# National Nanotechnology Initiative Supplement to the President's 2021 Budget

*A Report by the*

NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY SUBCOMMITTEE

COMMITTEE ON TECHNOLOGY

*of the*

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

October 2020

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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 that science and technology policy decisions 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. The National Nanotechnology Initiative (NNI) is managed by the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the NSTC Committee on Technology. More information is available at www.whitehouse.gov/ostp/nstc.

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## About this document

This document is a supplement to the President's 2021 Budget request submitted to Congress on February 10th, 2020, and serves as the Annual Report for the National Nanotechnology Initiative called for under the provisions of the 21st Century Nanotechnology Research and Development Act (15 USC §7501). The report also addresses the requirement for Department of Defense reporting on its nanotechnology investments (10 USC §2358). Additional information regarding the NNI is available on the NNI website at www.nano.gov.

## About the cover

**Outside Back Cover:** Micrograph of 1024-element (32 x 32) near-infrared imaging array of superconducting nanowire single photon detectors (SNSPDs) developed by researchers at NIST and NASA's Jet Propulsion Laboratory, with funding from NASA and DARPA. The array has an active area of 0.96 x 0.96 mm, making it the largest SNSPD array reported to date, in terms of both active area and pixel count. Applications for large SNSPD arrays include imaging, spectroscopy, or particle detection. For example, the array could be used in future space-based telescopes to search for chemical signs of life on other planets, or to search for dark matter. The 32-by-32 detector array is surrounded by pink and gold wires connecting to electronics that compile the data. For technical details, see: *Optics Express* **27**, 35279 (2019) (https://doi.org/10.1364/OE.27.035279). Image credit: V. Verma/NIST.

**Inside Back Cover:** The inside face of the back cover includes a collage of images illustrating examples of NNI outreach activities. Collage content and design is by Mallory Hinks and Kristin Roy of the National Nanotechnology Coordination Office (NNCO).

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*National Nanotechnology Coordination Office:*
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**Treye A. Thomas, CPSC**

*Coordinator for Global Issues:*
**Stacey Standridge, NNCO**

*Coordinator for Environmental, Health, and Safety Research:*
**Treye A. Thomas, CPSC**

## NSET Subcommittee Participants

**Office of Science and Technology Policy (OSTP)**
Lisa E. Friedersdorf

**Office of Management and Budget (OMB)**
Cassie L. Boles
Danielle Jones
William McNavage

**Consumer Product Safety Commission (CPSC)†**
Joanna Matheson
Treye A. Thomas

**Department of Agriculture (USDA)**

**Agricultural Research Service (ARS)**
Gene E. Lester
James Lindsay

**Forest Service (FS)**
World L.-S. Nieh

**National Institute of Food and Agriculture (NIFA)**
Hongda Chen

**Department of Commerce (DOC)**

**Bureau of Industry and Security (BIS)**
Kelly Gardner

**International Trade Administration (ITA)**
Tracy Gerstle

**National Institute of Standards and Technology (NIST)**
Heather Evans
R. David Holbrook
J. Alexander Liddle

**Patent and Trademark Office (USPTO)**
Chris Hannon
Dan Ryman

**Department of Defense (DOD)**
Jeffrey DePriest
Eric W. Forsythe
Mark H. Griep
Akbar Khan
JihFen Lei
Antti J. Makinen
Heather Meeks
Brian D. Pate
Gernot S. Pomrenke
Victor Pugliano
David M. Stepp

**Department of Energy (DOE)**
Linda Horton
Tina M. Kaarsberg
Harriet Kung
George Maracas
Andrew R. Schwartz

**Department of Health and Human Services (HHS)**

**Agency for Toxic Substances and Disease Registry (ATSDR)/National Center for Environmental Health (NCEH)**
Candis M. Hunter
Custodio V. Muianga

**Food and Drug Administration (FDA)**
Anil Patri

**National Institute for Occupational Safety and Health (NIOSH)**
Charles L. Geraci
Laura Hodson
Vladimir V. Murashov

**National Institutes of Health (NIH)**
Piotr Grodzinski
Lori A. Henderson

† An independent commission that is represented on NSET but is non-voting

**Department of Homeland Security (DHS)**
Kumar Babu
Angela Ervin

**Department of the Interior (DOI)**

**Bureau of Reclamation (USBR)**
Yuliana Porras Mendoza

**Bureau of Safety and Environmental Enforcement (BSEE)**
Candi Hudson

**Geological Survey (USGS)**
Michael Focazio
Jeffery Steevens

**Department of Justice (DOJ)**

**National Institute of Justice (NIJ)**
Mark Greene

**Department of Labor (DOL)**

**Occupational Safety and Health Administration (OSHA)**
Janet Carter

**Department of State (DOS)**
Meg Flanagan
Andreea Paulopol
Maher Tadros

**Department of Transportation (DOT)**
Jonathan R. Porter

**Department of the Treasury (Treasury)**
Rodney P. Feazell

**Environmental Protection Agency (EPA)**
Jeffrey B. Frithsen

**Intelligence Community (IC)**

**National Reconnaissance Office (NRO)**
Matthew Cobert

**International Trade Commission (USITC)†**
Elizabeth R. Nesbitt

**National Aeronautics and Space Administration (NASA)**
Tiffany S. Williams

**National Science Foundation (NSF)**
Khershed Cooper
Lawrence S. Goldberg
Fred Kronz
Lynnette Madsen
Mihail C. Roco
Nora Savage
Charles Ying

**Nuclear Regulatory Commission (NRC)†**
Louise Lund

† An independent commission that is represented on NSET but is non-voting

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## Executive Summary

The President's 2021 Budget requests over $1.7 billion for the National Nanotechnology Initiative (NNI). This investment expands the boundaries of nanoscience, underpins key Industries of the Future, supports nanotechnology research infrastructure, and advances education and workforce development efforts. Cumulatively totaling over $31 billion since the inception of the NNI in 2001 (including the 2021 request), this support reflects the importance of investments that advance the fundamental understanding of and ability to control matter at the nanoscale, as well as the translation of that knowledge into technological breakthroughs that benefit the American people. Past research has led to applications in areas as diverse as consumer electronics, energy, water purification, aerospace, automotive, infrastructure, sporting goods, textiles, agriculture, and medicine. For example, former NNI investments have established a strong foundation of understanding at the nanoscale that is being applied in current efforts to address the coronavirus pandemic. Active efforts are using nanotechnology in the development of vaccine candidates, sensors for testing strategies, and preventative measures such as masks, filters, and antimicrobial coatings.

The NNI investments in 2019 and 2020 and those proposed in 2021 reflect a sustained emphasis on broad, fundamental research in nanoscience. Through this sustained support, the President's Budget includes nanotechnology investments that will further the progress of the NNI to advance a world-class research portfolio, facilitate commercialization of nanotechnology-enabled applications, support a dynamic infrastructure and skilled workforce, and ensure responsible development of nanotechnology. These efforts underpin key Industries of the Future by, for example, using artificial intelligence (AI) to design nanostructured materials, devices, and systems; developing specialized nanoscale computing hardware for AI systems; utilizing the NNI infrastructure and atomically precise nanoscale methods to manufacture quantum components for sensing, communication, and computing; and enabling sustainable nanomanufacturing such as cellular nanobiomanufacturing.

This document serves as the annual report for the National Nanotechnology Initiative as called for under the provisions of the 21st Century Nanotechnology Research and Development Act (15 USC §7501). In addition to reporting proposed and past investments, this report includes the NNI response to the Quadrennial Review of the National Nanotechnology Initiative recently released by the National Academies of Sciences, Engineering, and Medicine.

## What is Nanotechnology?

Nanotechnology encompasses science, engineering, and technology at the nanoscale, which is about 1 to 100 nanometers. Just how small is that? A nanometer is one-billionth of a meter. For reference, a sheet of paper is about 100,000 nanometers thick. Nanoscale matter can behave differently than the same bulk material. For example, a material's melting point, color, strength, chemical reactivity, and more may change at the nanoscale.

Nanotechnology underpins key Industries of the Future such as artificial intelligence, quantum information science, and advanced manufacturing. Nanotechnology innovations are ensuring continued U.S. leadership in the semiconductor and strategic computing industries, and are advancing many other national priorities, including space exploration, energy, medicine, agriculture, and national security.

Examples of nanotechnology innovations are illustrated below: (a) a highly sensitive wearable gas sensor; (b) nanoparticles (shown in orange) absorbed by plants to deliver nutrients; (c) durable, conductive yarns made with MXene; (d) electrodes that incorporate nanoparticles and enable the conversion of sunlight to hydrogen fuel; (e) nanoengineered pores in a membrane for water filtration; (f) drug-loaded nanoparticles (blue) carried by red blood cells; and (g) the first programmable memristor computer, enabling low-power AI applications. Nanotechnology advances are impacting a variety of other sectors including consumer electronics, aerospace, automotive, infrastructure, sporting goods, and agriculture.

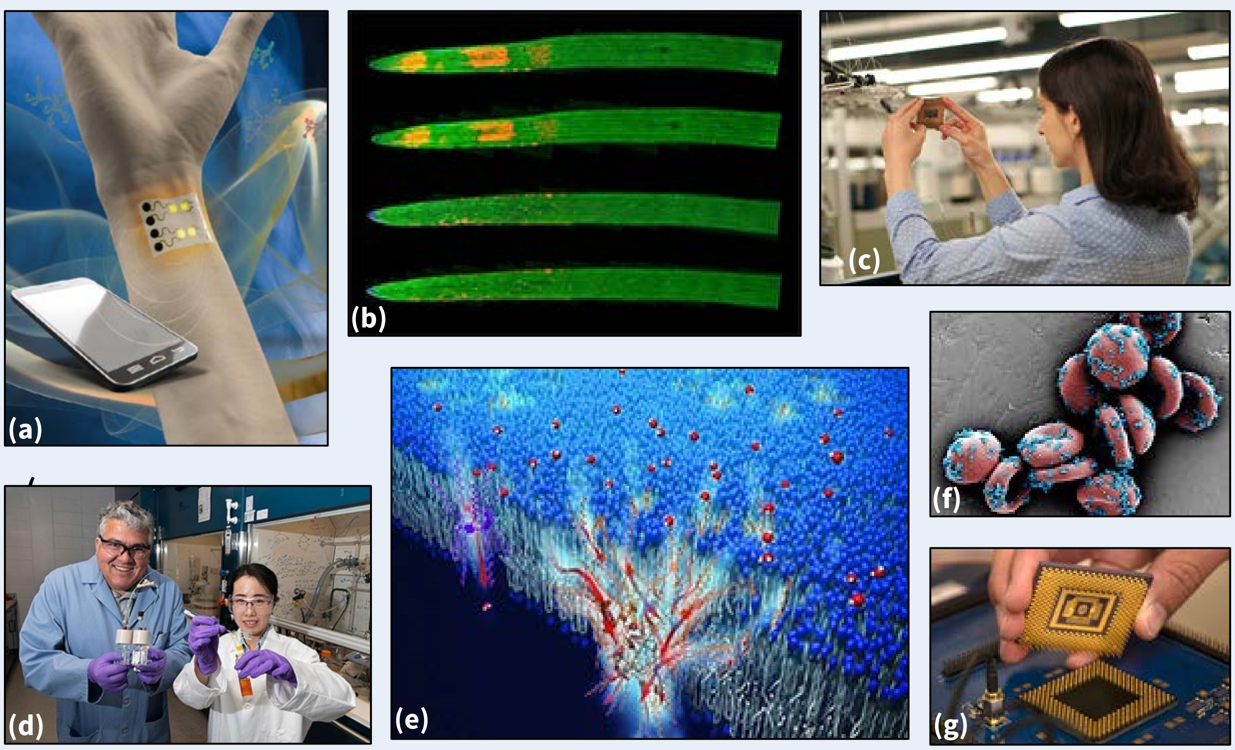


**Image credits: (a) Jennifer M. McCann/Penn State; (b) Carnegie Mellon University, College of Engineering; (c) Drexel University; (d) Brookhaven National Laboratory; (e) Erik Zumalt, Cockrell School of Engineering, The University of Texas at Austin; (f) Wyss Institute at Harvard University; and (g) Robert Coelius, Michigan Engineering. For more information on nanotechnology benefits and applications, please visit www.nano.gov/you/nanotechnology-benefits.**

# 1. Introduction

The National Nanotechnology Initiative (NNI) is a U.S. Government research and development (R&D) initiative. Twenty Federal departments, independent agencies, and commissions work together toward the shared vision of *a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society*. The NNI enhances interagency coordination of nanotechnology R&D, supports a shared infrastructure, enables leveraging of resources while avoiding duplication, and establishes shared goals, priorities, and strategies that complement agency-specific missions and activities. Table 1 lists the agencies currently participating in the NNI. More information about the structure, goals, and priorities of the NNI can be found on Nano.gov.

The ability to understand and control matter at the nanoscale enables unique physical, chemical, and biological properties with broad applications across disciplines and industrial sectors. Building on current nanotechnology-enabled applications in areas as diverse as consumer electronics, medicine, energy, water purification, aerospace, automotive, infrastructure, sporting goods, textiles, and agriculture, the nanotechnology research underway today will enable entirely new capabilities and products. Nanotechnology also underpins key Industries of the Future. For example, new architectures and paradigms exploiting nanotechnology are providing the foundation for artificial intelligence (AI), quantum information science (QIS), next-generation wireless communications, and advanced manufacturing. While advances in modern electronics have long been at the nanoscale, new nanomaterials and designs will ensure the continued strength of the U.S. semiconductor industry, which powers computing, e-commerce, and national security. Nanotechnology also enables the rapid genomic sequencing and sensing required to advance medicine and biotechnology. Nanotechnology R&D has enabled early detection of emerging diseases and will lead to the treatments of the future. Past investments in nanotechnology research and development have provided a foundation to support the response to the COVID-19 pandemic. Nanotechnology-enabled applications include vaccines, sensors, masks, filters, and antimicrobial coatings.

The NNI participating agencies work together to unleash discovery and innovation across the nanotechnology R&D enterprise. The NNI portfolio ranges from early-stage fundamental science to applications-driven research and extends across many diverse fields of science and technology. The NNI brings together representatives from multiple agencies to leverage knowledge and resources and involve academia and the private sector as appropriate to promote technology transfer and facilitate commercialization. Strategic collaborations, including public-private-nonprofit partnerships, strengthen key aspects of the nanotechnology ecosystem. In addition to R&D efforts, the NNI is helping to build the nanotechnology workforce of the future, with efforts aimed across the spectrum from K-12 through postgraduate research training.

The NNI provides a focal point for engagement with a broad range of stakeholder groups including like-minded regions and countries. Nanotechnology remains an area of intense R&D activity worldwide. The National Nanotechnology Coordination Office (NNCO) and NNI agencies engage with international regulatory and research agencies and nanotechnology associations from around the world to share best practices, explore opportunities for collaboration, and promote science-based regulation. NNCO also facilitates international communities of research to exchange scientific information regarding nanomedicine and nanotechnology-related environmental, health, and safety (EHS) issues.

| Table 1: Federal Departments and Agencies Participating in the NNI |
|---|
| Consumer Product Safety Commission (CPSC)*† |
| Department of Agriculture (USDA) |
| Agricultural Research Service (ARS)* |
| Forest Service (FS)* |
| National Institute of Food and Agriculture (NIFA)* |
| Department of Commerce (DOC) |
| Bureau of Industry and Security (BIS) |
| Economic Development Administration (EDA) |
| International Trade Administration (ITA) |
| National Institute of Standards and Technology (NIST)* |
| Patent and Trademark Office (USPTO) |
| Department of Defense (DOD)* |
| Department of Education (ED) |
| Department of Energy (DOE)* |
| Department of Health and Human Services (HHS) |
| Agency for Toxic Substances and Disease Registry (ATSDR) |
| Food and Drug Administration (FDA)* |
| National Center for Environmental Health (NCEH)* |
| National Institute for Occupational Safety and Health (NIOSH)* |
| National Institutes of Health (NIH)* |
| Department of Homeland Security (DHS) |
| Department of the Interior (DOI) |
| Bureau of Reclamation (USBR)* |
| Bureau of Safety and Environmental Enforcement (BSEE)* |
| Geological Survey (USGS) |
| Department of Justice (DOJ) |
| National Institute of Justice (NIJ)* |
| Department of Labor (DOL) |
| Occupational Safety and Health Administration (OSHA) |
| Department of State (DOS) |
| Department of Transportation (DOT) |
| Federal Highway Administration (FHWA)* |
| Department of the Treasury (Treasury) |
| Environmental Protection Agency (EPA)* |
| Intelligence Community (IC) |
| International Trade Commission (USITC)† |
| National Aeronautics and Space Administration (NASA)* |
| National Science Foundation (NSF)* |
| Nuclear Regulatory Commission (NRC)† |

* Denotes agencies (or organizations within agencies) reporting funding for nanotechnology R&D
† Denotes an independent commission that is represented on NSET but is non-voting

Chapter 2 of this report presents budget information and highlights of agency plans and priorities by Program Component Area (PCA). Chapter 3 includes examples of progress toward the four NNI goals. Additional information regarding agency priorities for nanotechnology is provided on the budget pages of Nano.gov. Appendices include a list of abbreviations and acronyms used throughout this document and contact information for agency representatives to the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council and NNCO staff.

## Quadrennial Review of the NNI

### *Background*

As required by the 21st Century Nanotechnology R&D Act (15 USC §7501), the National Academies of Sciences, Engineering, and Medicine (NASEM) released *A Quadrennial Review of the National Nanotechnology Initiative* on April 7, 2020.[1] The committee was tasked with analyzing the international position of the United States with respect to nanotechnology R&D and assessing the current state of nanoscience and nanotechnology resulting from the NNI. Based on this assessment, the panel was tasked with considering if and how the NNI should continue.

### *Report Summary*

The report emphasizes the increased impact of nanoscience and nanotechnology on the economy and suggests continued focus and investment in these areas: "*Global advances in medicine, food, water, energy, microelectronics, communications, defense, and other important sectors of the economy are increasingly driven by discoveries in nanoscience and the development of nanotechnologies and justify a continued focus by the United States on, and investments in, these fields.*"

The committee's international assessment determined that global competition in this area is intensifying: "*…the United States maintains a strong nanoscience and technology R&D program.*" and "*…this program's coordination is becoming more critical in the current era of intensifying global competition from developed nations such as Japan and those within the European Union, and from developing nations such as India, but especially from China.*"

To promote a renewed focus in nanotechnology and respond to the dynamic global research environment, the committee recommends that the NNI continue and that it be reorganized and relaunched: "*Given these concerns about national competitiveness, and with the priority placed on economic prosperity, the health of U.S. citizens, and national security in considering the future of the NNI, the committee recommendations arising from this quadrennial NNI review should provide a framework for an urgent redesign of the NNI and its coordination with the goal of achieving a U.S. resurgence in nanotechnology. Going forward, the NNI should be restructured to (1) improve its alignment with the stated national priorities for R&D, (2) broaden its work to accelerate technology transfer to relevant markets, (3) strengthen state-of-the-art enabling R&D infrastructure, and (4) expand domestic workforce education and training.*"

### *NNI Actions in Response to the Report*

The Office of Science and Technology Policy commends the work of the committee and recognizes that the NNI has been a beacon for nanotechnology R&D, and that the United States must continue to be a global leader in this important field. Nanotechnology not only underpins key Industries of the Future, but also is the foundation for a wide variety of vital applications, including those identified in the Academies report. The United States must remain the place where discoveries are made, and where these discoveries are translated and manufactured into products for the benefit of the American people.

The NNI agencies are working together through the NSET Subcommittee of the National Science and Technology Council to carefully review the NASEM recommendations and develop a framework for the urgent redesign of the NNI.

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[1] https://www.nap.edu/catalog/25729/a-quadrennial-review-of-the-national-nanotechnology-initiative-nanoscience-applications

Over the coming months, the restructuring of the NNI will be considered through a comprehensive strategic planning process, as required by 15 USC §7501. Teams established by the NSET Subcommittee will review the NASEM recommendations and consider additional means or mechanisms to achieve the desired outcomes presented in the report. Future directions will build upon the activities that the report identified as existing strengths, such as support of fundamental research; international engagement on environmental, health, and safety issues; and initial steps to support entrepreneurship. The teams are focused on world-class research, commercialization, research infrastructure, education and workforce development, and responsible development, and will engage the private and academic sectors for additional input on the 2021 NNI Strategic Plan.

Updated information will be available on Nano.gov.

## 2. NNI Budget and Program Plans

### Budget Summary

The President's 2021 Budget requests over $1.7 billion for the NNI, with an increased investment in the foundational research that will lead to discoveries that will advance a wide range of areas including key Industries of the Future. Cumulatively totaling over $31 billion (including the 2021 request), this support reflects the continued importance of research to understand matter at the nanoscale and to translate this knowledge into technological breakthroughs that benefit the American people. The NNI investments in 2019 and 2020 and those proposed for 2021 reflect a continued emphasis on fundamental research in nanoscience; research to advance applications, devices, and systems; and the infrastructure to support overall research and development efforts. The NNI budget represents the sum of the nanotechnology-related investments allocated by each of the participating agencies (the "NNI crosscut"). Each agency determines its budget for nanotechnology R&D in coordination with the Office of Management and Budget (OMB), the Office of Science and Technology Policy (OSTP), and Congress. NNI agencies collaborate closely—facilitated through the NSET Subcommittee, its working groups and coordinators, and the NNCO—to create an integrated R&D program that leverages and amplifies resources and efforts to advance NNI goals and meet individual agency mission needs and objectives. NNI agencies support significant investments in research infrastructure, developing new research tools, and making these tools available through user facilities. The NNI also supports science, technology, engineering, and mathematics (STEM) education to inspire students and prepare the workforce of the future.

NNI agencies are using existing appropriations as well as emergency supplemental funding to support research addressing the COVID-19 crisis. Agencies are funding a variety of research projects as part of this effort, including many that utilize nanotechnology to detect, treat, and prevent the disease; and to understand the virus and how it spreads.

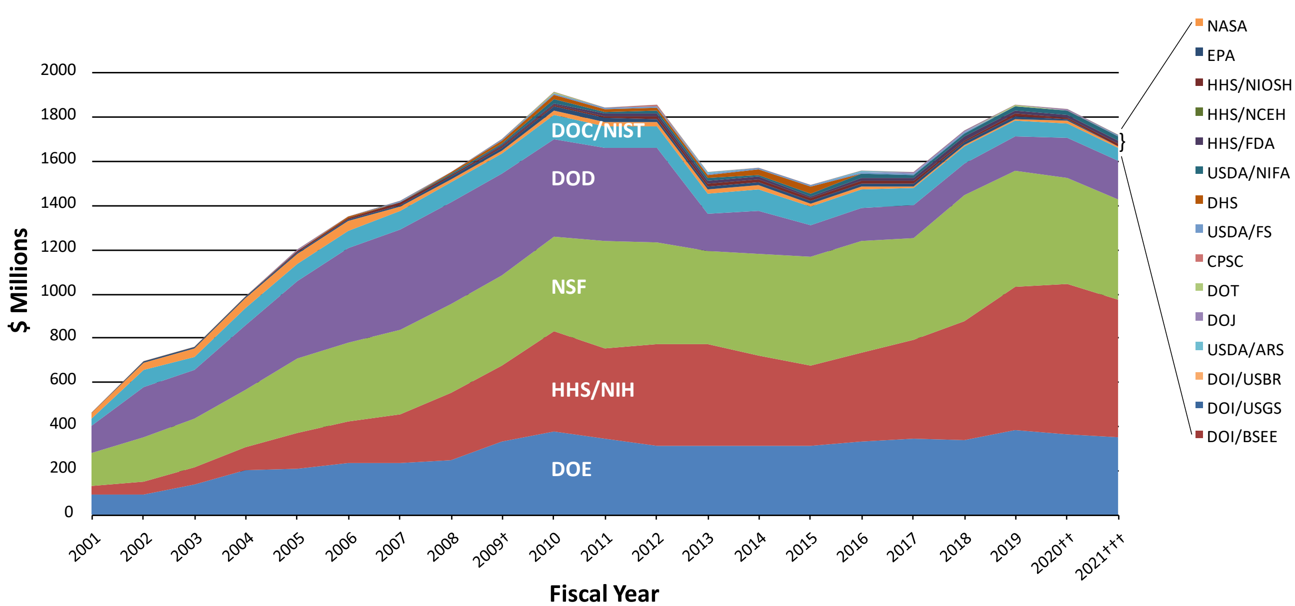


**Figure 1. NNI Funding by Agency, 2001–2021.**

† 2009 figures do not include American Recovery and Reinvestment Act funds for DOE, NSF, NIH, and NIST.
†† 2020 numbers are based on appropriated levels.
††† 2021 Budget.

**Table 2: Actual 2019 Agency Investments by Program Component Area**
(dollars in millions)*

| Agency | 1. Nanotechnology Signature Initiatives (NSIs) and Grand Challenge | 1a. Nanomanufacturing NSI | 1b. Nanoelectronics NSI | 1c. NKI NSI | 1d. Sensors NSI | 1e. Water NSI | 1f. Future Computing GC | 2. Foundational Research | 3. Nanotechnology-Enabled Applications, Devices, and Systems | 4. Research Infrastructure and Instrumentation | 5. Environment, Health, and Safety | NNI Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CPSC** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 0.9 |
| **DOC**/NIST | 17.0 | 3.7 | 7.2 | 0.0 | 0.8 | 0.3 | 5.1 | 10.9 | 6.7 | 33.2 | 2.4 | 70.2 |
| **DOD** | 29.1 | 0.4 | 20.8 | 0.9 | 2.1 | 2.2 | 2.7 | 95.2 | 28.9 | 3.5 | 3.4 | 160.1 |
| **DOE** | 0.4 | 0.0 | 0.0 | 0.0 | 0.4 | 0.0 | 0.0 | 180.4 | 60.3 | 143.9 | 0.0 | 385.0 |
| **DOI**/USBR | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 |
| **DOJ**/NIJ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 0.0 | 0.0 | 0.9 |
| **DOT**/FHWA | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.5 | 0.0 | 0.0 | 1.5 |
| **EPA** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 10.6 | 10.6 |
| **HHS (total)** | 26.8 | 0.5 | 1.4 | 2.5 | 21.8 | 0.0 | 0.6 | 158.8 | 410.1 | 36.2 | 44.5 | 676.4 |
| FDA | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 15.4 | 15.4 |
| NCEH | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 |
| NIH | 26.8 | 0.5 | 1.4 | 2.5 | 21.8 | 0.0 | 0.6 | 158.8 | 410.1 | 36.2 | 17.8 | 649.7 |
| NIOSH | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 11.2 | 11.2 |
| **NASA** | 1.3 | 0.4 | 0.5 | 0.0 | 0.4 | 0.0 | 0.0 | 4.0 | 3.6 | 0.0 | 0.1 | 9.0 |
| **NSF** | 150.9 | 40.1 | 51.8 | 22.7 | 11.6 | 12.8 | 12.0 | 271.4 | 57.7 | 27.9 | 12.8 | 520.7 |
| **USDA (total)** | 9.3 | 4.3 | 0.0 | 0.0 | 3.0 | 2.0 | 0.0 | 2.3 | 8.0 | 1.0 | 2.1 | 22.7 |
| ARS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 0.0 | 0.0 | 3.0 |
| FS | 3.3 | 3.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.1 | 3.7 |
| NIFA | 6.0 | 1.0 | 0.0 | 0.0 | 3.0 | 2.0 | 0.0 | 2.0 | 5.0 | 1.0 | 2.0 | 16.0 |
| **TOTAL*****| **235.1** | **49.4** | **81.7** | **26.1** | **40.1** | **17.6** | **20.4** | **723.0** | **577.8** | **245.7** | **76.7** | **1858.3** |

* Tables 2–5 show dollars in millions. Headings in Tables 3 and 4 are abbreviated to PCA numbers.
** Abbreviated titles for Nanotechnology Signature Initiatives and Grand Challenges used in Table 2. See Nano.gov for full titles.
*** In Tables 2–6, totals may not add, due to rounding.

The President's 2021 Budget supports nanoscale science, engineering, and technology R&D at 11 agencies. The five Federal organizations with the largest investments (representing 96% of the total) are:

- HHS/NIH (nanotechnology-based biomedical research at the intersection of life and physical sciences).
- NSF (fundamental research and education across all disciplines of science and engineering).
- DOE (fundamental and applied research providing a basis for new and improved energy technologies).
- DOD (science and engineering research advancing defense and dual-use capabilities).
- DOC/NIST (fundamental research and development of measurement and fabrication tools, analytical methodologies, metrology, and standards for nanotechnology).

**Table 3: Estimated 2020 Agency Investments by Program Component Area**

| Agency | 1. | 1a. | 1b. | 1c.* | 1d. | 1e. | 1f. | 2. | 3. | 4. | 5. | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CPSC** | 0.0 | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 |
| **DOC**/NIST | 15.7 | 3.7 | 6.4 | - | 0.8 | 0.3 | 4.5 | 10.1 | 5.9 | 31.8 | 2.0 | 65.5 |
| **DOD** | 34.5 | 0.3 | 27.6 | - | 3.8 | 0.0 | 2.8 | 113.9 | 32.4 | 3.2 | 0.3 | 184.3 |
| **DOE** | 0.4 | 0.0 | 0.0 | - | 0.4 | 0.0 | 0.0 | 178.9 | 36.4 | 146.8 | 0.0 | 362.5 |
| **DOI (total)** | 0.5 | 0.0 | 0.0 | - | 0.0 | 0.5 | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 1.2 |
| BSEE | 0.0 | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 0.7 |
| USBR | 0.5 | 0.0 | 0.0 | - | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 |
| **DOJ**/NIJ | 0.0 | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.0 | 1.5 | 0.1 | 0.0 | 1.6 |
| **DOT**/FHWA | 0.0 | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 |
| **EPA** | 0.0 | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.5 | 5.5 |
| **HHS (total)** | 25.6 | 0.6 | 1.5 | - | 22.8 | 0.0 | 0.7 | 170.8 | 430.8 | 40.1 | 43.1 | 710.4 |
| FDA | 0.0 | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 13.6 | 13.6 |
| NCEH | 0.0 | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 |
| NIH | 25.6 | 0.6 | 1.5 | - | 22.8 | 0.0 | 0.7 | 170.8 | 430.8 | 40.1 | 18.5 | 685.8 |
| NIOSH | 0.0 | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 10.9 | 10.9 |
| **NASA** | 1.1 | 0.4 | 0.5 | - | 0.2 | 0.0 | 0.0 | 4.2 | 4.6 | 0.0 | 0.1 | 9.9 |
| **NSF*** | 100.0 | 32.0 | 34.5 | - | 8.5 | 13.0 | 12.0 | 275.6 | 56.7 | 28.3 | 15.1 | 475.7 |
| **USDA (total)** | 9.0 | 4.0 | 0.0 | - | 3.0 | 2.0 | 0.0 | 2.4 | 8.0 | 1.0 | 2.0 | 22.4 |
| ARS | 0.0 | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 0.0 | 0.0 | 3.0 |
| FS | 3.0 | 3.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.4 | 0.0 | 0.0 | 0.0 | 3.4 |
| NIFA | 6.0 | 1.0 | 0.0 | - | 3.0 | 2.0 | 0.0 | 2.0 | 5.0 | 1.0 | 2.0 | 16.0 |
| **TOTAL** | **186.8** | **41.0** | **70.5** | **-** | **39.5** | **15.8** | **20.0** | **756.0** | **577.4** | **251.3** | **68.2** | **1839.7** |

**Table 4: Proposed 2021 Agency Investments by Program Component Area**

| Agency | 1. | 1a. | 1b.** | 1c.* | 1d. | 1e. | 1f.** | 2. | 3. | 4. | 5. | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CPSC** | 0.0 | 0.0 | - | - | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 |
| **DOC**/NIST | 4.7 | 3.7 | - | - | 0.7 | 0.3 | - | 10.0 | 16.1 | 25.8 | 1.8 | 58.4 |
| **DOD** | 13.2 | 0.4 | - | - | 12.8 | 0.0 | - | 127.5 | 29.4 | 1.7 | 0.2 | 172.0 |
| **DOE** | 0.0 | 0.0 | - | - | 0.0 | 0.0 | - | 182.3 | 33.9 | 136.6 | 0.0 | 352.8 |
| **DOJ**/NIJ | 0.0 | 0.0 | - | - | 0.0 | 0.0 | - | 0.0 | 1.5 | 0.1 | 0.0 | 1.6 |
| **DOT**/FHWA | 0.0 | 0.0 | - | - | 0.0 | 0.0 | - | 0.0 | 0.5 | 0.0 | 0.0 | 0.5 |
| **EPA** | 0.0 | 0.0 | - | - | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 2.0 | 2.0 |
| **HHS (total)** | 21.4 | 0.5 | - | - | 20.9 | 0.0 | - | 155.8 | 392.6 | 35.9 | 41.4 | 647.1 |
| FDA | 0.0 | 0.0 | - | - | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 13.6 | 13.6 |
| NCEH | 0.0 | 0.0 | - | - | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 |
| NIH | 21.4 | 0.5 | - | - | 20.9 | 0.0 | - | 155.8 | 392.6 | 35.9 | 16.8 | 622.5 |
| NIOSH | 0.0 | 0.0 | - | - | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 10.9 | 10.9 |
| **NASA** | 0.6 | 0.4 | - | - | 0.2 | 0.0 | - | 4.7 | 4.6 | 0.0 | 0.1 | 10.0 |
| **NSF** | 53.5 | 32.0 | - | - | 8.5 | 13.0 | - | 282.3 | 73.8 | 33.4 | 10.5 | 453.5 |
| **USDA (total)** | 7.5 | 2.5 | - | - | 3.0 | 2.0 | - | 3.8 | 11.0 | 1.0 | 2.0 | 25.3 |
| ARS | 0.0 | 0.0 | - | - | 0.0 | 0.0 | - | 0.0 | 3.0 | 0.0 | 0.0 | 3.0 |
| FS | 1.5 | 1.5 | - | - | 0.0 | 0.0 | - | 1.8 | 0.0 | 0.0 | 0.0 | 3.3 |
| NIFA | 6.0 | 1.0 | - | - | 3.0 | 2.0 | - | 2.0 | 8.0 | 1.0 | 2.0 | 19.0 |
| **TOTAL** | **100.9** | **39.5** | **-** | **-** | **46.1** | **15.3** | **-** | **766.4** | **563.3** | **234.6** | **58.0** | **1723.2** |

* The NKI signature initiative was retired as a budget reporting category at the end of 2019; agencies are reporting 2020 and 2021 funding for NKI-related programs and activities in other PCAs.

** The Nanoelectronics signature initiative and Future Computing Grand Challenge were retired as a budget reporting categories at the end of 2020; agencies are reporting 2021 funding for programs and activities related to these topics in other PCAs.

*** NSF 2020 totals include $14.3 million in CARES Act funding for nanotechnology R&D addressing COVID-19: PCAs 2 ($7.7 million), 3 ($4.1 million), & 5 ($2.5 million).

| Table 5: NNI Budget, by Agency, 2019–2021 (dollars in millions) | | | |
|---|---|---|---|
| **Agency** | **2019 Actual** | **2020 Estimated*** | **2021 Proposed** |
| **CPSC** | 0.9 | 0.2 | 0.1 |
| **DOC**/NIST | 70.2 | 65.5 | 58.4 |
| **DOD** | 160.1 | 184.3 | 172.0 |
| **DOE**** | 385.0 | 362.5 | 352.8 |
| **DOI (total)** | 0.3 | 1.2 | 0.0 |
| BSEE | 0.0 | 0.7 | 0.0 |
| USBR | 0.3 | 0.5 | 0.0 |
| **DOJ**/NIJ | 0.9 | 1.6 | 1.6 |
| **DOT**/FHWA | 1.5 | 0.5 | 0.5 |
| **EPA** | 10.6 | 5.5 | 2.0 |
| **HHS (total)** | 676.4 | 710.4 | 647.1 |
| FDA | 15.4 | 13.6 | 13.6 |
| NCEH | 0.1 | 0.1 | 0.1 |
| NIH | 649.7 | 685.8 | 622.5 |
| NIOSH | 11.2 | 10.9 | 10.9 |
| **NASA** | 9.0 | 9.9 | 10.0 |
| **NSF** | 520.7 | 475.7 | 453.5 |
| **USDA (total)** | 22.7 | 22.4 | 25.3 |
| ARS | 3.0 | 3.0 | 3.0 |
| FS | 3.7 | 3.4 | 3.3 |
| NIFA | 16.0 | 16.0 | 19.0 |
| **TOTAL** | **1858.3** | **1839.7** | **1723.2** |

* 2020 numbers are based on appropriated levels.

** Funding levels for DOE include the combined budgets of the Office of Science, the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy, and the Office of Nuclear Energy.

A significant proportion of agencies' nanotechnology investments now come from "core" R&D programs, which makes it difficult to predict the number of and success rate of nanotechnology-related proposals. As a result, the actual investments reported are often higher than the previously published estimates or proposed values. For example, the actual NNI investment for 2019 ($1.86 billion) is higher than the 2019 estimated level ($1.57 billion) published in the NNI Supplement to the President's 2020 Budget, or the 2019 requested value published in the 2019 supplement ($1.40 billion).

## Programmatic Plans and Changes by PCA

A broad array of NNI R&D activities is represented by the budget details presented in this document. This section provides highlights of agency plans relating to each of the NNI Program Component Areas for 2021. Additional details and examples can be found on Nano.gov along with the definitions for each PCA.

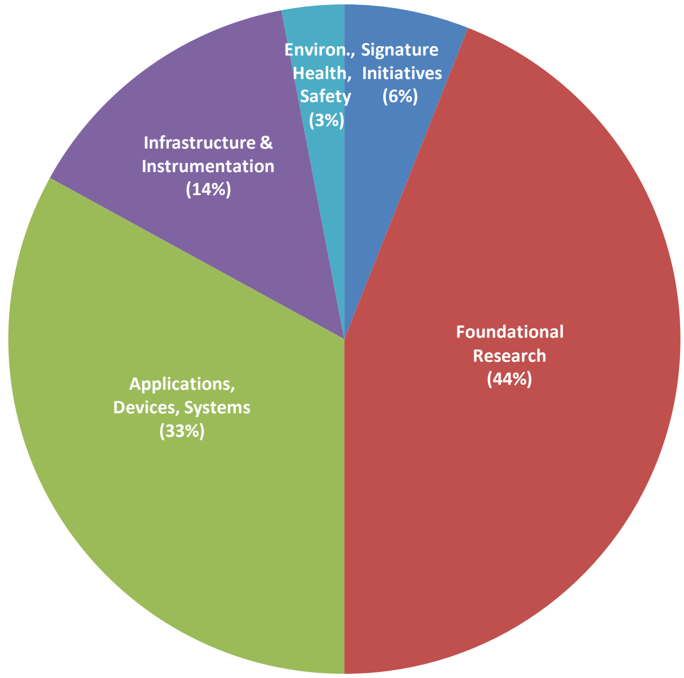


**Figure 2. Breakout of NNI Funding by Program Component Area in the 2021 Budget.**

### *PCA 1. Nanotechnology Signature Initiatives*

The Nanotechnology Signature Initiatives (NSIs) focus on topics of national importance where significant advances can be made through enhanced interagency coordination and collaboration. The NNI agencies, collectively and individually, utilize a variety of mechanisms to accelerate nanotechnology research and development in these areas. Agency representatives join regular teleconferences to discuss technical challenges and accomplishments, share information on plans and activities, and organize collaborative activities. The NSI portfolio is intended to be dynamic, adapting as science advances and the needs of the community evolve. The *Nanoelectronics for 2020 and Beyond* NSI and *Nanotechnology-Inspired Grand Challenge for Future Computing* are sunsetting. The research efforts that support these topics, and others, will be coordinated under the recently established Semiconductor Leadership R&D Working Group. New NSI topics are under consideration.

The *Nanotechnology for Sensors and Sensors for Nanotechnology* signature initiative (Sensors NSI) continues to be a vibrant and active collaborative effort. For 2021, the Sensors NSI team will prioritize stakeholder engagement to share information regarding agency programs and needs, as well as resources available to support nanosensor development. Cross-agency discussions will address topics such as novel sensing modalities, energy harvesting and storage, reproducible device fabrication, and standards. These areas will be explored through activities such as public webinars, internal Federal discussions, and symposia at technical conferences.

Agency-specific nanosensor activities will include NIH efforts to develop point-of-care diagnostics, as well as technologies to monitor disease progression and therapeutic response. Multiple institutes across NIH will support research on imaging and sensing devices for biomedical and clinical applications. DOD has broad interests in sensing technologies for a variety of applications, including monitoring the health, performance, and physical environment of warfighters. NSF's Biosensing program[2] encourages proposals incorporating emerging nanotechnology methods and will support

[2] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505720

fundamental engineering research on devices and methods for measurement and quantification of biological analytes.

USDA/NIFA has interests in nanotechnology-enabled sensors for food and agricultural applications such as food contaminant detection and intelligent precision agriculture. Low-cost sensor and manufacturing technologies that can be translated to commercial markets are particularly relevant to the food and agriculture sectors. NIST will develop hybrid sensors that integrate plasmonic nanoparticles with nanoscale pores to enable control and study of molecular transport in confined liquid environments. NIST will also develop novel materials and devices at the atomic scale to improve nanoelectronic biosensing and enable new sensors for precision medicine applications.

Efforts at DOE's Office of Fossil Energy (FE) will support basic and applied R&D on improved sensors and controls for fossil-based electric power generation, including the use of nanostructured materials and novel architectures. NASA nanosensor efforts will include developing a nanophotonic bio-/chemical-sensor platform for cryogenic environments, and integrating and testing the sensor elements with an on-chip photodetector. This work builds on previous research co-funded by NASA, NSF, and NIH.

The *Water Sustainability through Nanotechnology* signature initiative (Water NSI) will explore technical needs for transitioning promising technologies from the bench to pilot scale through mechanisms such as workshops and embedded sessions at relevant conferences. Water NSI efforts emphasize interagency discussion to identify mutual interest areas and opportunities to leverage knowledge and resources. Thematic focus areas include technologies to enable decentralized water treatment, sensors for water monitoring, and the food-energy-water nexus. Technical issues related to water quality and sustainability extend beyond nanotechnology, and the Water NSI engages with other relevant interagency interest groups to share information and avoid duplication.

Agency-specific activities that support the goals of the Water NSI include core nanoscience-related programs on water applications at NSF. NSF also supports the Nanosystems Engineering Research Center (NERC) for Nanotechnology-Enabled Water Treatment Systems (NEWT).[3] Research at the NEWT center is focused on the development of high-performance, easy-to-deploy drinking water and industrial wastewater treatment systems enabled by nanotechnology. Building on NASA's interest in the use of nanoparticle silver as a biocide in potable water for human spacecraft applications, NASA engineers will collaborate with NEWT researchers with unique expertise in the stability, efficacy, and detection of nanoparticle silver in water systems. More broadly, NASA water treatment research efforts will seek to reduce complexity, decrease size and consumable mass, improve safety and reliability, and achieve a higher degree of spacecraft autonomy. Water recovery from wastewater sources is key to long-duration human exploration missions.

The U.S. Army's University Affiliated Research Centers (UARCs)[4] have ongoing and planned research activities focused on the application of emerging nanotechnologies for water treatment and systems development. Example topics include electrochemically modulated mitigation of contaminated water sources, highly efficient compact thermal adsorption desalination, and nanostructured aquaporin-silica membranes for water purification applications. DOE/FE will support basic and applied R&D on manufacturing coal-based carbon materials for separation membranes that will remove hydrocarbons and other unwanted species from contaminated water and industrial waste streams.

[3] http://www.newtcenter.org/

[4] https://www.arl.army.mil/business/uarcs/

NIFA's Agriculture and Food Research Initiative (AFRI) has supported multidisciplinary systems approaches that integrate new technologies and strategic management through a Challenge Area on Water for Food Production Systems.[5] One large project in this Challenge Area has been exploring nanotechnology and smart decision analytics for irrigation water quality management. The project impacts multiple agricultural systems across different states and has an education component that has been developing highly engaging programs for students and learners. NIST engages with representatives from the pharmaceutical industry to identify and address measurement challenges associated with water bioburden analysis.

While the original goals and milestones of the *Sustainable Nanomanufacturing* signature initiative (Nanomanufacturing NSI) have been met, nanomanufacturing remains a priority for the NNI agencies. The interagency community is actively discussing future directions for this collaborative activity. Individual agencies will continue to advance nanomanufacturing R&D through a variety of programs and activities. NSF has a Dear Colleague Letter (DCL), Supporting Fundamental Research to Enable Innovation in Advanced Manufacturing at Manufacturing USA Institutes,[6] which will run through 2021. This DCL solicits proposals addressing critical fundamental research needs in advanced manufacturing, including nanomanufacturing, that leverage resources from one or more institutes and member companies. Several NSF directorates organize activities on engineering biology at the nanoscale for advanced manufacturing. The Hierarchical Nanomanufacturing (NanoMFG) node of nanoHUB[7] develops software tools aimed at creating smart nanomanufactured structures and devices. Examples of exploratory research directions at NSF are manufacturing of nanomachines and nanobiostructures, cellular nanobiomanufacturing, atomically precise manufacturing, and nanomanufacturing for quantum devices and sensors. The NSF Advanced Manufacturing program[8] includes support for nanoscale fundamental research and encourages cross-disciplinary research. Activities in support of the Nanomanufacturing NSI in the Advanced Manufacturing Office (AMO) at DOE will focus on atomically precise manufacturing.

NASA researchers will advance the development of processing methods to retain the mechanical properties of commercial carbon nanotube (CNT) materials in composites. Computational modeling is being coupled with experimentation to explore non-traditional composite processing techniques. USDA/FS nanotechnology investments will prioritize research and development in the manufacturing and development of science and technology for new products with cellulose nanomaterials. FS collaborates with industry and academia through a public-private partnership to accelerate projects with commercial potential.

NIST supports the Nanomanufacturing NSI through research on device fabrication, imaging, and emerging areas. NIST will study the fundamental science and advance the practical limits of precision and accuracy of focused ion beam (FIB) nanofabrication. NIST researchers will study DNA nanofabrication to understand and mimic biological self-assembly on the nanoscale for pharmaceutical, chemical, and energy-harvesting applications. NIST will develop fabrication processes to enable the integration of quantum emitters into nanophotonic devices such as bright, on-demand single-photon sources. Advancing new capabilities in imaging and characterization of quantum emitters, NIST will also develop novel instruments that implement fluorescence microscopy,

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[5] https://nifa.usda.gov/program/afri-water-food-production-systems-challenge-area
[6] https://www.nsf.gov/pubs/2017/nsf17088/nsf17088.jsp
[7] https://nanohub.org/groups/nanomfg/workflow-for-hierarchical-nanomfg/
[8] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505572

spectroscopy, and photon counting. These efforts are examples of how nanotechnology fabrication and characterization techniques and tools support the Administration's priority on QIS.

### *PCA 2. Foundational Research*

Foundational research continues to be the largest area of investment, accounting for 44% of the NNI total for 2021. NSF is the largest contributor to this PCA, followed by DOE, NIH, and DOD. NSF, DOE, and DOD invest 62%, 52%, and 74% of their totals, respectively, in this category. Continued investment by these and other NNI agencies in foundational research ensures new discoveries to fuel the innovations of the future.

The NSF 2021 budget includes funding for the discovery and development of fundamental knowledge pertaining to new phenomena in the physical, biological, and engineering sciences that occur at the nanoscale. Also included is funding for research aiming to understand scientific and engineering principles related to nanoscale systems, structures, processes, and mechanisms; research on the discovery and synthesis of novel nanoscale and nanostructured materials including biomaterials and modular structures; and research directed at identifying and quantifying the broad implications of nanotechnology for society, including social, economic, ethical, and legal implications.

DOE's Office of Basic Energy Sciences (BES) supports fundamental nanoscience research in the fields of materials science, chemical science, geoscience, and bioscience, with the goal of understanding, predicting, and ultimately controlling matter and energy at the level of electrons, atoms, and molecules. This research will be carried out primarily at universities and DOE national laboratories through single-investigator and small group projects as well as larger centers such as Energy Frontier Research Centers[9] and Energy Innovation Hubs.[10] This broad and diverse research provides the foundation for future new energy technologies and supports the DOE mission in energy, environment, and national security.

NIH investments in foundational research reflect the discovery and understanding of scientific principles in medical research. NIH will leverage nanotechnology to produce structures that induce regeneration and repair of biological tissues, deliver biomolecules to tissues with pre-defined kinetics, and control tissue infection and inflammation, among other uses. A significant change for NIH is the conclusion of the National Cancer Institute (NCI) Centers of Cancer Nanotechnology Excellence (CCNEs) in 2020, as scheduled. See highlights of CCNE accomplishments in Chapter 3. The Innovative Research in Cancer Nanotechnology (IRCN) program[11] will continue to support research projects focused on the fundamental understanding of nanomaterial and nanodevice interactions with biological systems. The focus of the IRCN program is the innovative use of nanotechnology to solve compelling cancer biology and oncology problems. Investigator-initiated nanotechnology applications to NCI have been increasing steadily, demonstrating the interest in and viability of implementing these new technologies into cancer research and care. While nanotechnology submissions in the past were reviewed by the Nanotechnology (NANO) Study Section, the increasing maturity and utility of nanotechnology approaches and growing acceptance of highly innovative nanotechnologies into biomedical research are reflected by the assignment of these submissions to other study sections, including Gene and Drug Delivery Systems, Clinical Molecular Imaging and Probe Development, Developmental Therapeutics, and Radiation Therapeutics and Biology.

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[9] https://science.osti.gov/bes/efrc
[10] https://www.energy.gov/science-innovation/innovation/hubs
[11] https://grants.nih.gov/grants/guide/pa-files/par-17-240.html

Foundational nanoscience research is an important part of the overall DOD nanotechnology investment portfolio to support future military missions and the needs of the warfighter. PCA 2 investments by DOD agencies span the full spectrum of fundamental nanotechnology R&D including nanobiotechnology; nanoelectronics, -photonics, and –magnetics; catalysis; and research on novel nanomaterials with potential structural, electronic, and biological applications. DOD research will emphasize exploration of novel phenomena associated with fundamental processes at the nanoscale or arising from nanostructural features in materials and devices. Research will focus on the development of lightweight, stronger materials to protect against blast waves, ballistic impacts, and mechanical vibrations using various mechanisms of energy absorption including phase transitions and materials deformation. Specific materials include molecular composites, organic polymers, superelastic metal alloys, and ultrahigh-strength ceramic formulations. DOD will investigate novel polymer nanocomposite formulations with multiple functionalities for combined strength, chem/bio degradation, self-sensing, or other properties. DOD will invest in the understanding of fundamental optical, electronic, and transport/reaction phenomena in nanostructured materials, and in learning how to apply these phenomena to enable major advances in portable power, communications, signal processing, and detection. DOD will investigate nanophotonic approaches to quantum information processing and reservoir computing and develop heterostructures of two-dimensional (2D) materials for spintronic applications. DOD will also invest in efforts in phonon-polariton lattices, controlling magnetism in metamagnetic nanostructures, enhanced optical properties in hybrid nanostructures, and quantum-coherent networks in DNA origami structures.

NIST's foundational nanotechnology research portfolio includes the development of cutting-edge approaches to design and accurately measure the size, shape, quantity, and physico-chemical complexity of nanoparticles, nanostructured films, and nanocomposites. For example, NIST is developing a suite of measurements to monitor and characterize dynamic DNA nanostructures for manufacturing. This measurement platform will enable the creation of quantitative, validated theory and models to guide the development of DNA nanotechnology by achieving molecular resolution of the critical details of structural self-assembly. NIST is also developing high-performance optomechanical devices that trap photons in nanoscale structures to strongly increase interactions between light and matter. These devices, including probes, sensors, and transducers, can advance the understanding of nanoscale phenomena and be used for magnetometry and emerging quantum applications. NIST will also expand its efforts in characterization of soft nanomaterials, particularly aimed at applications in biotherapeutics, plastics recycling, and marine debris characterization.

NIFA continues to support fundamental research in nanoscale science and engineering for solving significant societal challenges facing agriculture and food systems. The scope of investigation ranges from discovery and characterization of novel nanoscale phenomena, processes, and properties that are relevant and important to agriculture and food; to new platforms leading to novel applications; the exploitation of bio-nano interfaces; systems biology; additive manufacturing technology; and the broad social, ethical, economic, and legal implications of major emerging nanotechnology applications to society, agricultural markets, and consumer acceptance.

### *PCA 3. Nanotechnology-Enabled Applications, Devices, and Systems*

The agencies participating in the NNI support R&D on nanotechnology-enabled devices and systems across many applications, including advanced material systems for infrastructure; nanoscale vacuum tube, electronic, and photonic devices; particle tracking systems; and biomedical devices.

Nanotechnology-enabled applications, devices, and systems is the largest PCA in the NIH NNI investment portfolio, accounting for over 63% of its request. NIH funds nanotechnology-related proposals covering the major diseases (e.g., cardiac, cancer, diabetes, kidney). Programs and projects in PCA 3 include medical devices, nanotherapeutics, drug-delivery systems, novel radiotherapeutics, and nanotechnology-based vaccine platforms/products for clinical studies. NIH will also support investigation of chemical and physical properties of dental nanomaterials for diagnosis and treatment of disease, as well as nanomaterials for bioimaging applications and for implants and functionalized surface coatings. In efforts to develop targeted nanomaterials for the diagnosis and/or treatment of cardiovascular, lung, and blood diseases, NIH investments will focus on the development of nanomaterials as artificial blood substitutes, nanostructured surface coatings on mechanical devices to reduce thrombosis and/or infection, and nanoscaffolds to promote myocardial regeneration. The trans-NIH effort (led by the National Center for Advancing Translational Sciences), Microphysiological Systems for Disease Modeling and Efficacy Testing,[12] will continue until 2022. This initiative, executed in partnership with DOD, FDA, and industry partners, supports studies to develop and validate tissue chips. NCI also established a new program called Toward Translation of Nanotechnology Cancer Interventions to mature promising cancer nanomedicines and enable their subsequent entry into further scale-up and evaluation in clinical trials.[13]

The NSF request is for research that applies the principles of nanoscale science and engineering to create novel devices and systems, or to improve existing ones. The incorporation of nanoscale or nanostructured materials and the processes required to achieve improved performance or new functionality, including metrology, scale up, manufacturing technology, and nanoscale reference materials and standards, will be addressed. Core programs in NSF's directorates for Engineering, Mathematical and Physical Sciences, and Computer and Information Science and Engineering support development of new principles, design methods, and constructive solutions for nanodevices. A special focus will be on smart, autonomous nanoscale-based devices and systems. NSF will also support the Industries of the Future by using artificial intelligence to design nanostructured materials, devices, and systems; developing specialized nanoscale computing hardware for AI systems; utilizing the NNI infrastructure and atomically precise nanoscale methods to manufacture quantum components for sensing, communication, and computing; and enabling sustainable nanomanufacturing such as cellular nanobiomanufacturing.

DOD will support research programs focused on the use of advanced materials with aspects of nanotechnology in materials, modeling, and characterization to support requirements for advanced force protection systems. Use of nanoscale graphene, carbon nanofibers, nanocellulose, carbon nanotube forests, and other additives in composites and multilayered composite assemblies, and nanoceramic additives for hardening of metals, will be explored. Focus areas include nanomaterial additions to construction materials such as asphalt and concrete composites for improved performance in military and infrastructure applications. DOD will advance the development of new approaches to interface with and control biological systems, such as the development of "protonic" devices for actuating cells and self-assembled nanoscale transducers that can wirelessly control living cells. The DOD request for PCA 3 also includes funding for the Three Dimensional Monolithic System-on-a-Chip (3DSoC) program at the Defense Advanced Research Projects Agency (DARPA), which seeks to develop the monolithic 3D technology required to build logic, memory, and input/output on a single die using legacy lithography while improving performance by more than 50 times compared with current leading-edge semiconductor technology nodes.[14]

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[12] https://grants.nih.gov/grants/guide/rfa-files/RFA-TR-16-017.html
[13] https://grants.nih.gov/grants/guide/pa-files/PAR-20-116.html
[14] https://www.darpa.mil/program/three-dimensional-monolithic-system-on-a-chip

The Federal Highway Administration will pursue advances in the performance, durability, and resiliency of transportation infrastructure materials. Innovations in nanoscale characterization techniques and modeling material interactions at multiple scales have the potential to make a broader selection of materials—including recycled materials—available for use in the design, construction, and repair of the Nation's transportation infrastructure.

NASA will build on the wafer-scale fabrication of nanoscale vacuum channel transistors (NVCTs) demonstrated in both silicon and silicon carbide materials systems. In 2021, logic circuits based on NVCTs will be developed and tested for radiation immunity. NASA is also collaborating with the Air Force on projects related to nanoscale vacuum electronics. To support the need for on-demand embedded electronics for sustainable space exploration, NASA will develop printed versions of chemical sensors, biosensors, and supercapacitors using carbon nanomaterial inks and compare with conventional microfabrication techniques. In collaboration with DOE researchers and industry partners, NASA will develop novel solid-state batteries to power urban air mobility vehicles.

NIST will advance research on nanoscale devices and systems for applications from microelectronics to coatings and pharmaceutical products. Efforts include nanophotonic devices, nanoparticle tracking systems, atomically precise lithography, and nanocomposites. NIST will work with FDA to develop optical microscopy and nanoparticle tracking methods to characterize complex liposomal products to support measurement for quality control and validation of product equivalence. In 2021, the NIST single-atom device project expects to demonstrate operation of three- and four-qubit systems made from precisely placed phosphorus dopants in silicon to establish the manipulation of quantum information in silicon dopant devices. In parallel, extended arrays of dopant arrays will be systematically studied to establish their operation as quantum simulators to attack quantum and many-body problems that cannot be addressed with traditional computing. In collaboration with a major U.S. aerospace company, NIST is advancing nanoscale light emitters for microdisplays and virtual/augmented reality devices.

NIFA continues to emphasize its support for innovative and applied research on nanotechnology-enabled applications, devices, and systems for a wide range of agriculture and food priorities. The scope includes rapid detection and effective intervention technologies for ensuring food safety and biosecurity, effective treatments to improve animal health, value-added novel products, and utilization and protection of natural resources, the environment, and agricultural production ecosystems. USDA/ARS will initiate two new five-year research plans on efforts to turn biomass into high-value-added nanotechnology-enabled products and to enable nanotechnology food safety methods.

### *PCA 4. Research Infrastructure and Instrumentation*

The research infrastructure, including physical and cyber resources as well as education and workforce development efforts, is critical to support the entire NNI ecosystem, and agencies will continue to invest in these important areas. Agencies use a wide variety of mechanisms to support the research infrastructure, including center grants, instrumentation development or acquisition programs, training grants, fellowships, and collaborative programs that support workforce development. The NSF request includes the establishment and operation of user facilities and networks; acquisition of major instrumentation; workforce development; and other activities that develop, support, and/or enhance the Nation's physical and human infrastructure for nanoscale science, engineering, and technology. These activities include research pertaining to the tools needed to advance nanotechnology research and commercialization, e.g., next-generation instrumentation for characterization, measurement, synthesis, and design of materials, structures, devices, and systems. This category also captures dedicated educational and workforce efforts ranging from curriculum development to advanced training in support of the human infrastructure of the NNI. NSF plans to invest a total of $84.0 million over five years in a renewal of the National Nanotechnology Coordinated Infrastructure (NNCI), a user facility network at sites across the country.[15] NSF will increase coordinated research on its Mid-Scale Research Infrastructure priority area.

DOE/BES operates five Nanoscale Science Research Centers (NSRCs),[16] user facilities for interdisciplinary R&D at the nanoscale that serve as the basis for a national program that encompasses new science, tools, and computing capabilities. The NSRCs contain cleanrooms, nanofabrication resources, one-of-a-kind signature instruments, state-of-the-art electron microscopy, and other instruments not generally available except at major user facilities. Operating funds enable scientific staff to perform cutting-edge research and provide technical support through the user programs at these facilities. NSRC users have opportunities to access co-located x-ray synchrotrons, neutron sources, and high-performance computing facilities for nanoscience research. The facilities are made available to academic, government, and industry researchers through an external peer-review process. The NSRCs provide training for graduate students and postdoctoral researchers in interdisciplinary nanoscale science, engineering, and technology research. Plans for 2021 include recapitalization investments to upgrade and acquire instrumentation and capabilities.

NIST provides scientists from academia, industry, and other government agencies access to unique, world-class facilities and research instrumentation to advance emerging technology areas and understanding of nanoscale phenomena and systems. Facilities include the Center for Neutron Research[17] and the Center for Nanoscale Science and Technology (CNST) NanoFab.[18] The NIST Boulder Microfabrication Facility[19] enables development of nanoelectronic devices for chip-based quantum standards, sensors, integrated and quantum photonics, and advanced computing. Planned acquisitions include state-of-the-art tools for atomic layer deposition of ultrathin films, plasma-enhanced chemical vapor deposition, aluminum electron-beam deposition of Josephson junctions, and atomic force microscopy. NIST intends to deploy miniaturized, multiplexed, x-ray and gamma-ray superconducting transition-edge sensors and the second-generation Linac Coherent Light Source (LCLS-II) and other national x-ray light sources to support materials research in areas including nanoscale materials dynamics, heterogeneity, and fluctuations; fundamental dynamics of energy and charge; and emerging phenomena in quantum materials.

NIFA will continue supporting educational institutes for curriculum development and future workforce training. NIFA's AFRI Education and Workforce Development program supports various aspects of education for building institutional capacity and enhancing the pipeline for producing more STEM graduates to meet the projected shortfall in agriculture-related fields.

### *PCA 5. Environment, Health, and Safety*

Research and development efforts focused on the potential environment, health, and safety implications of nanotechnology (nanoEHS) are critical to responsible development, a key goal of the NNI. Agencies continue to build on the rich body of nanoEHS knowledge and to collaboratively protect researchers, workers, consumers, and the environment. NIOSH plans to develop, test, and evaluate direct-reading instruments capable of detecting and measuring airborne nanoparticles. The portable

[15] https://www.nnci.net/
[16] https://nsrcportal.sandia.gov/
[17] https://www.nist.gov/ncnr
[18] https://www.nist.gov/cnst
[19] https://www.nist.gov/programs-projects/boulder-microfabrication-facility

aerosol multi-element spectrometer developed by NIOSH will be field tested at nanomaterial producer and user facilities. NIOSH will build on its past efforts and develop occupational safety and health guidance that can be incorporated into business plans to both protect worker safety and promote application development and commercialization. NIOSH will work with industry to develop practical, "real-world" evaluations of hazard and risk represented by nanomaterials through their life cycles, and will assess the toxicology of carbon and metal-based nanomaterials, nanocellulose, and nanoclay-enabled materials. NIOSH will also work with trade unions and industrial partners to evaluate nanotechnology-enabled spray coatings, composites, and other nanomaterials in construction and manufacturing. NIOSH and CPSC will collaborate to study the release of engineered nanomaterials from three-dimensional (3D) printers.

NIST will establish a research effort on nanofluidic measurement devices and optical microscopy methods to characterize nanoplastics. NIST is also developing nanoparticle Standard Reference Materials (SRMs) of different materials and sizes including polystyrene, gold, and silica to enable accurate calibration of instruments used to characterize nanoparticles. NIST is studying the performance of vinyl siding made of polyvinyl chloride and particulate additives on the micrometer and nanometer scales. Performance measures include appearance, impact performance, and flammability before and after UV exposure. NIST continues to refine computational tools to evaluate consumer exposure to airborne engineered nanoparticles by incorporating enhancements associated with transport phenomena, usability, and input data into its models.

The NSF request in support of PCA 5 is primarily directed at understanding nano-bio phenomena and processes, as well as EHS implications and methods for reducing the risks of nanotechnology development. The Engineering Directorate's nanoEHS program has changed its name to Nanoscale Interactions.[20] NSF supports the Center for Sustainable Nanotechnology.[21]

The nanoEHS efforts of NIH's National Institute of Environmental Health Sciences (NIEHS) are designed to gain a fundamental understanding of the molecular and pathological pathways involved in mediating biological responses to engineered nanomaterials. The Nanotechnology Health Implications Research (NHIR) Consortium[22] will continue through 2021 with efforts to evaluate engineered nanomaterial (ENM)-biological interactions using diverse *in vitro*, tissue-on-chip, and *in vivo* models. NIEHS will continue studies to better understand the immune system response to the inhalation of CNTs in rodent models, as well as CNT chronic cancer bioassays. The NIEHS Superfund Research Program[23] plans to emphasize research that includes nanotechnology-enabled structures to enhance sustainable remediation. Collaborative efforts with FDA under the National Toxicology Program[24] and active participation in the interagency discussion of nanoplastics will continue to be a priority. FDA's National Center for Toxicological Research (NCTR) and Office of Regulatory Affairs (ORA) will invest in advanced tools, safety assessment, staff training, standards methods, and methodology development to better understand emerging issues with nanomaterials in FDA-regulated products.

NIFA supports EHS research relevant to agricultural production and food applications. Risk assessments of nanotechnology uses in food and agricultural systems include characterization of hazards, exposure levels, and transport and fate of engineered nanomaterials in crops, soils (and soil biota), livestock, and production environments. The program also supports research on transport and

[20] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505696
[21] https://susnano.wisc.edu/
[22] https://www.niehs.nih.gov/research/supported/exposure/nanohealth/grantees/index.cfm
[23] https://www.niehs.nih.gov/research/supported/centers/srp/index.cfm
[24] https://ntp.niehs.nih.gov/

fate of engineered nanoparticles or nanomaterials associated with food production, processing, and interactions with microbiota in the human gastrointestinal tract.

## Use of SBIR and STTR Programs to Advance Nanotechnology

As called for by the 21st Century Nanotechnology Research and Development Act, this report includes information on use of the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs to support nanotechnology development, as well as highlights of agency SBIR and STTR topics and other programs and activities that directly support the accelerated deployment and application of nanotechnology R&D in the private sector. Table 6 shows agency funding for SBIR and STTR awards for nanotechnology R&D from 2015 through 2018 (the latest year for which data are available). Even though few agencies specifically call out nanotechnology in their SBIR/STTR solicitations, it is enabling innovations in many R&D application areas.

**Table 6: 2015–2018 Agency SBIR and STTR Awards**
(dollars in millions)

| | 2015 | | | 2016 | | | 2017 | | | 2018 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Agency** | **SBIR** | **STTR** | **Total** | **SBIR** | **STTR** | **Total** | **SBIR** | **STTR** | **Total** | **SBIR** | **STTR** | **Total** |
| **DHS** | 4.0 | 0.0 | 4.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.3 |
| **DOC**/NIST | 0.2 | 0.0 | 0.2 | 0.3 | 0.0 | 0.3 | 0.7 | 0.0 | 0.7 | 0.5 | 0.0 | 0.5 |
| **DOD** | 24.6 | 2.8 | 27.4 | 41.9 | 7.3 | 49.2 | 61.5 | 14.5 | 76.0 | 38.3 | 23.3 | 61.6 |
| **DOE** | 20.5 | 4.0 | 24.5 | 26.2 | 4.7 | 30.9 | 25.1 | 5.4 | 30.5 | 36.6 | 5.2 | 41.8 |
| **EPA** | 0.9 | 0.0 | 0.9 | 1.7 | 0.0 | 1.7 | 0.3 | 0.0 | 0.3 | 0.5 | 0.0 | 0.5 |
| **HHS**/NIH | 21.8 | 3.2 | 24.9 | 18.2 | 5.7 | 24.0 | 27.2 | 7.1 | 34.3 | 34.9 | 7.1 | 42.0 |
| **NASA** | 3.3 | 0.9 | 4.2 | 3.5 | 1.1 | 4.6 | 12.2 | 2.6 | 14.8 | 4.7 | 1.5 | 6.2 |
| **NSF** | 19.6 | 3.8 | 23.4 | 22.9 | 3.5 | 26.5 | 18.2 | 5.5 | 23.7 | 17.4 | 3.1 | 20.5 |
| **USDA** | 1.5 | 0.0 | 1.5 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.3 | 1.6 | 0.0 | 1.6 |
| **TOTAL** | **96.4** | **14.7** | **111.0** | **114.8** | **22.4** | **137.2** | **145.5** | **35.2** | **180.7** | **134.8** | **40.2** | **175.0** |

Topics supported by agency SBIR and STTR awards (and enabled by nanotechnologies) include the following:

- Nanocomposite coatings to reduce wear and improve efficiency of mechanical gears (DOD).
- 3D-printed controlled-release nanomedicines to treat bacterial infections in burn victims (DOD).
- Nanoengineered electrodes for less expensive, safer, longer-lasting, and/or higher-energy-density batteries, enabling a variety of commercial and military applications (DOD, DOE).
- Nanostructured hydrophobic anti-reflective surfaces for military sensor platforms (DOD).
- Gecko-inspired nanostructures to hermetically seal chemical/biological protection systems (DOD).
- Nanoengineered vaccines for malaria and human immunodeficiency virus (HIV) (DOD, NIH).
- Nanoliposomes for targeted delivery of cancer therapeutics (NIH).
- Nanopatterned electrode arrays for measuring and promoting cardiac tissue development (NIH).
- Bioresorbable nanoparticles for visual detection of early-stage dental decay (NIH).
- Models and field-deployable *in vitro* devices for testing toxicity of engineered nanomaterials (NIH).
- High-resolution, low-cost vias for 3D integrated sensors (DOE).

- Highly parallel scanning tunneling microscopy lithography/hierarchical assembly for atomically precise manufacturing (DOE).
- Bioinspired nanostructured antireflective materials for high-efficiency lighting (DOE).
- Integrating software/hardware approaches for compressive sensing to enhance the performance of ultra-high-speed electron cameras (DOE).
- *In-situ* transmission electron microscopy characterization of electrochemical processes in solid-state energy storage devices with air-sensitive materials (DOE).
- Low-cost hybrid plasmonic and photonic “campanile” near-field probes by nanoimprint lithography (DOE).
- Scanning tunneling microscope-based hydrogen depassivation lithography automation via artificial intelligence (DOE).
- Mass-produced paper filters with nanosilver for affordable point-of-use water disinfection (NSF).
- Nanocomposite foams for pressure mapping to prevent bed sores in long-term care (NSF).
- Synthetic nanomaterials for cell scaffoldings to promote infection-free tissue regeneration (NSF).
- Nanomanufacturing of photocatalyst floor coatings to reduce volatile organic compounds (NSF).
- Nano-plasmonic grating sensors for 100X increased sensitivity in tuberculosis detection (NSF).
- Nanoscale silica-based materials to reinforce natural rubber for “green” tires (NSF).
- Detecting biomarkers for life in ocean worlds with solid-state nanopores (NASA).
- Shear-thickening suspensions of nanoparticles for puncture-resistant space suits (NASA).
- Sensors, surfaces, and membranes for spacecraft water monitoring, recovery, and recycling (NASA).
- Automation of scanning electron microscopy image analysis for semiconductor industry process development (NIST).
- Silicon nanowire sensors to measure host-cell proteins at a biomanufacturing line (NIST).
- Chiroptical spectrometer for distinguishing left and right enantiomers of nanomaterials (NIST).
- Inexpensive, low-power nanosensors for detecting methane leaks (EPA).
- “Nanobubble” washing solutions for removal of pathogens in fresh produce (USDA).
- Nanosensors for detecting chemicals from insect infestations in food storage containers (USDA).
- Nanomaterials enabling highway paint to communicate safety/hazard messages to vehicles (DOT).

## 3. Progress towards the NNI Goals

The following selected highlights illustrate progress toward each of the four goals of the NNI. For more information and additional highlights, please see Nano.gov.

### Goal 1. Advance a World-Class Nanotechnology Research and Development Program

Nanoscience and nanotechnology continue to be areas of active research and development all over the world. The NNI participating agencies are committed to supporting basic and early-stage applied research to expand the boundaries of understanding and keep the United States at the forefront of this important area. These continued investments will enable future discoveries that build on the strong foundation developed over the course of the NNI and ensure that the benefits to America's national and economic security are realized.

**Eliminating HIV from the genomes of living animals.** In a major collaborative effort, researchers funded by NIH have for the first time eliminated replication-competent HIV-1 DNA—the virus responsible for AIDS—from the genomes of living animals. The study marks a critical step toward the development of a possible cure for human HIV infection. The researchers developed a strategy known as long-acting slow-effective-release antiretroviral therapy (LASER ART). A modified antiretroviral drug was packaged into nanocrystals that readily distribute to tissue where HIV is lying dormant. The nanocrystals stored within the cells slowly released the drug. About one-third of the HIV-infected mice treated with LASER ART and subsequent CRISPR-Cas9 showed complete elimination of HIV DNA.[25]

**Fabricating quantum devices with near atomic precision**. DOE, NIST, and collaborators from industry and academia made donor quantum dot devices using single or clusters of phosphorous atoms as donor dopants deterministically placed in silicon. The quantum dots were aligned with gates and leads, all fabricated with near atomic precision. The quantum dot acts as a sensor of the charge or spin on the donor. This setup allows for the single-shot readout of dopant-based qubits necessary for any quantum computing device. Extended 3 x 3 arrays of dopants have now been fabricated, and transport through these arrays has been measured for the first time.

**Developing the first universal nanoparticle adsorption model.** For the first time, researchers funded by NSF have developed a model that is able to predict the adsorption on any metallic nanoparticle, as well as screen for stability. By utilizing computational chemistry and machine learning, the researchers were able to fit large sets of data to predict adsorption trends not previously observed. The universal adsorption model considers the structural properties of the nanoparticle composition, size, and shape, along with the type of adsorbate.[26]

**Revealing a magnetic topological insulator.** In experiments conducted at Oak Ridge National Laboratory's Spallation Neutron Source, an international team of researchers showed the presence of magnons, collective spin excitations. Analogous to the quantum and relativistic behavior of electrons in graphene, the team has shown similar behavior in a magnetic material, chromium triiodide ($CrI_3$). This was the first time this behavior was observed in the absence of a magnetic field. The work included NIST collaborators and was funded in part by NSF and DOE.[27]

[25] https://www.nature.com/articles/s41467-019-10366-y
[26] https://advances.sciencemag.org/content/5/9/eaax5101
[27] https://journals.aps.org/prx/abstract/10.1103/PhysRevX.8.041028

**Breaking the record for the blackest black.** By growing carbon nanotubes vertically aligned on an aluminum substrate, researchers funded by NSF and DOD have developed a material that is ten times darker than anything previously reported.[28] Very black materials are important in optical and space applications to eliminate glare and shield telescopes from stray light.

**Enabling testing for viruses**. FDA has utilized nanosensors to develop novel and sensitive diagnostic assays for HIV, influenza, West Nile virus, dengue virus, and Zika virus.

**Developing biosensors to detect life in oceans and space**. Researchers funded by NASA, NSF, and NIH have developed metallic photonic crystal (MPC) structures that consist of plasmonic gold nanogratings for lab-on-chip biosensing applications. The sensors, coupled to a photonic waveguide, were operational over a wide temperature range, including at cryogenic temperatures. These nanoplasmonic sensors have potential for use in ocean exploration and also for Venus upper atmosphere life detection and characterization.

**Advancing nanotechnology to address brain health.** NIST, in collaboration with NIH, demonstrated novel biosensors based on field-effect transistors fabricated with single-atomic-layer semiconducting films, achieving unprecedented pH resolution. These biosensors enabled precise measurements of biomolecular enzymes implicated in Alzheimer's disease at sub-physiological concentrations. This work enables diagnostic tests to speed up drug discovery for several debilitating neurological diseases. Another team of researchers funded by NSF has developed a nanoparticle-based sensor to provide rapid detection of dopamine. The level of dopamine may be associated with Parkinson's, depression, and some brain cancers.[29] Naval Research Laboratory (NRL) scientists have developed small gold nanoparticles that bind to the plasma membrane of neurons, harvest incident visible light, and heat the plasma membrane just enough to open ion channels and activate neurons. This approach may help lead to the development of new diagnostics and therapeutics for traumatic brain injury.

**Rapidly detecting pathogens for food safety**. ARS researchers have developed a nanotechnology-enabled system for rapid detection of pathogens in fresh vegetables and fish. This method is sensitive enough to detect as few as 10 bacterial cells in a food sample and can be easily adopted by the food industry. ARS researchers also have developed a novel nanobiosensor for detecting fungal toxins in corn and camembert cheese. Cyclopiazonic acid is a naturally occurring neurotoxin that can infest a variety of commodities and foods. The new nanobiosensor technology uses surface plasmon resonance imaging and can be used as a tool to quickly screen for this toxin.

**Monitoring the stomach with ingestible expanding pill.** Engineers have designed an ingestible hydrogel-based device that swells when it reaches the stomach and can continuously monitor temperature for up to a month. A drinkable solution triggers the pill to return to its original size and be safely passed out of the body. This research, funded in part by NSF and NIH, could lead to long-term monitoring of additional parameters for ulcers, cancer, and other gastrointestinal issues.[30]

**Avoiding antibiotics in aquaculture**. ARS research found that nanoparticles of trans-cinnamaldehyde can modify the gut microbiota composition in a positive direction by increasing the abundance of beneficial bacteria and serve as a promising alternative to antibiotics in aquaculture.

**Understanding DNA origami**. NIST measured the thermodynamics of the essential building block of DNA origami, a single fold, as well as the relative yield of that single fold. This is the first study to confirm

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[28] https://pubs.acs.org/doi/10.1021/acsami.9b08290

[29] https://pubs.acs.org/doi/full/10.1021/acs.nanolett.8b04253

[30] http://news.mit.edu/2019/ingestible-expanding-pill-monitors-stomach-0130

the existence of an intermediate state that acts as a kinetic defect during nanostructure assembly. This work informs the design of DNA origami when scaled to a production level, where defect minimization is critical.

**Advancing understanding and control of spin states**. NIST researchers theoretically predicted the occurrence of a unique form of spin current present in ferromagnets. Working with collaborators, signatures of this spin current were measured experimentally. These spin currents were previously unrecognized and exhibited the unusual property that flowing spins are misaligned from the magnetization. This novel spin current may be useful for magnetic random access memory technology. In a landmark experiment, researchers funded by the Office of Naval Research (ONR) succeeded in coherently controlling and manipulating the spin state in a single titanium atom. The coherent control of spins arranged with atomic precision provides a solid-state platform for quantum-state engineering and simulation of many-body systems.

**Designing vaccines to improve cancer immunotherapies**. By comparing a series of vaccines that had the same composition but varying structures, a team of researchers demonstrated the importance of structure and the potential for rational design of vaccines. The spherical nucleic acids (SNAs) in one vaccine significantly outperformed the others by eliminating tumors in 30% of the mice, improving their overall survival rate from cancer, and protecting the animals from reemerging tumors. This study, funded in part by NIH and DOD, illustrates how strategic design of active components and 3D structure may accelerate the development of new vaccines for diseases, including many types of cancer.[31]

***Detecting cancer and other diseases with a urine test***

*University researchers funded in part by NIH and NSF have developed a novel diagnostic tool that reports on the presence of cancer by changing the color of urine, using nanosensors composed of gold nanoclusters tethered to protein carriers. In the presence of disease biomarkers detected within the body, the bonds between the nanoclusters and the protein carriers are broken and the released gold nanoclusters travel through the blood to the kidneys, where they are efficiently filtered into the urine due to their small size (<5 nm). In tests on laboratory mice, colon cancer biomarkers (enzymes that signal tumor growth) were successfully detected; gold nanoclusters in the urine of diseased mice catalyzed a reaction that turned the urine from yellow to blue. The nanosensors were eliminated from the body within four weeks with no toxic side effects. This method could enable early diagnosis of cancer, could be used in low-resource settings where simple, sensitive diagnostic tools are needed, and could also lead to rapid detection of other diseases.*

**Urine from healthy mice is yellow (top row), while urine from mice with colon cancer turns blue (bottom row). Image credit: Imperial College London/MIT.**

**Exploiting the properties of light for autonomous vehicles and detecting distant galaxies.** Engineers funded by NSF and DOD have developed a small, portable camera that can image polarization, the orientation of lightwaves, using nanostructured metasurfaces. Imaging the polarization can provide insight into depth and textures not possible with only color and intensity of light captured by traditional cameras. Potential applications include autonomous vehicles, machine vision, and study of atmospheric chemistry.[32] Researchers funded by NASA, DOD, NSF, and DOE have developed a sensor system that can detect terahertz radiation at room temperature. This ultrasensitive light-detection system resolves details not visible in other

[31] https://www.pnas.org/content/116/21/10473

[32] https://www.seas.harvard.edu/news/2019/07/camera-brings-unseen-world-light

spectra and is not susceptible to interference from the atmosphere. This technology may help scientists view galaxies, stars, and planetary systems in better detail and gain new insight into the composition of astronomical objects.[33]

**Accelerating wound healing**. Researchers supported by NIH's National Heart, Lung, and Blood Institute have developed adhesive hydrogels containing nanoparticles to control the polarization of tissue macrophages during wound healing. The hydrogels adhered to and covered wounds in an acute wound model and efficiently promoted the formation of uniform vascularized skin at the wound site, demonstrating the acceleration of wound healing. NRL scientists have fabricated state-of-the-art biomaterials in which the chemistry and topography can be independently tuned at the nanoscale. Live cells placed on these materials exhibited enhanced adhesion and migration, which is central to accelerating wound healing and regeneration. These platforms form an enabling suite of technologies for advanced wound pack and implant materials. Another group of researchers funded by NIH's National Institute of Bioimaging and Bioengineering (NIBIB) have developed a technique to seal tissues using silk and gold. By heating the material with a laser, the tissue and silk molecules interlace, creating a bioactive sealant, essentially welding an open wound shut.[34] NIBIB-funded bioengineers have developed implantable and wearable nanogenerators made from piezoelectric and dielectric materials that create electrical pulses when compressed by body motions. This technology can be used to help wounds heal more quickly and to promote weight loss by suppressing appetite through stimulation of the vagus nerve.

**Enhancing battery capacity.** Researchers funded by DOE have developed a cathode made of nanostructured selenium–carbon composite that provides a new approach for high-energy-density batteries. The cathode enables battery designs that store significant energy in a small volume, charge quickly, and are durable. These attributes are ideal for automotive and other high-power battery applications.[35]

**Printing and powering wearable sensors and electronic tattoos.** Researchers have developed a technique to print electrical leads and components such as transistors directly on surfaces, including skin, at low temperatures. Funded by DOD, NIH, and NSF, this research could lead to applications such as custom bandages with sensors and electronic tattoos.[36] Using crumpled carbon nanotube forests, researchers funded in part by USDA/NIFA, NSF, and DOD have created flexible supercapacitors to provide power to wearable and implantable electronic systems. The devices perform even when stretched to several times their original size in various directions over thousands of cycles.[37]

**Removing salts and pollutants to make water drinkable**. DOE-funded researchers have designed a new molecule to extract salt from water. The rigid 3D cage consisting of carbon and hydrogen bonds performs several orders of magnitude better than cages made with nitrogen-hydrogen bonds and could help increase access to drinkable water.[38] Another team of researchers funded by DOE and NSF has shown that metal-organic frameworks (MOFs) can be designed to capture fluorinated compounds known as perfluorooctane sulfonate (PFOS), a global contaminant. They demonstrated excellent

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[33] https://newsroom.ucla.edu/releases/light-sensing-distant-galaxies-unprecedented-detail
[34] https://asunow.asu.edu/20190925-discoveries-bonding-experience-repairing-wounds-gold-silk-and-lasers
[35] https://www.energy.gov/science/bes/articles/novel-electrodes-enhance-battery-capacity
[36] https://pubs.rsc.org/en/content/articlehtml/2019/nr/c9nr03378e, https://pubs.acs.org/doi/10.1021/acsnano.9b04337
[37] https://onlinelibrary.wiley.com/doi/abs/10.1002/aenm.201900618
[38] https://www.energy.gov/science/bes/articles/how-build-better-salt-trap-fresh-water

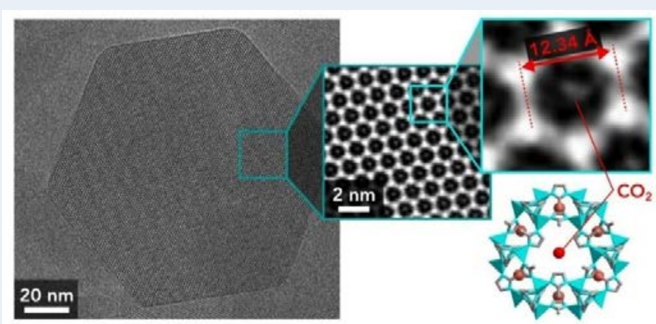
capture rates at high concentrations of PFOS and can reuse the MOFs.[39] The team is working on a field-deployable system as well as a sensor based on the technology to help guide cleanup efforts.

**Tailoring enzymes to make eco-friendly fuels and materials**. Researchers funded by NSF and NIST have activated specific enzymes in a common microbial species with quantum dots. Exposure to sunlight activates the microbes to take in $CO_2$ and convert it into products such as biodiesel, ammonia, and biodegradable plastic. The researchers are working toward process optimization and envision household systems that could consume $CO_2$ emissions in a simple process.[40] NRL scientists have developed self-assembled nanoparticle enzyme systems that are capable of overcoming diffusion limitations and increasing enzyme pathway activity by several orders of magnitude. This advancement paves the way for designer enzyme clusters that are capable of synthesizing molecules such as nutraceuticals, drugs, critical chemicals, and food from common simple molecule feedstocks and even waste.

**Enabling smart textiles**. NNI agencies have supported nanotechnology development to enable smart textiles. Applications include energy harvesting to power devices and coatings to repel or deactivate chemical or biological agents. Now researchers funded by NSF have developed a dye used in threads that can detect a variety of gases, including ammonia and hydrogen chloride. The thread changes color when exposed to analytes in concentrations as low as 50 parts per million and can be read visually or with a smartphone camera. When woven into fabric, these threads could provide a reusable, washable, easy-to-use method for alerting workers and first responders to the presence of hazardous gases.[41]

***Imaging carbon dioxide molecules in a cage for the first time***

*Researchers funded by DOE, NIH, NSF, and the intelligence community imaged two configurations of $CO_2$ in a metal-organic framework for the first time. Direct imaging of a host-guest structure—such as an MOF (host) and carbon dioxide (guest)—by using conventional transmission electron microscopy has not been possible. By using a cryogenic electron microscope, which stabilizes the host-guest structure and can resolve its atomic surface, the researchers were able to show two configurations of the $CO_2$ molecule in its cage, reveal that the cage expands slightly as the $CO_2$ enters, and zoom in on details of the MOF edges that grow by adding more cages.[42] This work advances the fundamental understanding of MOFs, which have potential in applications such as storing fuel, separating gases, and removing $CO_2$ from the atmosphere.*




**Images show a slice through a single MOF nanoparticle in atomic detail (left), revealing cage-like molecules (center) that can trap other molecules inside. The image at right shows $CO_2$ molecules trapped in one of the cages. Bottom right: a drawing of the molecular structure of the cage and the trapped carbon dioxide. Image credits: Y. Li et al., Stanford.**

**Catalyzing fuels and materials**. A team of researchers funded in part by DOE and NSF has developed catalysts based on the function of enzymes in living systems. The catalysts were designed with nanocrystals of a precious metal embedded in polymer layers. In a model system, the catalyst

[39] https://pubs.acs.org/doi/10.1021/acs.inorgchem.9b00380
[40] https://pubs.acs.org/doi/10.1021/jacs.9b02549
[41] https://www.nature.com/articles/s41598-019-42054-8
[42] https://www.cell.com/matter/fulltext/S2590-2385(19)30053-0

converted carbon monoxide and oxygen to carbon dioxide, even regulating the production by trapping $CO_2$ in the polymer layers. This technology could have implications in a broad range of chemical reactions, including potentially converting methane into methanol at low temperatures.[43] In another approach, an international team of researchers funded in part by DOE and NSF has developed a nanostructured copper and silver catalysis system that converts $CO_2$ to methane in a single reactor.[44]

**Making plant-based insulation better than petroleum-based foams**. Researchers funded by NIFA have developed an environmentally friendly insulating material made from cellulose nanocrystals. This is the first time that a plant-based material surpassed the insulating performance of polystyrene foam. The nanocrystals from wood pulp make up about 75 percent of the material, and the manufacturing process uses water instead of other harmful solvents. After use, the lightweight foam degrades well and does not produce a polluting ash when burned.[45]

**Dissipating heat for hypersonics.** Academic researchers funded by the Air Force Research Laboratory (AFRL) developed a resin-infused carbon nanotube veil with superior heat dissipation characteristics for future hypersonic aeroshells. The composite sheets are highly anisotropic, and the CNTs have orders of magnitude higher thermal conductivity in-plane than carbon fiber. This CNT composite can disperse heat at about $1/16^{th}$ the thickness of conventional composites.

**Directly writing quantum light sources**. AFRL and NRL scientists have developed a method to directly write quantum light sources, or single photon emitters, into monolayer semiconductors such as tungsten diselenide. Overcoming a long-standing roadblock, this quantum calligraphy enables real-time design of arbitrary patterns and arrays of single-photon emitters, key components in a wide range of nascent quantum-based technologies including computing, secure communications, sensing, and metrology.

**Producing higher-quality graphene oxide paper**. Academic researchers funded by ONR have shown improvements in graphene oxide (GO) paper by mixing strong, solid GO flakes with weak, porous GO flakes. These insights will enable production of higher-quality GO and address the challenge of building a macroscopic material from nanoscale material without losing desirable properties.

**Understanding the lifetime of tooth enamel**. Using specialized imaging techniques and computer simulations, researchers funded by NIH, DOE, NSF, and DOD have determined that the orientation of the individual enamel nanocrystals in human teeth prevents crack growth. The small degree of misalignment of the crystals, ranging from 1 to less than 30 degrees, deflects cracks at the nanoscale, enabling teeth to last a lifetime.[46]

**Detecting and degrading contaminants in water and the environment**. Researchers supported by NIFA have developed a sensor platform that is able to detect organophosphates, a type of insecticide, at levels forty times below the EPA recommended levels. The sensor technology can also be adapted to detect pathogens and other compounds to promote food safety and monitor the environmental ecosystem.[47] Another team of researchers funded in part by NIFA has developed a process using nanoscale zerovalent iron to degrade common flame retardants that are associated with cancer and

[43] https://www.nature.com/articles/s41929-019-0322-7
[44] https://www.nature.com/articles/s41467-019-11292-9
[45] https://doi.org/10.1016/j.carbpol.2019.04.059
[46] https://www.nature.com/articles/s41467-019-12185-7
[47] https://pubs.rsc.org/en/content/articlehtml/2019/nh/c8nh00377g

hormone disruption. The two-step process advances efforts to develop safe and effective methods to remediate groundwater and soil contaminated with these persistent pollutants.[48]

**Making ceramics that are ductile like metals**. Researchers supported by ONR have developed a new process for making more ductile and durable ceramics. By "flash sintering" (which adds an electric field to the conventional sintering process), the team showed that the ceramics surprisingly deform plastically before fracture when compressed at high strain rate. The resulting ceramic material was almost as easily reshaped at room temperature as a metal.

**Harvesting Wi-Fi signals to power devices.** Researchers funded by NSF and DOD have demonstrated a fully flexible, inexpensive rectenna, a device that converts AC electromagnetic waves into direct current. The device consists of a radio-frequency (RF) antenna that can capture electromagnetic waves such as Wi-Fi, Bluetooth, cellular, and other signals. The flexible RF antenna is connected to a 2D rectifier made of molybdenum disulfide ($MoS_2$) that converts the AC signal into the DC power required for devices such as phones, computers, wearable electronics, and maybe even swallowable sensors.[49]

**Transforming the way nutrients are delivered to plants**. For the first time, researchers have systematically studied how nanoparticles move through the leaf, into the plant, to the root, and exude into the soil. This research, funded by NSF, DOE, and EPA, has shown an efficient delivery method to treat the microenvironment surrounding roots with less chemicals, at lower cost, and with reduced environmental impact.[50]

**Utilizing materials by design for high-performance concrete**. Army researchers have characterized nanosilica morphology, molecular structure, and defect chemistries for the first time. This effort is focused on developing advanced nanomaterials and modeling capabilities for use in high-performance concrete materials for structural hardening. This work has led to models that capture the impact of nanomaterial composition, morphology, and molecular structure on rheology, kinetics, and mechanical properties of concrete materials. These models are now being used in applied materials-by-design research.

**Understanding the interface between living cells and synthetic surfaces**. AFRL researchers identified the mechanism that mediates energy conversion and charge transmission at the interface between living cells and synthetic surfaces. These findings have implications for cell physiology and bioelectronics and may lead to the development of new hybrid materials and renewable energy technologies that combine the exquisite biochemical control of nature with the synthetic building blocks of nanotechnology.

**Inventing artificial muscles**. Researchers funded by AFRL have invented several types of strong, powerful artificial muscles using materials ranging from carbon nanotubes to ordinary fishing line. Concepts such as sheath-run artificial muscles provide even greater design flexibility, and are attractive for intelligent structures such as robotics and comfort-adjusting clothing.

**Confirming predicted behavior that could lead to a four-way switch**. For the first time, a team of researchers from DOE and academia experimentally observed a predicted material phase in copper indium thiophosphate (CIPS). CIPS is a layered crystal that is ferroelectric and piezoelectric. The properties of the material depend on the location of the copper atoms in the crystal, with four potential minima or energy

[48] https://pubs.acs.org/doi/10.1021/acs.est.8b06834
[49] https://www.nature.com/articles/s41586-019-0892-1
[50] https://pubs.acs.org/doi/10.1021/acsnano.8b09781

wells. The transition between these four polarization states can be controlled using temperature, pressure, and electric fields, resulting in the potential for a four-way switch. The van der Waals structure of CIPS makes it compatible with nearly all 2D materials and may enable the means to manipulate electrical conduction in other materials such as graphene.[51]

## Goal 2. Foster the Transfer of New Technologies into Products for Commercial and Public Benefit

Federal investments in nanotechnology R&D have led to thousands of products in the marketplace, from consumer electronics to nanomedicines. Continued scientific advancements provide significant potential for nanotechnology to enable and inspire entirely new devices and systems in a broad array of applications, from quantum computing to food safety. To realize this potential, the focus of Goal 2 is to facilitate the transfer of nanotechnology R&D breakthroughs into technologies that the private sector can bring to market. The NNI fosters commercialization by sharing information, promoting access to user facilities, leveraging resources through public-private partnerships, and participating in international standards activities that are critical to commercialization. In addition to these mechanisms, NNCO has a devoted industry liaison staff member who supports the industry ecosystem by conducting outreach, sharing best practices, and suggesting collaborations as appropriate.

**Fostering the entrepreneurial ecosystem**. The NNI agencies support the entrepreneurial ecosystem through a variety of mechanisms including the SBIR and STTR programs, the expanding Innovation Corps (I-Corps), and NNCO's Nanotechnology Entrepreneurship Network (see sidebar, next page). For example, at NSF the transfer of technology is carried out through publication of papers and patents, center activities and outreach, and dedicated programs in the Division of Industrial Innovation and Partnerships. NSF supports translational innovation programs including Grant Opportunities for Academic Liaison with Industry (GOALI), Industry-University Cooperative Research Centers (IUCRC), I-Corps, Partnership for Innovation (PFI), and its technology translation (PFI-TT) and research partnerships (PFI-RP) tracks. The NSF SBIR program has an ongoing nanotechnology topic with subtopics for nanomaterials, nanomanufacturing, nanoelectronics and active nanostructures, nanotechnology for biological and medical applications, and instrumentation for nanotechnology. In 2019 NSF had nine active I-Corps nodes, including nanotechnology projects in partnership with DOE, NIH, and NASA. There were 36 new I-Corps awards related to nanotechnology in 2019.

The transfer of new technologies into products depends on the protection of new ideas and investments in innovation and creativity. USPTO is at the cutting edge of the Nation's innovation system, providing intellectual property policy advice and guidance to the Executive Branch, and granting patents on applications that meet the statutory requirements for patentability, including with respect to nanotechnology. To keep pace with the rapid advances being made in nanotechnology, USTPO has provided in-depth nanotechnology-specific training events for patent examiners. In addition, USPTO established a subset of patent examiners across all technology disciplines who serve as points of contact to assist other examiners with nanotechnology issues. USPTO has moved to a new patent classification system, the Cooperative Patent Classification, which is jointly managed with the European Patent Office. This change has created a more harmonized, internationally consistent classification of nanotechnology-related patent documents.

[51] https://www.nature.com/articles/s41563-019-0532-z

***Nanotechnology Entrepreneurship Network shares best practices in commercialization***

*In November 2019 NNCO launched the Nanotechnology Entrepreneurship Network (NEN),[52] which brings new and seasoned entrepreneurs together to share best practices for advancing nanotechnology commercialization and the lessons learned along the technology development pathway. Current and planned NEN activities include podcasts, webinars, workshops, and town hall discussions. A February 2020 webinar provided information from the U.S. Patent and Trademark Office on best practices in protecting intellectual property. Podcast guests have included CEOs of nanotechnology companies and the Chief Scientist of the Small Business Administration.[53]*


**On March 31, 2020, NNCO hosted an NEN podcast interview with Dr. Jennifer Shieh, discussing resources for small businesses impacted by COVID-19.**

**Translating nanotechnology from bench to bedside.** The NCI-funded Centers of Cancer Nanotechnology Excellence produced a large body of basic and applied research, but even more importantly provided technologies to establish several start-up companies, which are engaged in commercialization of nanotechnology-based cancer diagnostics and therapeutics. Research funded by NCI has led to the development of spherical nucleic acids (SNAs) and new strategies for cancer vaccines. The SNA structure has a critical influence on immune-stimulatory performance, and mechanistic studies have enabled the prediction of the effectiveness of different SNA designs. A spin-off company pursues commercialization of SNA-based vaccines. Separate NCI-funded research on nanoscale metal-organic frameworks and coordination polymer constructs is being commercialized. These materials enhance the efficacy of x-ray radiotherapy, are intrinsically non-toxic, and greatly reduce the dose needed to eradicate local tumors in mouse models.

The Integrated Preclinical/Clinical AIDS Vaccine Development (IPCAVD) program[54] at NIH's National Institute of Allergies and Infectious Diseases has funded the development of mRNAs in lipid nanoparticles (LNPs). The research team is developing a process for Good Manufacturing Practice (GMP) production of mRNA immunogens and mRNA-LNP formulations for use in human Phase 1 clinical trials. Other researchers have been funded to develop and GMP manufacture a novel virosomal HIV vaccine that is administered as a nasal spray.

AFRL's Nano-Bio Materials Consortium (NBMC), including industrial, academic, and venture capital partners, is advancing aeromedical monitoring capabilities for En Route Care and Aeromedical Evacuation missions. This collaboration has advanced technologies and components that enable stress monitoring, tissue-level oxygen/biochemical monitoring, AI for multimodal physiological monitoring, and wireless vital sign monitoring devices for ambulatory patient monitoring. These efforts are establishing a foundation for dual-use products in digital health and personnel medicine that address strategic AFRL requirements.

NIST developed a uniform process to determine nanoparticle count in environmental or biological samples. This research, in collaboration with industry and an international federal laboratory, resulted

[52] https://www.nano.gov/nanoentrepreneurshipnetwork
[53] https://www.youtube.com/playlist?list=PLy4wjGabGUTbzen-YVrWrDVWJvXAvtlda
[54] https://grants.nih.gov/grants/guide/pa-files/PAR-20-120.html

in a simplified process used by pharmaceutical researchers for testing a nanoparticle-based therapeutic.

**Collaborating to support current and future electronic systems**. Exemplary public-private partnerships have involved collaboration between NNI agencies and the semiconductor industry, including programs such as the Nanoelectronics Research Initiative (NRI),[55] the Nanoelectronics Computing Research (nCORE) consortium,[56] the Semiconductor Technology Advanced Research Network (StarNET),[57] and the Joint University Microelectronics Program (JUMP).[58] Agencies continue to collaborate with this industry critical to America's national and economic security through a variety of mechanisms including the DARPA Electronics Resurgence Initiative (ERI). A key milestone was demonstrated at the 2019 ERI Summit: the first monolithic 3D integrated circuit fabricated in a U.S. foundry. The technology consists of layers of logic made with carbon nanotube-based transistors and nonvolatile memory layers of resistive random access memory that are stacked and vertically connected with vias. This technology may offer advanced performance without requiring access to leading-edge manufacturing facilities.

***Clinical trial of nanoparticle-based universal flu vaccine candidate***

**Volunteer receives experimental flu vaccine. Image credit: NIAID.**

*Influenza (flu) is a significant public health threat and a burden on global health systems. Each year, new flu vaccine variants must be developed and produced to match the evolving mix of flu virus strains predicted to be most prevalent during that year. NIH, academic, and industry scientists have been working for years on universal flu vaccines. One approach uses nanoparticle vaccine molecules that display only the conserved part of the viral spike and stimulate the production of antibodies to fight against the ever-changing flu virus. In 2019 that basic research moved closer to the clinic, with the initiation of the first clinical trial of a nanoparticle-based universal flu vaccine candidate. Scientists at NIAID's Vaccine Research Center developed the vaccine and are leading the clinical trial. If successful, a universal flu vaccine would be effective against any influenza strain, avoiding the need to predict specific outbreaks for the annual flu shot.*

NIST has a cooperative R&D agreement with industry to improve processes for substrate cleaning and die bonding needed for nanoscale device fabrication. NIST also developed and disseminated the Nanolithography Toolbox for use in industry and academia. This design software enables rapid design and layout of nanoscale devices and includes structure libraries for microelectromechanical systems (MEMS), nanoelectromechanical systems (NEMS), and nanophotonic devices.

**Advancing materials and optics**. AFRL is leading the development of cooperative partnerships between industry and national laboratories to establish synchrotron-based facilities to accelerate the establishment of processing-structure-property relationships for nanomaterials. These efforts, which include collaboration with DOE and NIST, have led to new insights and also support the goals of the Materials Genome Initiative. AFRL has also expanded the supplier base of nanocomposite optical ceramics through validation of NanoSpray Combustion℠ manufacturing.

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55 https://www.src.org/program/nri/
56 https://www.src.org/program/ncore/
57 https://www.darpa.mil/program/starnet
58 https://www.darpa.mil/program/joint-university-microelectronics-program

NIST developed a suite of fast, reliable laboratory methods for simulating scratch damage at the nano-, micro-, and macroscales on automobile clearcoat finishes. The suite of test methods provides an improved mechanistic understanding to enable the development of more durable and scratch–resistant coatings.

AFRL scientists and academic collaborators have developed and tested a hyperspectral filter made up of 3D plasmonic nanoarrays to detect human pathogens that are otherwise difficult to distinguish. These structured nanoscale metamaterial filters are more than 100 times smaller than conventional hyperspectral imaging optics and are being developed for Air Force space and airborne applications.

Researchers funded by NSF and DOE showed for the first time that a low-cost cobalt phosphide (CoP) catalyst can split water, and demonstrated the translation of the concept to commercial scale. The inexpensive catalyst was produced on a high-surface-area carbon support that could be integrated into an industrial polymer electrolyte membrane fabrication process. The CoP performance is stable under the harsh operating conditions of a traditional device and illustrates the potential of non-precious-metal catalysts for commercial hydrogen production.[59]

**Contributing to voluntary consensus standards**. U.S. leadership and participation in the development of international standards helps shape the strategic and technical direction of global nanotechnology development. Federal scientists collaborate with experts from U.S. industry and the international community to develop consensus standards that are technically robust, timely, and fit-for-purpose. NNI agencies participate in and lead standards efforts through organizations such as ASTM International, the International Electrotechnical Commission, and the International Organization for Standardization (ISO). The NNI Standards Coordinator works with NNI agencies engaged in nanotechnology standards development to facilitate information sharing and coordination. A representative from NIOSH chairs the U.S. Technical Advisory Group (TAG) responsible for formulating positions and proposals on behalf of the United States regarding ISO nanotechnology standardization activities.

Agency efforts in the standards development space often relate to mission-specific needs. For example, USDA/FS experts continue to participate in cellulose nanomaterials international standards development projects. An interagency agreement between NIH’s National Institute of Dental and Craniofacial Research and NIST supports development of performance-based, clinically relevant standards for dental materials, including nanomaterials. The FDA Nanotechnology Task Force established a subcommittee on nanotechnology standards to prioritize standards and liaise to relevant working groups in United States Pharmacopeia (USP) and the Organisation for Economic Co-operation and Development (OECD). The use of documentary standards can increase predictability, streamline premarket review, and facilitate market entry and use. In 2019, FDA’s Center for Devices and Radiological Health added five ASTM standards and four ISO standards to its list of recognized consensus standards for nanotechnology.

## Goal 3. Develop and Sustain Educational Resources, a Skilled Workforce, and a Dynamic Infrastructure and Toolset to Advance Nanotechnology

The research infrastructure includes physical equipment, digital models, simulations, and data, as well as resources for education and workforce development, and is critical to all of the NNI goals. One of the driving forces for establishing a national initiative in nanotechnology was the need for very expensive and specialized instrumentation and facilities for the fabrication and characterization of

[59] https://www.nature.com/articles/s41565-019-0550-7

nanomaterials. The development of new tools and methods to conduct breakthrough experiments has pushed the boundaries of science, and user facility access has been a hallmark of the NNI, with benefits reaching far beyond nanotechnology R&D. NNI agencies support advances in tool development, establishment of facilities, creation and dissemination of cyber resources, and educational and training programs through mechanisms such as individual grants, collaborative centers, and networks of user facilities.

**Expanding capabilities with development of new tools and techniques**. NIST developed novel processes of FIB nanofabrication that achieved sub-nanometer vertical resolution and generalized a method of achieving lateral super-resolution. These capabilities enable the rapid prototyping of complex nanostructures that perform metrology functions such as spatial calibration of optical microscopes and dimensional and optical characterization of colloidal nanoparticles. A multidisciplinary team supported by NSF and DOD has developed a new technique called variable temperature liquid-phase transmission electron microscopy. This technique enabled researchers to image for the first time nanoscale tubular materials while they are being formed.[60]

NIST installed and commissioned a superconductor transition-edge x-ray sensor array in the NIST Electron Beam Ion Trap spectrometer. The sensor array allows the instrument to make x-ray reference measurements with a resolution 40 times better than previously possible, enabling high-precision measurements of ionized gases in minutes instead of weeks. NIST also expanded capabilities at the National Synchrotron Light Source II (NSLS-II) at Brookhaven National Laboratory, supplementing the existing NIST “hard” x-ray beamline by commissioning two additional beamlines with “softer” x-rays. Once complete, nine end stations will take advantage of the unique broad and brilliant spectrum at NSLS-II to provide a world-leading suite of measurements of the atomic, molecular, and electronic structure of nanostructured materials. ONR utilized the Defense University Research Instrumentation Program to support the acquisition of equipment to support academic nanotechnology research, including a bioelectronics characterization suite for biohybrid devices and next-generation sequencing equipment to augment bionanotechnology research.

**Supporting user facilities and networks for research and development**. NSF supports the National Nanotechnology Coordinated Infrastructure. This university-based user facility network consists of 16 nodes and 13 partner sites providing access to 69 unique facilities and over 2,000 tools. In the fourth year of the NNCI, the network had over 13,350 unique users; ~29% were external users, including nearly 2,000 from industry, who collectively accumulated nearly 1,150,000 facility hours. These facilities provide access to cutting-edge tools and support the entire NNI ecosystem. For example, in year four of the NNCI, 5,754 funding sources were identified by users. NSF and industry accounted for the largest share (21.5% and 17.7%, respectively), with the balance made up of grants from DOD, NIH, DOE, NASA, USDA, and other sources. In addition to supporting research projects funded by other agencies that benefit from access to the equipment, the NSF investment is also leveraged by user fees (~$44 million/year) and support from other sources to purchase or update equipment ($87 million/year). The NSF-funded Nanotechnology Computational Network advances nanoscience and nanotechnology modeling, simulation, and networking through nanoHUB, a scientific end-to-end cloud computing environment. NanoHUB hosts over 3,000 resources for research, collaboration, teaching, learning, and publishing and served over a million users in 2019 in multiple domain networks.

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[60] https://pubs.acs.org/doi/10.1021/jacs.9b04586

***NNI infrastructure supports many national priorities***

*Investments in nanotechnology research infrastructure support many other national priorities, including advanced manufacturing, semiconductor R&D leadership, and the National Quantum Initiative. For example, DOE announced $30 million for research and new equipment to support quantum information science efforts at the NSRCs.[61] The NSF NNCI infrastructure also includes significant QIS capabilities, e.g., the NSF Center for Integrated Quantum Materials at Harvard relies on the nanoscale fabrication facilities at the Harvard NNCI node.[62] NIST facilities contributing to QIS and nanoelectronics/semiconductor research include the CNST NanoFab[63] and beamlines and specialized instrumentation at DOE's NSLS-II at Brookhaven National Laboratory.[64] NIST is upgrading its nanofabrication capabilities at NIST/Boulder (right),[65] which will also support QIS research.[66]*

**NIST/Boulder cleanroom showing specialized tools and facilities. Image credit: NIST.**

The Nanoscale Science Research Centers are DOE's premier user facilities for interdisciplinary research at the nanoscale. Each center has expertise and capabilities in selected theme areas, such as synthesis and characterization of nanomaterials; catalysis; theory, modeling, and simulation; electronic materials; nanoscale photonics; soft and biological materials; imaging and spectroscopy; and nanoscale integration. The centers have provided access to approximately 4,000 researchers from academia, industry, and government based on a peer-reviewed proposal system. The NIST Center for Nanoscale Science and Technology has continued to provide companies with access to state-of-the-art nanofabrication resources, and several DOD laboratories have adopted an open innovation posture enabling access to resources at their facilities.

**Growing the human infrastructure**. Many NNI agencies support nanotechnology education, training, and workforce development activities through a variety of existing mechanisms. NSF programs include research experiences for teachers and undergraduates as well as focused efforts for technicians through its Advanced Technological Education program.[67] The NNCI has a devoted associate director focused on education and outreach (E&O) efforts who coordinates across the network sites. The 16 sites have separate E&O programs, and collectively in year four of the NNCI, these efforts reached more than 66,000 people. Activities included classroom visits, teacher workshops, remote sessions, short courses, seminars, symposia, community events, booths at conferences, tours, and internships. The workforce development and community college working group of NNCI also held conversations to explore opportunities to leverage industry workforce efforts.[68] NNCO supports and amplifies NNI agencies' education and outreach efforts, hosts a series of podcasts, and facilitates communities of interest. Select highlights are on the inside back cover of this report.

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[61] https://www.energy.gov/articles/department-energy-invest-30-million-quantum-science-initiative
[62] http://ciqm.harvard.edu/facilities.html
[63] https://www.nist.gov/cnst
[64] https://www.nist.gov/news-events/news/2019/12/new-nist-beamlines-now-open-brookhaven-materials-research
[65] https://www.nist.gov/pml/quantum-electromagnetics/microfabrication/boulder-microfabrication-facility-tools-capabilities
[66] https://www.nist.gov/news-events/news/2017/09/nist-boulder-microfab-lab-goes-nano
[67] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5464
[68] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1939219&HistoricalAwards=false

## Goal 4. Support Responsible Development of Nanotechnology

Since the beginning of the NNI, responsible development has been a primary goal of the initiative. Responsible development of nanotechnology includes understanding and addressing both nanoEHS issues and potential ethical, legal, and societal implications (ELSI). A thorough understanding of nanoEHS considerations helps protect workers, consumers, and the environment. This knowledge also helps establish public confidence and regulatory certainty, facilitating the transition of nanotechnology innovations into the marketplace. Given the diversity of market segments where nanotechnology is being applied, well-coordinated nanoEHS research is vital to American innovation and economic competitiveness.

**Developing and disseminating information**. The NNI participating agencies have cumulatively supported over $1.3 billion in research on the potential EHS implications of nanotechnology since the initiative was established. This research forms a broad and robust body of knowledge to inform the responsible development of nanotechnology, and NNI agencies target current research activities to build on this foundational knowledge. The NIH/NIEHS National Toxicology Program recently completed an evaluation of the immune system impact of inhalation of multiwalled carbon nanotubes in rodent models to better understand the potential health effects from low-dose exposures in workers. This research complements exposure assessment of nanomaterial manufacturing facilities conducted in collaboration with NIOSH. NIST developed two computational tools to evaluate consumer exposure to airborne engineered nanoparticles. The first is an online tool that provides estimates of indoor occupant exposure to airborne particles. The second tool, referred to as the size-resolved tool, includes additional physical models that account for the properties of nanoparticles that may impact their transport within the built environment.[69]

NNCO and NNI agencies continue to prioritize the dissemination and incorporation of nanoEHS knowledge into practice. Mechanisms for sharing information include guidance documents and intelligence bulletins, peer-reviewed publications, and webinars. Examples of documents published in the last year include an FDA document entitled *Nanotechnology—Over a Decade of Progress and Innovation*[70] and two workplace posters from NIOSH to share information on 3D printing.[71]

**Developing protocols and methods.** NIST and CPSC collaboratively developed protocols and methodologies for characterizing size, morphology, and composition of ENMs released from floor coatings and paints by abrasion and/or weathering. NHIR consortium investigators developed the Scatter Enhanced Phase Contrast method, which provides a generalized label-free approach for monitoring nanoparticle transport in living cells. The technique works for a variety of metal and metal oxide nanoparticles and is expected to contribute to the design of next-generation drug delivery systems.

FDA continues to develop analytical methods for the characterization of nanomaterials in FDA-regulated products. Such methods will enable FDA to identify potential risks associated with products that contain nanomaterials and will provide guidance to sponsors/reviewers for the future approval of products. FDA also continues research to addresses fundamental data gaps and challenges associated with safety assessment of medical devices containing nanomaterials. Research efforts have been focused on evaluating and refining biological test methods, as well as investigating the interaction of

[69] https://pages.nist.gov/CONTAM-apps/
[70] https://www.fda.gov/media/140395/download
[71] https://www.cdc.gov/niosh/docs/2020-115/pdfs/2020-115.pdf?id=10.26616/NIOSHPUB2020115, https://www.cdc.gov/niosh/docs/2020-114/pdfs/2020-114.pdf?id=10.26616/NIOSHPUB2020114

pulsed lasers with plasmonic nanoparticles used in emerging optical diagnostic and therapeutic products.

**Understanding and mitigating potential impacts in the workforce.** NNI agencies support efforts to understand potential impacts in the workplace and protect workers as the introduction of nanomaterials and nanotechnology-enabled products accelerates into commerce. For example, NIOSH performs real-world evaluations of hazard and risk represented by various nanomaterials through their life cycles, including the characterization of aerosols generated in spray coating of paints, sealants, and disinfectants. Environmental chambers are used to evaluate a variety of nanotechnology-enabled construction materials in a controlled environment. NIOSH also has collaborated with national and international universities and numerous industrial partners in the characterization of toxicological effects of pulmonary and dermal exposure to a wide range of industrially relevant nanoparticles and nanotechnology-enabled materials.

Agencies participating in the NNI are actively engaging with industry to share nanoEHS knowledge and best practices. NIOSH has used its research findings to develop guidance documents and other communication tools to protect workers from occupational injury and illness. NIOSH representatives also have participated in numerous webinars and seminars, providing hundreds of workers and employers with information on how to work safely with nanomaterials and other advanced materials. NIOSH collaborates with industry to conduct voluntary on-site assessments of workplace exposures. Collaborating organizations gain access to NIOSH's expertise in nanomaterial characterization and exposure control technology. In 2019 NIOSH collaborated with 12 companies and completed 20 field assessments. Return visits to companies demonstrated that guidance was followed and exposure potential was reduced. NIOSH is also evaluating workplaces such as schools that are using 3D printers and is working with a printer manufacturer that is developing a local exhaust ventilation system for its newest model of fused filament fabrication printer.

**Leveraging efforts to address emerging concerns**. Through the years, the NNI agencies have worked together to develop a broad body of knowledge and supporting tools related to the nanoEHS implications of ENMs. This collaborative ecosystem is poised to apply the lessons learned from research on engineered nanomaterials to emerging incidental materials, including nanoscale plastic particles arising from the degradation of plastic waste in the environment. Agencies participating in the NNI proactively organized a series of interagency discussions, including a day-long meeting with 50 representatives from 14 agencies, of how the various agencies' responsibilities, interests, and capabilities align. The Federal community continues to collaborate and engage with external stakeholders to communicate shared needs and opportunities.

Many agency activities related to nanoplastics are focused on understanding the EHS implications of these materials. For example, agencies such as FDA, ATSDR, NCEH, USGS, and NIST are interested in the development of sampling and measurement protocols. NIST developed a measurement system that enables dimensional and optical metrology of single nanoparticles with record precision, accuracy, and efficiency, and that can inform the characterization of environmental nanoplastics. NIST also developed a method to characterize the concentration of metal, oxide, and plastic nanoparticles in water involving microdeposition of aqueous suspensions by inkjet printing. The measurement achieves a relative uncertainty that is an order of magnitude better than the benchmark method of microdroplet gravimetry. NSF is interested in fundamental scientific questions underlying nanoplastic characterization, behavior, and reactivity in the environment, including in relation to animal and human health. Additional efforts by DOE and NSF are focused on technologies to improve recycling and upcycling of plastics to minimize plastic waste.

**Collaborating internationally to accelerate progress.** The U.S. Government shares an interest in ensuring the safety of nanomaterials and nanotechnology-enabled products with regulatory and research agencies around the world. NNI agencies and NNCO share information with international counterparts through bilateral discussions and a variety of multilateral forums. For example, In September 2019, FDA co-organized the Global Summit on Regulatory Science (GSRS19) on Nanotechnology and Nanoplastics, in collaboration with the Joint Research Center, European Commission, in Stresa, Italy. Regulators and stakeholders from over 30 countries participated in the summit to identify research gaps and priorities in regulatory science for nanotechnology and nanoplastics, and to facilitate collaboration and harmonization across the globe. NNI agencies are also engaged with relevant international organizations working on nanoplastics research and round-robin testing. NNCO and the European Commission actively facilitate the U.S.-EU NanoEHS Communities of Research (CORs).[72] The seven thematic communities that compose the CORs have produced many tangible products and collaborations, such as the *EU-US Roadmap Nanoinformatics 2030*.[73]

***A vibrant, international nanoEHS community***

*The NNI has fostered the emergence of a dynamic and vibrant community that works to study and address the potential EHS implications of nanotechnology. Key platforms such as the U.S.-EU NanoEHS Communities of Research, NCIP Nanotechnology Working Group,[74] and European NanoSafety Cluster[75] help facilitate the open collaboration and communication that are the hallmarks of the nanoEHS ecosystem.[76] This community has developed an extensive body of knowledge and resources to help researchers, policymakers, and the public understand nanomaterial behavior, and how to successfully minimize potential risks. Examples of resources include the suite of tools for the environmental risk assessment for advanced materials developed by the Army[77] and control banding approaches for risk management developed by NIOSH[78] and DOE's Lawrence Livermore National Lab.[79] The community has also adapted quickly and applied knowledge gained to emerging issues, such as the presence of incidental plastic nanoparticles in the environment.[80] This thriving ecosystem is critical to ensuring the continued responsible development of nanotechnology.*

**2018 U.S.-EU nanoEHS COR workshop participants.**

[72] https://us-eu.org/communities-of-research/
[73] https://www.nanosafetycluster.eu/outputs/eu-us-roadmap-nanoinformatics-2030/
[74] https://ncihub.org/groups/nanowg
[75] https://www.nanosafetycluster.eu/
[76] https://doi.org/10.1038/s41565-019-0574-z
[77] https://nano.el.erdc.dren.mil/tools.html
[78] https://www.cdc.gov/niosh/docs/2019-132/default.html?s_cid=3ni7d2NIOSH-Update-2019-132-July2019
[79] https://controlbanding.llnl.gov/
[80] http://nas-sites.org/emergingscience/environmental-health-effects-of-microplastics/

## Appendix A. Abbreviations and Acronyms[81]

| | |
|---|---|
| **2D** | two-dimensional |
| **3D** | three-dimensional |
| **AFRI** | Agriculture and Food Research Initiative (USDA/NIFA) |
| **AFRL** | Air Force Research Laboratory |
| **AI** | artificial intelligence |
| **BES** | [Office of] Basic Energy Sciences (DOE) |
| **BIS** | Bureau of Industry and Security (DOC) |
| **CNST** | Center for Nanoscale Science and Technology (NIST) |
| **CNT** | carbon nanotube |
| **DARPA** | Defense Advanced Research Projects Agency |
| **EHS** | environment(al), health, and safety |
| **ENM** | engineered nanomaterial |
| **EU** | European Union |
| **GC** | grand challenge |
| **GOALI** | Grant Opportunities for Academic Liaison with Industry (NSF) |
| **HIV** | human immunodeficiency virus |
| **MOF** | metal-organic framework |
| **nanoEHS** | nanotechnology environment, health, and safety (research, etc.) |
| **NCI** | National Cancer Institute (HHS/NIH) |
| **NCNR** | NIST Center for Neutron Research |
| **NEHI** | Nanotechnology Environmental and Health Implications Working Group of the NSET Subcommittee |
| **NHIR** | Nanotechnology Health Implications Research consortium (NIH/NIEHS) |
| **NIEHS** | National Institute of Environmental Health Sciences (HHS/NIH) |
| **NKI** | Nanotechnology Knowledge Infrastructure (Nanotechnology Signature Initiative) |
| **NNCI** | National Nanotechnology Coordinated Infrastructure (NSF) |
| **NNCO** | National Nanotechnology Coordination Office |
| **NNI** | National Nanotechnology Initiative |
| **NRL** | Naval Research Laboratory |
| **NSET** | Nanoscale Science, Engineering, and Technology Subcommittee of the NSTC |
| **NSI** | Nanotechnology Signature Initiative |
| **NSRC** | Nanoscale Science Research Center (DOE) |
| **NSTC** | National Science and Technology Council |
| **OMB** | Office of Management and Budget (Executive Office of the President) |
| **ONR** | Office of Naval Research |
| **OSTP** | Office of Science and Technology Policy (Executive Office of the President) |
| **PCA** | Program Component Area of the National Nanotechnology Initiative |
| **QIS** | quantum information science |
| **R&D** | research and development |
| **SNA** | spherical nucleic acid |
| **SBIR** | Small Business Innovation Research Program |
| **STEM** | science, technology, engineering, and mathematics |
| **STTR** | Small Business Technology Transfer Research Program |

[81] See Table 1, p. 2, for abbreviations of NNI participating agencies not spelled out in this appendix.

# Appendix B. Contact List

**Affiliations are as of August 2020.**

**OSTP**

Dr. Lisa E. Friedersdorf
NSET Co-chair, EOP Liaison
Office of Science and Technology Policy
Executive Office of the President

Dr. Tracie Lattimore
Executive Director
National Science and Technology Council
Office of Science and Technology Policy
Executive Office of the President

**OMB**

Ms. Cassie L. Boles
Office of Management and Budget
Executive Office of the President

Ms. Danielle Jones
Office of Management and Budget
Executive Office of the President

Dr. William McNavage
Office of Management and Budget
Executive Office of the President

**NNCO**[82]

Dr. Lisa E. Friedersdorf
Director
National Nanotechnology Coordination Office
lfriedersdorf@nnco.nano.gov

Dr. Stacey Standridge
Deputy Director
National Nanotechnology Coordination Office
sstrandridge@nnco.nano.gov

**CPSC**

Dr. Joanna Matheson
Toxicologist - Nanotechnology
Program Manager, Nanotechnology
Health Sciences Directorate
Consumer Product Safety Commission
jmatheson@cpsc.gov

Dr. Treye Thomas
NEHI Co-chair, NSET Coordinator for EHS Research
Program Manager, Chemicals, Nanotechnology and Emerging Materials
Office of Hazard Identification & Reduction
Consumer Product Safety Commission
tthomas@cpsc.gov

**DHS**

Mr. Kumar Babu
Office of Research and Development
Science and Technology Directorate
Department of Homeland Security
kumar.babu@hq.dhs.gov

Dr. Angela Ervin
Science and Technology Directorate
Department of Homeland Security
Angela.Ervin@hq.dhs.gov

**DOC/BIS**

Ms. Kelly Gardner
Export Policy Advisor
Office of National Security and Technology Transfer Controls
Bureau of Industry and Security
U.S. Department of Commerce
kelly.gardner@bis.doc.gov

**DOC/ITA**

Ms. Tracy Gerstle
International Trade Specialist
Office of Materials Industries
International Trade Administration
U.S. Department of Commerce
Tracy.Gerstle@trade.gov

**DOC/NIST**

Dr. Heather M. Evans
Senior Program Analyst
Program Coordination Office
National Institute of Standards and Technology
heather.evans@nist.gov

Dr. R. David Holbrook
Leader, Nanomaterials Research Group
Materials Measurement Science Division
Material Measurement Laboratory
National Institute of Standards and Technology
Dave.holbrook@nist.gov

Dr. J. Alexander Liddle
Scientific Director
Microsystems and Nanotechnology Division
Physical Measurement Laboratory
National Institute of Standards and Technology
james.liddle@nist.gov

**DOC/USPTO**

Mr. Chris Hannon
Patent Attorney
Office of Policy & International Affairs
Patent and Trademark Office
Christian.hannon@uspto.gov

[82] Additional NNCO staff contacts are on p. 41.

Mr. Daniel Ryman
Senior Advisor to Deputy Commissioner for Patent Quality
Patent and Trademark Office
Daniel.ryman@uspto.gov

**DOD**

Dr. Jeffrey DePriest
New Technologies Program Manager
Counterforce Systems Division
Defense Threat Reduction Agency
jeffrey.c.depriest.civ@mail.mil

Dr. Eric W. Forsythe
Staff Physicist
Army Research Laboratory
eric.w.forsythe.civ@mail.mil

Dr. Mark H. Griep
Materials Engineer
Army Research Laboratory
mark.h.griep.civ@mail.mil

Dr. Akbar S. Khan
Senior Microbiologist & S&T Manager
Strategic Operations Division
Chemical Biological Technologies
Defense Threat Reduction Agency
akbar.s.khan.civ@mail.mil

Dr. JihFen Lei
Acting Director of Defense Research and Engineering for Research and Technology
Office of the Under Secretary of Defense for Research and Engineering
Department of Defense
jih-fen.lei.civ@mail.mil

Dr. Antti J. Makinen
NSET Co-chair
Program Officer
Office of Naval Research
antti.makinen@navy.mil

Dr. Heather Meeks
Physical Scientist
Basic & Supporting Research Div.
Defense Threat Reduction Agency
heather.meeks@dtra.mil

Dr. Brian D. Pate
Physical Scientist
Basic & Supporting Research Div.
Defense Threat Reduction Agency
brian.pate@dtra.mil

Dr. Gernot S. Pomrenke
Program Manager, Optoelectronics, THz and Nanotechnology
Directorate of Physics and Electronics
Air Force Office of Scientific Research
gernot.pomrenke@afosr.af.mil

Mr. Victor Pugliano
Director of Materials
Office of the Under Secretary of Defense for Research and Engineering
Department of Defense
victor.pugliano.civ@mail.mil

Dr. David M. Stepp
Chief, Materials Science Division
Army Research Office
AMSRD-ROE-M (Materials Science Division)
david.m.stepp.civ@mail.mil

**DOE**

Dr. Linda Horton
Associate Director of Science for Basic Energy Sciences
Department of Energy
linda.horton@science.doe.gov

Dr. Tina M. Kaarsberg
Advanced Manufacturing Office
Office of Energy Efficiency and Renewable Energy
Department of Energy
tina.kaarsberg@ee.doe.gov

Dr. Harriet Kung
Deputy Director for Science Programs
Office of Science
Department of Energy
harriet.kung@science.doe.gov

Dr. George Maracas
Division of Scientific User Facilities
Office of Basic Energy Sciences
Department of Energy
george.maracas@science.doe.gov

Dr. Andrew R. Schwartz
NSET Co-chair
Senior Technical Advisor for Energy Frontier Research Centers
Office of Basic Energy Sciences
Department of Energy
andrew.schwartz@science.doe.gov

**DOI/BSEE**

Dr. Candi Hudson
Response Research Branch Chief
Oil Spill Preparedness Division
Department of the Interior
Bureau of Safety & Environmental Enforcement
Candi.Hudson@bsee.gov

**DOI/USBR**

Yuliana E. Porras Mendoza
Desalination and Water Purification Research Program Manager
Advanced Water Treatment Research Coordinator, Science and Technology Program
Department of the Interior
U.S. Bureau of Reclamation
yporrasmendoza@usbr.gov

**DOI/USGS**

Dr. Jeffery A. Steevens
Research Toxicologist
Department of the Interior
U.S. Geological Survey
Columbia Environmental Research Center
jsteevens@usgs.gov

**DOJ/NIJ**

Dr. Mark Greene
Policy and Standards Division Director
Office of Science and Technology
National Institute of Justice
Department of Justice
Mark.Greene@ojp.usdoj.gov

**DOL/OSHA**

Dr. Janet Carter
Senior Health Scientist
Department of Labor
Occupational Safety and Health Administration
carter.janet@dol.gov

**DOS**

Dr. Meg Flanagan
Foreign Affairs Officer
Office of Science and Technology Cooperation
Department of State
FlanaganML@state.gov

Dr. Andreea Paulopol
Physical Scientist
Bureau of Arms Control, Verification and Compliance
Department of State
PaulopolAI@state.gov

Dr. Maher Tadros
Physical Scientist
Bureau of Arms Control, Verification and Compliance
Department of State
TadrosME@state.gov

**DOT**

Dr. Jonathan Porter
Chief Scientist, Office of Research, Development, and Technology
Federal Highway Administration
Department of Transportation
Turner-Fairbank Highway Research Center
jonathan.porter@dot.gov

**Treasury**

Dr. Rodney P. Feazell
Technology Integration Division Manager
Bureau of Engraving and Printing
Office of Technology Development
Department of the Treasury
Rodney.Feazell@bep.gov

**EPA**

Dr. Jeffrey B. Frithsen
National Program Director
Chemical Safety for Sustainability Research Program
Office of Research and Development
Environmental Protection Agency
Frithsen.Jeff@epa.gov

**FDA**

Dr. Anil K. Patri
Chair, Nanotechnology Task Force
Director, NCTR-Office of Regulatory Affairs Nanotechnology Core Facility
National Center for Toxicological Research
Food and Drug Administration
anil.patri@fda.hhs.gov

**NASA**

Dr. Tiffany S. Williams
NASA Glenn Research Center
Materials and Structures Division
Tiffany.S.Williams@nasa.gov

**NIH/FIC**

Dr. Christine F. Sizemore
Director, Division of International Relations
Fogarty International Center
National Institutes of Health
christine.sizemore@nih.gov

**NIH/NCI**

Dr. Piotr Grodzinski
Chief, Nanodelivery Systems and Devices Branch (NSDB)
Cancer Imaging Program
Division of Cancer Treatment and Diagnosis
National Cancer Institute
National Institutes of Health
grodzinp@mail.nih.gov

Dr. Lori Henderson
Program Director, Clinical Investigations Branch, Cancer Therapy Evaluation Program
Division of Cancer Treatment and Diagnosis
National Cancer Institute
National Institutes of Health
hendersonlori@mail.nih.gov

**NIH/NHLBI**

Dr. Denis Buxton
Basic and Early Translational Research Program, DCVS
National Heart, Lung, and Blood Institute
National Institutes of Health
buxtond@nhlbi.nih.gov

**NIH/NIBIB**

Dr. Steven Zullo
Scientific Review Officer
Office of Scientific Review
National Institute of Biomedical Imaging and Bioengineering
National Institutes of Health
steven.zullo@nih.hhs.gov

**NIH/NIEHS**

Dr. Sheila Newton
Director, Office of Policy, Planning & Evaluation
National Institute of Environmental Health Sciences
National Institutes of Health
Sheila.Newton@nih.hhs.gov

Dr. Nigel Walker
Chief, Toxicology Branch
Division of the National Toxicology Program
National Institute of Environmental Health Sciences
National Institutes of Health
Nigel.Walker@nih.hhs.gov

**NIH/OD**

Dr. Tyrone Spady
Director, Science Policy Coordination, Collaboration, and Reporting
Office of Science Policy
Office of the Director
National Institutes of Health
tyrone.spady@nih.gov

**NIOSH**

Dr. Charles L. Geraci, Jr.
Associate Director for Emerging Technologies
National Institute for Occupational Safety and Health
cgeraci@cdc.gov

Ms. Laura Hodson
Coordinator, NIOSH Nanotechnology Research Center
National Institute for Occupational Safety and Health
gey7@cdc.gov

Dr. Vladimir V. Murashov
Special Assistant to the Director
Office of the Director
National Institute for Occupational Safety and Health
vladimir.murashov@cdc.hhs.gov

**NRC**

Ms. Louise Lund
Director, Division of Engineering
Agency Standards Executive
Office of Nuclear Regulatory Research
Nuclear Regulatory Commission
Louise.Lund@nrc.gov

**NSF**

Dr. Khershed Cooper
Program Director, Advanced Manufacturing
Division of Civil, Mechanical and Manufacturing Innovation
Directorate for Engineering
National Science Foundation
khcooper@nsf.gov

Dr. Lawrence S. Goldberg
Senior Advisor
Division of Electrical, Communications & Cyber Systems
Directorate for Engineering
National Science Foundation
lgoldber@nsf.gov

Dr. Fred Kronz
Program Director, Division of Science, Technology, and Society
Directorate for Social, Behavioral, and Economic Sciences
National Science Foundation
fkronz@nsf.gov

Dr. Lynnette D. Madsen
Program Director, Division of Materials Research
Directorate for Mathematical and Physical Sciences
National Science Foundation
lmadsen@nsf.gov

Dr. Mihail C. Roco
Senior Advisor for Nanotechnology
Directorate for Engineering
National Science Foundation
mroco@nsf.gov

Dr. Nora F. Savage
Program Director, Division of Chemical, Bioengineering, Environmental, and Transport Systems
Directorate for Engineering
National Science Foundation
nosavage@nsf.gov

Dr. Charles Ying
Program Director
Division of Materials Research
Directorate for Mathematical and Physical Sciences
National Science Foundation
cying@nsf.gov

**USDA/ARS**

Dr. Gene E. Lester
National Program Leader, Product Quality, New Uses, and Bioprocessing
Agricultural Research Service
U.S. Department of Agriculture
gene.lester@usda.gov

Dr. James Lindsay
National Program Leader, Food Safety and Health
Agricultural Research Service
U.S. Department of Agriculture
james.lindsay@usda.gov

**USDA/FS**

Dr. World Nieh
National Program Leader, Forest Products and Wood Utilization
U.S. Forest Service
U.S. Department of Agriculture
world.nieh@usda.gov

**USDA/NIFA**

Dr. Hongda Chen
National Program Leader, Bioprocess Engineering/Nanotechnology
National Institute of Food and Agriculture
U.S. Department of Agriculture
hongda.chen@usda.gov

**USITC**

Ms. Elizabeth R. Nesbitt
International Trade Analyst for Biotechnology and Nanotechnology
Chemicals and Textiles Division
Office of Industries
U.S. International Trade Commission
elizabeth.nesbitt@usitc.gov

**Additional Staff Contacts, National Nanotechnology Coordination Office (NNCO)**

Dr. Rhema Bjorkland
Staff Scientist
NNCO
rbjorkland@nnco.nano.gov

Dr. Maria Fernanda Campa
Staff Scientist
NNCO
mcampa@nnco.nano.gov

Dr. Mallory Hinks
Staff Scientist
NNCO
mhinks@nnco.nano.gov

Mr. Geoffrey M. Holdridge
NSET Executive Secretary
NNCO
gholdridge@nnco.nano.gov

Dr. Jaclyn Kellon
AAAS S&T Policy Fellow
NNCO
jkellon@nnco.nano.gov

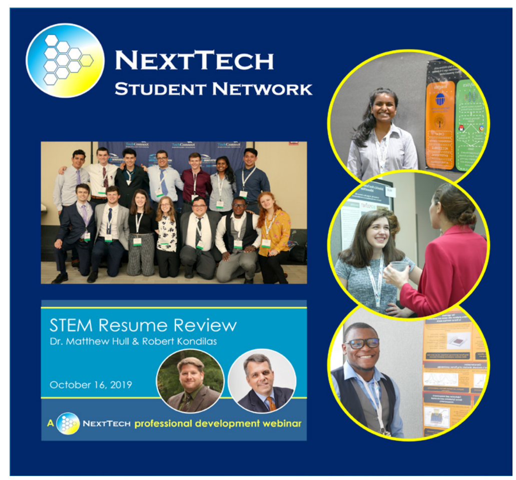
Mr. Mike Kiley
Industry Liaison
NNCO
mkiley@nnco.nano.gov

Dr. Patrice Pages
Communications and Public Affairs Liaison
NNCO
ppages@nnco.nano.gov

# Public Outreach to Students, Teachers, the General Public, and the NNI Community through:

The NNI family of podcasts





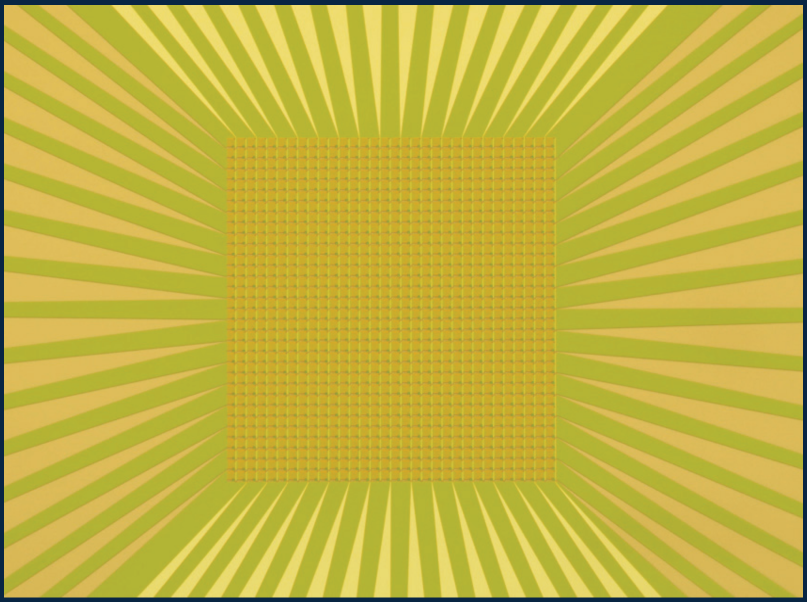


Left – The NNI family of podcasts (nano.gov/podcasts)

- Stories from the NNI – experts share their perspectives on advances that have been made and future prospects of nanotechnology.
- Nano Matters – explores specific examples of nanotechnology and how it impacts everyday life.
- Nano Entrepreneurship Network (NEN) – brings new and seasoned entrepreneurs together with the people and resources available to support them and highlights best practices, resources, and advice from entrepreneurs.

Right

- National Nanotechnology Day on October 9 (nano.gov/nationalnanotechnologyday).
- NextTech Student Network (nexttechnetwork.org).
- Webinars to share information with the general public and the nanotechnology research and development community (nano.gov/PublicWebinars).



Superconducting nanowire single photon detectors (SNSPDs)
Image credit: V. Verma/NIST. See inside front cover.

National Nanotechnology Coordination Office
2415 Eisenhower Avenue, Alexandria, Virginia  22314