing*, a blueprint for U.S. leadership in high-technology industrial sectors released in 2018 by the NSTC Subcommittee on Advanced Manufacturing. The strategy highlighted the importance of developing digital manufacturing, advanced robotics, and cybersecurity strategies as part of the overall goal of developing new manufacturing technologies.[126] An emphasis on manufacturing and supply chains has also been included in the *National Security Strategy of the United States of America*, which includes a section addressing the Defense Industrial Base and recommends enhancing manufacturing, ensuring the sufficiency of domestic sources for critical components, and encouraging investment in the U.S. industrial base.[127] The FY 2022 OMB/OSTP R&D priorities memo highlights biotechnology as one facet of its "American Public Health Security and Innovation" section.[128]

Multi-sector Partnerships

Multi-sector partnerships—such as collaborations across government, industry, and academia—have been gaining increased attention in the United States and abroad as a mechanism through which to accelerate advances in NIT. For example, NIT research plans such as China's *Made in China 2025* initiative and Japan's Cross-Ministerial Strategic Innovation Promotion Program have emphasized coordination across sectors to accelerate translation of research to practice and commercialization.[129,130] The European Union's *Horizon 2020* research initiative emphasizes information and communication technologies[131] and includes "research-to-retail" and public-private partnerships

[124] See https://www.darpa.mil/program/spectrum-collaboration-challenge.
[125] See https://www.nsf.gov/pubs/2020/nsf20557/nsf20557.htm.
[126] *Strategy for American Leadership in Advanced Manufacturing*, *op. cit.*
[127] The White House. 2017. *National Security Strategy of the United States of America*. Washington, DC: The White House. https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905-2.pdf.
[128] *FY2022 Administration Research and Development Budget Priorities and Cross-cutting Actions*, *op. cit.*, page 2.
[129] Sutter, Karen M. 2020. *"Made in China 2025" Industrial Policies: Issues for Congress*. CRS Report No. IF10964. Washington, DC: Congressional Research Service. https://crsreports.congress.gov/product/pdf/IF/IF10964.
[130] Cabinet Office, Government of Japan. n.d. "Science, Technology and Innovation." Accessed December 16, 2020. https://www8.cao.go.jp/cstp/english/index.html.
[131] European Commission. n.d. "Horizon 2020: Information and Communication Technologies." Accessed December 29, 2020. https://ec.europa.eu/programmes/horizon2020/en/h2020-section/information-and-communication-technologies.

in their scope. In areas such as electronics, joint technology initiatives have been created that rely on industry to set the research agenda and that explicitly incorporate participation by small businesses.[132]

The NSTC International S&T Coordination Subcommittee is an NSTC structure charged with enhancing coordination of Federal agencies' international science and technology cooperation and partnerships. It also can facilitate international coordination on NIT R&D topics. As of 2020, the NITRD NCO does not track NITRD Program-related international efforts, but there have been discussions with the NITRD Program's newest member, the U.S. Department of State, on how the NITRD Program and the Department of State can help agencies with international efforts.[133]

The Trump Administration has identified multi-sector partnerships as having the potential to increase the return on Federal investment to the American public and maintain global competitiveness. Specifically, the FY2022 OMB/OSTP Research and Development Budget Priorities and Cross-cutting Actions memorandum directs that, "Departments and agencies should prioritize funding for cooperative projects that align organizational incentives and advance new external partnership opportunities through multi-sector engagement."[134] A prime example is the COVID-19 High Performance Computing Consortium, which was launched as a public-private partnership as part of the U.S. COVID-19 response to enable researchers to take advantage of cloud computing and supercomputing capabilities of U.S. National Laboratories, industry, and academia.[135]

PCAST emphasized the importance of novel multi-sector partnerships in its 2020 report, which included a recommendation for the formation of multi-sector institutes to catalyze innovative R&D partnerships between government, industry, academia, and non-profit organizations, referring to them as "IotF Institutes."[136] In addition to being multi-sectoral, these IotF Institutes would be multi-disciplinary, leveraging the combination of two or more IotF areas to address challenges of societal importance.

While the primary role of the NITRD Program is to coordinate R&D across the Federal Government, some Program activities also involve non-Federal stakeholders. Workshops such as *The Convergence of High Performance Computing, Big Data, and Machine Learning* convened in 2018 by the Big Data and HEC IWGs have involved experts from academia, industry, and Federal laboratories.[137] RFIs such as the 2018, "Request for Information on Update to the 2016 National Artificial Intelligence Research and Development Strategic Plan"[138] and listening sessions such as the Federal Listening Session on Interoperability of Medical Devices, Data, and Platforms to Enhance Patient Care supported by the

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[132] European Commission. n.d. "Horizon 2020: The New EU Framework Programme for Research and Innovation 2014-2020." Accessed December 29, 2020. https://ec.europa.eu/programmes/horizon2020/sites/horizon2020/files/281113_Horizon%202020%20standard%20presentation.pdf.

[133] Personal communication with Kamie Roberts, Director of the NITRD NCO.

[134] *FY2022 Administration Research and Development Budget Priorities and Cross-cutting Actions*, op. cit., page 9.

[135] OSTP. 2020. *White House Announces New Partnership to Unleash U.S. Supercomputing Resources to Fight COVID-19*. March 23, 2020. https://www.whitehouse.gov/briefings-statements/white-house-announces-new-partnership-unleash-u-s-supercomputing-resources-fight-covid-19.

[136] *Recommendations for Strengthening American Leadership in Industries of the Future*, *op. cit.*

[137] Workshop website: https://www.nitrd.gov/nitrdgroups/index.php?title=HPC-BD-Convergence
List of workshop participants: https://www.nitrd.gov/nitrdgroups/images/5/50/HEC-BD-ML-Workshop-Participants.pdf.

[138] NSF. 2018. "Request for Information on Update to the 2016 National Artificial Intelligence Research and Development Strategic Plan." 83 *Federal Register* 48655, September 26, 2018. https://www.federalregister.gov/documents/2018/09/26/2018-20914/request-for-information-on-update-to-the-2016-national-artificial-intelligence-research-and.

HITRD IWG described above offer external stakeholders the opportunity to participate in IWG efforts through providing comments and insights to Federal Government representatives.

Translation of Research to Practice

The 2015 NITRD Review noted the importance of the translation of NITRD-supported research results into practice. Although it did not devote a specific section or group of recommendations to the topic, some recommendations, such as the cybersecurity recommendations, included specific suggestions related to translation.[139]

Some IWG strategic plans address transition to practice. The *Federal Cybersecurity Research and Development Strategic Plan* includes a section titled "Transition to Practice" that recommended increasing Federal funding for mechanisms intended to support translation, such as research consortia, small business innovation research awards, and system integrator forums; the use of special contracting mechanisms such as other transaction authority was also recommended for use by agencies that are authorized to employ them.[140] Both *The National Artificial Intelligence Research and Development Strategic Plan: 2019 Update* and the *National Strategic Computing Initiative Update: Pioneering the Future of Computing* included a section on the importance of partnerships among Federal agencies, industry, and academic researchers to accelerate the translation of research into practice so that inventions can be deployed to benefit the public and serve agencies' missions.[141,142] Another vital aspect of research is sometimes referred to as "reverse translation," whereby real-world practical problems, deployment observations, and general lessons learned are identified and used to drive lines of inquiry in foundational research. This closed-loop arrangement can accelerate the usual forward-looking translational research perspective while also potentially stimulating new areas of investigation.

Coordination with NSTC Subcommittees in Areas Related to NIT

NIT, especially computing and data analytics, has become critical to progress in science and technology. Accordingly, many NSTC Subcommittees focus on areas that involve substantial use of IT, big data, or other NITRD-related topics. For example, within the Committee on Environment there are subcommittees such as the U.S. Group on Earth Observations Subcommittee, Subcommittee on Global Change Research, and Earth System Predictability Fast Track Action Committee—all of which coordinate research in domains requiring large-scale data collection, and analysis using high-end computing and sophisticated modeling. The Committee on Homeland and National Security includes a Special Cybersecurity Operations Research and Engineering Subcommittee that considers the national security implications of cybersecurity research and technology development. Furthermore, the Committee on Technology includes, in addition to the MLAI Subcommittee that the AI IWG supports, the Subcommittee on Advanced Manufacturing, the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee, and the Materials Genome Initiative Subcommittee—all areas that are related to or benefit from NIT.[143]

[139] *Federally Funded Research and Development in Information Technology*, *op. cit.*, page 23.
[140] *Federal Cybersecurity Research and Development Strategic Plan 2019*, *op. cit.*, page 25.
[141] *The National Artificial Intelligence Research and Development Strategic Plan: 2019 Update*, *op. cit.*, page 40.
[142] *National Strategic Computing Initiative Update: Pioneering the Future of Computing*, *op. cit.*, page 7.
[143] For the full list of NSTC Subcommittees, see https://www.whitehouse.gov/ostp/nstc.

As mentioned earlier, the NSET Subcommittee overlaps with NITRD Program interests in the context of microelectronics. R&D towards new materials and designs for computing hardware components will affect the future of NIT and could help to sustain growth in computing performance post-Moore's Law. The NNCO contributes to coordination of this work. Similarly, QIS, the national coordination of which was spurred with the launch of the National Quantum Initiative and the National Quantum Coordination Office (NQCO) in 2018, focuses on future information processing and communications capabilities that could help to fill gaps in the post-Moore's Law landscape—though much R&D still needs to be undertaken to fully realize these capabilities.

There are opportunities for coordination across some of these areas through the network of NCOs, whose directors (including the NITRD NCO Director) meet regularly to share information.[144] Another mechanism for coordination that some agencies have employed is designating the same expert to sit on multiple subcommittees or IWGs, thus facilitating the diffusion of information across groups working in related research domains.

Emerging Approaches to NIT-related Workforce and Training

In 2018, the NSTC released *Charting a Course for Success: America's Strategy for STEM Education*, intended to guide Federal investment in STEM education through 2023. Three pathways associated with the strategy are of particular relevance to NITRD: 1) Develop and enrich strategic partnerships; 2) Engage students where disciplines converge; and 3) Build computational literacy. The strategy also identified promoting diversity and inclusion in STEM as one of its primary goals.[145]

The STEM strategic plan's emphasis on strategic partnerships addresses an emerging need for multi-sector collaboration to promote work-based learning and credentialing as a complement to traditional K-12 and university educational experiences. As noted in Executive Order 13859, "Maintaining American Leadership in Artificial Intelligence,"[146] AI-related education and workforce development could help American workers from a range of educational backgrounds gain skills relevant to a wide spectrum of professions. Similarly, PCAST recommended in June of 2020 that all sectors work together to develop programs to help provide workers from any field with opportunities to gain professional competencies that will help them participate in the Workforce of the Future, and to create skills-based professional licenses and certifications for IotF in developing fields such as QIS and AI.[147]

Convergence across multiple disciplines is particularly relevant to NIT. Today, computing plays a major role in R&D and exploration in nearly every area of inquiry—from social sciences to engineering to high energy physics—and drives the development of new fields, such as digital humanities and computational science. For example, computing is critical to the field of genomics, where it is required to sequence and assemble DNA, to locate genes of biomedical significance, and to find similarities between sequences of different organisms. The relevance of computing across a wide range of fields and professions also contributes to the high demand for computer science classes—and classes in related fields such as electrical engineering (including signal processing) and data sciences—that has

[144] Personal communication with Charles Tahan, Director of the NQCO.

[145] *Charting a Course for Success: America's Strategy for STEM Education*, *op. cit.*, pages v-vi.

[146] Other countries are making progress toward attracting and sustaining talent in AI via fellowship programs, such as the United Kingdom's Sixteen Centers for Doctoral Training, which in collaboration with UK Research and Innovation will train 1,000 Ph.D. students to leverage the potential of AI. For more information, see https://www.ukri.org/research/themes-and-programmes/ukri-cdts-in-artificial-intelligence.

[147] *Recommendations for Strengthening American Leadership in Industries of the Future op. cit*., page 32.

been observed at the undergraduate level in recent years. Another indicator of this trend is the piloting of hybrid undergraduate programs that combine courses and curriculum from computer science and another field, known as "CS + X."[148] Achieving computational literacy requires promoting digital literacy and basic computational tools and skills across all areas of education in order to enable students to leverage the NIT tools that they will encounter in their education, careers, and daily life.

As described in PCAST's June 2020 report, *Recommendations for Strengthening American Leadership in Industries of the Future*, globalized access to information and the accelerating pace of technology development are shortening the timescale for innovation in NIT fields. Given that U.S. leadership in NIT technologies benefits greatly from the contributions of its international students, scientists, and engineers, PCAST considered it vital that the United States remain a destination for individuals possessing critical skills in order to maintain American leadership in these areas. PCAST further noted the importance of continuing to provide opportunities for highly qualified individuals committed to American values to study and work in the United States.[149]

[148] NASEM. 2018. *Assessing and Responding to the Growth of Computer Science Undergraduate Enrollments*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24926.

[149] *Recommendations for Strengthening American Leadership in Industries of the Future, op. cit*., pages 10-11.

Findings and Recommendations

The review concludes with PCAST's findings and recommendations related to the future of the NITRD Program. PCAST recognizes that implementing these recommendations may warrant additional funding.

Finding 1: The NITRD Program, including the NITRD NCO and Subcommittee, helps to ensure U.S. NIT R&D funding, management, coordination, implementation, and activities are appropriate and effective.

- ***PCAST finds*** that the tripartite structure of the NITRD Program—the Subcommittee, the NCO, and the IWGs—has proven to be an effective mechanism for coordinating interagency NIT R&D efforts, for providing strategic guidance and management to Federal NIT R&D efforts, and for implementing activities (e.g., strategic planning, workshops, and reporting) that advance a whole-of-government approach to NIT R&D. The long-term relationships developed through the NITRD Subcommittee and IWGs promote beneficial information sharing and programmatic coordination across NITRD agencies. The NITRD NCO serves as an efficient single point of contact and coordinator of programmatic efforts. Finally, the NITRD PCAs serve as a useful mechanism for tracking funding in NITRD topic areas over time, balancing the need for incremental evolution as fields change with the value of tracking spending levels longitudinally.
- ***PCAST finds*** that sustained Federal support for foundational research in NIT fields is needed and that coordination of agencies' support of these efforts remains of critical importance for the Nation.
- ***PCAST finds*** that the activities the NITRD Program has undertaken since 2015 have been responsive to the 2015 NITRD Review and that the NITRD Program's continued work in and coordination of research in these critical areas remains vital.

PCAST's 2015 NITRD Review recommended that the NITRD Program review the PCAs every 5 to 6 years and implement proposed modifications. It also recommended that the NITRD Subcommittee, in collaboration with the NCO and OSTP, define a process and timeline for periodic review of each group, with a recommendation for continuation, modification, or sunset.

- ***PCAST finds*** that the NITRD Program has effectively implemented processes for reviewing and modifying the IWGs and PCAs since 2015. One concern we have identified in the current review is that because NITRD Budget Supplements use current-year PCA definitions as the basis for their reporting, information regarding historical expenditures may become difficult to track and compare longitudinally when PCAs are created or re-organized. A second concern identified here is that because NIT fields can evolve rapidly, a PCA review cycle every 5 to 6 years may not be frequent enough.

Recommendation 1: The current NITRD Program model and its approach to coordinating foundational research in NIT fields across participating agencies should continue as constituted, with the following modifications.

- NITRD should continue to review the PCAs regularly using an FTAC and adjust as needed (perhaps every 3 years rather than every 5 to 6 years, as had been recommended in the 2015 NITRD Review). It should also continue to review IWGs periodically, as recommended in the 2015 NITRD Review.

- The NITRD Program should continue to pursue incremental modifications of existing structures (e.g., IWGs, PCAs) rather than engage in wholesale reorganizations at this time.
- When launching wholly new IWGs and PCAs (e.g., such as the AI IWG and AI PCA), NITRD should consider showing clearly in the annual NITRD Program Supplement to the President's Budget which lines of effort derive from previous structures and which are wholly new programmatic areas and funding lines. This will be especially important should NITRD increase the frequency with which the program reviews and modifies PCAs.

Finding 2: While the NITRD Program is effective in coordinating activities across the Federal Government, it can do more to accelerate innovation and keep pace with non-U.S. coordinated NIT efforts through enhanced engagement across all sectors (industry, academia, non-governmental organizations, Federal agencies, and National and Federal Laboratories) and international collaboration on NIT efforts.

Peer competitors such as China, the European Union, and Japan also are undertaking coordinated NIT R&D efforts. These efforts emphasize multi-sector R&D partnerships and support for small- and medium-sized enterprises. As of 2020, the NITRD Program does not track these coordinated efforts or pursue international collaborations. The NITRD Program already includes some convening structures that involve industry and academia. Examples include workshops that many IWGs convene and the teams affiliated with the AI and LSN IWGs.

- ***PCAST finds*** that some IWGs do not report emphases on multi-sector meetings and conferences as part of their activities.
- ***PCAST finds*** that while some IWG strategic plans explicitly include transition to practice and multi-sector partnerships (e.g., AI, CSIA, HEC) as core elements of their approach, others (e.g., HITRD, WSRD) do not.

Recommendation 2: The NITRD Program should examine current structures and operations to identify opportunities for greater multi-sector and international engagement in its activities. Opportunities include the following:

- Amplify multi-sector outreach and engagement efforts. While the NITRD Program notifies the public about its convening activities, it could augment its outreach.
- Expand the NITRD Program's efforts to track non-U.S. coordinated NIT efforts and collaborate with international efforts where appropriate and in coordination with the NSTC International S&T Coordination Subcommittee.

Finding 3: Given the importance of IotF for the U.S. economy and research competitiveness (currently and in the future), there is a need to strengthen coordination in these areas, and NITRD coordination groups are well situated to play this role.

The Trump Administration has highlighted five fields—collectively known as Industries of the Future—with the potential to create high-paying jobs and economic prosperity while improving security and quality of life for all Americans: AI, QIS, advanced communications networks, advanced manufacturing, and biotechnology. Three of these industries—AI, QIS, and advanced communications networks—fall within the realm of NIT. R&D in biotechnology and advanced manufacturing rely on computing technologies and infrastructure, and could be accelerated by developments in AI, QIS, and advanced communications networks.

- ***PCAST finds*** that the NITRD Program's AI activities represent an exemplar for coordination in one particular IotF area. The AI IWG was created in 2018 and supports activities tasked by both the NSTC Select Committee on AI and the MLAI Subcommittee. In addition, an AI PCA was established in the FY2020 Budget Supplement. Since the AI IWG's formation in 2018, the group has supported the development of a 2019 AI strategic plan and multiple workshops that engage stakeholders from across the research enterprise on AI-related topics.

- ***PCAST finds*** that the NITRD Program does not have an explicit focus on the other four IotF areas, although aspects of some of them are incorporated into NITRD activities. Research regarding advanced communications networks is coordinated by the LSN and WSRD IWGs, with LSN focusing on networking challenges and WSRD on research to increase the efficient use of the wireless spectrum. But there is no integrated structure within the NITRD Program responsible for coordinating all research related to next-generation networking technologies. QIS research coordination is occurring, but it is under the auspices of the NQCO, which is outside the NITRD Program. Nor are there explicit structures within the NITRD Program to address coordination of IT-related research that would enable advanced manufacturing or biotechnology, although the COVID-19 High Performance Computing Consortium is an example where the NITRD Program has helped to foster new activities in response to a national need.

Recommendation 3: The NITRD Program should examine current structures and operations to identify opportunities for improving coordination in IotF areas related to the program. Opportunities could include:

- AI—continue coordination efforts within the NITRD Program and between NITRD IWGs and the NSTC Select Committee on AI and the MLAI Subcommittee.
- Advanced communications networks—enhance coordination efforts within the NITRD Program through the Subcommittee and the LSN and WSRD IWGs, particularly on topics such as spectrum sharing that may require new lines of research; spectrum sharing may also involve coordination with other IWGs, such as the AI IWG for applications of artificial intelligence to flexible spectrum assignment and the CSIA IWG related to securing advanced communications networks from cyber-threats.
- QIS—increase coordination with the NQCO and the NSTC QIS Subcommittee, particularly on topics such as post-quantum cryptography R&D and other implications of the development of quantum technologies on the NIT landscape with advances in QIS, and the role of NIT in realizing integrated quantum information systems.
- Biotechnology—coordinate with NSTC bodies working in biosciences-related areas such as the Biodefense R&D Subcommittee and the Biological Sciences Subcommittee.
- Advanced manufacturing—coordinate with the NSTC Subcommittee on Advanced Manufacturing and large-scale manufacturing R&D efforts such as the ManufacturingUSA Institutes.

Finding 4: Microelectronics are fundamental to virtually all aspects of NIT and an efficient and secure microelectronics supply chain is critical for NIT industries.

The Trump Administration has prioritized research on electronics, including microelectronics, as one element of a broader strategy to emphasize domestic manufacturing and supply-chain security for critical industries. Microelectronics, and the semiconductors from which they are fabricated, underlie the hardware that powers the computing and networking technologies for which the NITRD Program was authorized to coordinate Federal R&D efforts. Security assurance for SoC and multi-chip modules across the hardware and software interface will remain a significant and important challenge requiring new R&D efforts. Moreover, the security implications of hardware design have become more visible in the wake of discovery of vulnerabilities in the processors that underlie computers and mobile devices (e.g., Spectre and Meltdown).[150] The cybersecurity vulnerabilities of microelectronics components may require new research foci. As of 2020, NITRD IWGs focus on coordinating Federal R&D related to hardware architectures and software but not on the components themselves.

- ***PCAST finds*** that coordinating microelectronics research represents a gap in the NITRD Program's activities. Moreover, while the NNI has a microelectronics focus area, as of 2020 there are no explicit joint NNI-NITRD Program activities related to ensuring that research coordinated under the aegis of the NNI flows seamlessly into areas of research coordinated through NITRD.
- ***PCAST finds*** there to be the potential for gaps in research coordination and joint research planning that spans the hardware-software and system architecture boundary in microelectronics research.

Recommendation 4: The NITRD Program should incorporate microelectronics R&D explicitly into its programmatic activities.

- This could take the form of a separate IWG or incorporating hardware/components R&D into existing IWGs.
- There should be stronger NNI-NITRD coordination to ensure alignment of R&D strategies and programmatic activities.

Finding 5: Given the importance of ensuring the United States continues to stay at the forefront of NIT and the need to train future scientists, NITRD groups should expand their efforts to coordinate and integrate education and workforce activities of Federal agencies in NIT fields. In 2018, the NSTC released *Charting a Course for Success: America's Strategy for STEM Education*, intended to guide Federal investment in STEM education through 2023. Three pathways associated with the strategy are of particular relevance to the NITRD Program: 1) Develop and enrich strategic partnerships; 2) Engage students where disciplines converge; and 3) Build computational literacy. The strategy also identified promoting diversity and inclusion in STEM as one of its primary goals.[151]

- ***PCAST finds*** that the NITRD Program is already engaging in coordination of NIT education and workforce activities. The PCA on education and workforce tracks investments in how to better develop the next generation of cyber-capable individuals and professionals, and this subject area is already incorporated into many of the priorities of NITRD's IWGs.
- ***PCAST finds*** that there is a need to expand the number of Americans trained to work in NIT fields at all levels of education, ranging from technician-level trainees to postsecondary degree-level. As referenced in *Charting a Course for Success: America's Strategy for STEM Education*, improving digital and computational literacy helps boost the capabilities of the workforce.
- ***PCAST finds*** that it is essential that the United States continues to be the beacon for highly-skilled global talent in NIT and related areas, and renews its emphasis on attracting and retaining highly-skilled foreign students, scientists, and engineers. As PCAST noted in *Recommendations for Strengthening American Leadership in Industries of the Future,* U.S. leadership in many areas of science and technology has benefitted greatly from the contributions of its international students, scientists, and engineers.[152]

[150] *Beyond Spectre: Confronting New Technical and Policy Challenges: Proceedings of a Workshop*, *op. cit.*
[151] *Charting A Course for Success: America's Strategy for STEM Education*, *op. cit.*
[152] PCAST. *Recommendations for Strengthening American Leadership in Industries of the Future*, *op. cit.*, page 11.

Recommendation 5: The NITRD Program should further examine ways it can coordinate its participating agencies—such as through an IWG or other multiagency bodies—to ensure they support and emphasize the following:

- STEM education, including PhD fellowships, in NIT.
- Programs at the intersection and convergence of computational science and other fields (CS + X) at 2-year and 4-year educational institutions.
- Retraining and upskilling the non-technical workforce to participate in the cyber-ready workforce.
- A diverse and inclusive NIT workforce across all levels of technical staff, engineers, and scientists.
- Strengthen efforts to attract and retain international students, scientists, and engineers who wish to contribute to NIT R&D in the United States. These efforts should be informed by conducting studies of the role that international talent plays in the U.S. NIT workforce and any factors affecting recent changes in recruitment and retention.

Conclusion

The United States is a world leader in NIT fields, and NIT advances have provided ubiquitous benefits to American society. The NITRD Program was established to coordinate and track activities across the Federal Government's primary sources of R&D in areas related to NIT fields. We determine that the NITRD Program's funding, management, coordination, implementation, and activities over the past 5 years have been appropriate and effective, although there are opportunities to strengthen the program going forward. Implementation of PCAST's recommendations presented in this report will help to ensure economic competitiveness, secure U.S. leadership in critical industries of the future, enhance national security, and increase the quality of life for all Americans. PCAST stands ready to assist with implementation of these recommendations.