NATIONAL STRATEGIC OVERVIEW FOR RESEARCH AND DEVELOPMENT INFRASTRUCTURE

A Report by the

SUBCOMMITTEE ON RESEARCH AND DEVELOPMENT INFRASTRUCTURE

COMMITTEE ON SCIENCE AND TECHNOLOGY ENTERPRISE

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

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The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the Federal research and development enterprise. A primary objective of the NSTC is to ensure science and technology policy decisions and programs are consistent with the President's stated goals. The NSTC prepares research and development strategies that are coordinated across Federal agencies aimed at accomplishing multiple national goals. The work of the NSTC is organized under committees that oversee subcommittees and working groups focused on different aspects of science and technology. More information is available at http://www.whitehouse.gov/ostp/nstc.

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The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976 to provide the President and others within the Executive Office of the President with advice on the scientific, engineering, and technological aspects of the economy, national security, homeland security, health, foreign relations, the environment, and the technological recovery and use of resources, among other topics. OSTP leads interagency science and technology policy coordination efforts, assists the Office of Management and Budget with an annual review and analysis of Federal research and development in budgets, and serves as a source of scientific and technological analysis and judgment for the President with respect to major policies, plans, and programs of the Federal Government. More information is available at http://www.whitehouse.gov/ostp.

About the NSTC Subcommittee on Research and Development Infrastructure

The Subcommittee on Research and Development Infrastructure (RDI) coordinates Federal investments in infrastructure supporting research and development (R&D) across the Nation under the auspices of the NSTC's Committee on Science and Technology Enterprise. This coordination ensures that U.S. R&D infrastructure and the scientific and engineering workforce it supports remain preeminent, relevant, and ready to address the Nation's economic and national security priorities.

About this Document

This strategic overview provides a high-level landscape of federally supported RDI in national priority areas. The strategic overview aims to identify gaps and opportunities that could benefit from new or improved interagency coordination and/or partnerships both nationally and internationally. It also outlines policy or coordination objectives in critical and emerging priority areas to address near-term (5–10-year) and emergent future RDI needs, considering long-term sustainability for R&D infrastructure investments (40 years +). This strategic overview was developed by the NSTC RDI Subcommittee with contributions from member agencies across the Federal Government listed on page ii.

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Abbreviations and Acronyms

AI artificial intelligence

ALICE A Large Ion Collider Experiment

BRAIN Brain Research through Advancing Innovative Neurotechnologies

CERN The European Organization for Nuclear Research

CDC Centers for Disease Control and Prevention

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

CMS Compact Muon Solenoid

CNIPA The State Intellectual Property Office of the People's Republic of China

DDC Data Distribution Center

DHS Department of Homeland Security

DLE Defense Laboratory Enterprise

DNA Deoxyribonucleic acid

DoD Department of Defense

DOE Department of Energy

DOT Department of Transportation

EHT Event Horizon Telescope

ENSO El Niño-Southern Oscillation

EPA Environmental Protection Agency

ESP Earth system predictability

EUIPO European Union Intellectual Property Office

FACA Federal Advisory Committee Act

FFRDC federally funded research and development center

FDA Food and Drug Administration

FS R&D Forest Service Research and Development

GEOSS Global Earth Observation System of Systems

GPS Global Positioning System

HPC high-performance computing

HSE Homeland Security Enterprise

IPCC Intergovernmental Panel on Climate Change

JPO Japan Patent Office

KIPO Korean Intellectual Property Office

LIGO Laser Interferometer Gravitational-wave Observatory

LHC Large Hadron Collider

ML machine learning

MMA multi-messenger astrophysics

NASA	National Aeronautics and Space Administration
NBACC	National Biodefense Analysis and Countermeasures Center
NBS	National Biodefense Strategy
NCO	National Coordination Office
NIAID	National Institute of Allergy and Infectious Diseases
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NITRD	Networking and Information Technology Research and Development
NNI	National Nanotechnology Initiative
NOAA	National Oceanic and Atmospheric Administration
NSLS	National Synchrotron Light Source
NSF	National Science Foundation
NSTC	National Science and Technology Council
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
QIS	quantum information science
R&D	research and development
RDI	research and development infrastructure
RFI	request for information
RFP	request for proposal
RNA	ribonucleic acid
S&T	science and technology
STEM	science, technology, engineering, and mathematics
USDA	United States Department of Agriculture
USGS	U.S. Geological Survey
USPTO	United States Patent and Trademark Office

Executive Summary

National Strategic Overview: Purpose and Vision

The purpose of the National Strategic Overview for Research and Development Infrastructure (RDI) is to **provide a strategic vision that presents key policy opportunities** to optimize Federal RDI investments and planning over the next 20 years. This National Strategic Overview completes the report to Congress on Federal RDI investments mandated by the America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science (COMPETES) Act.[1] It also describes the current Federal RDI landscape and the integral role of RDIs in enabling and sustaining the Nation's R&D enterprise. Through its strategic vision and key policy opportunities, this National Strategic Overview lays the groundwork to develop coordinated and enhanced approaches for Federal RDI investments that address short- and long-term needs.

The National Science and Technology Council (NSTC) Subcommittee on RDI, composed of agency representatives spanning the Federal Government, developed a consensus definition for RDI. The scope of RDI for the National Strategic Overview is inclusive of and reaches beyond "physical assets" and "major equipment."[2] This National Strategic Overview defines RDI as:

> *Facilities or systems used by scientific and technical communities to conduct research and development (R&D) or foster innovation.*

RDI elements include experimental and observational infrastructure, knowledge infrastructure, and research cyberinfrastructure—all of which are integrated resources relied upon by our Nation's R&D enterprise. For the purposes of this National Strategic Overview, RDIs are limited in scope to federally supported RDIs, which include those owned, managed, or funded by the Federal Government. In general, there are two broad classes of RDI: (1) RDIs that directly support research in areas that have direct bearing on economic competitiveness, national security, and public health, and (2) those facilities that support research into purely discovery-oriented science (e.g., elementary particle physics, astronomy/astrophysics, and nuclear physics). Facilities in some domains are so large the size and scale are often beyond the ability of any one country to design and build. In these instances, the United States should seek to collaborate with international partners to share costs, build international cooperation, and extend our scientific reach.

Summary of Key Policy Opportunities

The Nation's RDIs support leading R&D capabilities and serve as models for our international partners. A number of factors—including national security, economic competitiveness, and growing awareness of inherent privacy concerns—influence how we advance RDIs and the research capabilities they enable. Informed and rigorous RDI planning across the Federal Government should be guided by a

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[1] Section 1007 of the Act, entitled National Coordination of Research Infrastructure, stipulates that the Office of Science and Technology Policy shall provide an annual report containing "a description of the deficiencies in research infrastructure" and "a list of projects and budget proposals of Federal research facilities, set forth by agency, for major instrumentation acquisitions" with "an explanation of how the projects and instrumentation acquisitions…relate to the deficiencies and priorities identified."

[2] For instance, Office of Management Budget (OMB) Circular A-11 defines "physical assets" as the "land, structures, equipment, and intellectual property … that have an estimated useful life of two years or more; or commodity inventories." "Major equipment" includes "information technology, vehicles, ships, machine tools, aircraft, tanks, satellites and other physical assets in space, and nuclear weapons."

strategic vision that aligns with agency missions, interagency coordination goals, and emerging needs for advanced RDI capabilities. This National Strategic Overview provides the following key policy opportunities that support these goals and help agencies optimize the use of existing and future RDIs:

Maintaining Strong and Integrated RDI Planning and Coordination

- Adopt a cohesive definition of RDI that encompasses experimental, observational, as well as knowledge- and cyber-infrastructure, in Federal planning processes
- Identify complementary RDI—and their capabilities—across the Federal Government and external R&D communities to inform agency priority-setting processes
- Plan for, invest in, and deploy the necessary knowledge infrastructure and research cyberinfrastructure to keep pace with the rate of growth of data acquisition in research, as well as published research data, to ensure the efficiency and trustworthiness of scientific pathways and pipelines
- Ensure consistent, sufficient, and timely RDI capabilities, strategically addressing episodic efforts that can undermine the ability to meet long-term needs
- Regularly review and document RDI needs and develop planning processes that encompass repurposing, reusing, or decommissioning low-priority RDI

Ensuring RDIs Support a Flexible and Agile R&D Enterprise

- Foster R&D community engagement to inform Federal RDI planning and prioritization, for instance through assessments and cross-sector coordination
- Seek input from Federal Advisory Committee Act (FACA) and NSTC committees, as these committees are capable of providing valuable insight on future RDI needs and coordination possibilities
- Integrate agile design and decision processes in planning and maintaining RDIs so that capabilities keep pace with the growth in data and advancements in computing and analytics
- Support remote access to RDI capabilities, tools, and platforms, where appropriate
- Build strategic, long-term relationships with contractors and suppliers to enable agility in procurement, development, design, and portability of RDI systems
- Incorporate lifecycle considerations, such as upfront costs of construction, operation, and maintenance, and anticipate future modernization needs for planned and existing RDIs
- Incorporate lifecycle resourcing considerations to ensure RDIs sustain or enhance privacy and other legal protections
- Ensure large or complex RDI projects are managed by staff with appropriate design and project management experience to safeguard delivery on schedule and within budget
- Continue to create and promote STEM education programs that directly engage with and support the use of RDIs as education and training platforms
- Ensure processes that allow the Nation's R&D enterprise to thrive by fostering the participation of talent that reflects the diversity of America

Advancing RDI Capabilities to Support the Convergence of Disciplines and Sectors

- Invest in RDIs that complement core disciplinary needs while identifying opportunities to enhance connections across disciplines and sectors
- Consider the potential use of RDIs beyond a single agency's mission context in developing coordination efforts, especially for the Nation's largest RDI investments
- Ensure RDIs foster convergence through partnerships and research information exchange

Balancing RDI Openness with Security Needs

- Seek international collaborations for the development of RDIs as appropriate to foster international cooperation
- Operate RDIs using research security frameworks that balance open science with appropriate levels of vigilance and that uphold U.S. principles of integrity
- Ensure proper protections for RDIs that are vital to competitiveness, public health and safety, resilience, and national security (e.g., intellectual property, certain classes of research data, implications from climate change)

Key Next Steps

This National Strategic Overview concludes with a vision for leveraging resources, soliciting expertise, and applying key policy opportunities to optimize Federal RDI capabilities and ensure critical RDI needs are addressed in the near- and long-terms. Gaps in RDI capabilities could be addressed through new or improved interagency coordination, public-private partnerships, and national and international collaborations, as appropriate.

Introduction

Federal investments in world-class basic and applied research and development infrastructure (RDI) after World War II marked a new era for scientific and technological innovation in the United States. Federal investments in the Nation's RDIs have stimulated the development of transformative technologies, such as the internet and the Global Positioning System (GPS), leading to the creation of new industries and markets, including our aerospace and semiconductor industries. Over the past 75 years, our Nation's RDI investments have led to capabilities that have significantly increased human lifespans; eradicated smallpox and helped to control several widespread diseases; expanded understanding of the nature of matter at the nanoscale; and enabled exploration of our universe.

The capabilities provided by our Nation's RDIs have historically bolstered America's leadership position in the global research and development (R&D) enterprise. While some RDI support capabilities that lead to R&D with direct economic or national security implications are not likely avenues for global collaboration, other RDI support capabilities are oriented towards discovery and are more domestically and internationally collaborative in nature. Across various RDIs, the U.S. seeks global collaboration to share RDI resources, costs, and expertise and bolster global research communities. However, the U.S. position as a global leader in the development and advancement of new industries and disciplines is increasingly being challenged by competition from other nations. At the same time, the ability to maintain advanced RDIs and their capabilities is influenced by a number of factors such as national security and economic competitiveness concerns. The United States needs a national strategic vision that outlines key policy opportunities for Federal RDI planning to continue our R&D achievements and leadership. This document is a first step toward creating such a strategic vision.

A Paradigm Shift

The nature of science has drastically changed within recent decades, with each new innovation enabling science to become more networked, flexible, and reconfigurable. During the initial post-war decades, most RDI investments were focused on "*Big Science*" consisting of large-scale, stand-alone and discipline-specific experimental platforms and facilities, such as particle accelerators, ground-based telescopes, and research reactors used in the physical sciences. In previous decades, researchers would typically visit large experimental facilities to conduct their research and return home with their data for analysis. However, this traditional view of RDIs is no longer an accurate representation of the U.S. and global R&D enterprise of the 21st century.

Today, both scientific demands and societal challenges require the use of multiple RDIs to achieve desired outcomes. RDIs are becoming more and more interconnected (Figure 1). For the research community, recent decades have also witnessed exponential growth in the scale and complexity of digital research data from numerous experimental and observational instruments. Research communities are increasingly relying on new RDI capabilities stemming from their interconnectedness. The advent of the internet and advances in control software for instrumentation allow many researchers to remotely access and use RDIs. Recent national crises, such as the COVID-19 pandemic, have placed greater needs on RDIs—such as research cyberinfrastructure—to support telework capabilities and high-speed broadband that assist in the continuity of work, education, and medical services. As a result, researchers in various fields, such as biological and materials sciences, are now able to work collectively at a broad, integrated scale comparable to that of more traditional, large-scale science fields, such as astronomy and high energy physics.

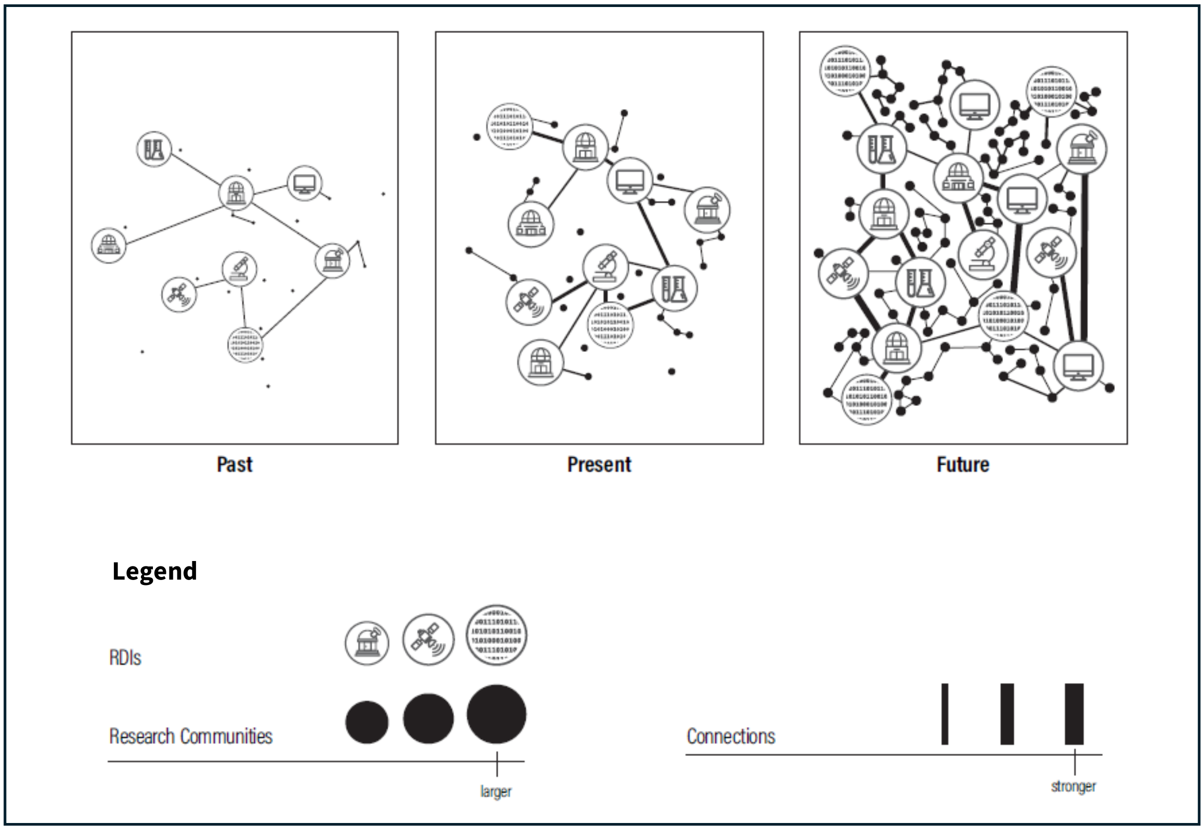

Figure 1. Evolving Interconnectedness and Interdependencies of RDIs and Research Communities

This graphic illustrates the past, present, and imagined future of national and international RDI networks. Scientific workflows and discovery pathways depend on a rich, integrated understanding of RDIs as a networked enterprise of experimental and observational infrastructure, knowledge infrastructure, and research cyberinfrastructure. RDIs, as generally depicted by the larger icons, are increasing in number and size (physical footprint and capabilities) over time. They are creating and fostering research communities, depicted by the small dots, which are clustering around RDIs to develop robust multidisciplinary communities across global networks and increasing in size and number over time. The conduct of R&D continues to shift from smaller to bigger science, driven in large part by advances in computing and other research cyberinfrastructure, which is providing researchers the ability to more easily access and interlink research data, perform big data analytics, and automate the remote control of experimental instrumentation. As a result, the connections and interdependencies among RDIs and research communities are strengthening, denoted by the increasing thickness and number of lines between the larger icons and black dots over time.

Definition and Elements of RDIs

This National Strategic Overview defines RDIs broadly as: facilities or systems used by scientific and technical communities to conduct R&D or foster innovation. Located and operated domestically and internationally, RDIs are important resources that extend beyond physical research facilities and include robust, sophisticated, and integrated capabilities across experimental and observational infrastructure, knowledge infrastructure, and research cyberinfrastructure (Figure 2). These three elements of RDIs are described in Box: Elements of RDIs.

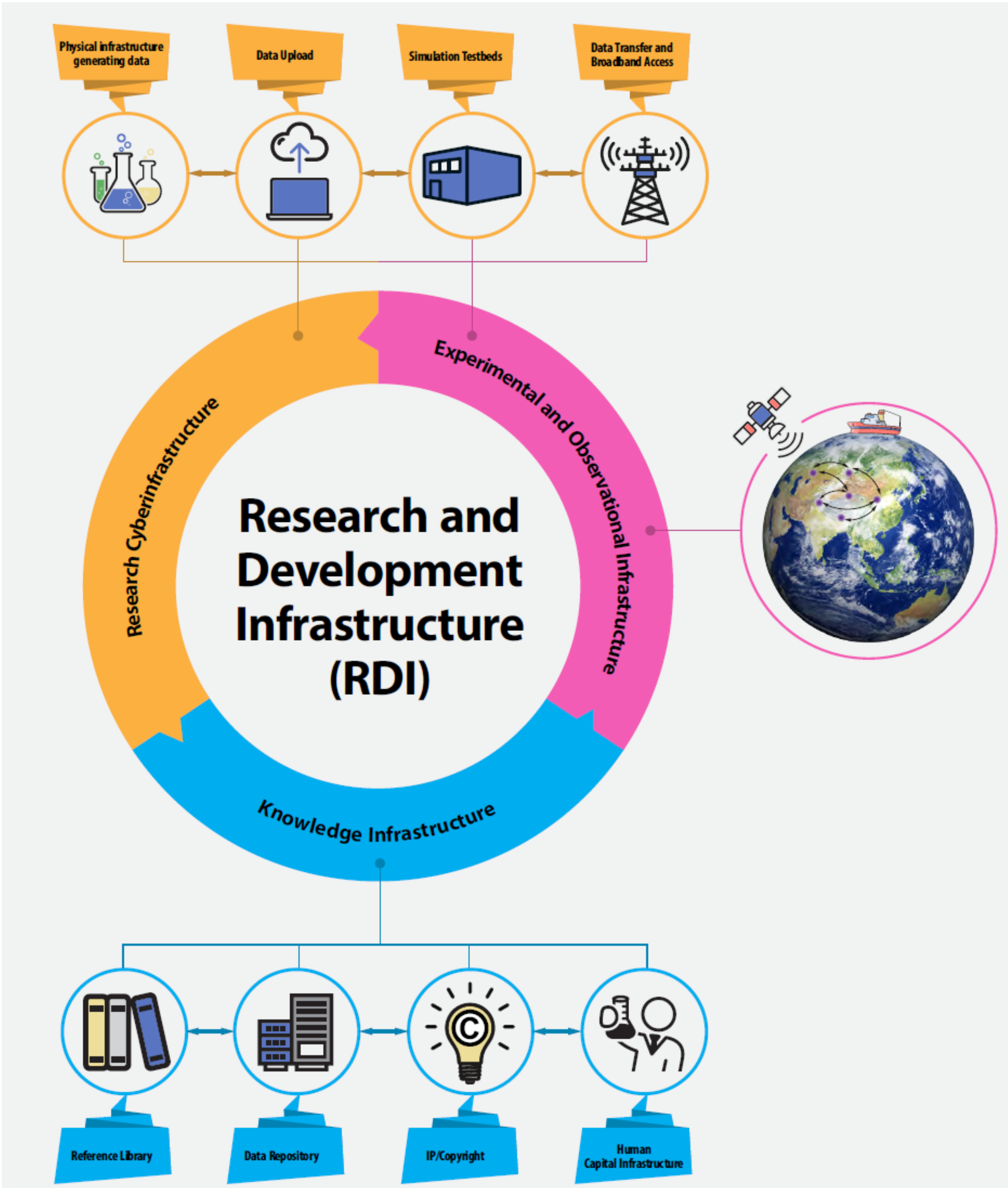

Figure 2. RDI Elements

This graphic illustrates examples of the three RDI elements comprising the RDI ecosystem and how they are integrated to support the R&D enterprise. Experimental and observational infrastructure—such as the research vessels, satellites, and laboratories—provide the tools and platforms for scientists and engineers to perform R&D. These systems work together and depend on human capital infrastructure and a skilled workforce for their development and operation. Results from certain R&D are shared across global networks and research communities through research cyberinfrastructure—including trustworthy information exchange capabilities, cloud infrastructure, computing, and broadband networks that support R&D data storage, access, processing, and analyses. These R&D data and cyberinfrastructure support the creation and utilization of knowledge infrastructure—including scientific collections, reference libraries, data repositories, intellectual property, and human capital—that maintain historical references for R&D communities and resources that may be demanded in the future.

Elements of RDIs

Experimental and Observational Infrastructure: Mid- and large-scale research platforms and facilities, to include instruments operating at small- and mid-scales that together may work at large scales and across global networks, as appropriate. The complexity of these platforms and facilities will increasingly necessitate a growth and nurturing of a technically proficient workforce, and integration of capabilities and operational infrastructure from many different disciplines, including those that may not have traditionally been integrated in the past.

Knowledge Infrastructure: Shared scientific data assets and resources, such as scientific collections, repositories and archives from many different disciplines; the standards, protocols, and services enabling deposit, integration, sharing, and reuse of those data and remote access to instruments and experiments; the analytic and computational algorithms and platforms critical to transform data into knowledge and discoveries; and human capital infrastructure.

Research Cyberinfrastructure: A complex, interconnected ecosystem of institutional-, regional-, national-, and international-scale advanced computing resources; data and software infrastructure and services; and high-speed research and education networks, all designed to broadly and reliably serve the research community.

A National Strategic Vision and Key Policy Opportunities

This National Strategic Overview provides a **strategic vision through key policy opportunities** in four areas:

- Maintaining Strong and Integrated RDI Planning and Coordination
- Ensuring RDIs Support a Flexible and Agile R&D Enterprise
- Advancing RDI Capabilities to Support the Convergence of Disciplines and Sectors
- Balancing RDI Openness with Security Needs

The key policy opportunities identify ways to optimize and pursue coordinated approaches for Federal RDI planning over the next 20 years.

Structure of the National Strategic Overview

This National Strategic Overview discusses these key policy opportunities in detail and provides six illustrative examples to describe the importance of RDIs and a future outlook for Federal RDI investments in Appendix A. The examples describe how our Nation's comprehensive suite of interdependent, networked RDIs enable innovation and discovery within a continuously evolving R&D enterprise. Appendix B provides summaries describing how RDIs support Federal agency missions. This National Strategic Overview concludes with a vision for enhancing Federal RDI planning and coordination in the future.

Key Policy Opportunities

Maintaining Strong and Integrated RDI Planning and Coordination

Federal agencies should ensure that RDI investments align with integrated R&D needs for physical infrastructure, knowledge infrastructure, and research cyberinfrastructure. These RDI elements are becoming increasingly interdependent. Coordination within and across agencies ensures that RDI planning continuously identifies complementary RDIs and their capabilities to inform agency priority setting processes. Strategic Federal RDI planning should be informed by cross-cutting R&D efforts and needs to enable U.S. S&T leadership into the future. Researchers continuously generate new scientific discoveries that catalyze the creation of and needs for new foundational RDIs. Federal RDI planning and coordination should support integration such that RDIs can be interconnected and leveraged to create new research capabilities and platforms.

While each agency has its own priority setting process, the holistic Federal RDI planning process is predicated on engagement between relevant agencies and extramural R&D communities. These entities help determine current and future research priorities, leverage investments needed for RDIs across their lifecycle, avoid unnecessary duplication, and maximize the long-term impact of Federal RDI investments. The White House Office of Science and Technology Policy (OSTP), through the National Science and Technology Council (NSTC), facilitates efforts for coordinated Federal R&D investments. National coordination offices (NCOs) play a large role in harmonizing R&D priorities across the Federal Government in areas of national importance and emerging priority areas (Box: Coordinating our Nation's Science and Technology Policy Goals). These efforts help optimize existing resources and increase the longevity of future RDIs.

Coordinating Our Nation's Science and Technology Policy Goals

OSTP works closely with Federal agencies through the NSTC to coordinate priorities across the Federal R&D enterprise. The NSTC was established by an Executive order in November of 1993 to develop R&D priorities that are coordinated with Federal agency and national goals, which also includes coordinating the investments needed to support such R&D.[3] Supported by the NSTC's Subcommittee on Networking and Information Technology Research and Development (NITRD) and its NCO,[4] the NITRD Program comprises 23 Federal member agencies, OSTP, and OMB—and supports advanced networking and information technology capabilities required by the Federal Government.[5] Another example is the National Nanotechnology Initiative (NNI), which is supported by the U.S. National Nanotechnology Coordination Office. The NNI is a government R&D effort to coordinate the nanotechnology-related activities of 20 departments and agencies, influencing the Federal budget planning process through its members and the NSTC. [6]

[3] The White House. "National Science and Technology Council," https://www.whitehouse.gov/ostp/nstc/
[4] NITRD. "NITRD National Coordination Office (NCO)," https://www.nitrd.gov/about/about_nco.aspx
[5] NITRD. "About the NITRDC Program," https://www.nitrd.gov/about/
[6] NNI. "What is the NNI?" https://www.nano.gov/about-nni/what

An integrated approach to Federal RDI planning includes planning for the needed research cyberinfrastructure—including cybersecurity capabilities—to ensure both the efficiency and the trustworthiness of scientific pathways and pipelines. Moreover, knowledge infrastructure capabilities need to keep pace with the growth of published and digital research data (Box: RDI for COVID-19 Research: TREC-COVID). The development of new Federal standards and norms for public access to federally funded research results necessitates that Federal agencies address the needs associated with maintaining, storing, and sharing R&D outputs over the long-term. Federal RDI planning should ensure consistent, sufficient, and timely RDI capabilities, addressing episodic efforts that can undermine the ability to meet long-term or evolving needs.

RDI for COVID-19 Research: TREC-COVID

OSTP, the National Institute of Standards and Technology (NIST), and private industry partners joined together to form a program called Text Retrieval Conference for COVID-19, or TREC-COVID, an information retrieval shared task to support clinicians and clinical research during the COVID-19 pandemic. TREC-COVID challenged academics, industry, and government worldwide to participate in using advanced digital research technologies to create research cyberinfrastructure, such as powerful search engines that extract pertinent knowledge from rapidly growing literature,[7] and help to discover methods that will assist in managing scientific information for future biomedical crises. TREC-COVID Complete, the cumulative collection of all rounds of this initiative, is now publicly available as a standard retrieval test collection.[8] The databases formed from this initiative can be tailored to the needs of researchers and health care communities, demonstrating how knowledge infrastructure works together with other forms of RDIs to make an impact. Federal RDIs, in many cases leveraged with private sector investments, supported the development of numerous innovations that are helping the U.S. pandemic response.[9]

Ensuring RDIs Support a Flexible and Agile R&D Enterprise

Inclusive approaches to agency planning and prioritization of investments help to ensure that RDIs support a flexible and agile R&D enterprise. Federal agencies can use numerous mechanisms to seek input from R&D communities, per their stated mission goals. For example, for Federal agencies that host user facilities, serving both intramural and extramural R&D communities, cross-sectoral community outreach is vital to predict future needs and necessary investments for shared resources. This engagement helps ensure stakeholders are both involved and invested in decisions on how to remain at the forefront of innovation and the future directions for our Nation's RDI investments. Coordination and assessments—such as through decadal surveys, Federal advisory committees, workshops, and other community engagement efforts—help agencies identify and prioritize leading-

[7] NIST. 2020. "NIST and OSTP Launch Effort to Improve Search Engines for COVID- 19 Research." https://www.nist.gov/news-events/news/2020/04/nist-and-ostp-launch-effort-improve-search-engines-covid-19-research

[8] NIST TREC-COVID website. "About the Challenge." https://ir.nist.gov/covidSubmit/about.html

[9] NIST. 2020. "NIST and OSTP Launch Effort to Improve Search Engines for COVID- 19 Research." https://www.nist.gov/news-events/news/2020/04/nist-and-ostp-launch-effort-improve-search-engines-covid-19-research

edge research questions and the RDI capabilities necessary to answer them (Box: Examples of Community Coordination Relevant to RDIs). Furthermore, these approaches are complemented by a whole-of-government equity agenda that R&D investments include and benefit underserved and underrepresented communities and advance racial equity through strategies such as the inclusion of minority serving institutions in the research enterprise and broadening participation across the STEM ecosystem.[10]

[10] For example: The White House. 2021. *Executive Order on Advancing Racial Equity and Support for Underserved Communities through the Federal Government*. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/20/executive-order-advancing-racial-equity-and-support-for-underserved-communities-through-the-federal-government/

Examples of Community Coordination Relevant to RDIs

Decadal Surveys

Decadal surveys set the broad vision for scientific discovery for the coming decade in a given scientific field, including the infrastructure and research capabilities needed to reach that promise. The National Academies of Sciences, Engineering, and Medicine, a nonprofit institution providing expertise to the government to help inform policy and the public, conducts decadal surveys in coordination with agencies and research communities.[11] Community engagement is often solicited via white papers and panels.[12] These decadal surveys help to inform agencies' goals, research priorities, and opportunities for collaboration.

Federal Advisory Committees

Federal agencies use Federal Advisory Committee Act (FACA) Committees to seek advice on issues pertaining to Federal programs and policies, including providing near-term strategic advice to programs, reviewing progress and key strategic initiatives, and advising on overall programmatic and managerial goals. FACA Committees can have participation from external R&D communities, including federally funded research and development centers (FFRDCs), operated by contractors such as universities, non-profits, or industrial firms.[13]

Workshops to Inform Cybersecurity Infrastructure

For the 2018 update of its Framework for Improving Critical Infrastructure Cybersecurity, NIST held multiple Cybersecurity Framework Workshops. The workshops were part of an ongoing collaborative effort to involve industry, academia, and the government in the creation of guidelines and practices to protect critical infrastructure from cyber risks.[14] NIST leverages public-private partnerships between industry, the government, and academic institutions to address industry-specific and cross-sector cybersecurity challenges, helping organizations and agencies stay ahead of adversaries.

Interagency coordination initiatives provide valuable forums for supporting timely dialogue in important emerging areas of R&D, such as the development of the National Quantum Initiative coordinated through OSTP.[15] Cross-agency coordination enhances knowledge transfer across R&D communities served by multiple agencies and can inform the prioritization of RDI investments and needs.[16] Requests for Information (RFIs) and Federal prize competitions are other public-facing

[11] The National Academies of Sciences, Engineering, Medicine. "About Us." https://www.nationalacademies.org/about/whoweare/index.html

[12] For example, The Astronomy and Astrophysics Decadal Survey (Astro2020): https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020

[13] Congressional Research Service. 2017. *Federally Funded Research and Development Centers (FFRDCs): Background and Issues for Congress*. December 2017.

[14] NIST Cybersecurity Framework. "New to Framework." https://www.nist.gov/cyberframework/new-framework

[15] National Quantum Coordination Office. "National Quantum Initiative." https://www.quantum.gov

[16] For example, the Particle Physics Project Prioritization Panel (P-5), a subpanel of the High Energy Physics Advisory Panel (HEPAP) that serves both the DOE and NSF, published the *Strategic Plan for U.S. Particle Physics in the Global Context* in 2014. The report emphasizes the need for reliable international partnerships to continue

mechanisms to crowdsource ideas from the public that help agencies stay abreast of breakthrough solutions related to their missions.[17]

The ability to adapt to evolving needs is an essential component of RDI planning. It is the responsibility of Federal agencies to continuously evaluate how existing RDIs meet current and future missions. It is imperative that the United States consider how to design and operate RDIs on more accelerated timelines to support the development of integrated capabilities as new R&D needs may rapidly emerge. For example, the COVID-19 pandemic has necessitated another dimension of agility, namely remote access. For some fields, remote access from home institutions or remote locations is already a common capability that sustains efficiency, especially in the physical science field (e.g., beamline synchrotron facilities, crystallography). Lessons learned from these fields can be applied to RDI policies that support RDI planners and research communities seeking to improve upon remote work capabilities.

Research cyberinfrastructure and knowledge infrastructure require agile design and decision processes to keep up with the astonishing growth of research data and the pace of developments in computing and analytics. Federal RDI planning should address big-data applications and capabilities to rapidly move and share very large datasets via robust, secure, expandable, and upgradable networking research cyberinfrastructure. Specialized requirements and equipment drive a need for greater agility in procurement, design, development, and portability of RDI systems. These RDIs, in turn, should be supported by strategic, long-term relationships with the ecosystem of contractors and suppliers that can supply these RDI components and systems.

Detailed budgeting and planning are paramount to the development of RDIs, which may include multi-decadal lifecycles for facilities. Effective long-term RDI planning, agility, and budgeting processes are dependent on active and sustained lifecycle management. Federal agencies should continue to incorporate lifecycle considerations as well as assurance processes into RDI planning—including costs for construction, operations, modernization needs over the expected life of the RDIs, and its eventual demolition and disposal (Box: Considerations for the RDI Lifecycle and Box: Assurance Processes for RDIs: Strategic Planning and Best Practices).[18]

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answering the full breadth of the field's most urgent scientific questions. https://www.usparticlephysics.org/wp-content/uploads/2018/03/FINAL_P5_Report_053014.pdf

[17] For more information on government challenges and prize competitions, see https://www.challenge.gov/

[18] For example, see Deloitte's *Investing in Infrastructure: Leading practices in planning, funding, and financing*. https://www2.deloitte.com/content/dam/Deloitte/us/Documents/risk/us-risk-infrastructure-investment-funding.pdf for further on the lifecycle of capital investments.

Considerations for the RDI Lifecycle

Conceptually, the RDI lifecycle comprises five basic stages: development, establishment, operation and maintenance, modernization, and repurposing or decommissioning—some of which may be recursive. After assessing needs and research questions in the development stage,[19] this process continues by planning, designing and establishing the necessary resources, determining how to fund and construct the proposed project within the available budget cycles, and establishing partnerships to leverage expertise and resources, as appropriate. Lifecycle planning for RDIs should be flexible to address the expected needs for modernizing and upgrading when necessary to prevent obsolescence. When RDIs are no longer serving their purpose or efforts to build additional capability are untenable, the prospect of repurposing or decommissioning arises.

Effective RDI planning and management balances these competing interests while continuously realigning activities with changing future needs. Thinking holistically about the entire lifecycle of RDI, including impacts to the local, regional, national and global research communities and economies, maximizes their impact, flexibility, and efficiency.

Assurance Processes for RDIs: Strategic Planning and Best Practices

Federal agencies heavily rely upon processes that provide assurance that existing and future RDIs are financially sound and accomplish the needs of the communities they serve. The various RDI lifecycle stages frequently require rigorous project management processes and expertise that confirm investments are justified and can be completed on-time and on-budget. To accomplish short- and long-term objectives, RDI planning importantly requires adherence to best practices documented through OMB's *Capital Planning Guide* and relevant agency policies.[20]

Effective RDI planning clearly articulates needs and examines how investments advance individual agency, national priorities, and collective Federal Government missions. The RDI planning process frequently consists of: (1) identification and engagement with relevant stakeholder roles, such as intramural and extramural R&D communities and Federal advisory committees, to help identify emerging needs and evaluate the adequacy of existing RDI capabilities; (2) identification and prioritization of RDI investments that meet those needs, including their justification as well as value to agency mission and the R&D enterprise; and (3) documentation of project management processes to identify and mitigate against risks and uncertainties that may occur throughout the RDI lifecycle, particularly during construction and commissioning.[21]

[19] For example, *see* NSF. 2018. *Study of Operations and Maintenance Costs for NSF Facilities*. https://www.nsf.gov/pubs/2018/nsb201817/nsb201817.pdf

[20] Office of Management and Budget. 2021. *Preparation, Submission, and Execution of the Budget.* https://www.whitehouse.gov/wp-content/uploads/2018/06/a11.pdf

[21] IDA Science and Technology Policy Institute. 2014. *Best Practices for Federal Research Development Facility Partnerships.* https://www.ida.org/-/media/feature/publications/b/be/best-practices-for-federal-research-and-development-facility-partnerships/ida-p-5148.ashx

Federal RDI planning should consider the delicate budgetary balance between prioritizing new RDIs and sustaining or revitalizing existing RDIs. Annual appropriations processes can complicate long-term planning and interagency coordination of RDIs. For large-scale RDI, strategic partnerships between U.S. agencies and other nations is one way to address long-term needs in areas where the scientific mission is in discovery science—which does not have strong economic or national security implications—such as astronomy, or nuclear and/or elementary particle physics. For such "discovery-oriented" research, the United States may not be able to address those needs alone and should seek to share costs through international partnerships, such as the international partnership with CERN in elementary particle physics.[22] For RDIs intended to be used by national and international R&D communities for discovery, planning can be done on a global scale, with consideration of the complexities for coordination due to differences in planning, approval, and funding processes. For RDI with economic and/or national security implications, the United States should plan for and construct those facilities to meet U.S. needs: collaborating, coordinating, or sharing information as appropriate.

A highly trained, diverse, and specialized R&D workforce is critical to maintaining U.S. competitive excellence in RDIs. Maintaining our Nation's RDIs at their highest standards fortifies our ability to attract and retain the best and brightest in R&D careers while providing an opportunity for Federal agencies to ensure the R&D workforce reflects the full diversity of the United States.[23] Further efforts by Federal agencies in catalyzing career pathways would support the development of a workforce equipped with the specialized skills necessary to design, construct, manage, and operate cutting-edge RDIs, ranging from experimental facility design to research software, data engineering, and data integration. To maintain preeminence, the Federal Government should simultaneously and affirmatively advance equity, civil rights, racial justice, and equal opportunity[24] and invest in science, technology, engineering, and mathematics (STEM) educational programs that sustain and improve the pipeline of diverse R&D workers.[25] A world-class R&D workforce, ranging from trade technicians to PhDs, engineers and scientists, is key to both maintaining existing and developing the next generation of RDIs. RDIs also support the training and tools to conduct R&D across diverse communities, which enhances the flexibility and agility of our R&D enterprise. The Federal Government should continue to create and promote programs that directly engage with RDIs as necessary learning and training platforms.

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[22] For example, the Large Hadron Collider not only requires collaboration between NSF and DOE, but the collaboration of both agencies with a host of other nations. Additionally, partnerships often help agencies develop best practices and coordinate research goals, such as the joint effort by DOE and NIH to develop a new synchrotron (NSLS-II) capable of synergistic instrumentation that can further biological science. https://www.bnl.gov/newsroom/news.php?a=111666

[23] For example: EOP. 2021. "Fact Sheet: President Biden to Sign Executive Actions Restoring America's Place in the World." https://www.whitehouse.gov/briefing-room/statements-releases/2021/02/04/fact-sheet-president-biden-to-sign-executive-actions-restoring-americas-place-in-the-world/; and "Memorandum on Revitalizing America's Foreign Policy and National Security Workforce, Institutions, and Partnerships." https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/04/memorandum-revitalizing-americas-foreign-policy-and-national-security-workforce-institutions-and-partnerships/

[24] The White House. 2021. *Executive Order on Advancing Racial Equity and Support for Underserved Communities through the Federal Government*. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/20/executive-order-advancing-racial-equity-and-support-for-underserved-communities-through-the-federal-government/

[25] NSTC. 2018. *Charting a Course for Success: America's Strategy for STEM Education*. https://www.nsf.gov/nsb/meetings/2019/0514/presentations/CS-Open-NSB-STEM-Ed-Plan-Marrongelle-Presentation.pdf

Advancing RDI Capabilities to Support the Convergence of Disciplines and Sectors

The world today faces both extraordinary opportunities enabled by technological progress and a complex set of global challenges, the solutions to which require diverse research teams that collaborate across traditional disciplinary boundaries. Transformative R&D emerges and flourishes at the boundaries of and interstices between traditional disciplines, with key recent examples in the fields of nanoscience, artificial intelligence (AI), quantum information science (QIS), and between the biological and physical sciences.[26] AI and QIS technologies are inherently privacy sensitive and require close collaboration to ensure these technologies sustain and do not erode privacy protections. Interdisciplinary work supported by RDIs that helps to integrate and transcend biological, physical, and socioeconomic sciences is necessary to address climate change, increase our knowledge of COVID-19, and build our society's resilience to future acute and chronic crises. Convergence efforts blur traditional boundaries, forge innovative partnerships, and stimulate transcendent research to address compelling societal challenges.

Federal agencies should strategically plan for RDIs that complement core disciplinary needs while identifying opportunities for RDIs to enhance connections among disciplines and sectors. Converging fields of science are encouraging the development of new and innovative RDIs. The successful maturation of these into our research capacity is important to maintaining our research competitiveness, as well as to grow the fundamental research capacity in rural and underserved areas to enable more diverse and inclusive innovation for the benefit of all.

Supporting convergence also requires coordination and consideration for the use of RDIs beyond a singular Federal agency mission context. Interagency and national coordination can help catalyze stakeholders to identify emerging topics at the cutting edge of R&D; provide a multi-stakeholder framework for shared goals; foster partnerships and collaborations across disciplines, fields, and sectors; and amplify the imagination and innovation of researchers beyond any singular entity's R&D efforts (Box: Examples of National Coordination to Advance Disciplinary Convergence and Box: RDIs Supporting Convergence in the Medical and Life Sciences).

[26] Massachusetts Institute of Technology. 2011. *The Convergence of the Life Sciences Physical Sciences and Engineering*.https://www.aplu.org/projects-and-initiatives/research-science-and-technology/hibar/resources/MITwhitepaper.pdf

Examples of National Coordination to Advance Disciplinary Convergence

The NSTC is the principal means within the executive branch to coordinate a national approach for R&D areas of national importance, including RDIs that enable a convergent scientific "ecosystem."[27] For example, the NNI provides a framework for the shared goals, priorities, and strategies of nanotechnology-related activities across various disciplines and 20 agencies,[28] including coordinating mechanisms to advance fundamental research, stimulate infrastructure, and foster workforce education and training. As another example, the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative engages scientists and engineers under a framework that leverages the efforts of Federal and non-Federal entities across the life sciences, chemistry, engineering, and physics disciplines.[29]

RDIs Supporting Convergence in the Medical and Life Sciences

The National Synchrotron Light Source (NSLS) at the Brookhaven National Laboratory, in operation since 1982, consists of partnerships among the Department of Energy (DOE) Office of Science, the National Institutes of Health (NIH), the National Science Foundation (NSF), and other Federal agencies, private companies, and foundations.[30] These entities conduct R&D to advance synchrotron technologies for the physical sciences field and to support advances in life sciences and medical research. The facility offers radiation energies from X-ray to ultraviolet and infrared light for experimentation supporting X-ray diffraction, scattering, spectroscopy, and other imaging techniques. These capabilities help researchers visualize molecule and protein structures, and other biological processes. In 2014, the next generation synchrotron NSLS-II was built to provide expanded capabilities for researchers in a variety of disciplines, such as chemical and materials science, genomics, and nanoscience. The NSLS-II is open to users from academia and industry to help fuel scientific discovery.[31]

RDIs should continue to be positioned at the nexus of multiple disciplines and sectors. Effective partnerships and research information exchange become critical components of fostering convergence, especially when stakeholders are divergent (e.g., separated by distance, institutional culture, and incongruous funding cycles) (Box: Convergence of RDIs to Enable Discoveries).

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[27] E.g., "Office of Science and Technology Policy: NSTC." https://www.whitehouse.gov/ostp/; National Research Council. 2014. *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*. Washington, DC: The National Academies Press.

[28] NNI. "What is the NNI?" https://www.nano.gov/about-nni/what

[29] NIH. "The Brain Initiative." https://braininitiative.nih.gov/

[30] IDA Science and Technology Policy Institute. 2013. *Federal Partnerships for Facilities, Infrastructure, and Large Instrumentation*. https://www.ida.org/-/media/feature/publications/f/fe/federal-partnerships-for-facilities-infrastructure-and-large-instrumentation/ida-d-4937.ashx

[31] NSLS-II: One of the world's most advanced synchrotrons: https://www.bnl.gov/ps/nsls2/about-nsls-ii.php

Convergence of RDIs to Enable Discoveries

RDI-enabled discoveries have enhanced the prestige of U.S. science and spawned new scientific approaches. One such approach, multi-messenger astrophysics (MMA), represents an exciting development in modern science whereby multiple areas of RDIs are coordinated to simultaneously detect, measure, and characterize astrophysical phenomena through multiple "messengers"—gravitational waves, electromagnetic waves (optical and radio), and subatomic particles.[32] Successful MMA research depends on a seamless distributed discovery pipeline starting with exquisitely sensitive gravitational wave detection systems, specialized software, rapid alert systems, and rapid remote commanding of many different observational RDIs. Advanced computing capabilities are used to identify the detected signals and collaborative management is required to organize and coordinate the use of and access to RDIs by researchers across the world.[33]

Balancing RDI Openness with Security Needs

Federal agencies work to ensure that RDIs bolster research security while maintaining openness and transparency; accountability and honesty; impartiality and objectivity; respect; freedom of inquiry; reciprocity; and merit-based competition.

Generally, the United States seeks to coordinate with other nations across R&D sectors, disciplines, and countries; collaborating and coordinating efforts spanning many scientific fields and numerous RDI capabilities. The United States has a long history of supporting joint investments in discovery-based, large-scale RDIs, such as particle accelerators for high energy and nuclear physics, and telescopes and observatories for astronomical and cosmological observations. In areas of intense global interest, the United States may be, simultaneously, partners and competitors with international partners on RDIs that support R&D designed to produce near-term technologically important discoveries so as to protect the intellectual property of the participating individuals and organizations and preserve expected national competitiveness outcomes.

The United States should protect RDIs that are vital to economic competitiveness, public health and safety, and national security—such as intellectual property and certain classes of research data—while promoting the long-term resilience of its RDIs. The determination for shared development of RDIs and access to them should involve community engagement through Federal planning. This process should ensure that fruitful domestic and international collaborations in foundational scientific research are promoted and that resources are leveraged in creative and effective ways. These efforts should also ensure our Nation's goals to advance particular areas of national and economic interests that affect U.S. security or that the development of new and innovative industries are not undermined.

Cutting-edge RDIs generate the tools that foster a skilled domestic and diverse R&D workforce while also attracting the world's top science and engineering talent. Interconnected RDI networks engage this talent, supporting their access to information and participation in scientific discovery across international R&D communities. Although the threat of foreign efforts to exploit, influence, and

[32] For example, The Nobel Prize in Physics. 2017. https://www.nobelprize.org/prizes/physics/2017/press-release/

[33] For example, *A Brief History of LIGO*. https://www.ligo.caltech.edu/system/media_files/binaries/313/original/LIGOHistory.pdf

undercut our national R&D activities remains complex,[34] Federal planners should work within the framework of research security and integrity to ensure our Nation maintains the open and internationally collaborative nature of our R&D enterprise that has been an essential aspect of its success.[35]

At the same time, care should be taken to balance U.S. national security concerns, economic interests, and fundamental science with basic research objectives such that appropriate protections for RDIs do not inhibit our capacity to collaborate and innovate.[36] Federal agencies can leverage partnerships to advance the progress of science, including partner nations sharing in similar goals. Shared responsibility and agreed-upon principles and values are critical to the success of these partnerships. Collaborating with global partners who value an open, transparent, reciprocal, and fair R&D enterprise is vital for the advancement of science and discovery (Box: Select International Coordination and Collaborations to Support the R&D Enterprise). Federal agencies should operate RDIs such that our Nation's tradition of open science is balanced with an appropriate level of vigilance to uphold U.S. principles of integrity and engender continued U.S. excellence in science and engineering.

Select International Coordination and Collaborations to Support the R&D Enterprise

International Intellectual Property Coordination and Collaboration

The U.S. Patent and Trademark Office (USPTO) participates in various collaborative frameworks with counterpart intellectual property offices in order to exchange views and identify opportunities for cooperation and coordination with regard to common challenges. For example, the IP5 is a forum of the world's five largest patent offices. IP5 discussions include patent examination workloads, backlogs, patent quality, and inefficiencies in the international patent system. Alongside the USPTO, the members of IP5 include the European Patent Office, the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), and the State Intellectual Property Office of the People's Republic of China (CNIPA). Another similar forum is the Trademark 5 (TM5), which includes the world's five largest trademark offices. The members of TM5 exchange information on practices and programs that aim at harmonization and improvement of trademark procedures. The five members of the TM5 are USPTO, CNIPA, JPO, KIPO, and the European Union Intellectual Property Office (EUIPO). These same five offices also meet for a separate collaborative forum known as the ID5, focusing on industrial designs and considering its increasing value and the significance in global and domestic markets.

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[34] For further on the threat of foreign efforts, *see* JASON. 2019. *Fundamental Research Security*. https://www.nsf.gov/news/special_reports/jasonsecurity/JSR-19-2IFundamentalResearchSecurity_12062019FINAL.pdf

[35] The White House. 2020. *Enhancing the Security and Integrity of America's Research Enterprise.*

[36] Presidential Policy Directive 21 (PPD-21): Critical Infrastructure Security and Resilience. Revised March 24, 2020. https://www.cisa.gov/critical-infrastructure-sectors

Select International Coordination and Collaborations to Support the R&D Enterprise (cont.)

International Collaboration for Global Earth Observation

The United States is one of more than 100 national governments working to create a Global Earth Observation System of Systems (GEOSS), which integrates observing systems and shares data by connecting existing RDIs using common standards. There are over 400 million open data resources in GEOSS from more than 150 national and regional providers, such as the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the European Space Agency; international organizations, such as the World Meteorological Organization; and the commercial sector. Further coordination of Federal and national stakeholder interests, alongside support from the Department of State, occurs under the United States Group on Earth Observations, which helps formulate the U.S. position for and coordinate U.S. participation in the international Group on Earth Observation.

Understanding Atmospheric Circulation

The El Niño-Southern Oscillation (ENSO), a recurring climate pattern that describes surface water temperatures in the central and eastern tropical Pacific Ocean, exerts a measurable influence on temperature and precipitation across the globe. Increasing the ability to understand and predict large-scale climate events, such as the ENSO, enables forecasters to make skillful seasonal outlooks on temperature and precipitation across the globe. These capabilities contribute to earlier and more informed warnings for emergency managers, businesses, government officials, and the public. Sustained coordination and long-term support from NOAA and Japan's Agency for Marine-Earth Science and Technology to networks that are part of the Tropical Pacific Observing System have been critical elements in advancing understanding and prediction of the ENSO. Global-scale platforms, such as ocean observing systems, require the United States to engage with international partners to help align efforts and coordinate technical support and required maintenance.

Exploring the Nature of the Universe

The European Organization for Nuclear Research, also known as CERN, established a particle physics laboratory in 1954 to provide particle accelerator facilities to researchers around the world.[37] CERN serves as the hub for world-class research in physics by providing access to the Large Hadron Collider (LHC), which is the most powerful accelerator in the world propelling charged particles to speeds close to the speed of light around a 27 kilometer long loop.[38] CERN supports multiple large-scale international experiments including the A Toroidal LHC Apparatus (ATLAS) Experiment, with about 3,000 researchers from 181 institutions around the world and 38 countries,[39] A Large Ion Collider Experiment (ALICE) Collaboration, with more than 1,000 scientists from 30 countries,[40] and the Compact Muon Solenoid (CMS) experiment, with more than 5,000 participants from 50 countries,[41] among others.

[37] CERN. "Our History," https://home.cern/about/who-we-are/our-history
[38] CERN. "The Large Hadron Collider," https://home.cern/science/accelerators/large-hadron-collider
[39] CERN. "ATLAS Experiment," https://atlas.cern/discover/collaboration
[40] CERN. "ALICE," https://home.cern/science/experiments/alice
[41] CERN. "CMS," https://home.cern/science/experiments/cms

Conclusion

This National Strategic Overview **highlights key policy opportunities** in five areas to advance our Nation's RDIs:

- Maintaining strong and integrated planning and coordination for the entire RDI lifecycle including decommissioning and/or reusing components and civil infrastructure
- Ensuring RDIs Support a flexible and agile R&D enterprise
- Advancing RDI capabilities to support the convergence of disciplines and sectors
- Balancing RDI openness with security needs
- Sharing costs broadly through international partnerships, as appropriate (e.g., discovery-oriented research)

Six illustrative examples are provided in Appendix A to describe the integral role of RDIs in enabling and sustaining the R&D enterprise and a future outlook for governing effective Federal RDI investments to maintain competitiveness. Appendix B provides summaries with additional context on how RDIs support Federal agency missions.

This National Strategic Overview outlines the foundational considerations for leveraging resources, soliciting expertise, and applying key policy opportunities to optimize Federal RDI capabilities. It has identified opportunities to continue and improve upon RDI planning through increased coordination and enhanced engagement across Federal agencies, advisory committees, broader R&D communities, and other stakeholders. Gaps in RDI capabilities could be filled through new or improved interagency coordination, public-private partnerships, and national and international collaborations. These efforts should be implemented in tandem with strategic planning processes around integrated RDIs, assurance practices already in place across agencies, and research security frameworks. These actions will help to ensure that critical RDI needs are addressed in the near-term (5–10-year timeframe) while considering long-term RDI capability needs.

Appendix A: Illustrative Examples of The Nation's World-Class RDIs

This Appendix highlights six illustrative examples to showcase the complementary capabilities and benefits accrued from our Nation's Federal RDI investments for: driving U.S. innovation and competitiveness in leading-edge R&D; ensuring our Nation's defense and resilience; understanding our planet; supporting our natural resource-based industries and ensuring food security; advancing human health and the biomedical sciences; and exploring the physics of our universe.

Driving U.S. Innovation and Competitiveness in Leading-Edge R&D

Driving U.S. Innovation and Competitiveness in Leading-Edge R&D—Overview

RDIs are a critical resource to conduct leading-edge R&D in emerging U.S. industries of the future—including AI, QIS, advanced communications and wireless technology, advanced manufacturing, and biotechnology. Continued progress in these fields necessitates RDIs that accommodate new capabilities as these fields advance. Increasingly sophisticated AI/machine learning (ML) systems depend upon advances in research cyberinfrastructure, including high-performance and high-throughput computing, software, and networking systems. The expanding demands to integrate data from multiple sources require new capabilities to store, organize, sort, and analyze extremely large datasets that facilitate discovery.[42] Research cyberinfrastructure coordination is driving new capabilities across industries, including R&D for pandemic response (Box: COVID-19 High-Performance Computing Consortium).

COVID-19 High-Performance Computing Consortium

The White House announced the COVID-19 High-Performance Computing (HPC) Consortium in March 2020. This public-private effort brings together Federal, industry, academic, and international partners to provide access to the HPC capabilities across sectors to advance COVID-19 research.[43] Federally supported RDIs include HPC facilities that enable researchers to access unique world-class computing and data services while providing a locus for new public-private collaborations. Projects are helping forecast the spread of COVID-19 for health systems and planning of critical equipment needs, identify virus binding sites or other molecular candidates, and perform molecular simulations to understand the protein structure of the virus.

The field of QIS is often considered the next technological revolution, with advances that underpin U.S. national economic and defense infrastructure. RDIs supporting the development of QIS technologies have made a crucial impact in many technology areas, including semiconductor microelectronics, photonics, GPS, and magnetic resonance imaging. The National Quantum Initiative, established in 2018, aims to accelerate QIS RDI investments in experimental and observational infrastructure that use

[42] NSTC. 2019. *The National Artificial Intelligence Research and Development Strategic Plan: 2019 Update*. https://www.nitrd.gov/pubs/National-AI-RD-Strategy-2019.pdf

[43] COVID_19 HPC Consortium. "The COVID-19 High Performance Computing Consortium." https://covid19-hpc-consortium.org/

multidisciplinary research to lay the foundation of computing, information processing, and the development of other technologies for future generations.[44]

Federal investments and partnerships for supportive infrastructure, such as advanced communications and wireless technologies, accelerate the development of AI/ML and QIS by enabling city-scale and regional simulation testbeds and R&D platforms for emerging wireless technologies.[45,46,47] This RDI will have wide societal impacts for telecommunications, public safety, new commercial applications, precision agriculture,[48] and protection of national infrastructure and security systems. High-speed network cyberinfrastructure enables effective data exchange between RDI assets and researchers and facilitates global collaboration among researchers through the use of shared resources, such as scientific collections, standards, and protocols. Advanced wireless technologies have accelerated capabilities in cloud computing to address R&D communities' growing needs for on-demand computing and continuous data access. These advances have promoted the adoption of edge computing, which allows some data to be processed closer to where they are created rather than being transmitted to a centralized computing resource. Edge computing helps reduce response time and increase bandwidth availability for time-critical experiments, thereby enabling new RDI capabilities and applications, such as for autonomous vehicles.[49]

RDIs for advanced manufacturing include technology testbeds for smart manufacturing, smart grids, and communications technologies—providing the R&D community and industry with platforms to benchmark and test innovative technologies in highly integrated and instrumented environments.[50] Experimental and observational infrastructure, such as the Manufacturing USA Institutes, promotes a robust and sustainable national manufacturing R&D enterprise through collaboration with industry, academic, and Federal partners.[51] AI/ML efforts enabled by research cyberinfrastructure have advanced

[44] DOE. 2019. "Department Seeks Stakeholder Input on Topic Areas and Selection Criteria." May 31, 2019. https://www.energy.gov/articles/department-energy-announces-plans-quantum-information-science-centers; NSF. 2020. "NSF establishes 3 new institutes to address critical challenges in quantum information science." July 21, 2020. https://www.nsf.gov/news/special_reports/announcements/072120.jsp

[45] DARPA. 2019. "World's Most Powerful RF Emulator to Become National Wireless Research Asset." https://www.darpa.mil/news-events/2019-09-03

[46] Advanced Wireless Research at NSF: https://www.nsf.gov/cise/advancedwireless/

[47] Platforms for Advanced Wireless Research: https://www.us-ignite.org/program/platforms-for-advanced-wireless-research/

[48] USDA. 2019. *A Case for Rural Broadband: Insights on Rural Broadband Infrastructure and Next Generation Precision Agriculture Technologies*. https://www.usda.gov/sites/default/files/documents/case-for-rural-broadband.pdf

[49] NSTC. 2019. *National Strategic Computing Initiative Update: Pioneering the Future of Computing*. https://www.nitrd.gov/pubs/National-Strategic-Computing-Initiative-Update-2019.pdf

[50] NSTC. 2018. *Strategy for American Leadership in Advanced Manufacturing*. https://www.manufacturing.gov/news/announcements/2018/10/strategy-american-leadership-advanced-manufacturing

[51] Defense Innovation Marketplace. "DoD Manufacturing Technology (ManTech) Program." https://defenseinnovationmarketplace.dtic.mil/business-opportunities/manufacturing-usa-institutes/

RDIs for 21st century manufacturing, including tools for smart and digital manufacturing, advanced industrial robotics, and analytics enabled by networks of sensors and the industrial Internet of Things.[52]

Driving U.S. Innovation and Competitiveness in Leading-Edge R&D—Future Outlook

Paramount to the effective use of these interrelated RDIs is the coordination provided by the communities that use them. The dramatic growth in the scale and complexity of data sources supporting innovation requires coordination of RDI investments for and in the use of advanced computing resources, analytics software services, and high-speed network capabilities across all fields and sectors.[53] These research cyberinfrastructure resources and networks increasingly serve as the glue connecting large-scale RDIs and fulfilling their scientific mission to turn information and data into discovery and innovation. Integrating trustworthy AI for reliability, safety, and accuracy will help build Americans' trust in AI, with the development of AI standards being an enabling factor to different entities coordinating R&D across sectors.[54]

Continued developments in RDI capabilities for QIS will enable the United States to create jobs, improve its industrial base, and enhance economic and national security benefits. Such efforts require the maintenance of robust and diverse platforms and collaboration with industry and the associated supply chain to identify future directions as well as perform and commercialize transformative R&D.[55],[56] Federal RDI investments in QIS can help spur collaborations across sectors to establish a network of accessible quantum hubs and develop pipelines to train the future workforce.

Federal RDI investments in enhanced wireless communication will enable transformational impacts across the entire economy. This supportive infrastructure will be required to fully realize the potential benefits in the areas of public safety and disaster response, especially as other nations have also realized their importance and have begun significant investments in an effort to leapfrog U.S. technical capabilities. Integrating trustworthy AI/ML can reliably exploit environmental data and take advantage of this system of systems, generating insights to support citizens and decision makers.

Federal RDI priorities in advanced manufacturing include smart and digital manufacturing, advanced industrial robotics, systems enabled by the Internet of Things, and cyberinfrastructure to enable the use of AI/ML.[57] The continued integration of low-cost distributed and continuous manufacturing methods into facilities, in particular for bio-based manufacturing, will enhance domestic access to important medicines and decrease U.S. reliance on other entities to provide our citizens lifesaving materials and equipment. In addition, the integration of nanotechnology with advanced manufacturing is showing potential to enhance existing manufacturing techniques, while creating new

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[52] NSTC. 2018. *Strategy for American Leadership in Advanced Manufacturing*. https://www.manufacturing.gov/news/announcements/2018/10/strategy-american-leadership-advanced-manufacturing

[53] NSTC. 2019. *National Strategic Computing Initiative Update: Pioneering the Future of Computing*. https://www.nitrd.gov/pubs/National-Strategic-Computing-Initiative-Update-2019.pdf

[54] The White House. 2019. *Executive Order on Maintaining American Leadership in Artificial Intelligence*.

[55] Public Law No: 115-368, National Quantum Initiative Act, 2018. https://www.congress.gov/bill/115th-congress/house-bill/6227

[56] Quantum Economic Development Consortium. https://quantumconsortium.org/

[57] NSTC. 2018. *Strategy for American Leadership in Advanced Manufacturing*. https://www.manufacturing.gov/news/announcements/2018/10/strategy-american-leadership-advanced-manufacturing

nanocomposites, alleviating the limitations of technologies.[58] There is an opportunity for industry, national laboratories, and academia to develop RDI capabilities such that nanodevices can be integrated into manufacturing techniques and increase capabilities for commercialization.

To support U.S. leadership in the nanotechnology industry, RDI capabilities will likely need to be expanded while also growing education, training programs to increase the number of those within the industry's workforce that will help commercialize products. RDIs should be planned and integrated in a fashion that eases the transition of innovations from the lab to the global commercial market by improving access to facilities and providing more opportunities for collaboration and public-private partnerships. Pilot and test-bed facilities are vital to achieve this goal and will help to improve returns on investments.

Ensuring Our Nation's Defense and Resilience

Ensuring Our Nation's Defense and Resilience—Overview

Since the birth of the United States, Federal support has fueled U.S. innovation behind our Nation's defense and resilience. Examples of early U.S. investment in defense-related RDIs include interchangeable machine-made parts for the first U.S. armory in 1797, which paved the way for mass production,[59] and the development of rockets, which delivered munitions and provided technologies for human space flight, exploration, and the satellite-based space economy. Ensuring the safety and security of the American public and defending our values are essential roles of the U.S. Government. Fulfilling this role is a complex challenge that requires the ability to defend American interests from foreign threats, and to ensure that communities across the country are resilient. Resiliency refers to capabilities for anticipating, mitigating, responding, and quickly recovering from human-made and natural disasters, including pandemics like COVID-19 and effects from climate change.[60]

Our Nation's critical infrastructure—a dynamic collection of assets, systems, and networks—provides goods and services that are essential to the competitiveness and vitality of the Nation's economy as well as the safety and welfare of its people.[61] Building resilience into our Nation's critical infrastructure requires coordination among government agencies (Federal, State, and local), communities, and the private sector to collectively define requirements and establish viable goals, as no single entity holds the resources or authority to accomplish them alone (Box: Community Coordination Relevant to Critical Infrastructure).

[58] For further on priorities for nanotechnology R&D and the National Nanotechnology Initiative, *see* https://nano.gov

[59] Singer, Peter L. 2014. *Federally Supported Innovations: 22 Examples of Major Technology Advances That Stem From Federal Research Support*. The Information Technology & Innovation Foundation (ITIF): https://dc.mit.edu/sites/default/files/pdf/2014-federally-supported-innovations.pdf

[60] The White House. 2021. *Interim National Security Strategic Guidance*. https://www.whitehouse.gov/wp-content/uploads/2021/03/NSC-1v2.pdf

[61] The White House. 2021. *Executive Order on America's Supply Chains*. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/

Community Coordination Relevant to Critical Infrastructure

Partnerships between the government and the private sector are vital to improve critical infrastructure supply chains and manufacturing capabilities as well as to ensure our Nation's productive capacity. Partnerships between governmental entities and industries were established under the Department of Homeland Security (DHS) Critical Infrastructure Partnership Advisory Council framework across 16 sectors, including critical manufacturing, defense industrial base, energy, food and agriculture, government, healthcare, information technology, transportations, water and wastewater systems, among others. Through these efforts, plans for each of the 16 sectors were developed through a collaborative process including state, local, tribal, and territorial government communities. These plans identify vulnerabilities and risks, such as those related to climate change, aging and deteriorating infrastructure, and continuity of the workforce in these sectors.[62]

Large-scale efforts are needed to protect communities, especially those that have been historically marginalized and impacted from the impacts of climate change, ecosystems, and infrastructure from the impacts of climate change through dedicated investments in resilience to sea level rise, extreme heat and cold, hurricanes, wildfires, and other weather events[63]. The Federal Government's continued partnerships with professional societies and standard-setting organizations, such as the American National Standards Institute, are crucial to address the needs for guidelines and standards in sustainability and resilience of RDIs.

RDIs for defense and resilience encompass world-class facilities, scientific equipment, data, human resources, and a high-speed, secure research cyberinfrastructure that ties all of these components together. These capabilities create a system for the discovery, innovation, testing, and application of solutions to secure and protect the Nation. RDIs provide platforms that support advanced military capabilities (e.g., hypersonics, resilient space systems,[64] and nuclear deterrent capabilities). RDIs include testing and engineering facilities that support robust supply chains for manufacturing semiconductors and the critical minerals essential for securing the technologies of tomorrow.[65,66] To build effective resilience to natural and human-made disasters, the United States requires a flexible and agile R&D enterprise supported by RDI capabilities that are integrated and promote convergence across

[62] Cybersecurity & Infrastructure Security Agency. "2015 Sector-specific Plans." https://www.cisa.gov/2015-sector-specific-plans

[63] "Executive Order on Tackling the Climate Crisis at Home and Abroad," January 27, 2021. This Executive Order established several initiatives, including Justice40, that will help to ensure that the Federal investments to address climate change benefit underserved communities. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/

[64] For example, the 2020 Presidential Executive Order on Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing Services identified how the interagency would work with OSTP to develop a national plan to address "approaches to integrate and use multiple PNT services to enhance the resilience of critical infrastructure." https://www.federalregister.gov/documents/2020/02/18/2020-03337/strengthening-national-resilience-through-responsible-use-of-positioning-navigation-and-timing

[65] For example, the 2021 Executive Order on America's Supply Chains. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/

[66] DoD. 2018. *Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States*.

fields and sectors (Box: National Biodefense Infrastructure). Large scale efforts are needed to protect communities, ecosystems, and infrastructure from the impacts of climate change through dedicated investments in resilience to sea level rise, extreme heat and cold, hurricanes, wildfires, and other weather events.

National Biodefense Infrastructure

The National Biodefense Strategy (NBS) brings together and puts in place a single coordinated interagency effort to orchestrate the full range of activity that is carried out across the U.S. Government to protect the American people from biological threats.[67] For example, critical components of the NBS include commitments to ensure a strong public health infrastructure that includes laboratory capabilities for conducting forensic analysis of biological agents, evidence-based biosafety and biosecurity practices, and a system of well-prepared hospital and health care facilities with the ability to maintain health care operations and provide necessary care during bio-incidents.

Ensuring Our Nation's Defense and Resilience—Future Outlook

Investing in RDIs that advance and protect our national innovation base while ensuring national security and resilience is critical for the United States, especially as other nations dramatically increase their R&D expenditures.[68] Sustained Federal RDI investments are essential to ensure that the United States remains able to secure and protect the American people in the face of this increased competition. While Federal agencies look to leverage private sector facilities where applicable, the support and maintenance of RDIs necessary to meet the needs of defense and resilience remains a primary responsibility and priority of the Federal Government.

Meeting current and future needs to address evolving challenges in national security and defense requires further support for Federal agencies as they seek to modernize their RDIs, technologies of the future,[69] and the networks that support them. In addition to bolstering technological capabilities and flexibility, investments focused on reducing vulnerabilities and strengthening supply chain resilience (e.g., for rare-earth and other critical minerals) will be key to securing the national economy and defense.[70, 71] This includes modernizing existing secured facilities to mitigate against unintended vulnerabilities, especially in areas critical to national security. With natural disasters at the nexus of

67 The White House. 2018. *National Biodefense Strategy*.

68 For example, Congressional Research Service. April 2020. *Global Research and Development Expenditures: Fact Sheet*. https://fas.org/sgp/crs/misc/R44283.pdf

69 Such technologies include AI/ML, microelectronics, cyber capabilities, QIS, biotechnology, enhanced real-time remote sensing capabilities, and the networks that support them. From: DoD. 2018. Summary of the National Defense Strategy of the United States of America: https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf

70 For example, DOC. 2019. *Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals*. https://www.commerce.gov/sites/default/files/2020-01/Critical_Minerals_Strategy_Final.pdf

71 The White House. 2021. *Executive Order on America's Supply Chains*. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/

public safety response and economic hardship, support for RDI capabilities that accelerate the pace of disaster response and resilience should continue and expand.[72]

Advancing our Nation's capabilities will require leveraging and strengthening partnerships among the dynamic, interdependent systems that underpin our defense and resilience R&D communities—and increasing interagency coordination. Furthermore, strategic partnerships with industry help develop the manufacturing skills, industrial facilities, and capacity needed to produce future military capabilities and resilient systems for critical infrastructure and biosecurity. Coordinated frameworks among industry, academia, and allied partners are necessary to discourage subversive and coercive efforts to obtain intellectual property and other sensitive information of national security concern. Partnerships with academic institutions to better convey concerns and share best practices will ensure our ability to protect U.S. citizens and respond to a variety of human-made and natural threats.

As the pace of security technology continues to accelerate across industry, Federal agencies will need to integrate across traditional (i.e., disciplinary) RDI capabilities and platforms to develop new secure pipelines for information exchange. Improved integration and communication across the Federal Government will help identify common threats to the U.S. R&D enterprise and facilitate improvement to RDIs that increase our Nation's resilience. This coordination will also maximize how RDIs can be used to address multiple major crisis events that can coincide and exacerbate each other's effects during a national emergency.

Understanding Our Planet

Understanding Our Planet—Overview

The U.S. and the world are currently facing a profound climate crisis in which immediate action is needed to avoid the catastrophic impacts climate change presents.[73] In order to better understand our Earth system, impacts from climate change, and increase our ability to forecast events and protect lives and property, the U.S. relies on continued R&D advancements that provide critical underlying science and observations.

Across multiple agencies, the Federal Government invests billions of dollars annually in civil Earth observations and interpretations of the data resulting from the observations. These investments maintain our Nation's leadership in understanding our planet, which comprises the geophysical, biophysical, and ecological processes that support life on Earth.[74] Scientific data collection and continued analysis of the Earth's climate and interconnected systems[75] are critical in protecting the lives and health of all citizens, strengthening the economy, preserving the natural and built

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[72] For example, DOC. 2019. *Driving Innovation for Disaster Response to Support America's First Responders and Build Resilient Communities*. https://www.commerce.gov/news/blog/2019/11/driving-innovation-disaster-response-support-americas-first-responders-and-build

[73] The White House. 2021. *Executive Order on Tackling the Climate Crisis at Home and Abroad*. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/

[74] The White House. 2019. *2019 National Plan for Civil Earth Observations.*

[75] For example, atmosphere, biosphere, hydrosphere, lithosphere, cryosphere, and anthroposphere.

environments,[76] and deepening our understanding of changes affecting the Earth-system.[77, 78 79] The need for R&D advances that meet today's societal challenges has never been greater, with opportunities to improve the critical services that local communities deliver to their residents, transform higher education to meet the needs of tomorrow's workforce, and stay on the cutting edge of global challenges.[80] To achieve this, we should continue to invest in the research infrastructure that supports our laboratories, universities, observing platforms, and computing networks.

RDIs for Earth observations include the platforms, technologies, and systems that support the collection and rigorous analysis of copious data needed to study our planet's dynamics and monitor its

RDIs Supporting our Understanding of the Arctic and Antarctic

The United States has long maintained substantial Arctic and Antarctic in-situ research capabilities and RDIs (e.g., research stations, telescopes, research vessels, observatories, and other assets) supported by a variety of agencies, including the National Science Foundation, NASA, NOAA, Department of Defense, and U.S. Geological Survey. Notable changes in climate and ice conditions at the Earth's poles have increased U.S. strategic focus in both regions. For example, improved access to the region's sea lanes and untapped natural resources due to diminishing Arctic sea ice necessitate robust and reliable U.S. maritime access for both research and rescue purposes. Meanwhile, changing weather and ice sheet dynamics in the Antarctic represent research areas where further RDI investment on the continent can play a role in strengthening and expanding existing observing and assessing capabilities. A major public-private initiative called ArcticDEM brought together RDIs spanning high-resolution imaging and advanced computing to produce the most detailed publicly available maps of the Arctic.[81] Expansion of the effort to the Antarctic and other remote regions is underway.

[76] In engineering and social sciences, "built environment" refers to the "human-made environment" ["the human-made space in which people live, work, and recreate on a day-to-day basis."] See also CDC's use: https://www.cdc.gov/nceh/publications/factsheets/impactofthebuiltenvironmentonhealth.pdf]]

[77] OSTP has established a Fast Track Advisory Committee on Earth System Predictability (ESP), the focus of which includes RDI needed to support ESP.

[78] The Earth system has two primary components: the geosphere (the collective name for the lithosphere, hydrosphere, cryosphere, and atmosphere) and the biosphere. Climatic processes, the hydrologic cycle, and the multiple biogeochemical cycles are interactive in the Earth system. https://pubs.usgs.gov/pp/p1386a/pdf/notes/1-8hydrocycle_508.pdf

[79] The Earth system has two primary components: the geosphere (the collective name for the lithosphere, hydrosphere, cryosphere, and atmosphere) and the biosphere. Climatic processes, the hydrologic cycle, and the multiple biogeochemical cycles are interactive in the Earth system. https://pubs.usgs.gov/pp/p1386a/pdf/notes/1-8hydrocycle_508.pdf

[80] The White House. 2021. *Executive Order Protecting Public Health and Environment and Restoring Science to Tackle Climate Crisis*. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/20/executive-order-protecting-public-health-and-environment-and-restoring-science-to-tackle-climate-crisis/

[81] University of Minnesota. "Arctic-DEM." https://www.pgc.umn.edu/data/arcticdem/

health.[82] From observatories that gather and interpret data on dynamic Earth processes (e.g., ecosystems, weather, climate) and the condition of key planetary resources (e.g., air, water, land) to laboratories that advance scientific discovery (e.g., synchrotron light sources, free-electron lasers) and engage in modeling and computer simulations, RDIs are a vital resource in furthering our understanding of the environment (Box: RDIs Supporting our Understanding of the Arctic and Antarctic).

RDIs are a crucial resource for the development, application, and maintenance of modeling systems used in a predictive capacity to understand climate change and support planning and resilience efforts. RDIs help provide capabilities that ensure long-term societal resilience through improved forecasting of and emergency management response during hazardous incidents and natural disasters caused by extreme weather and climate change driven events. A critical enabler is the research cyberinfrastructure that provides relevant stakeholders with actionable intelligence at the speed needed for accurate forecasting and decision making. Capabilities provided by such RDIs include predictive modeling of weather and climate that can improve estimations of future conditions of the Earth system as well as improved prediction of space weather events and their impact on power grids and information and communications systems. Observational infrastructure provides the platforms to analyze ecological and geophysical processes that enhance environmental information products and services, such as early warning systems for earthquakes and volcanos; tsunami and severe weather forecast and warning systems; air, soil and water-quality monitoring systems; and biomonitoring systems.

Understanding Our Planet—Future Outlook

Rapid advances in space, air, water, ground remote-sensing, and in-situ capabilities have enabled data collection in areas of the Earth that were previously inaccessible, and at spatial scales and measurement frequencies that were unthinkable only a few years ago. New and improved scientific instruments, satellite arrays, advanced sensors and other data collection methods, and computational approaches for analysis and visualization, along with collaborative contributions from the scientific and industry communities, will continue to vastly expand R&D data available to researchers across the planet. Legacy technologies, such as crewed ships and aircraft and existing laboratories, will continue to play a vital role for years to come. The maintenance, recapitalization, and modernization of such RDIs will need to be appropriately resourced.

In addition, as low-cost advanced sensors, sensor networks, and sensor platforms (e.g., unmanned systems) become increasingly available, the potential contributions from citizen science and the Internet of Things (e.g., emerging initiatives to gather weather, atmospheric, and environmental data from sensors on cars and smart phones) will increase. These developments raise challenges of ensuring data standards, integrity, privacy, quality, and data accessibility, as well as the need for robust methods of integrating and validating data from disparate sources. Continued improvements in cyberinfrastructure including data repositories, networks, high-performance computing, modeling, and quality assurance techniques will be critical in advancing the state of Earth observation science and improving public policy decision making.

As new technologies and tools become available to collect, assemble, analyze, and integrate data from different systems, other RDIs and partnerships across the R&D enterprise will play increasingly

[82] RDIs include instruments aboard the International Space Station and satellites; observatories, research stations and site-based facilities; regional and continental-scale terrestrial networked sensor arrays; environmental monitoring platforms; laboratories; and historical collections.

important roles in creating a “system of systems.” This integrated system will allow traditional monitoring and observational platforms to be augmented by new observational tools (e.g., sensors and remote sensing platforms) and create better-quality datasets (e.g., increased spatial and temporal coverage), improving prediction capabilities to respond to emerging environmental threats[83] and behaviors of the Earth system.

[83] USGCRP. “Fourth National Climate Assessment.” https://nca2018.globalchange.gov/

Supporting Our Natural Resource-Based Industries and Ensuring Food Security

Supporting Our Natural Resource-Based Industries and Ensuring Food Security—Overview

Our agriculture, forestry, and fisheries industries ensure the diversity, sustainability, and productivity of our Nation's natural resources. These activities are supported by the production of livestock, crops, and timber as well as freshwater and seafood production through open water harvesting and aquaculture. These industries nourish our Nation and the world while promoting the productivity and sustainability of Earth's interrelated ecosystems for generations to come.

RDIs have provided foundational capabilities to develop safe, nutritious, and affordable products that continue to sustain our Nation's citizens. Such RDIs include experimental and observational infrastructure, such as research sites for the interdisciplinary study of plant and animal population dynamics, ecological communities, and ecosystems (Box: Long-Term Natural Resource Research Efforts that Leverage Networked RDIs). This vast network includes Federal, State and university-based animal and wildlife health laboratories across the United States that aid in the Nation's resiliency, for instance in early detection, response, and recovery from animal disease emergencies.[84,85]

Long-Term Natural Resource Research Efforts That Leverage Networked RDIs

RDIs that contribute to food and nutritional security, by supporting agriculture, forestry, fisheries and aquaculture research, include National laboratory programs and field research sites. For example, the Land-Grant Agriculture Experiment Stations and the Cooperative Extension Services include hundreds of experimental stations, many integrated into universities. NSF funds 28 Long-term Ecological Research Program sites and a National Ecological Observatory Network that support ecological discoveries relating to long-term and large-scale phenomena utilizing the expertise of researchers from various disciplines including microbiology, hydrology, ecology, economics, and social science.[86] The United States Department of Agriculture (USDA) Long-term Agro-Ecosystem Research Network consists of a network of 18 research sites dedicated to using transdisciplinary science over different land regions to develop national strategies for the intensification of sustainable agricultural practices. The USDA Climate Hubs are a Federal network of research units that provides both research and extension activities ensuring our farmers, ranchers, and landowners have access to science, tools, and resources to manage their land in a changing climate.[87] In addition, the USDA Forest Service's network of 84 experimental forests and ranges contains an array of national site infrastructure such as climate stations, stream gauging stations, laboratories, and housing, which all support cross-disciplinary long-term research on issues including silviculture, water quality and quantity, restoration, carbon cycling, wildlife ecology, and forest fires and other disturbances.[88] These RDIs provide the education and tools to train the next generation of scientists, educators, and extension specialists.

[84] USDA. "National Animal Health Laboratory Network (NAHLN)." https://www.aphis.usda.gov/nahln
[85] U.S. Geological Survey. "National Wildlife Health Center." https://www.usgs.gov/centers/nwhc
[86] USDA Forest Service. "Forest Inventory and Analysis." https://www.fia.fs.fed.us/
[87] USDA Climate Hubs. https://www.climatehubs.usda.gov/about-us
[88] USDA Forest Service. "Research and Development: Experimental Forests and Ranges." https://www.fs.fed.us/research/efr/about.php

Knowledge infrastructure supported by these RDIs has enabled important human capacity building and training activities, such as agricultural extension services that facilitate the sharing of knowledge and practices across the industry. Knowledge infrastructure includes scientific collections, such as national scale soil databases that provide information on the physical characteristics, chemical composition, and mineralogical makeup of soils, or databases that integrate chemistry, toxicity, and exposure data of chemicals (Box: Integrated Chemical Databases to Inform Public Health). These RDIs provide key resources to inform agricultural practices and environmental baseline conditions in soils.[89] Germplasm collections provide vital genetics to build resiliency across crops, forest vegetation, and animals.[90] In the forest sector, the USDA Forest Service's Forest Inventory and Analysis program is the Nation's forest census and surveys public and private forest landowners and mills. The census measures dead trees, down dead wood, and regeneration—among other measures—samples forest floor and soils, and estimates forest area and area change. These data are used by researchers to conduct R&D on forest products and growth, sustainable forest assessments, invasive species, the impacts of climate change (e.g. the carbon cycle and greenhouse gases), remote sensing, ecosystem services, and long-term trends in forest health.[91]

Integrated Chemical Databases to Inform Public Health

Under Federal statutes, EPA makes a broad range of decisions to protect public health and the environment from unintended consequences of using chemicals. Decisions about chemicals are also made by other Federal Agencies, State environmental and health agencies, international governmental agencies and industry. To help support these efforts, EPA researchers are integrating available chemical information including physicochemical properties, environmental fate and transport, exposure, usage, in vivo toxicity, and in vitro bioassay into an online tool called the Computational Toxicology Chemicals Dashboard to help decision makers and scientists quickly and efficiently evaluate thousands of chemicals. The Dashboard is a one-stop-shop for chemistry, toxicity, and exposure information for over 875,000 chemicals. Data and models within the Dashboard also help with efforts to identify chemicals of most need of further testing and reducing the use of animals in chemical testing. These data in the Dashboard are compiled from sources including the EPA's computational toxicology research databases, and public domain databases such as the National Center for Biotechnology Information's PubChem database and EPA's Ecotoxicology Knowledgebase.

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89 For examples, *see* USDA, Natural Resources Conservation Service, "Soils Databases." https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/tools/?cid=nrcseprd1407024; and the U.S. Geological Survey soil geochemistry and mineralogy database for the conterminous United States. https://pubs.er.usgs.gov/publication/sir20175118

90 USDA, Agricultural Research Service. "Germplasm Resources Information Network (GRIN)." https://www.ars-grin.gov

91 For example, "Great Lakes Restoration Initiative: Edge of Field Monitoring." https://wim.usgs.gov/geonarrative/glri-eof/

Federal RDI investments in research cyberinfrastructure have been critical to developing and using AI/ML, advanced manufacturing capabilities,[92] automation, remote and advanced sensing, and cloud computing across these sectors. These capabilities, in turn, have helped generate, process, and store large volumes of natural resource data used for predictive modeling capabilities across these sectors. For instance, experimental infrastructure and cyberinfrastructure have enabled capabilities to develop robust scientific models that support sustainable fisheries production, including fishery stock assessments and habitat mapping.[93] Agricultural research cyberinfrastructure, such as fields instrumented with advanced sensor technologies and monitored by drones, serve as high-tech outdoor laboratories informing the development of effective and economical agricultural practices. These practices can help optimize the use of fertilizers, pest and weed control agents, as well as minimize potential for soil erosion, runoff, and dispersal of management chemicals into the environment.

Supporting Our Natural Resource-Based Industries and Ensuring Food Security—Future Outlook

The U.S. is among the leaders of the world's agriculture production.[94] However, despite more than doubling agricultural output in the last 50 years, our Nation faces continued climate change-related challenges to our resource-based economies, including rising water and air temperatures, water scarcity, changes in precipitation, intensifying droughts, ocean acidification, and declines in surface water quality.[95] With our world population likely to grow to about 9.7 billion people over the next 30 years, demands for goods and services provided by farms and forest lands are projected to increase by about 40 percent.[96] The U.S. is and will be increasingly dependent on imported aquaculture products to supply its seafood needs, and wild capture fisheries are nearing maximum sustainable production levels.

Continued and targeted Federal investments are vital to the progression of foundational RDIs that underpin scientific advances within the agriculture, forestry, and fisheries sectors. It is vital that Federal RDI investments support capabilities and technological advances to promote food systems that reduce the prevalence and severity of food insecurity, such as enabling sustainability, reducing environmental damage, and identifying promising plant-based and cell-based food alternatives. These food systems should also work to improve the nutritional quality of food products and integrate data collection and analyses to develop and promote nutritional guidance.[97]

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[92] Improved advanced manufacturing techniques provide many opportunities within the agricultural sector to process, test, and allow traceability within the supply chain, enhance food production and processing while preserving or enhancing food and nutritional security, and lowering the cost of processing and conversion of bio-based materials, as stated in the NSTC. 2018. *Strategy for American Leadership in Advanced Manufacturing*:

[93] NOAA. 2020. "NOAA finalizes strategies for applying emerging science and technology." February 18, 2020. https://www.noaa.gov/media-release/noaa-finalizes-strategies-for-applying-emerging-science-and-technology

[94] In 2018, the United States was ranked approximately third globally in agricultural output (https://worldinfigures.com/rankings/index/103); in 2019, the U.S. was one of the top forest producers of many of the main forest products (http://www.fao.org/forestry/statistics/80938@180723/en/); and globally was the third highest producer within the fisheries sector in 2016 (http://www.fao.org/3/i9540en/i9540en.pdf).

[95] USGCRP. "The Fourth National Climate Assessment." https://nca2018.globalchange.gov/

[96] USDA. 2019. *USDA Science Blueprint: A Roadmap for USDA Science from 2020 to 2025.* https://www.usda.gov/sites/default/files/documents/usda-science-blueprint.pdf

[97] USDA. 2019. *USDA Science Blueprint: A Roadmap for USDA Science from 2020 to 2025.* https://www.usda.gov/sites/default/files/documents/usda-science-blueprint.pdf

Within agricultural sectors, the intensification of sustainable agriculture and production shifts from climatic changes will necessitate interdisciplinary R&D using concepts from anthropology, biology, economics, chemistry, environmental science and more to improve our Nation's agricultural systems.[98] These outcomes can be achieved through coordinated RDI investments to support knowledge-based repositories and data; experimental stations, equipment, and tools to improve implementation of regenerative agriculture; and the use of analytics to increase agility and resilience of agricultural systems especially to economic shocks and extreme weather events driven by climate change. Investments in these future RDI capabilities will enable full use of precision agriculture and biotechnologies to improve the traits of agriculturally important organisms. In addition, as the development of vaccines for animal diseases becomes increasingly important, further RDI investments will be needed to support translational research capabilities.

Within the forestry sector, ecosystem shifts due to climate change will also require RDIs that support even more interdisciplinary R&D, leveraging sociology, ecology, wildlife management, hydrology, and economics to sustain our Nation's forest and grassland ecosystems. This can be achieved through Federal RDI investments aimed at improving R&D of sustainable ecosystems, translating that research into actionable management strategies, supporting innovation in forest products, and ultimately ensuring the resilience of our Nation's natural resources and communities. RDI capabilities for remote sensing and monitoring technologies will increase rigor of finer-scale estimation, including small-area estimate techniques of forest characteristics such as forest carbon.[99]

Within the fisheries and aquaculture sectors, extensive sensor networks will soon be deployed to monitor environmental deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), enabling detection in near real time of invasive fish and mollusks species in our Nation's waters.[100] These RDI capabilities can potentially provide early warning of various disease outbreaks, for example via monitoring of municipal wastewaters. In addition, the U.S. has unrealized potential in aquaculture. Federal RDI investments in offshore aquaculture demonstration sites and related onshore support activities, such as hatcheries, are needed alongside informed regulations and policies, education for the public, and economic incentives to de-risk industry-scale production technologies.

Cyberinfrastructure and electronic connectivity, including access to broadband services and wireless communication in all regions of the Nation, underpin the ability to enhance these R&D capabilities in these sectors. These operational RDIs leverage information technology to provide additional capabilities to analyze the enormous amounts of data created through agricultural and food systems. In addition, future investments in these operational RDIs should also focus on addressing potential vulnerabilities and ensure these capabilities are robust and secure. Continued support of cost-effective RDIs is needed to provide continued and improved capabilities to transfer scientific information, technologies, and applications within and among researchers, forest managers, and industry. These RDIs will help empower and enable science, technology, engineering, and mathematics (STEM) education to better serve communities, producing a skilled R&D workforce, extension specialists, and practitioners in the agricultural, wildlife, and forest management communities.

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[98] Our Nation's agricultural systems include soil health, plant and crop resiliency, nutrient efficiency, and plant and animal disease prevention.

[99] USDA Forest Service. 2016. *Forest Inventory and Analysis Strategic Plan*. FS-1079. https://www.fia.fs.fed.us/library/bus-org-documents/index.php

[100] U.S. Geological Survey. "Invasive Species Program." https://www.usgs.gov/ecosystems/invasive-species-program

Advancing Human Health and the Biomedical Sciences

Advancing Human Health and the Biomedical Sciences—Overview

RDIs supporting medical and biomedical science provide resources for discoveries that lead to new treatments, improve health care delivery, protect human health, and increase quality of life. The breadth of integrated RDIs in this domain enables R&D supporting a greater understanding of biology and attracts and renews a creative STEM workforce whose impact is felt across R&D fields and sectors. The iterative, often recursive, pattern of advances in basic, translational, and clinical science requires RDIs in each of these domains, drawing on convergence across all fields of science.[101]

This synergy engages both the support and mutual collaboration of multiple agencies (e.g., the longstanding joint efforts in groundbreaking synchrotron-based RDIs for structural biology, including crystallography, electron microscopy, and single molecule technologies). RDIs in the health and biomedical sciences include facilities that combine numerous specialized instruments and ancillary technologies to provide integrated platforms to support R&D activities.[102] Investment in components of such facilities may be incremental or represent turnover of single technologies to support the evolution of the overall capability. Federal agencies also fund and operate scientific collections used for the advancement of health and biomedical sciences (Box: RDIs and Response to COVID-19). These include physical specimens used as reference to identify unknown specimens; repositories that provide samples and hold specimens for researchers seeking to make advances in technologies; and exhibits to edify the public. Federal agencies maintain premier resources, including scientific literature and fundamental genomic and biological data, for access by researchers and the public.

[101] For example, many Federal agencies, including EPA, USGS, and OSHA routinely collaborate with NIH and the CDC to evaluate potential threats that environmental and occupational exposures to natural and human-sourced toxicants and pathogens pose to public and occupational health.

[102] For example, DoD's unique military medical RDI investments—designed to support its mission to protect the Joint Force and its beneficiaries against a range of health threats—have also provided strategies to the wider medical community for improved trauma care and survival; efficient traumatic brain injury identification and treatment; and enhanced prevention, containment, and treatment of infectious disease outbreaks.

RDIs and Response to COVID-19

The Operation Warp Speed and Rapid Acceleration of Diagnostics programs are enabled by RDIs across agencies and industry as part of a broader strategy to accelerate the development, manufacturing, and distribution of COVID-19 vaccines, therapeutics, and diagnostics.[103]

The first vaccine candidate to begin a Phase 3 clinical trial in the United States, mRNA-1273, was co-developed by industry and the National Institute of Allergy and Infectious Diseases (NIAID) Vaccine Research Center at NIH. Expertise in human papillomavirus vaccines and an advanced serology laboratory enabled National Cancer Institute's Frederick National Laboratory for Cancer Research to provide independent testing and validation of SARS-CoV-2 antibody tests in a collaborative effort with FDA, the Centers for Disease Control Prevention, NIAID, the Biomedical Advanced Research and Development Authority, and others. NIH data science and translational RDIs supported the rapid creation of a national repository of COVID-19 clinical data.

In addition, DOE-supported RDIs across National Laboratories provided capabilities for rapid advancement of molecular structure determination and computational modeling work in support of vaccine and therapy development. The DHS Science and Technology Directorate is using the unique capabilities of the National Biodefense Analysis and Countermeasures Center (NBACC)[104] to evaluate the impact of a range of conditions, such as temperature and humidity, to determine SARS CoV-2 survivability in the air, in respiratory fluids, and on surface types. NBACC provides a unique combination of capabilities in virology and aerobiology operating at high biocontainment levels. Biosafety laboratories and in-house wildlife disease expertise were vital resources for USGS, U.S. Fish and Wildlife Service, and other collaborators to carry out studies that are helping assess potential for transmission and mitigation of the virus that causes COVID-19 from humans to North American bats and other wildlife.

Advancing Human Health and the Biomedical Sciences—Future Outlook

As increasing amounts of data are generated during biomedical research, Federal RDI investments to improve collection, management, and analysis are essential. This includes the creation of tools to effectively share international and domestic physical or biological samples and associated data in a timely manner while appropriately safeguarding privacy, intellectual property, and national security.[105] Advances in HPC and AI/ML present important opportunities for partnerships across Federal agencies as new RDIs are created to secure and analyze data.[106] These advanced technologies are central to both

[103] Operation Warp Speed: https://www.hhs.gov/about/news/2020/06/16/fact-sheet-explaining-operation-warp-speed.html

[104] The National Biodefense Analysis and Countermeasures Center: https://www.dhs.gov/science-and-technology/national-biodefense-analysis-and-countermeasures-center

[105] For example, data management system interoperability and data quality were discussed in the National Science and Technology Council Conference on *Building Bridges Across the Science and Technology Enterprise*. https://stenterprise.org/

[106] For example, NIH identifies a related goal to host or make biomedical datasets more available and advance research data infrastructure to support research programs via partnerships. NIH. 2018. *Data Science Strategic Plan*. https://datascience.nih.gov/sites/default/files/NIH_Strategic_Plan_for_Data_Science_Final_508.pdf

research and health care, necessitating the development of agile, flexible capabilities supported by RDIs, such as highly specialized and rapidly evolving laboratory spaces.

For bioeconomy-related RDIs, prioritizing investments that strengthen supply chain resilience and support public-private partnerships will help drive innovative applications of technologies for health care, pharmaceuticals, and manufacturing.[107] Federal agencies should work to establish distributed and nationally coordinated interagency capabilities relevant to the bioeconomy, including cutting-edge biology design engineering, tools for biotechnology and engineering biology applications, innovative manufacturing techniques to overcome hurdles of scaling up and downstream processing, and the testing and evaluating of engineered biology products.

Opportune partnerships that leverage the respective expertise of the interagency and private industry will spur the creation of RDIs needed to promote and protect public health. Federal agencies are already creating a whole-of-government approach to coordinate investments in advanced development and manufacturing, which will be essential to facilitate the development of COVID-19 medical countermeasures, and will improve RDI capabilities to respond to future pandemics. Partnerships with industry will help ensure that the Federal Government can rapidly facilitate development and production of critical medical countermeasures with trusted industry stakeholders, employing the most relevant state-of-the-art manufacturing technologies.

Advancing human health going forward will also require continued investments in RDIs related to health care delivery that are intended to further our understanding of health and patient outcomes, especially of vulnerable populations.[108] For instance, to improve continuity of veteran health care, DoD and the Department of Veterans Affairs are implementing a new interoperable electronic health care system that will allow soldiers' health records to be easily accessed across health facilities. This initiative—coupled with the development of a national system to coordinate civilian and military trauma treatment facilities that can share RDIs, lessons learned, and best practices—will continue to improve patient outcomes during traumatic injury and facilitate storage of public health treatment information.

[107] The White House. 2021. *Executive Order on America's Supply Chains*. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/

[108] The White House. 2021. *Executive Order on Ensuring an Equitable Pandemic Response and Recovery.* https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/21/executive-order-ensuring-an-equitable-pandemic-response-and-recovery/

Exploring the Physics of Our Universe

Exploring the Physics of Our Universe—Overview

Understanding the physics of our universe involves R&D that examines the smallest scales of particle physics to the largest scales of astronomy and cosmology. Bridging these physical scales over many orders of magnitude requires specialized and integrated RDIs, such as Earth- and space-based observatories that can peer billions of years into the past; experimental facilities that can recreate, observe, and collect data on the conditions of the very early universe; and the cyberinfrastructure to collect, validate, and analyze that data. Because of the extreme scales involved, RDIs in this domain require state-of-the-art and unique instrumentation that pushes the limits of existing technologies.

Sustained Federal RDI investments have fueled U.S. leadership and excellence in the fundamental physical and astronomical sciences, producing major discoveries and advances—most recently including the confirmation of the Higgs Boson, detection of gravitational waves, and construction of the first image of a black hole (Box: First Image of a Black Hole). The development and operation of RDIs supporting the study of the physics of our universe are inherently international efforts due to their scale and high cost, and due to the globally distributed scientific, technical, and managerial expertise needed to accomplish R&D in these fields. R&D collaborations have become global in scope, typically involving hundreds of scientists, engineers, mathematicians, and computational experts across the world.

First Image of a Black Hole

In April 2019, the world saw the very first image of a black hole when the Event Horizon Telescope (EHT) project revealed this massive object at the heart of galaxy M87 fifty-five million light years distant from Earth. The EHT is a unique international collaboration that combines data from eight radio telescopes across the globe to create a single Earth-sized virtual imaging interferometer.[109] The EHT collaborative team used the technique of Very Long Baseline Interferometry in conjunction with specially developed algorithms to integrate data from M87 collected in 2017 and produced the image which was openly shared around the world.[110]

Large-scale RDIs and their associated capabilities require a wide range of skilled R&D workers and often rely on various underlying RDIs. For example, a highly trained workforce has been integral in helping the physics community develop specialized domestic industrial capabilities in advanced sensor design and manufacture, refine extreme signal filtering and processing capabilities, and enhance new techniques and software for adequately handling big data.[111] Mission-oriented, space-based RDIs depend on federally supported platforms for launching, landing, manufacturing, and collaborating.

[109] The Event Horizon Telescope: https://eventhorizontelescope.org/about

[110] National Science Foundation news release "Astronomers capture first image of a black hole." https://www.nsf.gov/news/news_summ.jsp?org=NSF&cntn_id=298276&preview=false

[111] The Federal Big Data Research and Development Strategic Plan: https://bigdatawg.nist.gov/pdf/bigdatardstrategicplan.pdf

Exploring the Physics of Our Universe—Future Outlook

Across the physical and astronomical sciences, the next decade will see revolutions in our understanding of our universe. These revolutions will capitalize on extraordinary recent discoveries and rapidly advancing technologies, such as the discovery of the Higgs Boson, using neutrino science to answer fundamental questions and understand the nature of antimatter, continuing to observe black holes, probing the nature of dark matter and dark energy, investigating the forces binding atomic nuclei with the Electron-Ion Collider project,[112] detecting exoplanets with ground and space assets, and much more. All these fields depend on continued investments and improvements in large-scale RDIs, including measurement technologies and cyberinfrastructure.

Coordination among agencies via advisory and Federal interagency bodies remains an important component in achieving these goals. Adoption of frameworks that accelerate data sharing and analysis—such as wide-scale utilization of cloud computing—will fundamentally change the way astronomical and high energy physics data are collected, processed, archived, and curated. [113]

Given the size and scale of the RDIs necessary to advance R&D in this area, the United States does not hold a monopoly on the RDIs for these discovery-oriented efforts, and rather seeks to partner with other leaders. Maintaining U.S. stature in associated fields is an important mechanism to attract and retain talent in the United States, as scientists seek the best facilities and technologies to address challenging scientific questions. Further, given the size and complexity of large-scale facilities, the costs of building and operating RDIs can be multi-billions of dollars. Continued international collaboration and coordination are needed to share costs and attract the best talent to design and operate these facilities.

Global R&D communities rely on international partnerships to provide reciprocal platforms for joint R&D in ways that are beneficial to all parties. A successful U.S. network of trusted partners already exists to help develop best practices, coordinate international investments, and promote the development of large-scale RDIs with like-minded partners. These goals are achieved through respected international fora, such as the Group of Seven, [114] Organisation for Economic Co-operation and Development, [115] and Global Research Council.[116] Examples of successful coordination with international counterparts include the U.S. involvement in the Large Hadron Collider project; [117] gravitational wave detection made possible by the U.S.-supported LIGO project in collaboration with the Virgo project;[118] the Atacama Large Millimeter/Submillimeter Array,[119] an effort involving many nations; and the newest giant space-based imaging facility under development—the James Webb Space Telescope—which is an international collaboration between NASA, the European Space Agency, and the Canadian Space Agency—managed by the NASA Goddard Space Flight Center.[120]

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[112] The Electron-Ion Collider: https://www.bnl.gov/eic/

[113] NSTC. 2019. *National Strategic Computing Initiative Update: Pioneering the Future of Computing*. https://www.nitrd.gov/pubs/National-Strategic-Computing-Initiative-Update-2019.pdf

[114] What is the G7 summit and what does it do? https://www.bbc.com/news/world-49434667

[115] Who we are: https://www.oecd.org/unitedstates/

[116] Global Research Council: https://www.globalresearchcouncil.org/

[117] The Large Hadron Collider: https://home.cern/science/accelerators/large-hadron-collider

[118] The Virgo collaboration: http://public.virgo-gw.eu/the-virgo-collaboration/

[119] Atacama Large Millimeter/submillimeter Array: https://www.almaobservatory.org/en/home/

[120] James Webb Space Telescope: https://www.jwst.nasa.gov/

Appendix B: The Role of RDIs in Agency R&D Communities and Missions

In this Appendix, Federal agencies of the NSTC Subcommittee on RDI provided brief summaries that describe the role of RDIs in supporting their R&D communities and missions.

Department of Defense (DoD)

The DoD laboratories engage in activities ranging from basic research to defense system acquisition support to direct operational support of deployed warfighters. Many of the DoD's military advantages are a product of the technological innovations that come from the defense laboratories. As the pace of globalization and technological change continues to accelerate, the need for a strong technical base continues to grow for DoD. The core of this DoD technical base is an in-house Defense Laboratory Enterprise (DLE), which provides a cadre of highly-skilled scientists and engineers and the infrastructure required to remain at the forefront of technology development and awareness. The purpose of the DLE infrastructure is to enable world-class research for the military and civilian communities across the spectrum of scientific disciplines, which requires cutting edge facilities and infrastructure to support its mission.

Department of Energy (DOE)

The mission of the Department of Energy is to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions. The Department catalyzes the transformative growth of basic and applied scientific innovation, a cornerstone of U.S. economic prosperity, through its network of 17 National Laboratories. The DOE Laboratories are a system of world-leading intellectual assets, including unique scientific facilities to drive scientific discovery and innovation. To support its missions, the Department develops and maintains an extensive R&D infrastructure, spanning its 17 National Laboratories, including infrastructure at several universities. DOE National Laboratories conceive, design, and construct unique and highly complex research facilities and infrastructure in support of American innovation and by making these unique facilities available to more than 34,000 researchers from academia, industry, and other federal agencies, as well as state and local entities. This includes particle accelerators for high-energy and nuclear physics, synchrotron and LINAC (linear accelerator) light sources for materials, chemical, and biological sciences, fusion research devices, and several of the world's most powerful supercomputers for modeling and simulation of physical systems, clean energy research, and climate modeling. DOE facilities include four Bioenergy Research Centers, 41 Energy Frontier Research Centers, five nanoscience centers for studying the structure and function of materials at the nano-scale (10-9 meters), genomic sequencing, and field laboratories for conducting atmospheric radiation measurements. The DOE laboratories are interconnected by a dedicated broadband 100 gigabits-per-second, high-speed network.

Department of Homeland Security (DHS)

The DHS Science and Technology Directorate (DHS S&T) mission is to enable effective, efficient, and secure operations across all homeland security missions by applying scientific, engineering, analytic, and innovative approaches to deliver timely solutions and support departmental acquisitions. DHS S&T conducts basic and applied research, development, demonstration, testing and evaluation activities relevant to DHS. DHS S&T manages a laboratory network that provides research capabilities and technology solutions in support of the unique requirements of the DHS Components and greater Homeland Security Enterprise (HSE). The DHS S&T lab network includes biosafety level 4 laboratories for biological forensics and threat characterization, and laboratories that support the varied Department missions in chemical security analysis, detection science, animal agricultural defense, and first responder technologies.

Department of State (DOS)

The U.S. Department of State leads America's foreign policy through diplomacy, advocacy, and assistance by advancing the interests of the American people, their safety and economic prosperity. The Department of State works with departments and agencies to promote international investment in domestic RDIs and to secure U.S. interests in international RDIs through bilateral and multilateral engagement. The Department of State leads engagement in the Intergovernmental Panel on Climate Change (IPCC) with support from interagency scientific agencies. The United States has been a driving force behind the IPCC since its creation in 1988 and is its largest donor historically. The IPCC assesses science related to climate change, and its findings use and support RDIs at national and international levels. Specifically, the Task Group on Data Support for Climate Change Assessments (TG-Data) provides guidance to Data Distribution Centers (DDCs) on curation, traceability, stability, availability, and transparency of data and scenarios related to the reports of the IPCC. These DDCs support RDIs to decision makers and stakeholders by providing climate, socio-economic, and environmental data, both from the past and also in scenarios projected into the future. Other DOS activities include direct advocacy for U.S. research objectives with foreign governments as well as assistance to agencies through programs and fellowships including, but not limited to, the Embassy Science Fellows Program and the Science Envoy program.

Department of Transportation (DOT)

The mission of the U.S. Department of Transportation (U.S. DOT) is to ensure America has the safest, most efficient and modern transportation system in the world, which boosts our economic productivity and global competitiveness and enhances the quality of life in communities both rural and urban. U.S. DOT consists of multiple modal Operating Administrations. U.S. DOT supports multiple pathways to deployment and operational transition of research results and new technologies to advance safety, mobility, accessibility, and environmental objectives. Many of these deployment pathways are created by research partnerships. DOT's research community has embraced a culture of innovation and actively supports and advances innovation across the entire breadth of its activities. Its programs help to ensure the safe, efficient, and reliable movement of people and goods by multiple modes of transportation through developing innovations and solutions to transportation problems. DOT conducts and sponsors research and safety testing of motor vehicles, airplanes, trains, buses and infrastructure through partnerships. It also supports advanced safety technologies to address human behavioral concerns.

Environmental Protection Agency (EPA)

EPA's mission to protect human health and the environment is dependent upon the sound science conducted within the Agency that is supported by the Agency's RDIs as well as the RDIs of the Agency's Federal partners. EPA and its partners operate experimental and observation networks to monitor the condition of the environment and inform future environmental decisions. In addition, the EPA operates a laboratory enterprise with locations across the country that conduct cutting edge research and provide a wide range of scientific and technical support and expertise. As part of the knowledge infrastructure and research cyberinfrastructure, the EPA also operates, utilizes, and produces computational tools and resources to advance environmental protection through high throughput analysis and big data analytics.

National Aeronautics and Space Administration (NASA)

NASA's vision is to discover and expand knowledge for the benefit of humanity. To achieve this, NASA's mission is to lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and bring knowledge and opportunities back to Earth. NASA executes this mission by supporting the growth of the Nation's economy in space and aeronautics, increasing the understanding of the universe and our place in it, working with industry to improve America's aerospace technologies, advancing American leadership, and sustaining the RDIs required for this mission.

National Institute of Standards and Technology (NIST)

The mission of the National Institute of Standards and Technology (NIST) is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology to enhance economic security and improve our quality of life. To accomplish this, NIST supports and depends on a broad array of RDIs including: world class laboratories, national user facilities, centers of excellence, joint institutes, and testbeds. The RDIs supported by NIST advance and secure the U.S. technology infrastructure, advance world-class research across wide scientific disciplines, and bridge the gap between fundamental research and application to push innovation forward. As needed, NIST works with other Federal agencies on nationally important RDI areas to ensure the United States remains competitive.

National Institutes of Health (NIH)

The mission of NIH is to seek fundamental knowledge about the nature and behavior of living systems and the application of that knowledge to enhance health, lengthen life, and reduce illness and disability. The NIH fosters fundamental creative discoveries and develops, maintains, and renews scientific human and physical resources that will ensure the Nation's capability to prevent disease and promote economic well-being. Through extramural and intramural programs NIH funds the construction of research facilities, development of innovative technologies for biomedical research and treatment, and information systems for collection and dissemination of research findings. The NIH also partners with other Federal agencies to develop and provide access to critical research infrastructure.

National Oceanic and Atmospheric Administration (NOAA)

NOAA's mission is to understand and predict changes in climate, weather, oceans, and coasts, to share that knowledge and information with others, and to conserve and manage coastal and marine ecosystems and resources. Research and development at NOAA are investments in the scientific knowledge, technology, and infrastructure that enable the United States to protect lives and property, sustain a strong economy, and address environmental challenges. NOAA's R&D priorities are accomplished with a wide breadth of partners and collaborators, including interagency, international, academic, non-governmental, and private organizations. NOAA transitions its R&D into operations, applications, and commercialization, providing reliable information to its stakeholders to reduce societal impacts from hazardous weather and other environmental phenomena, foster the sustainable use and stewardship of ocean and coastal resources (Blue Economy), and provide a greater understanding of Earth systems in a robust, effective R&D enterprise.

National Science Foundation (NSF)

The NSF mission is to promote the progress of science; to advance the national health, prosperity, and welfare; and to secure the national defense. NSF executes this mission by funding fundamental extramural research in all areas of science and education. The purpose of RDIs funded by NSF is to enable world-class fundamental research for the U.S. scientific community in disciplines that require advanced RDIs to make discoveries at the scientific frontier. As appropriate, NSF collaborates with other agencies and nations on RDIs to advance the goals in common with those organizations for the good of the Nation.

United States Department of Agriculture (USDA) - Forest Service

The USDA Forest Service mission is to sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations. The mission of Forest Service Research and Development (FS R&D) is to develop and deliver scientific knowledge and innovative technology to improve the health and use of all of the Nation's forests and rangelands, both public and private. The purpose of the RDIs funded by FS R&D is two-fold. It enables basic and applied research in forests and other treed lands, and it provides authoritative information and evidence for forest investments, reporting, and forest policy development.

United States Geological Survey (USGS)

As the Nation's largest water, Earth, and biological science and civilian mapping agency, the USGS collects, monitors, analyzes, and provides science about natural resource conditions, issues, and problems. Its diverse expertise and support of RDIs enables the USGS to carry out large-scale, interdisciplinary investigations and provide impartial and actionable scientific information to resource managers, planners, and other customers at the scales and timeframes needed for decision making. The USGS funds a broad range of RDIs, such as: analytical laboratories for the specialized chemical, mineralogical, microbiological, spectral, isotopic, environmental DNA/RNA and other types of analyses of many different sample types; national to global scale sensor networks that provide early warnings for earthquakes or volcanic eruptions, or that monitor water flow and quality; biosafety level 3 laboratories for understanding diseases in fish and wildlife; facilities that support the development of advanced analytical chemistry, hydrological monitoring, geophysical, and remote sensing technologies; facilities that support the development of complex hydrologic, geochemical, reactive transport, and ecological modeling capabilities; national scale databases of water quality, geochemical, geophysical, remote sensing, and geospatial data; archival collections of Earth materials, biological samples, and maps; ground facilities for the processing and delivery of over 40 years of Landsat remote sensing imagery; and the advanced IT infrastructure needed to support its full range of science activities. The USGS also engages in innovative partnerships and collaborations with a wide range of Federal and other partners to develop, support, and access other RDIs as needed.

United States Patent and Trademark Office (USPTO)

The USPTO is the Federal agency responsible for granting U.S. patents and registering U.S. trademarks. The USPTO fulfills its constitutional mandate to "promote the Progress of Science and useful Arts, by securing for limited Times to Authors and Inventors the exclusive Right to their respective Writings and Discoveries." The U.S. economy depends directly on effective mechanisms that protect new creations and investments in innovation. Because the USPTO is at the cutting edge of the Nation's technological achievement, it is a key component of our Nation's RDIs.