Future Advanced Computing Ecosystem Strategic Plan FY2022 Implementation Roadmap

A report by the

Subcommittee on Future Advanced Computing Ecosystem

Committee on Technology

and the

High End Computing Interagency Working Group

Networking & Information Technology Subcommittee

Committee on Science & Technology Enterprise

of the

National Science and Technology Council

May 2022

About the Office of Science and Technology Policy

Congress established the White House Office of Science and Technology Policy (OSTP) in 1976 to advise the President and others within the Executive Office of the President on scientific, engineering, and technological aspects of the economy, national security, homeland security, health, foreign relations, and the environment. OSTP leads efforts across the Federal Government to develop and implement sound science and technology policies, plans, programs, and budgets, and it works with the private and philanthropic sectors; state, local, tribal, and territorial governments; the research and academic communities; and other nations toward this end. OSTP also assists the Office of Management and Budget with its annual review and analysis of Federal R&D in budgets. OSTP's Senate-confirmed Director co-chairs the President's Council of Advisors on Science and Technology and the NSTC (https://www.whitehouse.gov/ostp).

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Established by Executive Order on November 23, 1993, the National Science and Technology Council (NSTC) coordinates science and technology (S&T) policy across the Federal research and development (R&D) agencies. Chaired by the President, the membership of the Cabinet-level National Science and Technology Council includes the Vice President, Director of the Office of Science and Technology Policy, and Cabinet Secretaries and Agency Heads with significant S&T responsibilities. A primary objective of the NSTC is to establish clear national goals for Federal S&T investments in a broad array of areas spanning virtually all the mission areas of the Executive Branch. The NSTC prepares R&D strategies that are coordinated across agencies to ensure that the Federal Government's investment packages and policies are smart and aimed at accomplishing multiple national goals (https://www.whitehouse.gov/ostp/nstc).

About the Subcommittee on Future Advanced Computing Ecosystem

The NSTC Subcommittee on Future Advanced Computing Ecosystem (FACE) coordinates the Federal agencies to pioneer, sustain, and enhance the advanced computing ecosystem necessary for U.S. scientific, technological, and economic leadership, in alignment with the Networking and Information Technology Research and Development (NITRD) Subcommittee and other subcommittees as appropriate. The Subcommittee on FACE is guided by the objectives, priorities, and recommendations outlined in the 2019 report, *National Strategic Computing Initiative: Pioneering the Future of Computing*, as applied in the 2020 guidance it authored, *Pioneering the Future Advanced Computing Ecosystem: A Strategic Plan*. The FACE Strategic Plan includes an operational and coordination structure to support implementation of the national FACE objectives.

About the NITRD High End Computing Interagency Working Group

The NITRD High End Computing Interagency Working Group (HEC IWG), guided by the NITRD Subcommittee of the NSTC Committee on Science and Technology Enterprise, focuses on R&D to advance high-capability, revolutionary computing paradigms, and to provide the Nation with state-of-the-art computing, communication, software, and associated infrastructure to promote scientific discovery and innovation in the Federal, academic, and industry research communities (https://www.nitrd.gov/coordination-areas/high-end-computing/).

About This Document

This Implementation Roadmap provides details of the R&D activities that Federal agencies are currently planning to implement in fiscal year 2022 and beyond to meet the four objectives and the various subobjectives of the FACE Strategic Plan.

Acknowledgements

The Subcommittee on FACE and the NITRD Subcommittee gratefully acknowledge the work of the HEC IWG, the NITRD IWGs, and the NITRD NCO staff for their contributions to this report.

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Introduction

The national advanced computing ecosystem is an essential strategic asset for our Nation's economy and security, for scientific and engineering discovery and innovation, and for implementing solutions to current and future challenges such as the COVID-19 pandemic, climate change, and development of sustainable energy. The 2020 NSTC report, *Pioneering the Future Advanced Computing Ecosystem: A Strategic Plan*,[1] laid out a vision for a Future Advanced Computing Ecosystem (FACE) and the objectives and initial planning necessary to achieve the vision. The FACE strategic plan, like the 2019 *National Strategic Computing Initiative (NSCI) Strategic Plan*[2] before it, focused on strategic objectives and outlined potential execution directions, leaving details to subsequent implementation plans such as outlined in this document. This Implementation Roadmap provides details of the research and development (R&D) activities that Federal agencies are currently planning to implement in fiscal year 2022 and beyond to meet the four objectives and the various subobjectives of the FACE Strategic Plan.

Strategic Priorities

Strategic Objective 1. Advanced Computing Ecosystem as a Strategic National Asset

Utilize the future advanced computing ecosystem as a strategic resource spanning government, academia, nonprofits, and industry.

Strategic Objective 1 aims to provide a federated set of resources and services that are heterogeneous in architecture, resource type, and usage mode to collectively meet the Nation's foundational needs for world-leading computing capabilities. The following subsections cover the five subobjectives identified in the FACE Strategic Plan that support Strategic Objective 1 and list the planned and ongoing work of Federal agencies in those areas.

1.1 Federate a spectrum of capabilities and capacities (including data, software, networking, and security) that can be used collectively as a strategic national asset.

Data, data management, networking, and data security are essential assets to address current and future challenges facing our Nation. New data management platforms that can ingest structured, semi-structured, and unstructured datasets are being developed to enable public access of data for experimental scientific research. Open knowledge network platforms and data sharing capabilities are also being developed to interrelate and integrate heterogeneous data and enable fully open data. Software development kits enable packaging, integration, and testing of various modeling capabilities across agencies. Development of end-to-end, virtualized, programmable, and self-optimizing network architectures, including quantum networking for multi-node mesh networks, could potentially enable secure data sharing between agencies across multiple tactical networks.

Providing solutions to our Nation's cybersecurity challenges across the advanced computing ecosystem through research, development, and collaboration will ensure the availability, integrity, and security of computational resources ranging from Internet of Things (IoT) and edge computing devices to protections for critical infrastructure such as U.S. energy delivery systems. Advanced methods in cryptography, artificial intelligence and machine learning (AI/ML) algorithms for malware and network threat detection, novel approaches to cyber-resiliency of hardware and

1 https://www.nitrd.gov/pubs/Future-Advanced-Computing-Ecosystem-Strategic-Plan-Nov-2020.pdf
2 https://www.nitrd.gov/pubs/National-AI-RD-Strategy-2019.pdf

software engineering, and continued investment in cybersecurity and privacy research will ensure that our computational foundation for research and innovation will continue to thrive.

Several cloud and hybrid computing platforms are being developed that will enable seamless integration of both on-premises government systems and commercial clouds. These cloud platforms will handle petabytes of data with multi-tier storage and computing capabilities and collaborative scientific and engineering research employing AI/ML.

Planned and ongoing agency activities and programs in this area include the following:

- Data management platforms. *DOE/NNSA, DOE/SC, DOT, NIH, NSF*
- Transportation research informatics platforms. *DOT*
- Knowledge integration platforms. *NIH, NIST, NSF*
- Software development kits, testing capabilities, and quantum networking. *DOE/NNSA, DOE/SC, NSF*
- Self-optimizing networks. *DoD, DOE/SC, NSF*
- Trustworthy platforms. *DHS, DoD, DOE/NNSA, NIST, NSF*
- Cybersecurity and information assurance. *DARPA, DHS, NSF*
- Secure computing on untrusted clouds. *DoD, NSF*
- Security enhancements to the IoT. *NSA, NSF*
- Tools and frameworks for energy delivery systems. *DOE/CESER*
- Identity and access management. *DoD, NIST, NSF*
- Utilization of AI/ML algorithms for threat detection. *DHS, DoD, NSF*
- Hybrid computing platforms. *DHS, DoD, NASA, NIH, NSF, USGS*
- On-premises and cloud systems integration. *DoD, NSF*

1.2 Address the needs of emerging application workflows (e.g., industries of the future) that have diverse advanced computing requirements as well as natural affinities to specific innovative technologies, system architectures, and usage modes.

Application workflows utilizing innovative technologies and advanced computing require development of modern pipelines, methods, and new data management paradigms and data infrastructure to support data ingestion and integration workflows and workflows from edge to high-performance computing (HPC). Codesign to promote data discoverability, interoperability, and reusability along with new paradigms for experimental science are being sought through broad community engagement and partnerships.

Planned and ongoing agency activities and programs in this area include the following:

- Persistent services frameworks. *DoD, NSF*
- Container workflows at scale. *DOE/NNSA, DOE/SC, NSF*
- Sensors for network monitoring. *DOE/SC, NSF*
- Support for accelerated ML and other algorithms on novel computing paradigms. *DOE/NNSA, DOE/SC, IARPA, NASA, NIST, NSA, NSF*
- Distributed computing services. *NSF*
- Data ingestion and integration workflows. *NIH, NSF*
- Foundational research on computing and data infrastructure from edge to HPC. *DoD, DOE/SC, IARPA, NSA, NSF*

- Codesign of data analysis and reuse at scientific user facilities. *DOE/SC, NSF*
- Innovative system architectures for data-intensive computations. *IARPA*

1.3 Promote/support the availability, integrity, and security of critical advanced computing components in the international software and hardware supply chains.

Security in the FACE spans multiple scales and architectures. It addresses clouds with secure computing on untrusted clouds; central processing units (CPUs) with computer architecture support for security mechanisms and the interaction of speculative execution with security; IoT with security mechanisms for real-time operating systems and trust anchors; and their integration into a data and compute infrastructure. It addresses automation with configuration security; design tools and frameworks for analysis, verification, and validation; and foundational research. Additionally, it includes aspects that touch the general public such as identity management and the adoption of trustworthy platforms, as well as efforts to provide early hardware access.

Planned and ongoing agency activities and programs in this area include the following:

- Resilient and secure computing on untrusted clouds. *DoD, NSF*
- Computer architecture support for and interaction with security. *DoD, NSA, NSF*
- Infrastructure for IoT security. *DARPA, DoD, DOE/CESER, NIST, NSA, NSF*
- Identity management and trustworthy platforms. *NIST, NSF*
- General research and integration in security. *DOE/NNSA, DOE/SC, NSF*

1.4 Accelerate access to innovative computing paradigms, technologies, and capabilities (e.g., post-exascale, neuromorphic, bioinspired, quantum, analog, hybrid, and probabilistic computing), while integrating and sustaining existing advanced computing systems critical to agency missions.

Innovative computing technologies will play an increasingly large role in the advanced computing ecosystem as advances from silicon technology slow. Quantum and neuromorphic computing are two innovative architecture approaches that could potentially enable new capabilities, with efforts already planned or underway by agencies. Developing and enabling testbeds will be important for the R&D of new algorithms and applications incorporating artificial intelligence. Quantum testbeds are currently being deployed by multiple agencies. Neuromorphic computing efforts are being investigated via agency research but have yet to mature to the point of a testbed being set up. Further research is also underway to investigate innovative access methods to HPC and advanced technologies.

Planned and ongoing agency activities and programs in this area include the following:

- Quantum computing testbeds to provide access to the research community. *DoD, DOE/SC, NASA, NSF*
- Quantum computing research to enhance understanding of quantum technologies. *DARPA, DoD, DOE/SC, IARPA, NASA, NIST, NSF*
- Accelerator platforms for enabling rapid deployment of a diverse range of quantum computing applications for such areas as advanced manufacturing, sensor technologies, and healthcare. *NSF*
- R&D in neuromorphic computing and artificial intelligence. *DARPA, DoD, DOE/NNSA, DOE/SC, NASA, NIH, NIST, NSA, NSF*

- Access mechanisms to support use of emerging high-end computing technologies. *DoD, DOE/NNSA, NIST, NSF*
- Molecular Information Storage. *IARPA*

1.5 Leverage crosscutting synergies and efficiencies across government, academia, nonprofits, and industry, and with like-minded allies and partners.

Several initiatives are being implemented to collaborate between key allied nations and international research communities in quantum networking, quantum computing, quantum computing simulators, data anonymization, and quantum computing testbeds. Many government agencies are emphasizing data understanding through digital platform readiness, early-stage collaborations, innovative cyberinfrastructure capabilities, and at-scale data storage. Research is being conducted through collaborative and public-private partnerships, advanced computing and data visualization using quantum technology, and fully transparent access to novel quantum computing hardware. Program mechanisms such as the Department of Energy (DOE) Exascale Computing Project's PathForward and the National Science Foundation (NSF) eXtreme Science and Engineering Discovery Environment projects allow for advanced research, computing, and data storage among academic institutions, national labs, and industry partners.

Planned and ongoing agency activities and programs in this area include the following:

- International collaboration. *DHS, DoD, DOE/NNSA, DOE/SC, NSF, State*
- Quantum networking. *DoD, DOE/SC, NIST, NSF*
- Quantum computing testbeds. *DoD, DOE/SC, NASA, NSF*
- Public-private partnerships. *DOE/NNSA, DOE/SC, NASA, NIH, NSF*
- Data visualization. *DOE/NNSA, DOE/SC, NIH, NSF*
- Collaboration among scientists and engineers. *DoD, DOE/NNSA, DOE/SC, NSA, NSF*

Strategic Objective 2. Robust, Sustainable Software and Data Ecosystem

Establish an innovative, trusted, verified, usable, and sustainable software and data ecosystem.

Strategic Objective 2 aims to establish a sustainable U.S. software and data ecosystem through realization of five subobjectives identified in the FACE Strategic Plan. The following subsections cover the five subobjectives and list the planned and ongoing work of Federal agencies in those areas.

2.1 Ensure a robust and sustainable software ecosystem that will translate technology innovations into national science and engineering (S&E) leadership.

A robust software ecosystem is a critical ecosystem element, because of both the evolution of the underlying technology ecosystem and the needs of society at large. Robustness is viewed not as a property of a fixed version of particular pieces of software but as a property of an evolving software ecosystem that represents its ability to adapt to both changing external factors and changes in functional requirements while ensuring safe, secure, and efficient operation.

Planned and ongoing agency activities and programs in this area include the following:

- Cyber systems and cybersecurity capabilities to ensure robustness against adversaries. *DoD, DOE/SC, NIST, NOAA, NSA, NSF*
- Robustness to requirements changes in methods, tools, and infrastructure. *DARPA, NSF*

- Trustworthiness and understandability in networking, complex data management, and data analytics. *DOE/NNSA, DOE/SC, NIST, NSA, NSF*
- Resilient, adaptable, and secure systems. *DARPA, NSF*
- Transition to operations: Testing technologies, R&D and deployment to next-generation platforms, and ensuring software sustainability and sharing of applications across computational disciplines. *DHS, DoD, DOE/NNSA, DOE/SC, IARPA, NOAA, NSF*

2.2 Support needs for novel software development (e.g., algorithms, programming systems, and runtimes).

The envisioned software and data ecosystem will require implementation of novel support paradigms and the discovery of novel software development approaches to accommodate the changing requirements of new algorithms; address the emerging features of new programming approaches, tools, and systems; and ensure compatibility with novel runtime schema.

Planned and ongoing agency activities and programs in this area include the following:

- Data management, storage systems, and input/output (I/O) connecting big data, AI, and HPC. *DOE/NNSA, DOE/SC, NSF, VA*
- Data integration and hardened algorithms. *NIH, NSF*
- Software stacks for extreme HPC heterogeneity, focusing on R&D for beyond exascale. *DOE/NNSA, DOE/SC, NSF*
- R&D to improve the reliability, robustness, explainability, and interpretability of big data and AI/ML technologies, including scientific ML; AI and decision support for complex systems; findable, accessible, interoperable, and reusable (FAIR) data and models for AI/ML; and algorithms for neuromorphic computing. *DARPA, DoD, DOE/NNSA, DOE/SC, NIH, NIST, NSA, NSF, VA*
- Software technologies to support the portable programming of various hardware architectures. *DOE/NNSA, DOE/SC, NSA, NSF*
- Domain-specific languages for heterogeneous computing environments. *NASA, NSF*
- R&D on software and data tools and services to support physical, life, and social sciences and engineering research. *NSF, VA*

2.3 Ensure a robust data ecosystem that includes collaborative data management platforms for real-time processing, curation, analysis, and sharing of data across hardware platforms and geographic locations; increased availability of data across government, academia, nonprofits, industry, and the public; and an accelerated pace of discovery.

A robust data ecosystem is crucial for guarding against disruption by adversaries in the short and long terms as new data delivery, process, and storage methods are developed.

Planned and ongoing agency activities and programs in this area include the following:

- Development of data commons, including cloud-based data science infrastructure and interoperable platforms. *NIH, NSF*
- Verification and validation of ML software, including integrating ML tools with archival data to produce "AI-ready" data and establish infrastructure and standards for data storage. *DOE/NNSA, NASA, NIH, NSF, VA*

- Ensuring AI applications are secure and resilient to vulnerabilities and adversarial attacks, including development of standards, best practices, and testbeds for assessing and managing ML security. *IARPA, NIST, NSA*
- Validating and evaluating AI methods for different domains such as biometrics, robot agility, and materials systems. *DHS, NIST, VA*
- Operationalizing connectivity for agency-wide transport to data lakes that enable sharing across high-end computing platforms. *DoD, NOAA*
- Curating data to ensure that it is FAIR and available for use to the government and the public. *DoD, DOE/SC, NIH, NIST, NOAA, NSF*
- Engaging in foundational research and partnerships to develop robust, integrated computing and data infrastructure, including the development of edge HPC capabilities; new paradigms of experimental science through data management; and libraries for high-performance I/O at large scale. *DOE/SC, NSF, VA*
- Harnessing the Data Revolution: Institutes for Data-Intensive Research in Science and Engineering program. *NSF*
- Data anonymization. *DOE/SC, NSF*

2.4 Develop, deploy, operate, and promote trusted services and capabilities that ensure secure and effective management and high utilization of resources.

AI can be used to create self-monitoring systems that both are robust and ensure data privacy. The deployment of these systems requires a careful accounting of risks, an understanding of the underlying technologies, and comprehensive testing.

Planned and ongoing agency activities and programs in this area include the following:

- Cybersecurity R&D to design, test, build, and continuously evaluate; integrate sensors and data-processing pipelines to collect, enrich, correlate, alert, and index various data sources at speed; detect anomalous or malicious network traffic; quantify performance metrics; and secure multiparty communication. *DHS, DoD, NIST, NSA, NSF*
- Managing risk across different sites and addressing security and privacy. *DoD, NSF, VA*

2.5 Explore innovative models for public-private partnerships aimed at developing models for software and data innovation and sustainability.

Public-private partnerships are important to the long-term sustainment of the software and data ecosystem. While the fundamental research to enable forward-looking developments is often performed in government labs and academia, the support for a sustainable product usually comes with additional development effort from the private sector.

Planned and ongoing agency public-private partnerships include the following:

- Networking research, including wireless spectrum and advanced wireless research, information-centric networking, and edge computing and associated edge network support. *DOE/SC, NIST, NSF*
- Testbeds to transition research technology into operational networks. *NIST, NSF*
- Foundational research for demonstrations in big data and for realizing the convergence of big data, AI, and HPC, focusing on composable tools and heterogeneous architectures. *DoD, DOE/SC, NITRD/LSN/JET, NSA, NSF*

- Software development initiatives to explore and deploy best practices in the areas of sustainable software development, innovation in development practices, evaluation, and virtual testing (including virtual platforms). *DHS S&T, DoD, DOE/NNSA, DOE/SC, DOT, NIST, NOAA, NSF, USDA*
- AI research activities at the scale of a center or institute to explore long-horizon national challenges such as extreme weather preparedness, bioengineering technologies, and sensor data analysis. *DHS S&T, DoD, DOE/NNSA, DOE/SC, DOT, NIST, NOAA, NSF, USDA*
- Foundational AI to provide trustworthiness and ML foundations. *DHS S&T, DoD, DOE/NNSA, DOE/SC, DOT, NIST, NOAA, NSA, NSF, USDA*
- The AI/ML Consortium to Advance Health Equity and Researcher Diversity (AIM-AHEAD) program will establish mutually beneficial and coordinated partnerships to increase the participation and representation of researchers and communities currently underrepresented in the development of AI/ML models and enhance the capabilities of this emerging technology. *NIH*
- The Bridge to Artificial Intelligence (Bridge2AI) program will propel biomedical research forward by setting the stage for widespread adoption of AI that tackles complex biomedical challenges beyond human intuition, including generation of new “flagship” datasets and best practices for machine learning analysis. *NIH*

Strategic Objective 3. Foundational, Applied, and Translational R&D

Support foundational, applied, and translational research and development to drive the future of advanced computing and its applications.

The current trends of the slowing of Moore’s Law and end of Dennard scaling, the data explosion, the growing use of AI, and the shift from concentrated advanced computing resources towards distributed edge-to-cloud confederations of compute and data resources require sweeping and innovative exploration into all levels of the ecosystem to ensure U.S. leadership in advanced computing, data, and science and engineering broadly. Strategic Objective 3 looks at potential technology building blocks at all levels of the computing ecosystem to drive the future of advanced computing, within six subobjectives identified in the FACE Strategic Plan. The following subsections cover the six subobjectives and list the planned and ongoing work of Federal agencies in those areas.

3.1 Ensure hardware leadership in a post-Moore/von Neumann era ensuring broad investments across diverse candidate technologies.

Computer hardware is evolving at a more rapid pace today than ever before. Most high-end resources now contain a mix of standard CPUs and graphics processing units (GPUs). There are increasing numbers of systems using Arm, wafer, and field-programmable gate array (FPGA) hardware. The future is likely to see systems containing neuromorphic and quantum processors. While these newer processors are unlikely to completely replace the more general-use CPUs, they will be used to considerably accelerate computations for select applications where their unique properties make them invaluable. Given this new computational landscape, it is essential to explore diverse technologies that will ensure hardware leadership in a post-Moore/von Neumann era. There are already significant government investments in prototype systems of neuromorphic and quantum technologies, for both computing and networking, that provide funds to the community for research and that support performance of intramural research in government laboratories. Some agencies are actively involved with employing these new technologies in a variety of applications.

This work is providing the detailed feedback required to harden research activities into new working tools and to pave the way for future developments.

Planned and ongoing agency activities and programs in this area include the following:

- Research in quantum algorithms, quantum networking, quantum computing, and qubit technologies. *DARPA, DoD, DOE/NNSA, DOE/SC, IARPA, NIST, NSF*
- Access to novel quantum hardware. *DoD, DOE/NNSA, DOE/SC, NASA, NSF*
- Research in neuromorphic materials, solid-state neuromorphic circuits, brain-inspired models and algorithms, and neuromorphic computing architectures. *DARPA, DoD, DOE/NNSA, DOE/SC, IARPA, NIST, NSA, NSF*
- Advanced architectures employing Arm-based and wafer-scale integrated systems. *DOE/NNSA, DOE/SC, NSA, NSF*
- Software refactoring to prepare for future technologies and requirements. *NASA, NIH, NOAA, NSF*
- Quantifying software performance on new architectures, including non-von Neumann systems. *DoD, NASA, NIST, NSF*
- Reversible and approximate computing. *DARPA, DoD, NSA, NSF*
- Microelectronics for AI applications. *DARPA, IARPA*

3.2 Advance software and software-hardware research to enhance the scale and resolution of important problems that are tractable.

Software is an essential aspect of the future computing landscape, and advances in hardware must be accompanied by advances in software at the systems and applications levels. As the hardware evolves, software needs to keep pace; otherwise, the size and scale of the problems that require high-end computation will stagnate. Without scalable software, the hardware capabilities will be underutilized. Scaling software often involves removing bottlenecks from centralized coordination, frequent synchronization, and other parts of the algorithms that require communication to manage work. In addition, as systems get larger, tolerance for defects and other implementation inefficiencies decreases, requiring new methods for testing and verification.

Planned and ongoing agency activities and programs in this area include the following:

- Software innovation and access to advanced cloud computing facilities. *NIH, NSF*
- Foundational research in AI/ML algorithms and implementation techniques. *DARPA, DoD, DOE/NNSA, DOE/SC, NIST, NSA, NSF*
- R&D on the software stack for heterogeneous computing platforms, including improvements in programmability, performance, and scalability, and developing the tools to adapt to new and emerging technologies. *DARPA, DoD, DOE/NNSA, DOE/SC, NIST, NSA, NSF*
- Research in testing, correctness, assurance, verification, and security of software. *DARPA, DoD, NASA, NIST, NOAA, NSF*

3.3 Address challenges and opportunities related to growing data volumes and successful translation of data into insights.

Large-scale data provides valuable knowledge and insights, but extracting its value requires R&D to improve the capture, curation, management, access, analysis, and presentation of large, diverse, and often multisource datasets. The need is increasing for real-time data analytics, which often requires different architectures and techniques from those designed for offline analysis and modeling. Sources of quickly growing data include scientific measurement instruments, simulation results, sensors (military and civilian), and ML training data.

Planned and ongoing agency activities and programs in this area include the following:

- Foundational research in storage, memory systems, and I/O addressing the increasing volume and complexity of data, data accessibility, and data sharing. *DARPA, DOE/NNSA, DOE/SC, IARPA, NSA, NSF*
- Exploration of transportable systems and of compute accelerators and their integration with more conventional architectures. *DARPA, DoD, NSA*
- Security and privacy of personal and medical data. *Census, DARPA, NIH, NIST, NSF, VA*
- Cybersecurity compatibility, interoperability, and protection. *DHS, NSF*

3.4 Enhance AI capabilities including real-time, at-scale, and with attributes of fairness and explainability.

AI and deep learning capabilities are increasingly being integrated with numerous other facets of modern technology, impacting many aspects of everyday life. It is critical that these capabilities can be trusted to operate in a robust manner free of risks from malicious actors and resilient to unanticipated natural events and to perform in ways that can be understood and explained to a wide spectrum of stakeholders. AI systems are subject to biases from training data, algorithmic structures, and interactions with real-world context; agencies should ensure that the systems operate fairly and focus on capabilities for advanced computing to understand and explain how the systems arrive at their conclusions. Since the *National AI R&D Strategic Plan*[3] was released, many agencies have been exploring new techniques that use advanced computing to ensure trust in AI systems. In addition, research activities that apply these methods to a broad spectrum of applications help ensure robust operation and validate these approaches for current and future operational and scientific purposes. The socioeconomic impact of the widespread use of cloud computing, AI, and deep learning affects the security and trustworthiness of the FACE, as mentioned in Section 1.3.

Planned and ongoing agency activities and programs in this area include the following:

- New approaches to ensure trust in AI systems from both security and decision-making perspectives. *DARPA, DHS, DoD, DOE/NNSA, DOE/SC, NIH, NIST, NSA, NSF*
- Applying AI approaches to applications that ensure robust operation and validation for current and future scientific and operations purposes. *DARPA, DHS, DoD, DOE/NNSA, DOE/SC, IARPA, NIST, NOAA, NSA, NSF*
- AI architectures. *DARPA, DoD, IARPA, NSA, NSF, VA*
- Advanced and rigorous ML models. *DOE/NNSA, DOE/SC, NSF, VA*
- AI for smart manufacturing using advanced computing. *NIST, NSF*
- Machine learning algorithms that are inspired by the human brain. *IARPA, VA*

[3] https://www.nitrd.gov/pubs/National-AI-RD-Strategy-2019.pdf

3.5 Expand availability of and access to testbeds, prototyping, and research infrastructure to encourage research, development, and sustainment of software tools needed to deploy applications onto increasingly complex systems.

Empirical evaluation is an essential prerequisite to the consistent and successful development and deployment of new and updated capabilities. Many Federal programs provide testbeds and prototyping resources for a broad spectrum of future technologies to enable research and preoperational activities. In addition, testbeds and related infrastructure enable R&D to evaluate new technologies that build upon the technologies provided by the testbeds. An important property of these resources is their scale: some R&D requires large-scale or widely distributed systems to validate production-relevant characteristics.

Planned and ongoing agency activities and programs in this area include the following:

- Testbeds focused on large-scale data analytics and AI. *DoD, DOE/NNSA, DOE/SC, NSA, NSF, VA*
- Networking, cybersecurity, distributed computing, and storage. *DoD, DOE/NNSA, DOE/SC, NSF*
- Advanced wireless. *NITRD/WSRD/AWTP, NSF*
- Edge computing. *NSF*
- Exascale and other high-end computing resources. *DOE/NNSA, DOE/SC, NASA, NSF*
- Architectures for high-end computing applied to both simulation and data-intensive computing. *DoD, DOE/NNSA, DOE/SC, NSA, NSF*

3.6 Address the need for technologies that ensure hardware supply chain security for the manufacturing, packaging, and integration of advanced and trusted computing ecosystem electronics.

Electronics and other hardware required for an advanced computational ecosystem must be delivered in a secure fashion and over extended time periods. Hardware supply chain security is critical to ensure that the availability and integrity of the design, manufacturing, packaging, and integration of advanced electronics are securely sustained. The U.S. Government is addressing various aspects of supply chain security.

Planned and ongoing agency activities and programs in this area include the following:

- The Electronics Resurgence Initiative pursues technology options to address the Nation's long-term need for hardware supply chain security, including in the manufacturing, packaging, and integration of advanced and trusted electronics. *DARPA, DoD*
- The SHIP (State-of-the-art Heterogeneous Integrated Packaging) and RAMP (Rapid Assured Microelectronic Prototypes Using Advanced Commercial Capabilities) programs provide resources for secure design and packaging to U.S. Government customers. *DoD*
- Analysis tools capable of imaging minimum-size circuit features on a silicon integrated circuit chip. *IARPA*
- National Cybersecurity Center of Excellence, whose standards work includes ensuring that the internal components of purchased computing devices are genuine and unaltered during manufacturing, and distribution, and/or after sale. *NIST*
- Foundational research on secure, trustworthy, assured, and resilient semiconductors and systems. *DOE/SC, NSF*

Strategic Objective 4. Fostering a Diverse, Capable, and Flexible Workforce

Expand the diverse, capable, and flexible workforce that is critically needed to build and sustain the future advanced computing ecosystem.

Effectively leveraging the future advanced computing ecosystem requires transforming resources and capabilities into usable forms. This transformation includes developing technologies to make advanced computing, software, and data systems and services more intuitive, accessible, and easier to use. It also requires a skilled workforce that can build tools, operate systems, and support a broad range of users. Rapid changes in technology landscapes and user needs, as well as the need for communities to foster the adoption of these evolving technologies, make these goals more difficult to achieve. Strategic Objective 4 tackles technology and workforce issues to enable the Nation to leverage the full power of the advanced computing ecosystem. The following subsections cover the five subobjectives identified in the FACE Strategic Plan that support Strategic Objective 4 and list the planned and ongoing work in those areas.

4.1 Create the diverse workforce necessary to achieve the goals of the future advanced computing ecosystem, support U.S. innovation, and push the leading edge of computation.

Fostering a diverse, capable, and responsive workforce is a multidimensional challenge. Responding to the challenge begins in K–12 with science, technology, engineering, and mathematics (STEM) education efforts. These efforts continue throughout higher education and on to continuing and lifelong learning. Collectively, these efforts strive to provide professional growth and opportunities that attract and retain a diverse, talented and adaptive workforce and encourage the establishment of equitable and inclusive career paths and education environments.

Planned and ongoing agency activities and programs in this area include the following:

- Internships and mentoring. *DHS, DoD, NIH, NSA, NSF, VA*
- Workforce Recruitment Program. *NIH*
- Promotion of undergraduate research experiences. *DoD, DOE/NNSA, DOE/SC, NIST, NSA, NSF, VA*
- Graduate student fellowships. *DOE/NNSA, DOE/SC, NIST, NSF, VA*

4.2 Develop training, upskilling, and reskilling strategies that exploit the use of state of-the-art technologies and anticipate future technologies and solutions.

To prepare the next-generation workforce for the increasingly high-tech world, agencies are developing and expanding workforce training programs and curricula through institutions of higher education, including community colleges and minority-serving institutions. These programs focus on topics such as AI/ML training, computing research infrastructure investments, and student support. They include outreach to future users and innovators of AI technologies to enable the broadest possible engagement with R&D communities.

Planned and ongoing agency activities and programs in this area include the following:

- Internships with special focus on people from backgrounds historically underrepresented in computing and related disciplines including persons with disabilities. *DHS, DoD, DOE/NNSA, DOE/SC, NIH, NIST, NSA*
- Multidisciplinary Academic Research Program. *DOE/NNSA, NSA*
- Training and hackathons. *DARPA, DOE/NNSA, DOE/SC, NIH, NSF*

4.3 Provide the necessary incentives, career paths, and reward structures for retaining computing (hardware, software, data, security) professionals, technologists, and practitioners.

It is important that institutions provide incentives, career paths, and appropriate reward structures to retain a diverse advanced computing and data science workforce over the long term. An equitable and inclusive work environment is just the start. Institutions should ensure that research scientists, teaching faculty, and research software/data/other professionals are recognized and rewarded for their role in successful research activities, with an emphasis on workforce members that are from backgrounds historically underrepresented in computing disciplines. Institutions could encourage professional development and advancement opportunities for current research software and data professionals as part of research programs; and provide career recognition opportunities at all levels, from students to faculty to software/data professionals, throughout all research activities and programs, among other things.

Planned and ongoing agency activities and programs in this area include the following:

- Graduate student research programs and fellowships. *DoD, DOE/NNSA, DOE/SC, NSA, NSF, VA*
- Early-career research programs for faculty and research scientists. *DOE/NNSA, DOE/SC, NSF, VA*
- Professional career development programs and career advancement opportunities for research software and data engineers. *DoD, DOE/NNSA, DOE/SC, NASA, NSF, VA*
- Professional career recognition activities. *DOE/NNSA, DOE/SC, NSF, VA*

4.4 Build synergies across government, academic, nonprofit, and industry stakeholders focused on workforce development and training.

Better integration of government, academic, nonprofit, and industry stakeholders' workforce development and training efforts will enable the Nation to foster a workforce that has the ability to anticipate and exploit future technologies and solutions. To support this integration, efforts in this area include (1) fostering exchange programs within and across agencies and governments to address key collaborative issues, gaps, and concerns; (2) developing public-private partnerships that enable continuous learning, skilling, upskilling, and reskilling strategies targeting the use of state-of-the-art computing technologies; and (3) anticipating and exploiting future technologies and solutions providing on-ramps for nontraditional and mid-career learners. There are ongoing and future activities that are dedicated to workforce development such as providing advanced training for existing staff; mentoring undergraduate, graduate, and postdoctoral students; and sponsoring speaker series to keep staff aware of the evolving computational landscape.

Planned and ongoing agency activities and programs in this area include the following:

- Training and teaching opportunities at the local, state, national, and international levels. *NSF, VA*
- National Initiative for Cybersecurity Education promotes a robust community to advance an integrated ecosystem of cybersecurity education, training, and workforce development. *NIST*

4.5 Foster relevant, mission-focused, on-the-job training in the form of fellowships, academic programs, internships, and sabbaticals in both intramural and extramural agency programs, federally funded R&D centers, and National Laboratories.

On-the-job-training is a primary method for engaging the future workforce and improving preparation for advanced computing employment. Institutions, including community colleges and minority-serving institutions, sponsoring on-the-job training opportunities should ensure equitable access to learners from all backgrounds and institution types. These training opportunities supplement background knowledge in advanced computing fields with real-world practice. They provide critical links to specialists who can provide mentoring opportunities and enable further career advancement. Additionally, Federal agencies are meeting workforce challenges by sponsoring industry experts and academic faculty to serve at agencies in temporary appointments. Agencies are also making investments in programs that develop educational curricula and other materials used for education and training activities, inclusive of all levels and institution types. Current programs focus on a wide spectrum of strategically important fields, including HPC, AI and data analytics, quantum computing, biomedicine, and cybersecurity.

Planned and ongoing agency activities and programs in this area include the following:

- Precollegiate internships. *DoD, NIH, NIST, NSA, NSF, VA*
- Undergraduate education programs. *DoD, NIST, NSA, NSF, USGS, VA*
- Graduate research programs. *DoD, DOE/NNSA, DOE/SC, NIST, NSA, NSF, VA*
- Postdoctoral fellowships. *DoD, NIST, NSF, VA*
- Training and hackathons. *DOE/NNSA, DOE/SC, NIH, NIST, NSF*
- Industry-expert embedding and hiring. *NIH, NSA, NSF, VA*

A Coordinated Path Forward

A key crosscutting strategy that underlies all the efforts previously listed involves ensuring collaboration and coordination across the Federal government. The NSTC Subcommittee on FACE and the NITRD Subcommittee commit to collaborating with other NSTC and Federal government groups to ensure progress on the FACE strategic objectives is coordinated with other initiatives and efforts.

These collaborations may take many forms, including overlapping leadership in relevant subcommittees, participation in interagency committees, regular meetings among committee and subcommittee co-chairs, and related activities. Relevant subcommittees that will be represented in these collaborative consultations include the following:

- Machine Learning and Artificial Intelligence (MLAI) Subcommittee (SC)
- National AI Research Resource Task Force
- Subcommittee on Quantum Information Science (QIS)
- Committee on Cyber Facilities and Infrastructure of the Interagency Council for Advancing Meteorological Services
- Subcommittee on Resilience Science and Technology
- Subcommittee on Disaster Reduction

Indeed, these collaborations are already ongoing, including the following examples over the past year:

- The Subcommittee on FACE and the NITRD SC meet jointly on a periodic basis.
- The NITRD National Coordination Office (NCO) Director has been serving as a co-chair of the Subcommittee on FACE.
- A Subcommittee on FACE co-chair has been serving as a co-chair of the NITRD SC.
- A Subcommittee on FACE co-chair has been serving as a co-chair of the National AI Research Resource Task Force.
- A Subcommittee on FACE co-chair has been serving as a co-chair of the Subcommittee on QIS. Another Subcommittee on FACE co-chair is a member of the Subcommittee on QIS.
- A Subcommittee on FACE co-chair has been serving as the co-chair of the Committee on Cyber Facilities & Infrastructure of the Interagency Council for Advancing Meteorological Services.

Additional current and planned collaborations include the following:

- The Subcommittee on FACE is working with NITRD, the Subcommittee on Resilience Science and Technology, and the Subcommittee on Disaster Reduction to further develop the concept of a National Strategic Computing Reserve.
- The FACE and NITRD Subcommittees will explore opportunities to work with the FC STEM community to advance the goals under Strategic Objective 4, particularly related to diversity, equity, inclusion, and accessibility.
- The FACE and NITRD Subcommittees will coordinate with NSTC leadership on diversity, equity, inclusion, and accessibility activities.

The Subcommittee on FACE will also explore opportunities with other relevant Federal government groups.

The Subcommittee on FACE will produce an annual report detailing agency accomplishments as well as plans and assessments of related risks for the next year.

Abbreviations and Acronyms

AI	artificial intelligence
AI/ML	artificial intelligence/machine learning
Arm	a company, and its family of reduced instruction set computing architectures for computer processors configured for various environments
CISE	Computer and Information Science and Engineering Directorate of NSF
CPU	central processing unit
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DHS S&T	DHS Science and Technology Directorate
DoD	Department of Defense
DOE	Department of Energy
DOE/CESER	DOE Office of Cybersecurity, Energy Security, and Emergency Response
DOE/NETL	DOE National Energy Technology Laboratory
DOE/NNSA	DOE National Nuclear Security Administration
DOE/SC	DOE Office of Science
DOT	Department of Transportation
FACE	Future Advanced Computing Ecosystem (NSTC Subcommittee)
FAIR	findable, accessible, interoperable, and reusable (data)
FHWA	Federal Highway Administration
FPGA	field-programmable gate array
GPU	graphics processing unit
HEC IWG	High End Computing Interagency Working Group
HHS	Department of Health and Human Services
HPC	high performance computing
HPCC	High Performance Computing and Communications Program (NOAA)
IARPA	Intelligence Advanced Research Projects Activity
I/O	input/output
IoT	Internet of Things
IWG	Interagency Working Group
LSN	Large-Scale Networking IWG
LSN/JET	LSN Joint Engineering Team
ML	machine learning
NASA	National Aeronautics and Space Administration
NCO	National Coordination Office of the NITRD Program
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NITRD	Networking and Information Technology Research and Development Program
NOAA	National Oceanic and Atmospheric Administration
NSA	National Security Agency
NSF	National Science Foundation
NSTC	National Science and Technology Council
OAC	Office of Advanced Cyberinfrastructure of NSF
OSTP	Office of Science and Technology Policy
QIS	quantum information science
R&D	research and development
S&E	science and engineering
USGS	United States Geological Survey
WSRD	Wireless Spectrum R&D IWG
WSRD/AWTP	WSRD Advanced Wireless Test Platforms Team