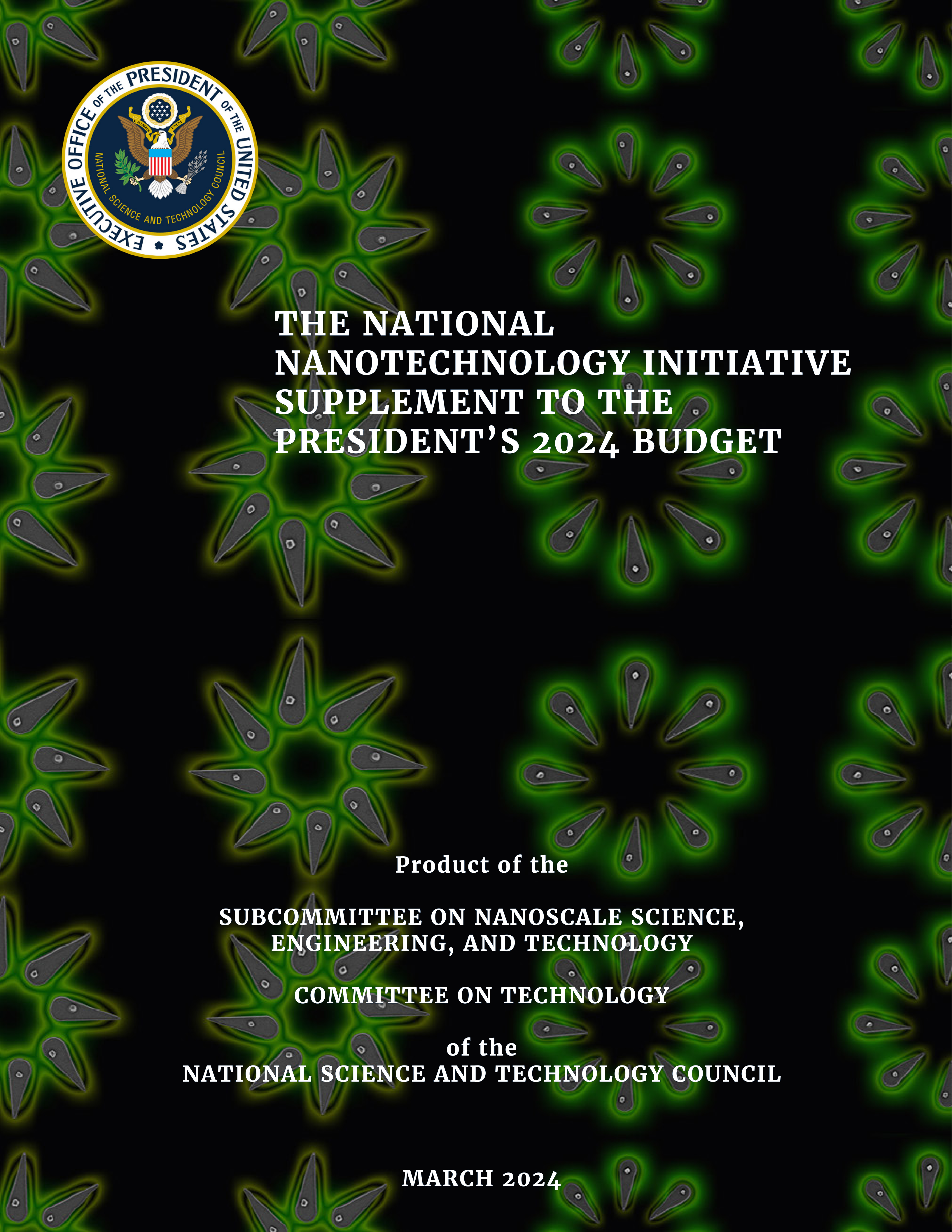

EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

THE NATIONAL NANOTECHNOLOGY INITIATIVE SUPPLEMENT TO THE PRESIDENT'S 2024 BUDGET

Product of the

SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

COMMITTEE ON TECHNOLOGY

of the
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

MARCH 2024

About the Office of Science and Technology Policy

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

About the National Science and Technology Council

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. More information is available at www.whitehouse.gov/ostp/nstc.

About the Subcommittee on Nanoscale Science, Engineering, and Technology

The Subcommittee on Nanoscale Science, Engineering, and Technology (NSET) contributes to the activities of NSTC's Committee on Technology. NSET's purpose is to advise and assist the NSTC and OSTP on policies, procedures, and plans related to the goals of the National Nanotechnology Initiative (NNI). As such, and to the extent permitted by law, the NSET Subcommittee defines and coordinates federal efforts in support of the goals of the NNI and identifies policies that will accelerate deployment of nanotechnology. NSET also tracks national priority needs that would benefit from the NNI, identifies extramural activities that connect to NNI goals, and explores ways the federal government can advance the development of nanotechnology. More information is available at https://www.nano.gov/.

About this document

This document is a supplement to the President's 2024 Budget request submitted to Congress on March 9, 2023, 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 about the NNI is available on the NNI website, www.nano.gov.

About the cover

Outside Covers: The front cover includes a scanning electron microscope image of halide perovskite crystals grown directly onto surfaces with precise alignment, enabling the fabrication of nanoscale light-emitting diodes (nanoLEDs). The image was initially taken by the Farnaz Niroui Group at MIT, then rendered by a graphic artist to make the final cover art. Credit: Sampson Wilcox, Research Laboratory of Electronics at MIT. The back cover is an electroluminescent image of the nanoLED arrays in operation taken with an optical microscope, where the crystals are not visible at this resolution, but their light emission is visible. Credit: the Farnaz Niroui Group at MIT. The shapes of the wells in which the crystals are grown are designed to precisely control the crystals' sizes and positions. This novel fabrication technique is scalable, versatile, and compatible with conventional fabrication steps, enabling integration of the nanocrystals into functional nanoscale devices. Potential applications include light-emitting diodes, lasers, on-chip quantum light sources, photodetectors, and memristors. The work was supported by NSF and used facilities of NSF's National Nanotechnology Coordinated Infrastructure (NNCI). For more information see: https://news.mit.edu/2023/researchers-grow-precise-arrays-nanoleds-0706 and https://doi.org/10.1038/s41467-023-39488-0. **Inside Back Cover:** The inside face of the back cover is a collage of images illustrating examples of NNI outreach activities. Collage content and design is by Patrice Pages and Kristin Roy of the National Nanotechnology Coordination Office (NNCO).

Acknowledgements and copyright information

The report was assembled and edited by Geoffrey Holdridge of NNCO. Cover design is by Kristin Roy of NNCO. Book design is by the NNCO staff.

Published in the United States of America, 2024.

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Thomas Libert
William McNavage

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Akbar Khan
Antti J. Makinen
Heather Meeks
Brian D. Pate
Gernot S. Pomrenke
Victor Pugliano
David M. Stepp

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

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

Department of Health and Human Services (HHS)

Agency for Toxic Substances and Disease Registry (ATSDR); National Center for Environmental Health (NCEH)
Custodio V. Muianga
Max Zarate-Bermudez

Biomedical Advanced Research and Development Authority (BARDA)
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Heather Hill

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Annette Guiseppi-Elie

International Trade Commission (USITC)[†]
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Tiffany S. Williams

National Science Foundation (NSF)
Khershed Cooper
Fred Kronz
Richard Nash
Mihail C. Roco
Nora Savage
Birgit Schwenzer

Nuclear Regulatory Commission (NRC)[†]
Steve Ruffin

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

Table of Contents

Abbreviations and Acronyms[1]

2D	two-dimensional
3D	three-dimensional
AFOSR	Air Force Office of Scientific Research
AFRI	Agriculture and Food Research Initiative (USDA/NIFA)
AFRL	Air Force Research Laboratory
AI	artificial intelligence
ARL	Army Research Laboratory
ARO	Army Research Office
ATE	Advanced Technology Education (NSF)
BES	[Office of] Basic Energy Sciences (DOE)
CCI	Center for Chemical Innovation (NSF)
CDER	Center for Drug Evaluation and Research (FDA)
CFSAN	Center for Food Safety and Applied Nutrition (FDA)
CNC	cellulose nanocrystal
CNST	Center for Nanoscale Science and Technology (NIST)
CNT	carbon nanotube
CREST	Center for Research Excellence (NSF)
DARPA	Defense Advanced Research Projects Agency
DMREF	Designing Materials to Revolutionize and Engineer our Future (NSF)
EHS	environment(al), health, and safety
ELSI	ethical, legal, and other societal implications
ENG	[Directorate for] Engineering (NSF)
ENM	engineered nanomaterial
ERC	Engineering Research Center (NSF)
FECM	[Office of] Office of Fossil Energy and Carbon Management (DOE)
I-Corps	Innovation Corps (program)
IDEA	inclusion, diversity, equity, and access
ISN	Institute for Soldier Nanotechnologies (Army)
ISO	International Organization for Standardization
LED	light-emitting diode
LNP	lipid nanoparticle
MGI	Materials Genome Initiative
ML	machine learning
mRNA	messenger RNA
MRSEC	Materials Research Science and Engineering Center (NSF)
nanoEHS	nanotechnology environment, health, and safety (research, etc.)
NCI	National Cancer Institute (NIH)
NCL	Nanotechnology Characterization Laboratory (NIH)
NCTR	National Center for Toxicological Research (FDA)
NE	[Office of] Nuclear Energy (DOE)
NEHI	Nanotechnology Environmental and Health Implications (Working Group)
NIAID	National Institute of Allergy and Infectious Diseases (NIH)
NIBIB	National Institute of Biomedical Imaging and Bioengineering (NIH)
NIDCR	National Institute of Dental and Craniofacial Research (NIH)
NIEHS	National Institute of Environmental Health Sciences (NIH)
NNC	National Nanotechnology Challenge
NNCI	National Nanotechnology Coordinated Infrastructure (NSF)
NNCO	National Nanotechnology Coordination Office
NNI	National Nanotechnology Initiative
NRL	Naval Research Laboratory
NSE	nanoscale science and engineering
NSET	Nanoscale Science, Engineering, and Technology Subcommittee of the NSTC
NSRC	Nanoscale Science Research Center (DOE)
NSTC	National Science and Technology Council
OECD	Organisation for Economic Co-operation and Development
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)
OUSD/R&E	Office of the Under Secretary of Defense for Research and Engineering

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

PCA	Program Component Area of the National Nanotechnology Initiative
PFAS	per- and polyfluoroalkyl substances
QIS	quantum information science
R&D	research and development
RADx-rad	Rapid Acceleration of Diagnostics-Radical (NIH initiative)
SBIR	Small Business Innovation Research program
SC	Office of Science (DOE)
SEM	scanning electron microscope
STC	Science and Technology Center (NSF)
STEM	science, technology, engineering, and mathematics
STRI	Space Technology Research Institute (NASA)
STTR	Small Business Technology Transfer Research program
TEM	transmission electron microscope
US-COMP	Ultra-Strong Composites by Computational Design (NASA STRI)

Executive Summary

The Biden-Harris Administration is working to leverage the power of science and technology, including nanotechnology, to benefit everyone in America. Nanotechnology—the understanding and control of matter at the level of atoms and molecules where unique phenomena enable novel applications—has led to revolutions in aerospace, agriculture, infrastructure, clean energy, water purification, consumer electronics, faster microchips, powerful mRNA vaccines, and more. Nanotechnology plays a role in combating climate change, delivering robust health outcomes, ensuring America’s national and economic security, providing food safety and abundance, and providing access to clean water. The President’s 2024 Budget requests $2.16 billion for the National Nanotechnology Initiative (NNI), totaling over $43 billion since the inception of the NNI in 2001.[2,3] This highest-ever request reflects the United States’ global leadership in the fundamental understanding and control of matter at the nanoscale.

Nanotechnology underpins technologies of the future, including energy-efficient artificial intelligence and edge computing, microelectronics, quantum information science, biotechnology, and advanced manufacturing. NNI investments in foundational nanoscale science, research infrastructure, and education support efforts to renew U.S. leadership in the semiconductor and microelectronics industries under the CHIPS and Science Act of 2022.

The NNI investments in 2022 and 2023 and those proposed in 2024 include strong support for broad, fundamental research in nanoscience, and increased funding for research on applications, devices, and systems in support of national priorities. The President’s Budget includes nanotechnology investments that will harness the full diversity of America’s research and development (R&D) community to advance the progress of the NNI to drive a world-class research portfolio, facilitate commercialization of nanotechnology-enabled applications, develop and sustain a dynamic infrastructure and skilled workforce, and ensure responsible development of nanotechnology for the benefit of all Americans.

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[2] With the approval by Congress of fiscal year 2001 appropriations, including increased funding for nanotechnology. The NNI was formally authorized in the 21st Century Nanotechnology Research and Development Act of 2003.

[3] References to years in this report are to fiscal years unless otherwise noted.

What is Nanotechnology?

Nanotechnology encompasses science, engineering, and technology at the atomic, molecular, and supramolecular level with the aim of creating materials, devices, and systems with fundamentally new molecular organization, properties, and functions. This level of understanding and precision is referred to as the nanoscale, a size range that gets its name from a nanometer, which is one-billionth of a meter. Nanoscale materials 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 represents the cutting edge of most scientific disciplines and therefore has broad application across many R&D priorities such as energy-efficient artificial intelligence, microelectronics, quantum information science, biotechnology, and advanced manufacturing. Nanotechnology innovations are ensuring renewed U.S. leadership in the microelectronics industry and in advanced computing and communications, and are fueling progress on many other national priorities, including global security and stability, meeting the challenge of the climate crisis, achieving better health outcomes, and ensuring future economic competitiveness.

Examples of nanotechnology innovations are illustrated below: (a) a nanoparticle-coated sponge that can remove toxic heavy metals and critical minerals from water; (b) triboelectric nanogenerators made from MXene and a graphene foam nanocomposite that can perform on human skin or the leaf of a plant; (c) a faster way to study two-dimensional materials, aided by artificial intelligence analysis, for next-generation quantum and electronic devices; (d) a novel pathway for creating stronger metals by understanding how crystal grains form during extreme deformation processes; (e) a new method to control electron spin, paving the way for efficient quantum computers; and (f) nanoscale “tattoos” to track the health of individual cells.

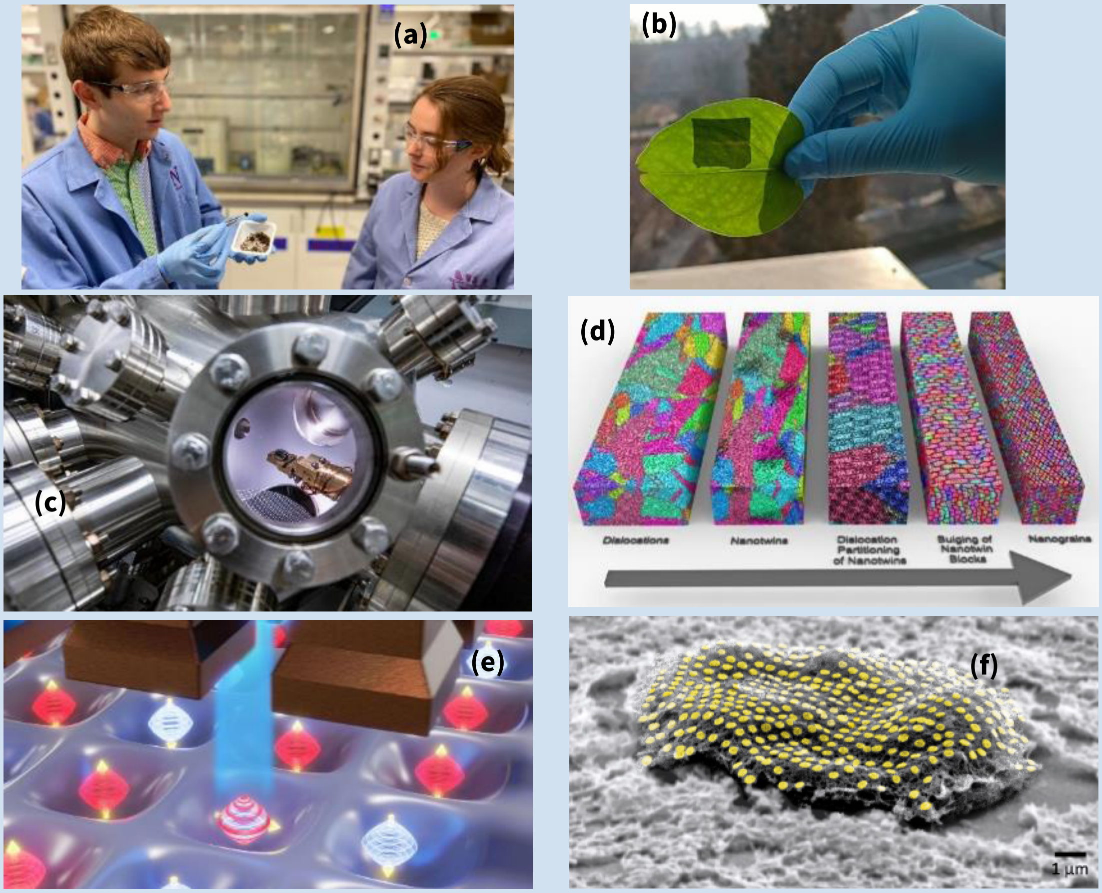

Image credits: (a) Northwestern University; (b) Penn State University; (c) DOE/Berkeley Lab, University of Central Florida, Penn State University; (d) Massachusetts Institute of Technology; (e) University of Rochester; (f) Johns Hopkins University. For more information on nanotechnology benefits and applications, please visit https://www.nano.gov/about-nanotechnology/applications-nanotechnology.

1. Introduction

About the National Nanotechnology Initiative

The National Nanotechnology Initiative (NNI) is a U.S. government research and development (R&D) initiative involving 20 federal departments, independent agencies, and commissions working together toward the shared vision of *a future in which the ability to understand and control matter at the nanoscale leads to ongoing revolutions in technology and industry that benefit society*. The NNI establishes national shared goals, priorities, and strategies to enhance global leadership through interagency coordination of nanotechnology R&D. This work builds on agency-specific missions and activities, and leverages resources while avoiding duplication. It also supports an extensive nanotechnology research infrastructure (including user facilities and multidisciplinary research centers) that facilitates the work of America's scientists, engineers, and entrepreneurs in many other fields of science and technology. Table 1 lists the agencies currently participating in the NNI.

The NNI contributes to multiple Administration and national priorities.[4] For example, in the areas of artificial intelligence (AI) and autonomous systems, the NNI is funding research on specialized hardware accelerators for AI (e.g., memristors that can act as artificial synapses[5]), low-power computing devices to reduce the drain of AI applications on our nation's energy supplies, and physically unclonable functions enabled by nanomaterials and devices to improve cybersecurity and trustworthiness.[6] As documented in this report, nanotechnology contributes to America's national security in many ways, enabling advances in a wide variety of critical and emerging technologies. In particular, NNI research, infrastructure, and workforce development efforts are foundational to achieving the goals of the CHIPS and Science Act of 2022 (Public Law 117-167), which are vital to both national and economic security.

The NNI is contributing to addressing the threats of climate change through the new National Nanotechnology Challenge, Nano4EARTH, coordinating research across the agencies on interfacial technologies (e.g., for reducing friction), novel energy storage technologies, greenhouse gas capture, and improved catalysis.[7] NNI funding for nanotechnology health research has reached an all-time high. This includes over $800 million in annual investments by NIH alone (along with other important contributions from FDA, CDC, BARDA and basic research agencies, e.g., NSF and DOE), as nanotechnology-enabled diagnostic and therapeutic technologies for a wide variety of human health threats, from cancer to antimicrobial resistance, per- and polyfluoroalkyl substances (PFAS), and many others, successfully compete for funding. This document includes selected examples of how the NNI participating agencies are harnessing nanotechnology R&D and education programs to reduce barriers and inequities, from workforce development to economic progress in historically underserved communities. NNI participating agencies support applied research, experimental development, pre-commercialization, and standards-related efforts that build the nation's economic competitiveness, facilitating the adoption of a wide range of nanotechnologies, and helping create good-paying jobs across the country, including in both traditional and emerging industries.

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[4] https://www.whitehouse.gov/wp-content/uploads/2023/08/FY2025-OMB-OSTP-RD-Budget-Priorities-Memo.pdf

[5] https://doi.org/10.1038/s41928-022-00869-w

[6] https://doi.org/10.1038/s41928-021-00569-x

[7] https://www.nano.gov/nano4EARTH; see examples of Nano4EARTH activities and progress beginning on p. 47.

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)
    - Biomedical Advanced Research and Development Authority (BARDA)*
    - 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 (State)
- 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 in Table 5 below.
† Denotes an independent commission that is represented on NSET but is non-voting.

The foundational nanotechnology research funded under the NNI continues to strengthen and advance America’s global leadership in science and technology, and the NNI’s research infrastructure provides free or affordable access to state-of-the art facilities and expertise that push the boundaries of science at the nanoscale. This report describes nanotechnology research accomplishments funded under the NNI, reviews plans for future R&D initiatives by the participating agencies, and provides a directory of program managers and other points of contact at NNI participating agencies—thus enhancing transparency and public access to federally funded programs and research results, and assisting emerging research institutions to compete for federal funding.

The NNI supports research across the spectrum from early-stage fundamental science to applications-driven R&D. It also provides research infrastructure and educational and workforce development activities (from K-12 through postgraduate research training) that are critical to many other areas of science and technology (e.g., microelectronics). The NNI serves as a model for the responsible development of emerging technologies; the purposeful coordination of interagency R&D efforts allows laboratory breakthroughs to be explored as promising technologies while investigations into their safe use are being performed in parallel. In 2023, NNI participating agencies are engaged in a concerted effort to update and refresh the 2011 NNI Environmental Health and Safety (EHS) Research Strategy.

Under the auspices of the NNI, multiple agencies work together to leverage their respective knowledge and resources, creating a program that is greater than the sum of the individual agency activities. The NNI works with academia and the private sector to promote technology transfer and facilitate commercialization, which is proceeding at an accelerating pace. Thanks in part to the NNI, nanotechnology generated approximately $42 billion in revenue in 2017, from over 3,700 U.S. companies conducting nanotechnology R&D alone.[8] Strategic collaborations, including with public-private partnerships, nongovernmental organizations, and international allies and partners, help to promote progress in nanoscale science, engineering, and technology; inclusion, diversity, equity, and access (IDEA) in the distribution of the benefits of nanotechnology; and the responsible development of nanotechnology.

All of these NNI activities are coordinated by the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council (NSTC).[9] The members of NSET also financially support the National Nanotechnology Coordination Office (NNCO), which plays an essential role in NSET activities, facilitating interagency communication and collaborations, communicating with the broader nanotechnology community, and promoting international partnerships. Per the 21st Century Nanotechnology R&D Act, NNCO provides technical and administrative support to the NSET Subcommittee (e.g., preparing this report); serves as the central point of contact for the NNI; conducts public outreach on behalf of the NNI (e.g., hosting the NNI's public website, Nano.gov); and promotes access to and early application of the technologies, innovations, and expertise arising from the NNI for the benefit of the nation. In recent years, NNCO has also played a particularly important role in advancing multidisciplinary nanotechnology education and workforce development activities. Each year NNI participating agencies review and approve the NNCO budget and voluntarily contribute to its funding.

External Reviews of the NNI

The NNI was reviewed in 2023 by the President's Council of Advisors on Science and Technology (PCAST), in its capacity as the National Nanotechnology Advisory Panel, as called for in the 21st Century Nanotechnology R&D Act. The PCAST report[10] includes three recommendations for updating federal government coordination and support for nanotechnology, reflecting the success of the NNI and the maturity and broad relevance of the field, that: (1) *the President work with Congress to sunset or substantially revise the 21st Century Nanotechnology Research & Development Act*; (2) *the Director of the Office of Science and Technology Policy (OSTP) work with the Executive Director of the National Science*

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[8] https://www.nano.gov/node/5257

[9] See the list of agencies and their representatives participating in the NSET Subcommittee in the front matter of this report.

[10] https://www.whitehouse.gov/wp-content/uploads/2023/08/PCAST_NNI_Review_August2023.pdf

and Technology Council (NSTC) to direct the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee to continue leadership for federal coordination of nanotechnology strategic planning, implementation, and outreach; and (3) *the NSET Subcommittee enhance experiential learning programs for nanotechnology students and scientists to create the collaborative, multi-disciplinary workforce needed for nanotechnology and other advanced technologies*. In consultation with OSTP and the Office of Management and Budget (OMB), the NNI participating agencies are considering actions to implement PCAST's recommendations.

The National Academies of Science, Engineering, and Medicine are commencing an additional review of the NNI in 2024, also in accordance with the Act.

Outline of this Report

Chapter 2 of this report is an overview of the budgets for nanotechnology R&D for 2022 (actual), 2023 (estimated), and 2024 (requested), as well as funding amounts and examples of nanotechnology R&D topics funded under the Small Business Innovation Research (SBIR) and Small Business Technology Transfer Research (STTR) programs. Chapter 3 presents examples of individual agency and collective NNI progress toward the goals set out in the 2021 NNI Strategic Plan[11] and highlights of agency plans and priorities by Program Component Area (PCA).[12] Contact information for agency representatives to the NSET Subcommittee and for NNCO staff is provided in Appendix A.

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[11] https://www.nano.gov/sites/default/files/pub_resource/NNI-2021-Strategic-Plan.pdf

[12] PCA definitions are posted on Nano.gov at https://www.nano.gov/pcadefinitions.

2. NNI Budget

Budget Summary

The President's 2024 Budget requests an all-time record of $2.16 billion for the NNI, with a sustained investment in foundational research that will fuel new discoveries, and increasing investments in application-driven R&D to advance technologies of the future and address national priorities. Cumulative NNI funding since its inception in 2001 totals over $43 billion (including the 2024 request); Figure 1 shows the funding trends over time. Table 2 shows total NNI funding by agency for fiscal years 2022 through 2024. NNI investments support research to understand matter at the nanoscale and to translate this knowledge into technological breakthroughs that benefit all Americans. The NNI investments in 2022 and 2023 and those proposed for 2024 reflect a continued emphasis on fundamental research in nanoscience; research to advance applications, devices, and systems; and support for the responsible development of nanotechnology. NNI agencies also support significant investments in research infrastructure, developing new research tools, and making these tools available through user facilities, as well as science, technology, engineering, and mathematics (STEM) education to prepare the workforce of the future. 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 OMB, OSTP, and Congress. NNI agencies collaborate closely—facilitated through the NSET Subcommittee, its Nanotechnology Environmental and Health Implications (NEHI) Working Group, several informal communities of interest, 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.

This document reports agency investments using existing appropriations, as well as supplemental funding. Major supplemental funding in 2020–2022 (shown in Figure 1 below) by the Biomedical Advanced Research and Development Authority related to the SARS CoV-2 pandemic is particularly noteworthy.

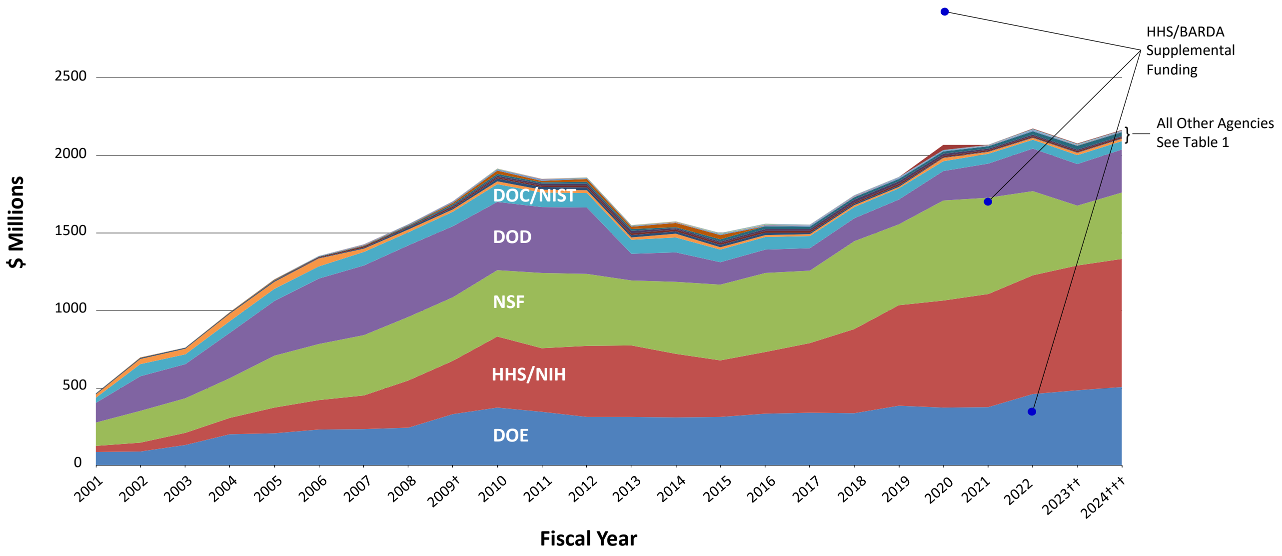

Figure 1. NNI Funding by Agency, 2001–2024.*

* 2021–2023 figures include supplemental funding. BARDA supplemental investments (blue dots) not included in line graph totals.

† 2009 figures do not include American Recovery and Reinvestment Act funds for DOE, NSF, NIH, and NIST.

†† 2023 numbers are based on appropriated levels.

††† 2024 Budget.

Table 2: NNI Budget, by Agency, 2022–2024
(dollars in millions)

Agency	2022 Actual	2023 Estimated*	2024 Proposed
CPSC	0.2	0.4	0.04
DOC/NIST	56.3	55.8	55.2
DOD**	274.1	268.7	276.2
DOE***	460.3	484.8	506.5
DOI/USBR	0.3	0.3	0.0
DOJ/NIJ	2.3	1.8	1.8
DOT/FHWA	0.0	0.2	0.5
EPA	4.1	4.2	2.8
HHS (total)	1134.0	824.5	844.9
BARDA	352.1	2.1	2.1
FDA	7.9	7.7	7.9
NIH	764.7	805.5	825.7
NIOSH	9.2	9.2	9.2
NASA	11.6	16.0	13.8
NSF	545.1	384.0	428.3
USDA (total)	32.9	33.3	33.7
ARS	5.0	5.0	5.0
FS	5.7	5.7	5.7
NIFA	22.2	22.6	23.0
TOTAL[†]	**2521.1**	**2073.9**	**2163.6**

* 2023 numbers are based on appropriated levels.

** Funding levels for DOD include the combined budgets of the Air Force, Army, Navy, Defense Advanced Research Projects Agency, Defense Threat Reduction Agency, Office of the Under Secretary of Defense for Research and Engineering, and the Joint Program Executive Office for Chemical, Biological, Radiological, and Nuclear Defense.

*** Funding levels for DOE include the combined budgets of the Office of Science, Office of Energy Efficiency and Renewable Energy, Office of Nuclear Energy, Office of Fossil Energy and Carbon Management, and the Advanced Research Projects Agency-Energy.

† In Tables 2–6, totals may not add, due to rounding.

The President's 2024 Budget includes a $2.16 billion request for nanotechnology R&D to support nanoscale science, engineering, and technology R&D at 11 agencies, including multiple departments/offices within several agencies such as DOD, HHS, USDA (see Table 2 above and the footnotes for DOD and DOE). The five federal organizations with the largest proposed 2024 investments (representing 97% of the NNI 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, and support for nanotechnology research infrastructure).
- 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).

For 2023 and 2024, some NNI participating agencies (NIST, DOE, NASA, NSF, and USDA/ARS) have estimated the approximate percentages of their investments that are in support of the Nano4EARTH

National Nanotechnology Challenge. Based on these estimates, collectively these agencies are spending just under $200 million on Nano4EARTH activities in 2023 and just over $200 million in the 2024 request.

Breakout of Funding by PCA

Tables 3–5 show the funding for 2022–2024 by agency and Program Component Area. The PCAs are aligned with the goals in the 2021 NNI Strategic Plan. PCA definitions can be found on Nano.gov[13] and at the beginning of each of the PCA sections of Chapter 3 of this report, below.

Table 3: Actual 2022 Agency Investments by Program Component Area
(dollars in millions)

Agency	1. Foundational Research	2. Nanotechnology-Enabled Applications, Devices, and Systems	3. Research Infrastructure and Instrumentation	4. Education and Workforce Development	5. Responsible Development	NNI Total
CPSC	0.0	0.0	0.0	0.0	0.2	0.2
DOC/NIST	15.4	9.2	28.2	0.0	3.5	56.3
DOD	184.0	73.8	15.1	0.0	1.2	274.1
DOE	220.7	88.8	150.8	0.0	0.0	460.3
DOI/USBR	0.0	0.3	0.0	0.0	0.0	0.3
DOJ/NIJ	0.5	1.8	0.0	0.0	0.0	2.3
EPA	0.0	0.0	0.0	0.0	4.1	4.1
HHS (total)	207.4	878.1	22.4	3.6	22.5	1134.0
BARDA*	0.0	352.1	0.0	0.0	0.0	352.1
FDA	0.3	4.3	1.6	0.0	1.8	7.9
NIH**	207.1	521.7	20.8	3.6	11.5	764.7
NIOSH	0.0	0.0	0.0	0.0	9.2	9.2
NASA	1.1	10.5	0.0	0.0	0.0	11.6
NSF	329.8	139.5	27.7	30.9	17.3	545.1
USDA (total)	4.8	23.3	1.1	1.2	2.6	32.9
ARS	0.0	5.0	0.0	0.0	0.0	5.0
FS	0.6	4.1	1.1	0.0	0.0	5.7
NIFA	4.2	14.2	0.0	1.2	2.6	22.2
TOTAL[†]	**963.6**	**1225.2**	**245.3**	**35.7**	**51.5**	2521.1

* BARDA's 2022 investment includes $350 million in supplemental funding, in PCA 2.
** NIH totals include $2.4 million in supplemental 2022 funding, for PCA 2.

Most of these nanotechnology investments come from "core" R&D programs, which makes it difficult to predict the success rate of nanotechnology-related proposals. Therefore, actual investments are often higher than the previously published estimates or proposed values. For example, the actual NNI investment for 2022 (over $2.5 billion, including $352 million from BARDA for COVID diagnostics and vaccine research) is significantly higher than the 2022 requested value published in the NNI Supplement to the President's 2022 Budget ($1.98 billion).

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[13] https://www.nano.gov/pcadefinitions

Table 4: Estimated 2023 Agency Investments by Program Component Area

(dollars in millions)*

Agency	PCA 1.	PCA 2.	PCA 3.	PCA 4.	PCA 5.	Total
CPSC	0.0	0.0	0.0	0.0	0.4	0.4
DOC/NIST	15.3	9.0	28.0	0.0	3.5	55.8
DOD	201.4	66.1	0.0	0.0	1.2	268.7
DOE	236.6	81.6	166.6	0.0	0.0	484.8
DOI/USBR	0.0	0.3	0.0	0.0	0.0	0.3
DOJ/NIJ	0.5	1.1	0.0	0.2	0.0	1.8
DOT/FHWA	0.0	0.2	0.0	0.0	0.0	0.2
EPA	0.0	0.0	0.0	0.0	4.2	4.2
HHS (total)	217.2	557.2	22.4	3.8	23.9	824.5
BARDA	0.0	2.1	0.0	0.0	0.0	2.1
FDA	0.2	4.4	0.7	0.0	2.4	7.7
NIH**	217.0	550.7	21.7	3.8	12.3	805.5
NIOSH	0.0	0.0	0.0	0.0	9.2	9.2
NASA	0.7	15.3	0.0	0.0	0.0	16.0
NSF* **	243.3	84.0	23.2	19.0	14.6	384.0
USDA (total)	4.9	23.4	1.1	1.4	2.6	33.3
ARS	0.0	5.0	0.0	0.0	0.0	5.0
FS	0.6	4.1	1.1	0.0	0.0	5.7
NIFA	4.3	14.3	0.0	1.4	2.6	22.6
TOTAL	**919.9**	**838.1**	**241.3**	**24.4**	**50.3**	**2073.9**

Table 5: Proposed 2024 Agency Investments by Program Component Area

(dollars in millions)

Agency	PCA 1.	PCA 2.	PCA 3.	PCA 4.	PCA 5.	Total
CPSC	0.0	0.0	0.0	0.0	0.04	0.04
DOC/NIST	15.3	8.5	28.0	0.0	3.4	55.2
DOD	204.0	70.5	0.4	0.0	1.3	276.2
DOE	259.9	84.6	162.0	0.0	0.0	506.5
DOJ/NIJ	0.5	1.1	0.0	0.2	0.0	1.8
DOT/FHWA	0.0	0.5	0.0	0.0	0.0	0.5
EPA	0.0	0.0	0.0	0.0	2.8	2.8
HHS (total)	228.2	566.1	22.6	3.9	24.1	844.9
BARDA	0.0	2.1	0.0	0.0	0.0	2.1
FDA	0.2	4.6	0.7	0.0	2.4	7.9
NIH	228.0	559.4	21.9	3.9	12.5	825.7
NIOSH	0.0	0.0	0.0	0.0	9.2	9.2
NASA	0.8	13.0	0.0	0.0	0.0	13.8
NSF	262.7	102.5	24.5	21.5	17.1	428.3
USDA (total)	5.6	22.2	1.1	1.7	3.2	33.7
ARS	0.0	5.0	0.0	0.0	0.0	5.0
FS	0.6	4.1	1.1	0.0	0.0	5.7
NIFA	5.0	13.1	0.0	1.7	3.2	23.0
TOTAL	**976.9**	**868.9**	**238.6**	**27.3**	**51.9**	**2163.6**

* Headings in Tables 4 and 5 are abbreviated to PCA numbers.

** NIH totals include $1.6 million in supplemental 2023 funding, for PCA 2.

*** NSF totals include $2.4 million in supplemental 2023 funding (PCA 1 $1 million; PCA 2 $1.1 million, PCA 3 $0.2 million, PCA 5 $0.1 million).

As nanotechnology and its applications mature, investments by some agencies and departments that perform research to facilitate their missions have risen in recent years. The total USDA investment has gone up from $28 million in 2016 to $34 million in the 2024 request. NIH's investments have doubled in the same period—from less than $400 million in 2016 to over $800 million in 2023 and 2024, even as some nanotechnology-specific NIH programs have sunset. The percentage of total NNI investments in the "applications, devices, and systems" PCAs has risen from under 24% in 2016 to over 40% in both 2023 and 2024. Nanotechnology is proving itself increasingly as a solution contributing to agency mission requirements.

Many of the proposed 2024 NNI investments outlined in this report support efforts to renew U.S. leadership in the semiconductor and microelectronics industries authorized and funded under the CHIPS and Science Act of 2022 (Public Law 117-167). Foundational nanomaterials research (PCA 1) and nanoelectronic devices and systems (PCA 2) are enabling leapfrog capabilities in microelectronics. The DOE Microelectronics Science Research Centers authorized in the CHIPS and Science Act, and for which DOE is requesting funding in 2024, will expand investments in early-stage innovations. Existing microelectronics research infrastructure supported through the NSF-funded National Nanotechnology Coordinated Infrastructure (NNCI), the DOE Nanoscale Science Research Centers (NSRCs), and the NIST Center for Nanoscale Science and Technology (CNST) and Boulder Microfabrication Facility, as well as several DOD-supported centers (PCA 3), also provide a strong foundation for the additional microelectronics infrastructure being developed with CHIPS and Science Act funding. NSF is expanding on its existing nanoscience and engineering education programs (PCA 4) to develop the semiconductor workforce and education activities funded under the CHIPS and Science Act. NSET and NNCO leadership participate in the NSTC's Subcommittee on Microelectronics Leadership (SML), and coordinate NNI investments to maximize the leveraging of existing NNI activities to benefit SML's whole-of-government efforts in microelectronics R&D, education, and infrastructure.

SBIR and STTR Funding to Advance Nanotechnology

This section of the report includes information on use of the Small Business Innovation Research and Small Business Technology Transfer programs to support nanotechnology development, as well as highlights of agency SBIR and STTR topics that support the accelerated deployment and application of nanotechnology R&D with potential for commercialization. Table 6 shows agency funding for SBIR and STTR awards for nanotechnology R&D from 2018 through 2021. (2021 is the latest year for which nanotechnology award data vetted by agencies and OMB are available.) NNI participating agencies have supported over $2.2 billion in nanotechnology SBIR and STTR awards (both Phase I and Phase II) since 2004.[14] Even though not all agencies specifically call out nanotechnology in their SBIR/STTR solicitations, it is enabling innovations in many R&D application areas. Information on progress and plans in programs other than SBIR/STTR in promoting commercialization of nanotechnology innovations is included in Chapter 3 of this report (Goal 2 and PCA 2 sections).

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[14] 2004 was the first year that the NNI began collecting SBIR/STTR data. See www.nano.gov/budget for cumulative NNI PCA funding data from 2001 and SBIR funding data from 2004.

Table 6: 2018–2021 Agency SBIR and STTR Awards
(dollars in millions)

	2018			2019			2020			2021		
Agency	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**
DHS	0.3	0.0	0.3	2.0	0.0	2.0	1.0	0.0	1.0	0.0	0.0	0.0
DOC/NIST	0.5	0.0	0.5	1.1	0.0	1.1	1.9	0.0	1.9	1.3	0.0	1.3
DOD	38.3	23.3	61.6	63.5	22.5	86.0	51.5	17.8	69.3	45.5	23.1	68.6
DOE	36.6	5.2	41.8	31.2	3.4	34.6	26.0	3.7	29.7	27.3	8.8	36.0
EPA	0.5	0.0	0.5	0.7	0.0	0.7	0.5	0.0	0.5	0.6	0.0	0.6
HHS/NIH	34.9	7.1	42.0	42.6	5.5	48.1	42.9	5.7	48.6	41.8	6.5	48.3
NASA	4.7	1.5	6.2	7.7	1.6	9.3	6.5	2.8	9.3	9.7	2.0	11.7
NSF	17.4	3.1	20.5	16.2	3.4	19.6	19.0	1.8	20.8	18.0	5.1	23.1
USDA	1.6	0.0	1.6	0.8	0.0	0.8	1.8	0.0	1.8	3.2	0.0	3.2
TOTAL	**134.8**	**40.2**	**175.0**	**165.7**	**36.4**	**202.1**	**151.0**	**31.9**	**182.8**	**147.4**	**45.4**	**192.8**

The following is a small sampling of the hundreds of nanotechnology SBIR and STTR topics funded by NNI participating agencies in 2021 that are supporting the development and application of nanotechnology R&D with potential for commercialization:

- Nanocomposite dielectric material and printing process for energy-efficient manufacturing of printed circuitry (NIST).
- Low-cost and scalable sorting of chiral-pure single walled carbon nanotubes (NIST).
- Quantum-dot-based lateral flow test strip for cyclospora detection (NIFA).
- Reduction of herbicide drift using a nanocellulose-based adjuvant (NIFA).
- Atomically precise ultra-high-performance two-dimensional (2D) microelectronics (DOE)
- Nanocomposite surface protection for hydrogen transport in existing steel pipelines (DOE).
- Nanolayer-coated flame-retardant fabrics for space crew clothing (NASA).
- Nanomembrane-based strain sensors for nondestructive evaluation (NASA).
- Nanoparticle-enabled membranes with reduced fouling for water purification systems (EPA).
- Nanomaterials-based sensor chip for low-cost handheld sulfur dioxide tester (EPA).
- Nanopore-based ion selective electrode system for rapid point-of-care and at-home testing of blood electrolytes (NIH).
- Mesoporous silica nanoparticles for delivery of bladder cancer chemotherapeutic agents to improve their specificity, dwell time, and tumor penetration (NIH).
- Colloidal quantum dot image sensors for low-cost short-wave infrared imaging (NSF).
- Nanomembrane process for rapid, low-cost, environmentally friendly recovery of battery-grade lithium from brine (NSF).
- Reactive nanoparticle bimetallic-carbon media for destruction of PFAS-containing aqueous fire-fighting foam stockpiles (DOD).
- Nanocrystalline magnetic materials for tunable, high-efficiency, low-loss magnetic structures for power electronics (DOD).

3. Highlights of NNI Progress and Plans

The five NNI goals are closely tied to the five PCAs that are intended to target funding toward advancing those goals. This chapter of the report includes selected highlights illustrating progress toward each of the NNI goals, followed by brief summaries of the current and future investment plans of the NNI participating agencies for the corresponding PCAs that will promote further progress on those goals. For more information and additional highlights, please see Nano.gov.

Progress on Goal 1. Ensure that the United States remains a world leader in nanotechnology research and development.

Central to the NNI is support for nanotechnology R&D, from the fundamental discoveries that expand the boundaries of knowledge to the applied and translational breakthroughs that enable new products and help address societal challenges. The NNI agencies utilize a variety of R&D support mechanisms (e.g., grants, contracts, cooperative agreements, intramural research) and topical foci, in keeping with their respective missions. Interagency coordination facilitated through the NNI leverages these individual efforts and prevents duplication, nurturing a nanotechnology R&D community that is making important advances in diverse areas of fundamental and applied science and that is maintaining U.S. international leadership in nanotechnology R&D. Just a few selected examples of NNI progress under Goal 1 are highlighted below.

Harnessing nanotechnology for pandemic virus detection. Researchers funded under the NIH Rapid Acceleration of Diagnostics-Radical (RADx-rad) Initiative have developed a number of novel techniques enabled by nanotechnology that hold promise for faster, more reliable, and less expensive detection of the SARS-CoV-2 virus. Examples include the following: (1) a nanosensor consisting of poly(ethylene glycol) (PEG)—phospholipid heteropolymers adsorbed onto near-infrared fluorescent single-walled carbon nanotubes that recognize the nucleocapsid and spike protein of SARS-CoV-2, enabling antibody-free detection of COVID within 5 minutes of viral protein injections;[15] (2) a magnetic particle spectroscopy platform for detecting SARS-CoV-2 spike and nucleocapsid protein biomarkers by monitoring the dynamic magnetic responses of iron oxide nanoparticles functionalized to bind to those biomarkers, a versatile approach that could allow for detection of a variety of other disease biomarkers by changing the surface functional groups on the nanoparticles;[16] and (3) a net-shaped DNA nanostructure designed to selectively recognize and capture intact SARS-CoV-2 virions through spatial pattern recognition and interactions between spike receptor-binding domain aptamers on the net and the spike proteins on the outer surface of the virus, which could allow rapid detection of the virus with a hand-held, inexpensive fluorimeter.[17]

Targeting cancer immunotherapy with nanotechnology. The NIH National Cancer Institute (NCI) has supported a number of exciting developments in nanotechnology applied to cancer immunotherapy. One group of university researchers used cowpea mosaic virus nanoparticles derived from plants to train the immune system to suppress cancer in mice. They developed a vaccine against a regulator of inflammation, which plays a central role in cancer progression and metastasis. This vaccine was effective in mouse models to prevent tumor seeding within the lungs and outgrowth of metastatic disease.[18] Another has pioneered the development of spherical nucleic acids for enhancing melanoma-

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[15] https://doi.org/10.1021/acs.analchem.1c02889

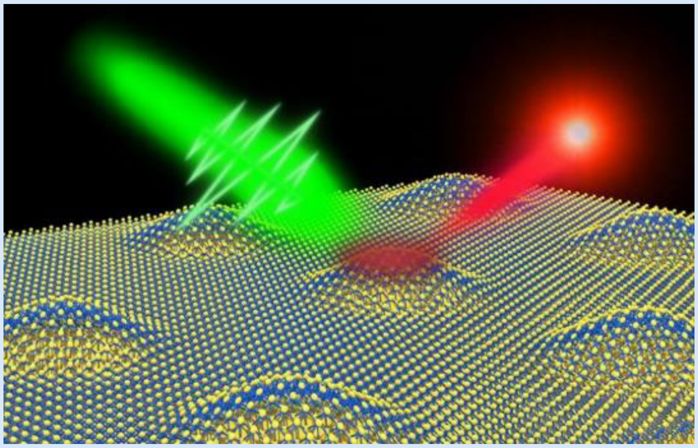
[16] https://doi.org/10.1021/acsami.1c14657

[17] https://doi.org/10.1021/jacs.2c04835

[18] https://pubmed.ncbi.nlm.nih.gov/37844250/

specific immune response and has created multi-antigen spherical nucleic acid cancer vaccines.[19] A third has developed hyaluronic acid nanoparticles conjugated with PD1 mimetic peptides that target and block PD-L1 function and tumor growth, and that activate cytotoxic T cells; an example application is translational development of targeted immunotherapy for metastatic colon cancer patients with comorbid atherosclerosis.[20]

Enabling the next-generation internet with quantum nanotechnology



A molybdenum ditelluride material (blue and yellow lattice) just atoms thick connects telecom-wavelength quantum emitters to optical fibers with minimal loss. The devices generate single photons (red) when triggered by optical signals (green). Image credit: Huan Zhao, LANL/CINT.

Researchers at the DOE Center for Integrated Nanotechnologies (CINT) at Los Alamos National Laboratory (LANL) have developed the first 2D telecommunication-compatible quantum light source, smoothing the path toward a quantum internet. They produced single-photon sources with operating wavelengths compatible with existing fiber communication networks, placing molybdenum ditelluride semiconductor layers just atoms thick on top of an array of nanoscale pillars. This makes it possible for the first time to integrate quantum light sources made of 2D materials into existing communication networks. In addition, the two-dimensional nature of the material makes it easy to construct devices layer by layer. This could help integrate these light sources into emerging quantum computers to construct larger, modular computing systems and achieve quantum advantage for practical applications.[21]

Developing higher-performance batteries without critical minerals. The Naval Research Laboratory (NRL) is developing three-dimensional (3D) all-solid-state batteries comprising U.S.-sourced materials (e.g., silver [Ag], zinc [Zn]) as an energy-storage solution that delivers high energy and power in a minimal geometric footprint for next-generation DOD and civilian applications. To realize 3D all-solid-state Ag–Zn batteries, non–line-of-sight deposition methods must be developed that generate nanoscale anion-conducting solid-state electrolytes. A team of NRL scientists recently demonstrated conformal, thickness-controlled deposition of nanoscale polystyrene-based films on 2D planar and 3D substrates using initiated chemical vapor deposition (a non–line-of-sight method). These films were subsequently converted to an anion-conducting solid-state electrolyte using mass-scalable vapor- and solution-phase methods. In 2023, the NRL team demonstrated that the nanoscale anion-conducting polymer film has sufficient ionic conductivity to function as a solid-state electrolyte and supports conventional Ag and Zn redox reactions, moving the program a step closer to an all-solid-state Ag–Zn battery. The anion-conducting, geometry-conformal polymer films generated in this program also have applications in alkaline-exchange fuel cells and memristors.

Inventing novel nanoscale additive manufacturing platforms. University researchers supported by the NSF scalable nanomanufacturing program are addressing fundamental challenges in additive

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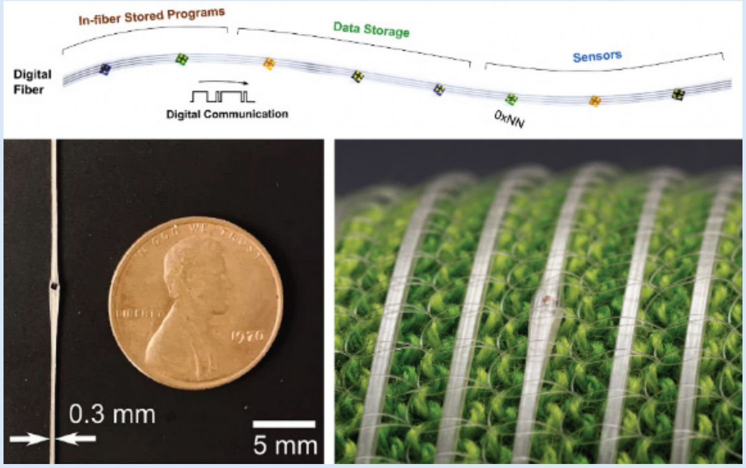
[19] https://doi.org/10.1038/s41551-022-01000-2

[20] https://doi.org/10.1158/1538-7445.AM2022-4152

[21] https://science.osti.gov/ascr/Highlights/2022/ASCR-2022-11-a

manufacturing and exploring new methodologies to directly print functional nanomaterials. They designed and constructed a new manufacturing platform that combines spatial atomic layer deposition (ALD) and electrohydrodynamic jet (E-jet) printing for 3D additive nanomanufacturing, and generated knowledge on the coupled surface chemistry/physics of additive nanomanufacturing of integrated systems at sub-μm length scales. This work has a wide variety of potential applications, including flexible electronics and personalized health care monitoring systems.[22]

Digital fibers: A new paradigm in versatile, low-power computation



Top: Illustration of the thermally drawn digital fiber encapsulating chips of different functionalities. Each of the chips is represented by a unique digital address in hexadecimal format (0xNN). Four wires within the fiber serve different functions: signal line for exchanging data between in-fiber devices, clock line, ground line, and power line. Bottom Left: Scale of a digital fiber. Bottom Right: Integration of digital fibers in a cotton-based fabric. Image credits: *Nature Communications*/Springer Nature BV (top and bottom left); MIT (bottom right).

Digital electronics are essential building blocks of modern devices and computation. Incorporating them into fibers will enable functional fabrics for exciting new applications in physiological monitoring, human-computer interactions, and on-body artificial intelligence and machine learning (ML). However, severe material and processing challenges have been major obstacles to the integration of digital electronics into fibers. With funding from the Army Research Office, researchers at the Army's Institute for Soldier Nanotechnologies (ISN) have overcome these challenges through a novel fiber drawing technique. This has allowed them to develop the first programmable fiber with digital functionalities, including digital circuits, interconnections, communication protocols, sensing, memory, and algorithms, which enables the fibers to sense, store, analyze, and interpret data when sewn into a fabric, including clothing. This novel fiber-drawing method provides a scalable fabrication strategy that harnesses precise control over the positions and angles of discrete particulates within a fluid flow to connect hundreds of microscale digital chips within tens of meters of fiber in a single continuous process. The fiber is controlled by a small external processor, so the next step is to design a new chip as a microcontroller that can be incorporated within the fiber itself. This study opens novel opportunities in the fields of fiber electronics, personal computing, and intelligent textiles.

Plans for PCA 1. Foundational Research

The foundational research under PCA 1 includes: (1) discovery and development of fundamental knowledge pertaining to new phenomena in the physical, biological, chemical, and engineering sciences that occur at the nanoscale; (2) elucidation of scientific and engineering principles related to nanoscale structures, processes, and mechanisms; and (3) research aimed at discovery and synthesis of novel nanoscale and nanostructured materials and at a comprehensive understanding of the properties of nanomaterials ranging across length scales, and including interface interactions. This PCA

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[22] https://doi.org/10.1021/acsnano.0c07297

encompasses basic research aimed at addressing national needs and priorities as well as undirected research aimed at expanding the frontiers of science and technology.

Foundational research continues to be the largest area of NNI investment, accounting for 45% of the proposed NNI total for 2024. NSF and DOE are the largest contributors to this PCA by dollar amount, followed by NIH and DOD.

NSF's planned PCA 1 investments in nanoscale science and engineering (NSE) include fundamental research on nanoscale phenomena and processes, nanosystems, and nanophotonics; biomaterials and modular structures; quantum biology for understanding natural phenomena and interfaces; and water nanofiltration systems. It includes foundational research on climate change understanding and mitigation—contributing to the National Nanotechnology Challenge (NNC), Nano4EARTH.[23] It also includes a new program on Predictive Intelligence for Pandemic Prevention,[24] which supports high-risk, high-payoff convergent research addressing future pandemics. Most of the research is sponsored in individual and small group research across NSF directorates. A subset of Engineering Research Centers (ERCs), Science and Technology Centers (STCs), Centers for Chemical Innovation (CCIs), and other centers programs support various NSE aspects. About 60% of the Materials Research Science and Engineering Centers (MRSECs) pursue NSE-related fundamental research. NSF invests in understanding the nanoscale machines that make up the nucleus of a cell and control cell function through its programs in Understanding the Rules of Life: Epigenetics,[25] the Physics Frontiers Center program,[26] and core programs on Genetic Mechanisms[27] and Chemistry of Life Processes.[28] NSF will expand its efforts in 2024 in nanobiotechnology associated with synthetic biology and synthetic cells through a new solicitation, Designing Synthetic Cells Beyond the Bounds of Evolution,[29] a new Dear Colleague Letter (DCL), Sentinel Cells for Surveillance and Response to Emergent Infectious Diseases,[30] and through core programs in the Division of Molecular and Cellular Biosciences and the Division of Chemical, Bioengineering, Environmental and Transport Systems.

NSF investments under this PCA also include foundational research supporting sustainable nanomanufacturing, nanoelectronics/semiconductors, sensors, future computing, and water availability, delivery, and monitoring. Semiconductor-related programs include DCLs on Supplements for Access to Semiconductor Fabrication[31] and on Partnership for Prototyping of CMOS+X Systems,[32] and a program on the Future of Semiconductors.[33] Nanotechnology-related programs in quantum information science include Expanding Capacity in Quantum Information Science and Engineering,[34] Quantum Sensing Challenges for Transformational Advances in Quantum Systems,[35] and a DCL on Quantum Manufacturing.[36] In support of the Nano4EARTH NNC are programs on Use-Inspired Research Addressing

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[23] https://www.nano.gov/nano4EARTH
[24] https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf21590
[25] https://www.nsf.gov/pubs/2020/nsf20512/nsf20512.htm
[26] https://www.nsf.gov/mps/phy/pfc_program.jsp
[27] https://new.nsf.gov/funding/opportunities/genetic-mechanisms-0
[28] https://new.nsf.gov/funding/opportunities/chemistry-life-processes-clp-0
[29] https://www.nsf.gov/pubs/2021/nsf21531/nsf21531.htm
[30] https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf22077
[31] https://www.nsf.gov/pubs/2022/nsf22113/nsf22113.jsp
[32] https://www.nsf.gov/pubs/2022/nsf22076/nsf22076.jsp
[33] https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf23552
[34] https://new.nsf.gov/funding/opportunities/expanding-capacity-quantum-information-science
[35] https://www.nsf.gov/pubs/2022/nsf22630/nsf22630.htm
[36] https://www.nsf.gov/pubs/2022/nsf22074/nsf22074.jsp

Global Challenges in Climate Change and Clean Energy,[37] a DCL on Critical Aspects of Sustainability: Innovative Solutions to Climate Change,[38] and the Critical Aspects of Sustainability program.[39] Multiple other programs across all of NSF's directorates support nanoscale science and engineering research related to PCA 1.

DOE support for PCA1 is primarily provided by the Office of Basic Energy Sciences (BES) in the Office of Science (SC). BES does not have a nanoscience program, but nanoscience is supported throughout most of the funding programs across the office. The BES mission is to understand, predict, and ultimately control matter and energy at the level of electrons, atoms, and molecules; this requires nanoscience. BES emphasizes discovery sciences and use-inspired basic research. Current priorities include clean energy, advanced manufacturing, critical materials, AI/ML, and quantum information science. BES supports a broad array of research projects, primarily at universities and DOE National Labs, through single investigator and small group projects, as well as larger multidisciplinary, multi-investigator team science projects. Contributing BES sub-programs that support nanoscience include core research in the Chemical Sciences, Geosciences, and Biosciences Division (including Fundamental Interactions; Photochemistry and Biochemistry and Chemical Transformations)[40] and the Materials Sciences and Engineering Division (including Condensed Matter and Materials Physics, Materials Design Discovery and Synthesis, and Scattering and Instrumentation Sciences);[41] Energy Frontier Research Centers;[42] Energy Innovation Hubs (e.g., Fuels from Sunlight and Batteries and Energy Storage);[43] Computational Materials and Chemical Sciences;[44] and National Quantum Information Science (QIS) Centers.[45] In addition, in 2023 the Office of Science initiated two funding opportunities in support of the Energy Earthshots Initiative (Energy Earthshot Research Centers and Science Foundations for Energy Earthshots). Some portion of awards will likely include significant nanoscience/nanotechnology; the 2024 Budget request includes an expansion of the Initiative.[46] The DOE Office of Nuclear Energy (NE) invests in PCA 1 through the Nuclear Science User Facilities program,[47] which funds competitively awarded nuclear fuel and materials research projects that include some topics focused on nanoscale science.

Nanotechnology is a key contributor to NIH's mission of advancing human health, with nanotechnology research being funded in almost every one of its 27 institutes and centers. For example, NCI supports basic, applied, and translational research in cancer nanotechnology. In particular, a funding opportunity on Innovative Research in Cancer Nanotechnology[48] covers mechanistic studies contributing to fundamental understanding of nanoparticle design rules and mechanisms behind their *in vivo* interactions.

The NIH National Institute of Biomedical Imaging and Bioengineering (NIBIB) supports nanotechnology research and development that spans the breadth of biomedicine, including nanomaterials for drug delivery, devices, diagnostics, and novel forms of therapy. Foundational nanotechnology research investments at NIBIB are geared at elucidating underlying mechanisms of nanomaterial interfaces with

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[37] https://www.nsf.gov/pubs/2023/nsf23557/nsf23557.htm

[38] https://www.nsf.gov/pubs/2021/nsf21124/nsf21124.jsp

[39] https://new.nsf.gov/funding/opportunities/critical-aspects-sustainability-cas

[40] https://science.osti.gov/bes/csgb

[41] https://science.osti.gov/bes/mse

[42] https://science.osti.gov/bes/efrc/

[43] https://science.osti.gov/bes/Research/DOE-Energy-Innovation-Hubs

[44] https://science.osti.gov/bes/Research/Computational-Materials-and-Chemical-Sciences-CMS-CCS

[45] https://science.osti.gov/Initiatives/QIS/QIS-Centers

[46] https://www.energy.gov/policy/energy-earthshots-initiative

[47] https://nsuf.inl.gov/

[48] https://grants.nih.gov/grants/guide/pa-files/PAR-23-246.html

biological systems and how this guides design principles, which can be applied translationally toward the development of platform technologies of biomedical relevance.

Research funded by the NIH National Human Genome Research Institute (NHGRI) is producing fundamental discoveries toward improving existing technologies for direct single-molecule RNA and DNA sequencing and developing entirely new ones utilizing nanotechnology. These efforts are contributing to cost decreases accompanied by capability and accuracy increases in nucleic acid sequencing technologies. Research topics include protein-based nanopores, zero-mode waveguides, precise methods and measurements of nucleic acids for sequence determination and accuracy improvements, Raman scattering at the nanopore entrance to determine base identity, and using enzymes as a conductor to determine individual base incorporations. Many of these novel approaches and technologies are supported by NHGRI's Genome Technology Program.[49] Funding opportunities are focused on the early stages of novel technologies that will enable improved DNA sequencing and direct RNA sequencing.[50]

The NIH National Institute of Allergy and Infectious Diseases (NIAID) develops and applies nanotechnology to advance understanding of immune system development and function. For example, targeted proteomics assays using nano-flow liquid chromatography coupled to selected reaction monitoring mass spectrometry provide data for mathematical models to characterize immune system signaling pathways that recapitulate *in vitro* data. Other projects are evaluating mechanisms of complement activation by nanoparticles, with the goal of applying these data to nanoparticle vaccine and therapeutic development. NIAID-supported investigators are using nanoparticles with targeting antibodies to deliver therapeutics directly to autoreactive T cells in the lymph nodes that drain the pancreas, to shift the immunological balance from auto-reactivity to tolerance against Type 1 diabetes antigens with minimal side effects.

The 2021–2026 Strategic Plan for the NIH National Institute of Dental and Craniofacial Research (NIDCR) prioritizes research to transform material and biomaterial products through innovations in engineering, chemistry, and biophysics, including building interdisciplinary expertise in nanotechnology. NIDCR leads an initiative launched in 2020 to support development of novel nanotechnology-based approaches for detection of the SARS-CoV-2 virus and biomarkers of the COVID-19 disease, which will also address future health emergencies. Projects funded through the RADx-rad Initiative[51] use nanotechnology and nanomaterial approaches to identify biomarkers emanating from skin or the oral cavity in patients with symptomatic and asymptomatic COVID-19.

Foundational nanotechnology research at the Naval Research Laboratory includes efforts in: (1) materials/assembly, where NRL is developing novel nanoscale materials through a combination of nanofabrication, growth, and directed chemical and biological assembly of both inorganic and bio/inorganic hybrid structures; (2) understanding the basic properties of nanostructures and how these materials interact with their environment; and (3) nanosystems, where layered materials, heterostructures, lattices, nanocomposite architectures, and DNA scaffolding provide novel and advantageous architectures for control and functionality. Excitonic, plasmonic, metamagnetic, and microbial optoelectronic phenomena are being exploited for electronic and sensor concepts.

The Office of Naval Research (ONR) is supporting bionanotechnology research with emphases on fabrication techniques for hierarchical, biologically-based materials; DNA nanotechnology and

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[49] https://www.genome.gov/Funded-Programs-Projects/Genome-Technology-Program

[50] e.g., https://grants.nih.gov/grants/guide/rfa-files/RFA-HG-21-006.html

[51] https://grants.nih.gov/grants/guide/rfa-files/rfa-od-20-020.html

applications for functional device platforms; synthesis and patterning of materials by microorganisms; and design and fabrication of bio-inspired and biomimetic materials and devices using nature's design principles. The ONR Nanoscale Computing Devices and Systems program[52] is supporting fundamental nanotechnology research for future computing technologies, with increased emphasis in 2024 on probabilistic computing, which, like quantum computing, has the potential to solve some of DOD's hardest computational tasks. These projects augment the concurrent ONR Multidisciplinary University Research Initiative (MURI) project, OptNet: Optimization with P-bit Networks. The ONR Nanoengineered Materials program[53] supports research to investigate scientific phenomena that define the unique properties of structural and multifunctional nanomaterials, with emphasis on identifying material systems and processes enabling the assembly of these materials at mesoscale and beyond while preserving and potentially enhancing their nanoscale material properties.

The Army Research Laboratory (ARL) is supporting intramural and extramural foundational research in nanophotonics (including hybrid plasmonic metasurfaces), nanocomposites (for passive radiative cooling), and nanocrystalline refractory alloys (e.g., using atomistic computational modeling to improve properties). In addition, ARL oversees the Institute for Soldier Nanotechnologies, which has been approved for continuation as a University Affiliated Research Center. The new ISN portfolio includes lipid- and DNA/RNA-based virus-like nanoparticles functionalized to elicit selective antibody production and for delivery of messenger RNA (mRNA) in vaccines, as well as efforts in lightweight materials and photovoltaic energy sources. ISN's strategic research areas include photonics, electronics, and quantum sciences; materials for extreme environments; energy; devices and materials with advanced functionalities; and soldier medicine.

The Air Force is supporting foundational science on nanoscale materials and devices, with particular interests in quantum materials, low-dimensional materials and their heterostructures, non-traditional concepts for computation, enhanced performance in extreme environments, high-power optics and electronics, and inorganic-organic hybridization chemistries. Additional efforts are establishing foundational materials physics that determine nanomaterial processability, either to create nanostructures or to be integrated into multifunctional coatings, devices, or bulk structures. The Air Force Office of Scientific Research (AFOSR) also helps to oversee the AIM Photonics Manufacturing Innovation Institute, funded by the Office of the Under Secretary of Defense for Research and Engineering (OUSD/R&E).

USDA's National Institute of Food and Agriculture supports nanotechnology R&D through its Agriculture and Food Research Initiative (AFRI) Foundational and Applied Science Program.[54] Foundational nanotechnology research supported by NIFA aims at the discovery and characterization of nanoscale phenomena, processes, and structures relevant and important to agriculture and food. The AFRI nanotechnology program[55] encourages applications with innovative ideas, connected to hypothesis-based fundamental sciences, to develop nanotechnology-enabled solutions for sustainable food and nutrition security, climate-smart agriculture, and the circular bioeconomy.

The application of nanotechnology to problems of crime and justice is an integral part of the National Institute of Justice's R&D portfolio, particularly in the investigative and forensic sciences, law enforcement technology, and graduate research fellowships. Under PCA 1, DOJ's National Institute of

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[52] https://www.nre.navy.mil/organization/departments/code-31/division-312/nanoscale-computing-devices-and-systems

[53] https://www.nre.navy.mil/organization/departments/code-33/materials-focus-area/nano-engineered-materials

[54] https://www.nifa.usda.gov/grants/funding-opportunities/agriculture-food-research-initiative-foundational-applied-science

[55] https://www.nifa.usda.gov/grants/programs/food-science-technology-programs/nanotechnology-program

Justice is funding ARL through an interagency agreement to partially support R&D on 2D polymers for next-generation body armor applications.

FDA invests in nanotechnology research to help address questions related to the safety, effectiveness, quality, and/or regulatory status of products that contain engineered nanomaterials or otherwise involve the use of nanotechnology. FDA also invests in research to develop models for safety and efficacy assessment, as well as to study the behavior of nanomaterials in biological systems and their effects on both human and animal health. Research is conducted at multiple FDA centers to address center-specific priorities and scope, and in collaboration other government agencies. FDA's Nanotechnology Task Force[56] coordinates FDA investments and facilitates communication and cooperation across the agency on nanotechnology research, and with national and international stakeholders.

Progress on Goal 2. Promote commercialization of nanotechnology R&D.

Federal investments in nanotechnology R&D have led to thousands of products in the marketplace, and today's scientific discoveries serve as the foundation for the next generation of applications. 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 staff member dedicated to liaison with industry who conducts outreach, shares best practices, and suggests collaborations as appropriate. A few examples of progress on Goal 2 are shown below.

Improving efficiency, performance, and longevity of transportation systems with nanomaterials. Army Research Laboratory researchers have developed a novel oil additive for internal combustion engines containing carbon nanotubes (CNTs) and hexagonal boron nitride (hBN) nanosheets that increases fuel economy (reducing greenhouse gas emissions), improves power and torque, and reduces engine wear (therefore likely increasing engine life). Typical engine oils used in internal combustion gas and diesel engines are not high in thermal conductivity and are limited in friction performance, which together limit engine efficiency and longevity. CNTs and hBN nanosheets allow for extreme friction reduction (12% in one test) and up to 47% wear reduction compared to commercial state-of-the-art synthetic motor oils. The nanotubes and nanosheets also improve thermal conductivity, in turn increasing engine efficiency. Tests of the selected formulation revealed up to 47% wear reduction and 12% friction reduction compared to industry standard full synthetic oils. An average fuel efficiency improvement of 18% was achieved in diesel engine-equipped trucks. In addition, gains of up to 11% in horsepower and 12% in torque were observed. Over 30 vehicles have been operated for a significant amount of time with the additive, including gasoline, turbocharged gasoline, and turbodiesel engines. All have shown significant improvement in efficiency and performance.

Exploiting the properties of cellulose nanomaterials. The Forest Service has worked with university researchers, industry, and other agencies (e.g., ARS and NIFA) to develop a number of promising applications of cellulose nanomaterials. The addition of 0.2% by volume of cellulose nanocrystals (CNCs) to cement has been shown to improve hydration and increase flexural strength of concrete by 30%.[57] Forest Service researchers worked with universities, State and local authorities, and an industry consortium to complete a demonstration bridge deck using this CNC-reinforced concrete formulation in 2021. Since less concrete is required to achieve the same strength, this development has potential to significantly reduce greenhouse gas (GHG) emissions from concrete production. Forest Service and industry collaborators have also demonstrated the use of cellulose nanofibrils (CNFs) coated with lignin as a replacement for carbon black in tires, resulting in more durable tires with lower rolling resistance, further reducing GHG emissions and the use of petroleum

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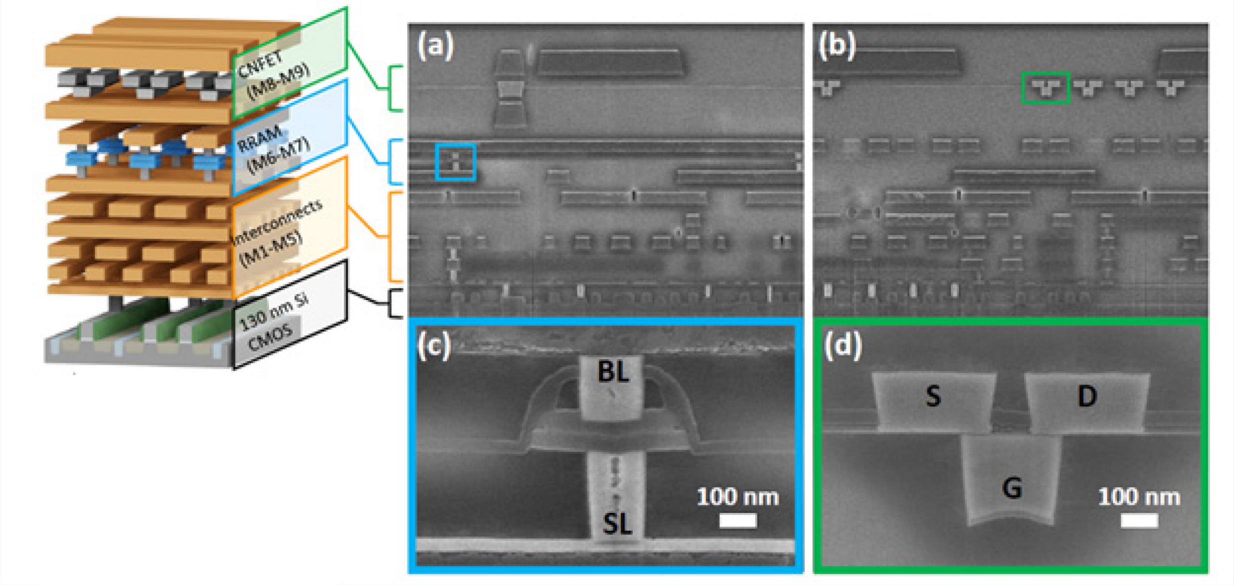
[56] https://www.fda.gov/science-research/nanotechnology-programs-fda/nanotechnology-task-force

[57] https://doi.org/10.1016/j.cemconcomp.2014.11.008

feedstocks for carbon black production. Other emerging applications of cellulose nanomaterials include the use of CNC filter material to remove PFAS from water and renewable packaging (as a potential replacement for PFAS in packaging), where cellulose nanofibril coatings have shown excellent grease resistance and improved drawability in molded paper products, and the addition of 1% cellulose nanocrystals has increased oxygen barrier properties by three fold in polylactic acid (PLA) films, with the potential to extend shelf life of agricultural produce. The Forest Service and ARS are working together to support a university-based pilot plant capable of producing 2000 lbs. per day of CNF.

Realizing the promise of 3D semiconductor device integration and CNT transistors

The Defense Advanced Research Projects Agency (DARPA) Three Dimensional Monolithic System-on-a-Chip (3DSoC) program has demonstrated the design and fabrication of a monolithic 3D integrated chip with silicon logic, non-volatile resistive random access memory (RRAM), and carbon nanotube field-effect transistors (CNFETs). This type of 3D circuit enables both a reduced footprint and increased parallelism through the use of the third dimension and is expected to result in increased efficiency and decreased delay within the chip. 3DSoC is developing design and fabrication technology for advanced 3D chips that stack logic and memory devices. 3DSoC is working to transition this technology by working with foundries to offer it commercially for use in high-performance computing applications.



Scanning electron micrographs (SEMs) of the 3D chip fabricated in the 3DSoC program. Partitions (a) and (b) show top-level images of the stacked chip featuring CNFETs, RRAM, interconnect layers, and silicon logic (CMOS). Partition (c) zooms in on the silicon RRAM and partition (d) zooms in on the CNFETs. Image credits: The Japan Society of Applied Physics. Work performed at MIT and Skywater Foundry. Right: SEM cross sections taken at SkyWater. Left: Diagram of 3D stack by Andrew Yu of MIT. Overall figure design by Andrew Yu.

Recent progress in this work includes demonstration of lift-off-free CNFETs fabricated with conventional processing at the 90 nm node on 200 mm substrates in a commercial silicon foundry[58] *and a back-end-of-line (BEOL) CNFET + RRAM stack through monolithic 3D integration that creates a new path for dramatically improved system-level energy and delay,*[59] *as well as several patent applications and awarded patents.*[60]

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[58] https://doi.org/10.1109/VLSI-TSA54299.2022.9771013

[59] https://doi.org/10.23919/VLSITechnologyandCir57934.2023.10185414

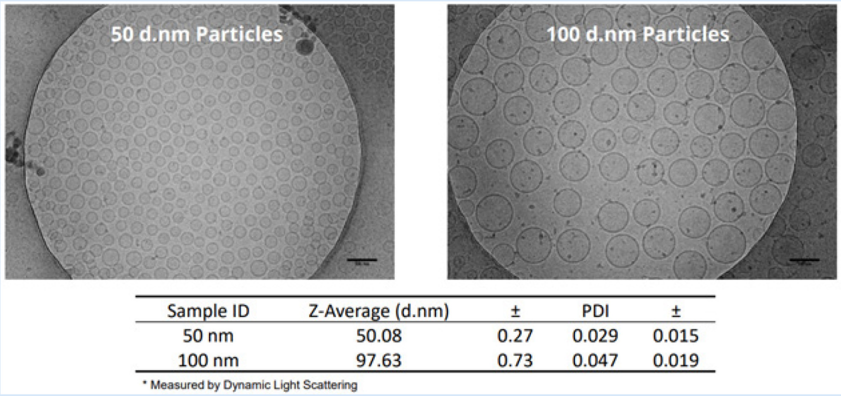
[60] e.g., *Carbon Nanotube Field-Effect Transistors and Related Manufacturing Techniques*, 2023, U.S. Patent App. 18/002,495.

Next-generation manufacturing of lipid nanoparticle therapeutics

Lipid nanoparticle (LNP) shells comprise a critical component of the two mRNA-based COVID-19 vaccines that were used during the pandemic and continue to be in use to prevent COVID-19. FDA has determined the mRNA COVID-19 vaccines to be safe and effective. To be effective, the mRNA carrier needs to protect the mRNA until taken up by cells, but once inside the cells allow the mRNA to be released so it can do its job training the immune system to identify the SARS-CoV-2 virus. LNPs achieve these tasks beautifully by mimicking the structure of cell membranes.

Current methods for LNP manufacturing are primarily mechanical in nature, relying on fluidics to produce spherical lipid droplets in an aqueous environment[61]*—similar to trying to mix oil and vinegar. The LNPs synthesized in these batch processes for the COVID-19 mRNA vaccines vary in size, but are on average 50–100 nm in diameter.*[62] *This size range enables the vaccines to function well, but enhanced control, replicability, and speed are desired for new applications of LNPs.*

Advanced continuous manufacturing processes are currently under development by FDA-funded researchers that not only produce LNPs more consistent in size, but offer the potential for higher production rates and reduced cost. The size of the LNPs produced by the new continuous process is very consistent and easily controlled (see figure).[63] *The process is also highly tunable, allowing for many different types of LNPs to be created. This is essential, since much research, including work from the DOE's Lawrence Berkeley National Laboratory in collaboration with a biomedical company,*[64] *shows how important LNP structure and formulation are to transport mechanics, stability of the particles, and stability of the therapeutic cargo. Access to easily manufactured, consistent LNPs could enable the next generation of therapeutics, stabilize mRNA vaccine supply chains for a number of different applications (including cancer vaccines), and minimize waste from poorly manufactured LNPs in the future.*



Sample ID	Z-Average (d.nm)	±	PDI	±
50 nm	50.08	0.27	0.029	0.015
100 nm	97.63	0.73	0.047	0.019

* Measured by Dynamic Light Scattering

Images of lipid nanoparticles generated by continuous manufacturing processes. The particles are highly consistent with average diameters that have standard deviations of less than 1%. Polydispersity index values less than 0.05 generally indicate that the products are uniform. Image credits: *International Journal of Pharmaceutics*/Elsevier.

Advancing the development of nanotechnology-enabled sensors. Multiple NNI participating agencies have been supporting the development and demonstration of nanotechnology-enabled sensing devices for a wide variety of applications, from chemical and biological pathogen detection to wearable health sensors. For example, NSF has been funding the Nanosystems Engineering Research Center for Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST) at a consortium of universities for over ten years.[65] Accomplishments to date include 67 disclosed inventions, 1307 publications, 54 patent applications and 10 awarded patents, and 8 spinoff companies with an estimated 172 employees. Just one example of the many

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[61] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3065896/

[62] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9864138/

[63] https://doi.org/10.1016/j.ijpharm.2022.121700

[64] https://doi.org/10.1021/acsnano.3c01186

[65] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1160483

ASSIST nanosensor technologies is a paper-based “power free” osmotic wearable health sensing system, developed in a partnership with industry and the Air Force Research Laboratory (AFRL) under the Air Force/industry Nano-Bio Materials Consortium (NBMC).[66]

AFRL has also been developing a variety of nanosensors, including for chemicals (e.g., NO_2, isopropanol, volatile organic compounds, naphthalene, and chem/bio threats) as well as for biological pathogens, achieving NO_2 detection as low as 63 ppt[67] and improving selectivity with 2D organic materials such as covalent organic frameworks. AFRL has been collaborating with industry and a university to develop a novel roll-to-roll process for production of low-cost pathogen sensors that has resulted in high-throughput fabrication of one million devices/day at $0.25 per device (compared to conventional PCR tests that cost $40 per test for reagents alone) and detection sensitivity of 0.01 pg/mL in less than 5 minutes, compared to the 1 pg/mL detection limit of PCR testing. AFRL works with NBMC to mature these technologies and transition them to industry; two cooperative research and development agreements are in place with industry collaborators to pursue FDA testing and commercialization for the pathogen sensors.

NASA is exploring applications of nanosensors that include colorimetric nanosensors for biofluids and CNT sensors for structural health monitoring. The CNT sensors are being explored for use to detect damage in vertical lift vehicles to ensure the safety of novel urban air mobility vehicles. In 2023, sensor prototypes were installed and evaluated in test crashes. Future applications may include adaptive flight controls.

Promoting commercialization and safety through standards. Standards play a critical role in enabling the commercialization of nanotechnology-enabled products by promoting international market acceptance of products and streamlining and harmonizing regulatory processes. NNI participating agencies represent the United States at international standards developing organizations such as the International Organization for Standardization (ISO), ASTM International, and the Organisation for Economic Co-operation and Development (OECD). NIST plays a leadership role in various international bodies working on nanotechnology standards, including chairing ASTM International’s Committee E56 on Nanotechnology and leading nanotechnology-related efforts in Technical Committee 113 of the International Electrotechnical Commission. NIST has also developed a number of nanotechnology-related standard reference materials, and played a leading role in the completion of four ASTM nanotechnology test methods. In 2022, FDA’s National Center for Toxicological Research (NCTR) Nanotechnology Core Facility (Nanocore),[68] with support from the NIH/National Institute of Environmental Health Sciences (NIEHS) Division of Translational Toxicology, published four documentary test method standards in collaboration with the ASTM International E56.08 subcommittee on nanotechnology-enabled medical products. Two of these standards were originally developed by the NCI-funded Nanotechnology Characterization Laboratory (NCL) and published after a multiyear analytical development and consensus-building process across multiple stakeholders. In collaboration with the ASTM International E56.03 subcommittee, NCL published three standards documents to support environmental and health safety studies of nanomaterials.[69] In addition to ASTM E56, NCL experts participate in ISO Technical Committee (TC) 229 (nanotechnologies) working groups. NCL is continuing these efforts, with several more standards currently in the review process. NIOSH also plays a key role in representing the United States at ISO TC 229. EPA leads the U.S. delegation to OECD’s Working Party on Manufactured Nanomaterials. OSHA leads the U.S. delegation to the United Nations Globally Harmonized System of Classification and Labeling of Chemicals (GHS), which includes a nanomaterials working group. The scientific data and information

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[66] https://doi.org/10.3390/mi12121513

[67] https://doi.org/10.1002/adfm.202270076

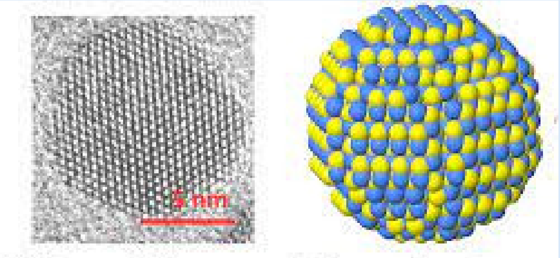
[68] https://www.fda.gov/about-fda/nctr-research-offices-and-divisions/nctr-office-scientific-coordination

[69] https://www.astm.org/get-involved/technical-committees/committee-e56/subcommittee-e56/jurisdiction-e5608

generated from this research and standards development work is used in capacity building and helps regulatory agencies ensure the safety of products containing nanomaterials.

Quantum dots: From novel physics to high-value commercial applications and the Nobel Prize

In October 2023, Moungi Bawendi, Louis Brus, and Alexei Ekimov were awarded the Nobel Prize in Chemistry for their pioneering work in the discovery and synthesis of quantum dots (QDs). Per the press release from the Nobel Prize organization, "They planted an important seed for nanotechnology. The Nobel Prize in Chemistry 2023 rewards the discovery and development of quantum dots, nanoparticles so tiny that their size determines their properties. These smallest components of nanotechnology now spread their light from televisions and light-emitting diode (LED) lamps, and can also guide surgeons when they remove tumour tissue, among many other things."[70]



Left: Transmission electron microscope (TEM) image of CdSe nanocrystal (quantum dot); Right: Nanocrystal actomic structure. Image credits: *ACS Nano*/American Chemical Society.

Quantum dots were first synthesized over 30 years ago. Many subsequent research projects supported by multiple NNI participating agencies (hundreds of awards from NSF alone, both predating the NNI, during the early years of the NNI, and up to the present day) have explored the novel physics of these semiconductor nanocrystals, their many potential applications, and various synthesis methods. After gradual technical progress and limited commercial impact, QDs in recent years have become instrumental to the functionality and enhanced performance of household name touch screen devices and most, if not all, state-of-the-art television sets. Beyond the consumer markets, progress is being made toward the development of nanocomposite solar cell materials, various sensor applications and anti-counterfeiting tools. Additionally, SBIR/STTR performers are researching multiple lines of research having high potential impacts:

- *DNA aptamer-quantum dot-based lateral flow test strips for detection of high-consequence toxins such as abrin, botulinum, and ricin in environmental soil and water samples from sites of suspected chemical or biological weapons attacks.*[71]
- *Flexible quantum dot electroluminescent light sources that will enable point-of-care antimicrobial photodynamic therapy for the treatment of multi-drug-resistant deep wound infections.*[72]
- *The design of infrared-absorbing colloidal quantum dots for high-performance infrared imaging.*[73]
- *An innovative manufacturing process to improve QD LED screens, including a bioassembly process to create ordered pixel arrays for functional, flexible display screens. This pixel generation method will rely on existing 3D printing technologies for producing flexible QD LED displays for a hybrid manufacturing system.*[74]

Plans for PCA 2. Nanotechnology-Enabled Applications, Devices, and Systems

PCA 2 covers research and development that applies the principles of nanoscale science and engineering to create novel devices and systems, or to improve existing ones. It includes the

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[70] https://www.nobelprize.org/prizes/chemistry/2023/press-release/; see also https://www.youtube.com/watch?v=kMCebcq_QBI.

[71] https://www.sbir.gov/node/2229825

[72] https://www.sbir.gov/node/2319329

[73] https://www.sbir.gov/node/2320025

[74] https://www.sbir.gov/node/2321681

incorporation of nanoscale or nanostructured materials and the processes required to achieve improved performance or new functionality. This PCA includes metrology, scale-up, manufacturing technology, and nanoscale reference materials and standards. To meet this definition, the enabling science and technology must be at the nanoscale, but the applications, systems, and devices themselves are not restricted to that size.

As discussed in the budget summary above (Chapter 2), NNI PCA 2 investments have been growing in recent years, from under 24% of the total in 2016 to over 40% in the 2024 request. PCA 2 is the largest category in the NIH NNI investment portfolio, accounting for nearly 68% of its 2024 request, up from 59% in the 2023 request.[75] Other agencies contributing to PCA 2 in the 2024 budget (in order of dollar amount of investments) include NSF, DOE, DOD, NIFA, NASA, NIST, ARS, FDA, FS, BARDA, DOJ, and FHWA.

Several NCI-funded efforts have applied focus and are dedicated to developing new and improved diagnostics and therapeutics with high sensitivity and multiplexed detection capabilities. Improvements in nanotechnology-based chemotherapeutics have migrated to gene therapies and immunotherapies. A funding opportunity on Translation of Nanotechnology Cancer Interventions[76] supports preclinical evaluations and entry of nanotechnology cancer interventions to mainstream translational and clinical programs.

NIBIB serves as the engineering hub of NIH, supporting diverse research on engineered nanotechnology for crosscutting applications. Examples include the use of targeted metallic (i.e., gold) nanozymes as bioorthogonal catalysts for chemotherapy, extracellular vesicle profiling via nanopore-enabled diagnostics for rapid stroke detection, dual-targeting nanoparticles to address drug resistance in non-small-cell lung cancer, 3D-nanoprinted soft robotic microcatheters for cerebrovascular surgery, and nanotechnology-enabled immunomodulatory and therapeutic tools.[77]

NIAID intramural and extramural scientists are applying nanotechnology to the development of medical countermeasures for public health threats. NIAID supports a customizable nanoparticle platform that enables researchers to rapidly create a candidate vaccine for a variety of pathogen-caused diseases. NIAID has launched seven large consortium program grants to support the development of broadly protective coronavirus vaccines that leverage nanotechnology approaches to neutralizing antibody responses against beta-coronavirus spike antigens. Nanoparticle technology is also advancing the development of “universal” influenza vaccines. The Adjuvant Discovery program[78] is identifying candidates to be formulated with various nanoparticle delivery platforms. The Adjuvant Characterization and Comparison program[79] is assessing the ability of nanoparticle-based adjuvants to induce protective immune responses to influenza and other diseases. The Adjuvant Development Program aims to advance to clinical trials novel vaccines that use nano-adjuvant formulations or nano-platforms for antigen delivery.[80]

NIDCR is supporting the Dental, Oral, and Craniofacial Tissue Regeneration Consortium (DOCTRC) through 2025. DOCTRC is facilitating the advancement of nanotechnology-based approaches for regeneration and reconstruction of DOC tissues, shepherding new therapies through pre-clinical studies and into human clinical trials, commercialization, and broad clinical adoption.

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[75] See https://www.nano.gov/sites/default/files/pub_resource/NNI-FY23-Budget-Supplement.pdf, p. 12.

[76] https://grants.nih.gov/grants/guide/pa-files/PAR-22-071.html

[77] https://reporter.nih.gov/project-details/9790435

[78] https://www.niaid.nih.gov/research/adjuvant-discovery-program

[79] https://www.niaid.nih.gov/research/adjuvant-comparison-characterization-acc

[80] https://www.niaid.nih.gov/research/adjuvant-development

NSF investments under PCA 2 include the Innovation Corps (I-Corps™)[81] and SBIR/STTR programs;[82] academia/industry partnerships, e.g., the Grant Opportunities for Academic Liaison with Industry,[83] Industry-University Cooperative Research Centers,[84] Partnerships for Innovation,[85] Accelerating Research Translation,[86] Regional Innovation Engines,[87] and Convergence Accelerator[88] programs, as well as collaborations with Manufacturing USA institutes. Translational programs in the Technology, Innovation, and Partnerships (TIP) and Engineering (ENG) directorates will support a diverse portfolio of nanotechnology projects. Additional programs supporting translational research in nanotechnology include NSF centers—e.g., Gen-4 ERCs,[89] the STCs: Integrative Partnerships program,[90] CCIs, MRSECs, and the Designing Materials to Revolutionize and Engineer our Future (DMREF) program.[91] Core programs in the ENG, Mathematical and Physical Sciences (MPS), and Computer and Information Science and Engineering (CISE) directorates also support research in PCA 2. Areas of emphasis include smart, autonomous nanoscale-based devices and systems, sustainable nanomanufacturing (including the Advanced Manufacturing[92] and Future Manufacturing[93] programs), nanoelectronics/ semiconductors (including the Semiconductor Synthetic Biology Circuits and Communications for Information Storage program[94]), sensors, future computing, water, and coordinated research in the Quantum Leap[95] and Future of Work at the Human-Technology Frontier[96] "Big Ideas" priority areas.

DOE is funding research under PCA 2 from core programs in its applied energy programs—the Office of Energy Efficiency and Renewable Energy (EERE), the Office of Fossil Energy and Carbon Management (FECM), and the Office of Nuclear Energy, as well as the Advanced Research Projects-Energy (ARPA-E). Within EERE, as part of its decarbonization focus, the Advanced Materials and Manufacturing Technologies Office (AMMTO)[97] has projects in nanoscale carbon, nanocellulose, nanocrystalline, and 2D materials as well as atomically precise manufacturing. Among DOE's crosscutting programs, SC/BES provides tools for characterizing matter at the smallest scale through x-ray, neutron, electron beam scattering, and nanoscience user facilities as well as advanced synthesis, fabrication, and computation. Microelectronics and power electronics programs in EERE—including AMMTO, the Building Technologies Office, the Solar Energy Technologies Office (SETO), and the Vehicle Technologies Office (VTO); SC; and the National Nuclear Security Administration include collaborations with industry. EERE's microelectronics efforts are centered in AMMTO, focusing on ultra-precise and energy-efficient technologies. EERE leads in supporting power electronics research, with key semiconductor materials and manufacturing efforts in AMMTO, device efforts in VTO and SETO, and system deployment in the Wind Energy Technologies Office and the Water Power Technologies Office.

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[81] https://new.nsf.gov/funding/initiatives/i-corps
[82] https://seedfund.nsf.gov/
[83] https://www.nsf.gov/eng/eec/goali.jsp
[84] https://iucrc.nsf.gov/
[85] https://new.nsf.gov/funding/initiatives/pfi
[86] https://new.nsf.gov/funding/opportunities/accelerating-research-translation-art
[87] https://new.nsf.gov/funding/initiatives/regional-innovation-engines
[88] https://new.nsf.gov/funding/initiatives/convergence-accelerator
[89] https://new.nsf.gov/funding/opportunities/gen-4-engineering-research-centers-erc
[90] https://www.nsf.gov/pubs/2022/nsf22521/nsf22521.htm
[91] https://new.nsf.gov/funding/opportunities/designing-materials-revolutionize-engineer-our
[92] https://new.nsf.gov/funding/opportunities/advanced-manufacturing-am
[93] https://new.nsf.gov/funding/opportunities/future-manufacturing-fm
[94] https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf22557
[95] https://www.nsf.gov/news/special_reports/big_ideas/quantum.jsp
[96] https://new.nsf.gov/funding/opportunities/future-work-human-technology-frontier-core
[97] https://www.energy.gov/eere/ammto/advanced-materials-manufacturing-technologies-office

DOE/NE funds research under PCA 2 through its Advanced Sensors and Instrumentation program,[98] which is supporting development of nanoparticle inks to facilitate the production of printed strain gauges and peak temperature melt wires; 2024 funding will expand the library of ink materials. ARPA-E also reports funding in PCA 2, from its Exploratory Topic on Low-Energy Nuclear Reactions (LENR).[99] The LENR investment is supporting exploration of potentially LENR-active palladium (Pd) nanoparticles or nanostructured composites using techniques such as coupling to thermally conductive carbon nanotubes for deuterium gas loading, as well as electrochemical or gas loading of deuterium under laser and/or ion beam irradiation. Project teams will manufacture the Pd nanoparticles and nanostructured composites using methods such as aqueous hydrothermal synthesis or nanopatterning and etching of Pd foils, with access to verified nanoparticle and nanostructure production and analysis capabilities.

The Navy's PCA 2 investments include NRL's development of architected nanoscale structures and dimensionally confined catalytic processes relevant to solid-state batteries, fuel production, and proton-conducting electrocatalytic nanocomposites. NRL is also working to understand and control the interactions of phonons and polaritions for nanophotonics, exploiting interplay between photonics and nanoscale chemical reactions, and developing nanophotonic components for neuromorphic networks. ONR's power electronics program plans 2024 investments in nanoclay insulation materials and in superparamagnetic nanocomposites and ferrite-based soft nanocomposite magnetics and novel additive manufacturing methods for use in high-frequency transformers.

Army PCA 2 investments include an ARL-supported program on Carbon Nanomaterials as Functional Additives, in-house research in collaboration with industry and university researchers, with the objective of developing engine and gearbox oils using carbon nanotubes and boron nitride nanosheets, to help extend the capability, range, and damage-tolerance of the Army's ground vehicles. Ongoing research in this project builds on the successes documented so far (see above in Goal 2 section).

Air Force research in PCA 2 includes quantum technology, specialty coatings, radio frequency (RF) devices, novel sensors, power electronics, lightweight structures, low-cost additively manufactured components, devices for edge computing, thermal protection coatings, and alternative materials to improve supply chain resiliency. Additional efforts are exploring biotechnology to synthesize, manufacture, or assemble nanomaterials for these applications, as well emerging AI/ML/autonomy technologies to accelerate discovery, development, and deployment of nanotechnology solutions (in keeping with the Materials Genome Initiative, MGI[100]). AFRL researchers supporting the Space Force are developing advanced electro-optical space sensor technologies that use single atomic layers of 2D nanomaterials throughout the sensor structure to improve sensitivity far beyond what would be possible if the same elemental constituents were incorporated as a conventional alloy. By studying highly manufacturable infrared sensor systems through the lens of nanotechnology, AFRL aims to deliver detector technologies that will enable the interconnected sensor networks of tomorrow.

The DARPA Coded Visibility (CV) program[101] falls under PCA 2. The CV program aims to demonstrate new obscurants (including nanomaterials) at field-scale that can provide asymmetric vision capability on the battlefield. Synthesis of obscurant nanomaterials will be scaled up to the multi-gram level to achieve aerosolized plumes for eventual pilot and field-scale demonstrations.

Priority goals for applied research funded by the NIFA/AFRI nanotechnology program include improved productivity and product quality; reduction of food waste/loss; improved nutritional value and

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[98] https://www.energy.gov/ne/neet-crosscut-advanced-sensors-and-instrumentation

[99] https://arpa-e.energy.gov/technologies/exploratory-topics/low-energy-nuclear-reactions

[100] https://www.mgi.gov/sites/default/files/documents/MGI-2021-Strategic-Plan.pdf

[101] https://www.darpa.mil/program/coded-visibility

efficiency of food and feed products; more effective therapies that significantly impact animal health and wellness; enhanced food safety and biosecurity; increased protection for natural resources, the environment, and agricultural ecosystems; and reduction of greenhouse gas emissions. NIFA collaborates with other USDA organizations (ARS and Forest Service) and other NNI participating agencies to support research on nanotechnology applications such high-value-added products from agricultural and forest origins; smart sensors for detecting targets of interest in agricultural production and food safety; distributed sensing networks to optimize application of agricultural inputs; and monitoring biomarkers for optimal crop or animal productivity and health.

NASA activities under PCA 2 include applied research on structural CNTs for aerospace applications such as lightweight space structures. In-house work was initially funded under the Game Changing Development program within NASA's Space Technology Mission Directorate. However, US-COMP,[102] a Space Technology Research Institute (STRI) project[103]—and Phase 3 SBIR funding for a U.S. manufacturer of CNT tapes, yarns, and sheets—have continued to make advancements toward the development of lightweight CNT reinforcements. Activities planned for 2024 include investing in manufacturing scale-up and engaging with small companies using the material in prototyping, providing feedback to the manufacturer on desired materials characteristics. An additional STRI, the Center for the Utilization of Biological Engineering in Space (continuing through 2025) is investigating the use of nanomaterial-bacteria hybrids to fix available carbon and nitrogen and transfer energy into biosynthetic processes, targeting applications for future missions to the moon and Mars. Two academia-led projects are underway to develop lightweight lunar power cables that can survive the extreme environments on the moon, including research to improve copper-graphene interfaces and 2D MXene nanocomposites as a multifunctional insulation system.

NASA’s Solid-state Architecture Batteries for Enhanced Rechargeability and Safety (SABERS) project, funded through the Aeronautics Research Mission Directorate, is integrating holey graphene as an electrically conductive scaffolding material in solid-state batteries, advancing use of carbon additives to improve battery capacity, and enabling fabrication of high energy, nonflammable, all-solid-state batteries for next-generation electric aviation.[104] Plans for 2024 call for scaling up to demonstrate SABERS performance in large cell formats. NASA is also exploring a variety of nanosensors projects, e.g., CNT sensors for use in monitoring structural health under the Revolutionary Vertical Lift Technologies Project,[105] and the use of gold nanoislands in colorimetric sensors for biofluids, for diagnostic applications.

USDA’s Agricultural Research Service is conducting applied nanotechnology research at three of its research centers: (1) Projects at the Western Regional Research Center in Albany, CA, include research on biomass from hemp-pulped nanofibers; thermoplastic starch blends of cellulose nanocrystals/nanofibrils; and straw residue, bagasse, and grass feedstocks for making nanocomposites and single-use packaging containers. (2) The National Center for Agricultural Utilization Research in Peoria, IL, is conducting research on phospholipid/polysaccharide nanoparticles for food and cosmetics; using agricultural waste as feedstocks for making commercial nanocelluloses and nanohemicelluloses; protein nanocapsules to encapsulate ingredients such as vitamin E; and nanocellulose from sorghum stover for paints and 3D printing. (3) At the Southern Regional Research Center in New Orleans, LA, there are projects on cotton fibers incorporated with (a)

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[102] Ultra-Strong Composites by Computational Design: https://www.nasa.gov/directorates/stmd/space-tech-research-grants/the-institute-for-ultra-strong-composites-by-computational-design-us-comp/

[103] https://www.nasa.gov/space-technology-research-institutes-stri/

[104] https://doi.org/10.1021/acs.accounts.2c00457

[105] https://www.nasa.gov/aeroresearch/programs/aavp/rvlt

silver nanoparticles for antimicrobial, thermal insulation, flame retardant, and hydrophobicity applications; (b) iron oxide nanoparticles to impart magnetic properties; and (c) copper ion nanoparticles for air and water purification applications. Each of these centers has multiple cooperative R&D agreements with industry. ARS provides funding (via federal pass-through contributions) to a university project for a pilot-scale nanocellulose production line that produces specialized fibers for developing a 3D wet forming process used in producing fiber-molded nanofiber laminated composite products with grease and water resistance. Complementary research on applications of cellulose nanomaterials is funded by the Forest Service (see below), NIFA, NSF, and DOE; NNCO is convening these agencies to help coordinate their efforts and promote collaboration.

Under PCA 2, FDA is conducting research to understand the potential and limitations of continuous-manufacturing technology for nanomaterials such as liposomes and lipid nanoparticles under the Collaborative Opportunity for Research Excellence in Science nanotechnology program.[106] One of the continuous-manufacturing platforms being studied was developed by a university as part of a previous research grant from FDA.[107] Other universities have been funded recently on similar topics, e.g., a project to develop an integrated continuous Current Good Manufacturing Practice (cGMP) facility for mRNA manufacturing.[108]

FDA's Center for Food Safety and Applied Nutrition (CFSAN)[109] is involved in R&D on nanotechnology-enabled sensors for contaminants, biological toxins, and pathogens in food products. The FDA/NCTR Nanocore works with international standards organizations to develop and publish documentary test method standards on nanotechnology-enabled medical products, with additional support from the NIH/NIEHS Division of Translational Toxicology,[110] to facilitate premarket review of product submissions and product entry to market. FDA's Center for Drug Evaluation and Research (CDER)[111] hosts the Nanotechnology Reviewer Network (NRN), an informal group of reviewers and researchers within CDER, NCTR, the Center for Biologics Evaluation and Research (CBER),[112] and the Center for Veterinary Medicine.[113] Research developments and case studies of recent nanomaterials applications are presented at NRN meetings, leading to discussion of common review approaches that helps harmonize comments sent to sponsors to ensure smooth commercial product development.

FDA/CBER's Office of Vaccines Research and Review[114] evaluates the safety, effectiveness, and quality of vaccines to prevent infectious diseases. Among several classes of nanoparticle vaccines that FDA reviews are the mRNA vaccines encapsulated in LNPs that have been used successfully to combat the COVID-19 pandemic. Because of their success against SARS-CoV-2, manufacturers are evaluating the safety and effectiveness of this class of vaccines against a wide variety of other infectious disease agents, as well as the development of other types of mRNA vaccines containing a replication system that amplifies the mRNA to multiple copies. The success of the LNP-mRNA vaccines has led to the standardization of the manufacturing process. CBER regulatory processes may be streamlined for additional vaccines manufactured by the same validated process.

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[106] https://www.fda.gov/science-research/nanotechnology-programs-fda/office-commissioner-nanotechnology-programs

[107] https://doi.org/10.1007/s11095-015-1798-8

[108] FDABAA-22-00123, https://www.fda.gov/vaccines-blood-biologics/industry-biologics/cber-advanced-technologies-program-extramural-research-funding

[109] https://www.fda.gov/about-fda/fda-organization/center-food-safety-and-applied-nutrition-cfsan

[110] https://www.niehs.nih.gov/research/atniehs/dtt/

[111] https://www.fda.gov/about-fda/fda-organization/center-drug-evaluation-and-research-cder

[112] https://www.fda.gov/about-fda/fda-organization/center-biologics-evaluation-and-research-cber

[113] https://www.fda.gov/about-fda/fda-organization/center-veterinary-medicine

[114] https://www.fda.gov/files/vaccines%2C%20blood%20%26%20biologics/published/Overview-of-the-Office-of-Vaccines-Research-and-Review.pdf

USDA/Forest Service projects contributing to PCA 2 include a biorefinery to make cellulose nanomaterials from biomass, exploring use of the organosolv process to make cellulose nanocrystals directly from forest thinnings, and several projects on renewable packaging made from nanocellulose: molded paper with cellulose nanomaterial coatings, cellulose nanomaterial fruit coatings, barrier films of cellulose nanomaterials coated on paper, and polyurethane foam with CNCs as nucleating agents. Additional projects include use of CNCs as filter media to remove PFAS from water, nanocellulose-coated paper substrates for printed sensors and electronics, development of a fast/robust instrument for measuring CNC size distribution, and CNC-enhanced cement (in collaboration with an industry group). These projects also include collaboration with and funding to university researchers, as well as funding contributions from USDA/NIFA.

Under PCA 2, DOJ/NIJ’s Forensic Science Research and Development program[115] funds projects applying nanotechnology toward the sensitive and selective detection and identification of trace chemical and biological materials collected as forensic evidence.

The Federal Highway Administration contributes to PCA 2 through three programs that support nanotechnology-related projects: (1) the Exploratory Advanced Research program[116] (including characterization and modeling performance of supplementary cementitious materials), (2) the SBIR program[117] (with awards on vehicle-to-Infrastructure communication via inductive paint), and (3) the Research Associateship program[118] (which is developing resilient asphalt materials and advanced corrosion modeling and monitoring techniques).

USPTO provides intellectual property policy advice and guidance to the Executive Branch, grants patents on nanotechnology applications that meet the statutory requirements, works with federal partners to identify key emerging technologies that the United States should focus on to enhance innovation, and supports an inclusive and accessible intellectual property system for all Americans, including independent inventors and entrepreneurs.

While the Nuclear Regulatory Commission does not have a specific budget allocation for nanotechnology, NRC’s participation in the NNI is important to maintain awareness of the relevant new technologies and ensure their readiness for use or application within the NRC licensee community.

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[115] https://nij.ojp.gov/topics/forensics/forensic-science-research-and-development

[116] https://highways.dot.gov/research/research-programs/exploratory-advanced-research/exploratory-advanced-research-overview

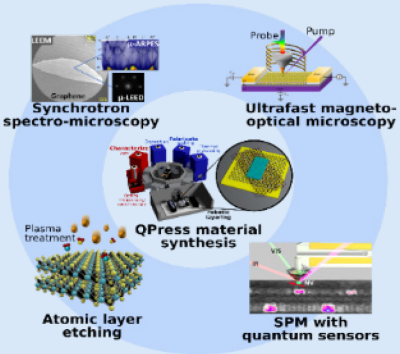
[117] https://highways.dot.gov/research/opportunities-partnerships/opportunities/small-business-innovation-research

[118] https://highways.dot.gov/research/research-programs/exploratory-advanced-research/nrc-research-associates-help-ear-program-solve-transportation-issues

Progress on Goal 3. Provide the infrastructure to sustainably support nanotechnology research, development, and deployment.

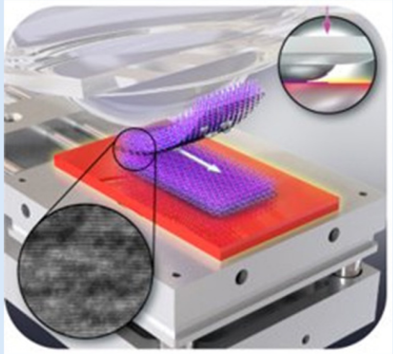
The physical equipment, digital models, simulations, and data that make up the research infrastructure are essential for all of the NNI goals. The need for expensive, specialized tools, as well as the expertise to utilize it, remains a key requirement for much of nanotechnology R&D. One distinguishing feature of the NNI is the shared infrastructure that provide researchers and developers with access to the tools required to create, characterize, and understand nanomaterials and nanotechnology-enabled components, devices, and systems. NNI participating agencies support advances in tool development, establishment and sustainment of facilities, and creation and dissemination of cyber resources. A few selected examples of Goal 3 progress are shown below.

Leveraging NNI user facilities to develop new tools for research and manufacturing



The QPress QM-IMCP platform provides a set of complementary tools for fabrication and characterization of 2D stacked heterostructures not found in nature. Image credit: BNL/CFN.

The Center for Functional Nanomaterials (CFN) at Brookhaven National Laboratory (BNL), one of five DOE NSRCs, has developed the Quantum Material Press, or QPress, a unique automated facility for the fabrication and study of stacked 2D heterostructure materials. The QPress functions by robotically peeling layers from 2D crystals and reassembling them into arrangements not found in nature. A quantum materials integrated multimodal characterization and processing (QM-IMCP) platform has also been integrated into the QPress cluster tool. The QM-IMCP platform offers atomic layer etching for atom-scale thickness control; synchrotron-based photoemission electron microscopy for characterizing electronic states, magnetic imaging, and chemical analysis; a magneto-optical ultrafast-microscope for studying carrier dynamics; and a scanned probe microscope with quantum sensors for mapping electrostatic potential of atomic defects and single spin detection. Full remote operability of the QPress tool is planned for 2024. QPress has recently been used to achieve systematic fabrication of atomically clean graphene heterostructures with record large dimensions (up to 7500 μm^2). The construction of such structures from graphene has been historically very difficult due to the inability to remove polymeric residues from interlayer interfaces during fabrication. However, research efforts have resulted in a new cleaning mechanism that combines mechanical and thermal processes to remove these residues and achieve an atomically clean layer of 2D graphene heterostructure useful for advanced devices.[119]



Stacking 2D layers on a heated substrate and applying pressure pushes out residues from contaminated graphene to form clean interfaces (TEM image, bottom inset). Image credit: BNL.

Supporting and sustaining research and manufacturing infrastructure for silicon photonics. The American Institute for Manufacturing Integrated Photonics (AIM Photonics, part of the Manufacturing USA network[120]) is headquartered in Albany, NY, where it has its photonic chip fabrication facility. It also runs a test, assembly, and packaging facility in Rochester, NY. AIM's mission is to advance integrated photonic circuit manufacturing technology development while simultaneously providing access to state-of-the-art

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[119] https://doi.org/10.1002/smll.202201248

[120] https://www.manufacturing.gov/

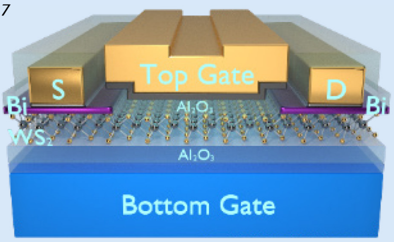
fabrication, packaging, and testing capabilities for small-to-medium enterprises, academia, and the government. Its educational goals are to create an adaptive integrated photonic circuit workforce capable of meeting industry needs and further increase domestic competitiveness. As of March 2023, 197 organizations were participating in AIM as members, observers, or users, including 87 small and 32 large businesses, 57 academic institutions, 14 government organizations, and several federally funded research and development centers (FFRDCs) and nonprofits. Government organizations that have used AIM services include AFRL, NRL, ARL, DARPA, ARPA-E, AFOSR, the Army Research Office (ARO), ONR, other DOD agencies, NIST, and NSF. Government projects supported through AIM include development of high-performance cost-effective silicon-based lasers, 2.5D integrated on-chip lasers, a quantum photonic integrated circuit platform, a wideband ultralow loss and fluorescence nitride-optimized sensors platform, and the NIST CARES Act Rapid Assistance for Coronavirus Economic Response program. Federal funding for AIM Photonics, with major cost sharing from industry and other non-federal sources, has been extended to sustain this vital national resource through September 2028.

Expanding biomedical nanotechnology research infrastructure to address pandemics. The National Cancer Institute, in collaboration with NIST and FDA, established the Nanotechnology Characterization Laboratory to perform preclinical characterization, including physicochemical, immunology, pharmacology and toxicity testing, of nanoparticles used in cancer research. NCL serves as a national resource and knowledge base for all cancer researchers to facilitate the regulatory review of nanotechnologies intended as cancer therapies and diagnostics. In its 19 years of operation, NCL has characterized more than 500 different nanomaterials with a wide range of nanotechnologies and therapeutic loads; established over 250 collaborations with academia, industry, and government labs; published over 260 peer-reviewed publications covering nanoparticle characterization, immunotoxicity, and safety; and established over 80 standardized protocols for nanoparticles assays. Twenty-four NCL collaborators have reached clinical trials with the aid of data produced at NCL, and several concepts have gained market authorization in the United States and the European Union as novel chemotherapeutic agents. In the effort to help combat the global COVID-19 pandemic, NCL is now accepting applications for characterization of novel nanomaterials used for prevention and treatment of COVID-19.

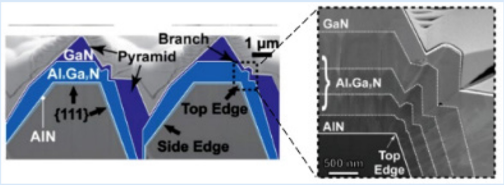
Advancing multiple national priorities with NNI infrastructure

The NNI research infrastructure includes user facilities and centers for research, education, and technology transfer, e.g., NIH's NCL; NSF's NNCI and Network for Computational Nanotechnology (NCN); DOE's NSRCs;[121] *DOE, DOD, and NIST nanotechnology-related Manufacturing USA institutes;*[122] *NRL's Institute for Nanoscience;*[123] *NIST's CNST*[124] *and Boulder Microfabrication Facility;*[125] *and many other associated light sources, beamlines, etc. These NNI-affiliated centers and user facilities contribute to many national priorities.*

Two representative academic examples funded by NSF are NNCI and NCN.[126] *NCN's mission is to advance nanoscience and nanotechnology modeling, simulation, and networking through nanoHUB.org, which has become a successful, scientific end-to-end cloud computing environment, hosting over 3,000 resources for research, collaboration, teaching, learning, and publishing. NCN served two million users in 2020, in multiple domains, advancing computational science and engineering broadly and contributing to the mission of the Materials Genome Initiative. The 16 sites of the NNCI*[127] *support research related to various industries of the future (e.g., AI, QIS, advanced manufacturing and wireless, biotechnology) and research communities organized around NSF and national priorities (convergence, earth and environmental sciences, Internet of Things, QIS, understanding the rules of life, and microelectronics). Activities include workshops, symposia, and webinars; roadmapping; and identifying future infrastructure needs. NNCI's annual report includes an appendix sorting research accomplishments by national priority.*[128] *Two examples in the microelectronics area are included in the figures at right and below.*



Schematic 3D cross-sectional diagram of dual-gated single-layer (1 nm thick) WS2 MOSFET with Bi contacts. Image credit: Lun Jin and Steven Koester, University of Minnesota.



GaN-on-Si LED fabrication (3D tetrapodal over 3D faceted Si). Cross-section SEM and TEM images show an AlN nucleation layer, an Al_xGa_yN buffer layer, and growth contours in the formation of branch GaN structures. Image credits: *Applied Surface Science*/Elsevier.

The DOE NSRCs are supporting the National Quantum Initiative with a funding increment for QIS research focused on developing advanced capabilities for quantum structures and phenomena, making the NSRC capabilities available to the QIS scientific community.[129] *The NIST CNST and Boulder Microfabrication Facility provide a foundation of capabilities and staff expertise on which the new National Semiconductor Technology Center and National Advanced Packaging Manufacturing Program will be built. The NIH NCL is being used to characterize materials for pandemic vaccines and therapeutics.*[130]

In September 2023, NNCO brought the interagency NNI infrastructure community together to share best practices and seek opportunities for collaboration, in a Nanotechnology Infrastructure Leaders Summit.[131]

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[121] https://nsrcportal.sandia.gov/
[122] https://www.manufacturing.gov/
[123] https://www.nrl.navy.mil/nanoscience/
[124] https://www.nist.gov/cnst
[125] https://www.nist.gov/programs-projects/boulder-microfabrication-facility
[126] https://nanohub.org/groups/ncn/
[127] https://nnci.net/
[128] https://nnci.net/sites/default/files/inline-files/NNCI%20Year%207%20Highlights%20by%20Priority.pdf
[129] https://www.energy.gov/articles/doe-announces-30-million-quantum-information-science-tackle-emerging-21st-century
[130] https://www.cancer.gov/nano/research/ncl
[131] https://www.whitehouse.gov/ostp/news-updates/2023/10/06/readout-of-the-nanotechnology-infrastructure-leaders-summit/

Plans for PCA 3. Research Infrastructure and Instrumentation

PCA 3 supports the establishment and operation of user facilities and networks, acquisition of major instrumentation, and other activities that develop, support, or enhance the nation's physical, data, and cyber infrastructure for nanoscale science, engineering, and technology. It includes R&D pertaining to the tools needed to advance nanotechnology research and commercialization, including informatics tools and next-generation instrumentation for characterization, measurement, synthesis, and design of materials, structures, devices, and systems.

NNI participating agencies will continue to invest in this research infrastructure, which provides critical support to the entire NNI ecosystem. The NNI R&D infrastructure also enables other priority research areas such as quantum information science, microelectronics, and the MGI. PCA 3 accounts for 32% of the DOE investment, and over half of the NIST investment, in the 2024 NNI budget request. Key NNI infrastructure investments include the DOE NSRCs, the NSF NNCI, and the NIST CNST and Boulder Microfabrication Facility.

The core of the DOE nanotechnology research infrastructure investments are the five Nanoscale Science Research Centers.[132] Each center has a particular focus: synthesis and characterization (the Center for Functional Nanomaterials at Brookhaven National Laboratory[133]); electronics/photonics and soft/hybrid materials assembly (Center for Integrated Nanotechnologies at Sandia National Laboratory and Los Alamos National Laboratory[134]); interfaces, interactions, and nanoscale assembly (the Center for Nanoscale Materials at Argonne National Laboratory[135]); materials science and quantum information science (the Center for Nanophase Materials Sciences at Oak Ridge National Laboratory[136]); and soft matter synthesis/functionality and energy conversion/storage (the Molecular Foundry at Lawrence Berkeley National Laboratory[137]). DOE/BES also supports other scientific user facilities across the nation that offer complementary capabilities of cutting-edge instrumentation and highly trained staff scientists. All of these facilities are available through a competitive peer-reviewed proposal process.

In 2023 and 2024, DOE/FECM is expanding ML and AI research computing infrastructure at the National Energy Technology Laboratory[138] to accelerate technology innovations for energy and environmental needs. This will help to enable functional and structural materials development focused on the design, synthesis, physical characterization, and performance testing of advanced materials, including nanomaterials, for carbon capture, gas separation, fuel cells, and hydrogen production, transportation, and storage technologies.

NSF has funded the National Nanotechnology Coordinated Infrastructure[139] sites for 2015–2024, with a national coordination office added in 2016. There are 16 NNCI sites and 13 partner organizations in 16 States, with a total of 71 facilities and over 2,200 specialized nanotechnology characterization and fabrication tools. Users come from all areas of science and engineering, conducting research across a wide variety of application areas, including industries of the future such as advanced manufacturing

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[132] https://nsrcportal.sandia.gov/
[133] https://www.bnl.gov/cfn/
[134] https://cint.lanl.gov/
[135] https://www.anl.gov/cnm
[136] https://www.ornl.gov/facility/cnms
[137] https://foundry.lbl.gov/
[138] https://netl.doe.gov/
[139] https://nnci.net/

(e.g., semiconductors), quantum information science, artificial intelligence, advanced wireless communications, and biotechnology. NNCI priorities for 2024 include growing the number and diversity of users, data collection and reporting to evaluate NNCI impact, supporting six research communities in key technology areas, and growing regional networks and partnerships.

Some NSF STCs, ERCs, CCIs, MRSECs, and DMREF awards have a focus on supporting the NNI, including the Center for Cellular Construction,[140] two nanotechnology ERCs (one each on nanobiotechnology and cell technology), and a CCI that investigates the fundamental molecular mechanisms by which nanoparticles interact with biological systems.[141] NSF will increase coordinated research on its Mid-scale Research Infrastructure priority area.[142] The Major Research Instrumentation program[143] serves to increase access to multiuser scientific and engineering instrumentation, including instrumentation needed for nanoscale science and engineering activities.

NIH/NCI continues to support the Nanotechnology Characterization Laboratory, which conducts the characterization of nanomaterial formulations for imaging and therapeutic applications developed by researchers from academia, industry, and government. NCL receives a broad range of nanomedicine technologies through its Assay Cascade program, and has experience with virtually all nanoparticle platforms, therapeutic agents, and applications employed in the pursuit of better treatments and diagnostics for cancer. NCL is expanding efforts toward the evaluation of nanomedicine bioequivalence and assessment of personalized vaccine strategies and immunotherapies. NCL has also started evaluation of nanotechnology strategies for the diagnosis and treatment of COVID-19.

Through a recently published Notice of Funding Opportunity,[144] NIH/NIBIB is seeking to establish a Biomaterials Network Technology Development Coordinating Center, with the aim to accelerate innovation, development, and early dissemination of biomaterials-based technologies, including nanoscale technologies, and overcome challenges to clinical translation.

The NIAID Vaccine Research Center has forged multiple avenues for the discovery and development of lipid nanoparticles for infectious disease vaccines. These include research collaborations with companies in low- and middle-income countries, such as South Africa and Rwanda, as well as internal efforts on discovery research. The aim is clinical demonstration of effective lipid nanoparticle technology and dissemination of the technology.

DOD supports nanotechnology research infrastructure through the Defense University Research Instrumentation Program, which is administered through a merit competition jointly by AFOSR, ONR, and ARO, in coordination with OUSD/R&E.[145] In addition, AFRL, in partnership with a university high-energy synchrotron source funded by NSF,[146] is supporting the Materials Solutions Network at CHESS, with the goal of transforming synchrotron x-ray techniques to engineering tools with standards, automation, and mature workflows through service lab–industry–academia collaborative research. Plans for 2024 and beyond include funding for two dedicated beamlines at CHESS, establishing a user consortium with a shared fee structure, and developing regional networks of users. AIM Photonics,

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[140] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1548297

[141] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2001611

[142] https://www.nsf.gov/news/special_reports/big_ideas/infrastructure.jsp

[143] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5260

[144] https://grants.nih.gov/grants/guide/rfa-files/RFA-EB-23-002.html

[145] https://www.defense.gov/News/Releases/Release/Article/2430566/dod-awards-50-million-in-university-research-equipment-awards/

[146] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1946998

NextFlex, and other Manufacturing USA institutes[147] also constitute major DOD contributions to the nanotechnology research infrastructure.

FDA's PCA 3 investments cover operating costs and equipment upgrades for nanotechnology research infrastructure across FDA, e.g., at the NCTR Nanocore facility in Jefferson, Arkansas. This facility is equipped with advanced analytical equipment, including electron, atomic force and optical microscopy; scattering; diffraction; spectroscopy; fractionation; chromatography; and elemental analysis facilities for nanomaterial assessment, including for *in vitro* and *in vivo* biological studies. Nanocore is collaborating with other agencies to characterize polymers to develop a spectral database for the identification and quantitation of micro- and nanoplastics in real-world samples.

Progress on Goal 4. Engage the public and expand the nanotechnology workforce.

Nanotechnology innovation relies on STEM talent and a highly skilled workforce. Thousands of students are trained every year in NNI-supported nanotechnology user facilities and research centers. There are also targeted curriculum-development efforts and internship programs, and NNI-funded research centers partner with community colleges to promote training of the technical workforce. There are particular efforts to promote opportunities and access to resources for people in traditionally underserved communities. NNCO works with NNI participating agencies, university-based student groups, and teachers organizations to conduct public outreach and help inspire students to learn about nanotechnology and to pursue STEM careers.[148] Just a few examples of NNI progress in Goal 4 are featured below.

Growing and diversifying a skilled technical workforce for the semiconductor and microelectronics industries. Micro- and nanotechnologies are increasingly critical to improving existing products and creating new ones, leading to rapid growth in related industries such as semiconductors and microelectronics. A highly skilled technical workforce is needed to keep pace with needs of these industries. To address this need, the NSF Advanced Technological Education (ATE) program funded the Micro Nano Technology Education Center (MNT-EC) to increase the numbers of community college faculty participating in micro- and nanotechnology technician education, thus supporting an increased number of students who receive technical education degrees and certificates in these fields.[149] The program includes strategic outreach to improve recruitment and retention of faculty and students from traditionally under-represented demographics. Based at a community college with strong partnerships with industry and research universities, MNT-EC provides cross-disciplinary programs in nanotechnology, photonics, nanobiotechnology, materials science, and semiconductor fabrication, and offers an Associate's in Science degree and certificates of achievement in biotechnology and laser technology. In June 2023, MNT-EC released a set of industry-validated knowledge, skills, and abilities (KSAs) for Microsystems Process Technicians and is developing a second document for Microsystems Equipment Technicians, expected to be available in early 2024. MNT-EC is collaborating with other NSF ATE centers and educators to assemble curricular resources in microsystems education that align with these KSAs. This will allow community colleges to integrate supplemental instruction into their existing classes and programs and address the current shortage of highly skilled technical graduates in the microelectronics and semiconductor industries. MNT-EC is just

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[147] https://www.manufacturingusa.com/institutes

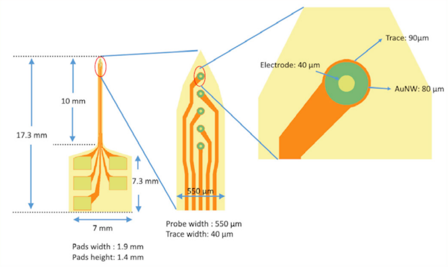
[148] See examples of NNCO outreach activities illustrated on the inside back cover of this report, and in the sidebar in this section of the report.

[149] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2000281

one example of an existing NNI education program that is well positioned to meet the goals of the CHIPS and Science Act of 2022.

Broadening participation of students from under-represented groups in stem education and microelectronics using nanotechnology

NSF has been supporting a regional center of excellence in southern Virginia consisting of a minority-serving university as the lead in collaboration with a major research university and a community college.[150] *The center uses nanotechnology as a conduit for engaging and inspiring talented students from traditionally under-represented minority populations. Through guided mentoring and opportunities for research and hands-on training experiences, students work with accomplished research professionals to utilize nanotechnology resources and connections.*



Neural electrode design. Image credit: Norfolk State University.

Students in clean-room suits. Image credit: Norfolk State University.

Activities include a "chip camp" offering experience working in a clean room, e.g., a project to design and fabricate a neural electrode. Students have remote access to characterization capabilities at the participating major research university.

Building the nanotechnology aerospace workforce of the future. NASA indirectly supports nanotechnology talent development through university student participation in research programs such as the Space Technology Research Institutes mentioned previously in this report. In addition to developing advanced technologies in conjunction with academia, two STRIs (Ultra-Strong Composites by Computational Design and the Center for the Utilization of Biological Engineering in Space) have resulted in talent growth which will contribute to the next-generation materials development workforce.

Nurturing nanotechnology talent in the biomedical community. FDA's CFSAN has supported and expanded the nanotechnology workforce by sponsoring postdoctoral and other trainees through opportunities such as the Oak Ridge Institute for Science and Education (ORISE) Training Fellowship Program[151] and other cooperative agreements. The ORISE trainees work closely with their designated CFSAN mentors to carry out cutting-edge nanotechnology research in CFSAN laboratories. CFSAN also utilizes the Joint Institute for Food Safety and Applied Nutrition internship program, which is administered jointly by a major research university and FDA, to allow undergraduate students to participate in research, including nanotechnology-related regulatory science projects, at FDA facilities. Finally, through its cooperative agreement with the Institute of Food Safety and Health (a food science research consortium comprised of a technology-focused research university, FDA, and the food industry), CFSAN offers graduate students at the university's Department of Food Science and Nutrition training opportunities in several of CFSAN's nanotechnology research programs. These students have gone on to enroll in PhD programs or obtain full-time employment.

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[150] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1826735

[151] https://orise.orau.gov/internships-fellowships/index.html

Using nanotechnology to inspire the next generation of entrepreneurs

In an effort to increase entrepreneurial training, and inspire nanotechnology-enabled solutions to global problems, the NSF-funded NNCI created the Nanotechnology Entrepreneurship Challenge (NTEC). In 2023, as part of the Nano4EARTH community-led efforts, the NTEC call highlighted the need for nanotechnology solutions for topics related to climate change. The seven-week NTEC program is designed to provide entrepreneurship education and experience to teams of undergraduate, graduate, and post-doctoral scholars. The program serves as a foundation/introduction to the NSF I-Corps program. Students are introduced to concepts such as customer discovery, NNI resources available to create a minimum viable product, and "pitch" training. The NTEC program culminates with a pitch competition where teams share their developed ideas. This year the winner of the pitch event won the opportunity to present her project at the Nano4EARTH "big idea" session at a professional conference. The winner developed a business plan to commercialize findings developed through a NIFA-funded project that explored the use of protein-based nanoparticles as bioengineered platforms for pesticide delivery. The Nano4EARTH big idea session was a space for researchers and entrepreneurs to present their nanotechnology-enabled climate solution ideas to panel of commercialization experts. The commercialization experts provided feedback and advice, and discussed various federal resources available for entrepreneurs.

NTEC pitch competition winner, Ivonne Gonzalez-Gamboa, presents her nanotechnology-enabled solution to widespread use of pesticides and agrochemicals to a panel of commercialization experts at the Nano4EARTH big idea session at a professional conference. Image credit: M. Fernanda-Campa, NNCO.

Plans for PCA 4. Education and Workforce Development

PCA 4 supports research on and development of curriculum and other tools for effective training of students at all stages of education (from K-12, to community colleges and vocational schools, through doctoral and postdoctoral education) in the skills needed to succeed in the nanotechnology workforce. While student support to perform research is captured in other categories, dedicated educational efforts ranging from outreach to advanced training are included here as resources supporting the nanotechnology workforce. PCA 4 also includes support for programs, partnerships, or personnel exchanges among government, academia, and industry to develop the desired workforce skills and competencies. This PCA further encompasses mechanisms for public engagement and informal education. Activities under PCA 4 are consistent with Recommendation 3 of the 2023 PCAST Assessment of the NNI, to enhance NNI activities related to supporting interdisciplinary, experiential learning.

Many NNI R&D and infrastructure programs support education and workforce development. For example, the NNI-supported user facilities (e.g., NSF's NNCI network) play a key educational role, giving access to state-of-the-art characterization and fabrication facilities to students from diverse backgrounds, partnering with community colleges and smaller universities (including minority-serving institutions), and conducting public outreach. A few examples of targeted nanotechnology education and workforce programs are discussed below.

In 2024, NSF will fund education and workforce development activities in all areas of nanoscale science and engineering, including engaging the public. Typical activities supported by the Directorate for STEM Education (EDU), the ENG Directorate's Division of Engineering Education and Centers, and other divisions are fellowships, single-investigator awards, and centers. A large part of NSF's support for education in nanotechnology is through funding participation of undergraduate and graduate students in research awards and centers. EDU's contribution will especially be in the Centers for Research Excellence (CREST) program;[152] the NSF Research Traineeship program,[153] for masters/doctoral graduate students; the Historically Black Colleges and Universities-Undergraduate program;[154] and the ATE program, for community colleges.[155] Examples of nanotechnology projects include "Supporting micro and nano technicians through hybrid teaching methods"[156] and "Water is Life," a project at a Tribal college that is developing core analytical laboratory facilities and engaging students and citizens to develop home-sized off-grid solar water nanofiltration systems."[157] NSF sponsors nanoscience communication contests through science museums and the Micro Nano Technology Education Center.[158] Additional NSF workforce development and training activities include programs that give high school and community college students, undergraduates, graduate students, postdocs, teachers, and veterans experience working in nanotechnology research centers in industry, government, and non-profits. Examples are the Non-Academic Research Internships for Graduate Students (INTERN),[159] Supplemental Funding Opportunity for Skills Training in Advanced Research & Technology,[160] Research Experiences for Undergraduates (REU),[161] Research Experience and Mentoring,[162] Research Experiences for Teachers,[163] Veterans Research Supplement,[164] Research Assistantships for High School Students,[165] Innovative Postdoctoral Entrepreneurial Research Fellowship,[166] and Experiential Learning for Emerging and Novel Technologies[167] programs. The INTERN program supports about 75 NSE-related internships for students in industry and government labs. Plans and priorities for 2024 include increasing the number of awards to K-12 institutions and REU programs.

NIH promotes a competent and diverse bioengineering workforce through a variety of training-related grants and programs. NIH also provides funding for research conferences and scientific meetings to facilitate knowledge sharing and scientific engagement, including many meetings focused on nanotechnology topics.

DOD education and workforce development efforts include support of students working on DOD-funded research projects. In addition, AIM Photonics uses a number of activities and approaches to

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[152] https://new.nsf.gov/funding/opportunities/centers-research-excellence-science-technology-0

[153] https://www.nsf.gov/pubs/2021/nsf21536/nsf21536.htm

[154] https://new.nsf.gov/funding/opportunities/historically-black-colleges-universities-1

[155] https://new.nsf.gov/funding/opportunities/advanced-technological-education-ate

[156] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2100402

[157] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2054903

[158] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2000281

[159] https://www.nsf.gov/eng/eec/intern.jsp

[160] https://new.nsf.gov/funding/opportunities/new-supplemental-funding-opportunity-skills-0

[161] https://new.nsf.gov/funding/opportunities/research-experiences-undergraduates-reu

[162] https://www.nsf.gov/eng/efma/rem.jsp

[163] https://new.nsf.gov/funding/opportunities/research-experiences-teachers-engineering-computer-0

[164] https://www.nsf.gov/pubs/2020/nsf20111/nsf20111.jsp

[165] https://www.nsf.gov/pubs/2018/nsf18088/nsf18088.jsp

[166] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1853888

[167] https://www.nsf.gov/pubs/2023/nsf23507/nsf23507.htm

teach concepts and skills for designing integrated photonic circuits for production in a foundry, including online courses and education kits.

The NIFA nanotechnology program includes support for graduate research programs and the use of the interesting, highly visible aspects of nanotechnology to excite young students and the public about agricultural science, food science and technology, and agricultural and biological engineering careers.

DOJ/NIJ's Graduate Research Fellowship program[168] typically funds one fellow engaged in nanotechnology research annually.

NASA STEM engagement activities are closely tied to its research programs, with funding reported under PCA 2. These include internships, fellowships, educational support, and student challenges, as ways of integrating students into the research projects. NASA's Established Program to Stimulate Competitive Research (EPSCoR) program[169] is supporting nanotechnology workforce training and economic development by providing funding support for students and faculty in EPSCoR jurisdictions. Additionally, as part of its technology portfolio, NASA's Space Technology Mission Directorate funds nanotechnology-related graduate research; the technology developers trained in this research then become the next generation of innovators in academia, industry, and government.

Progress on Goal 5. Ensure the responsible development of nanotechnology.

The responsible development of nanotechnology has been an integral part and goal of the NNI since its inception. This includes long-standing considerations such as understanding ethical, legal, and societal implications (ELSI) and nanotechnology-related environmental, health, and safety (nanoEHS) implications of nanotechnology development, as well as IDEA and the responsible conduct of research. These efforts support the other NNI goals by helping ensure the integrity of nanotechnology R&D and fostering public confidence and regulatory certainty. Just a few examples of these efforts are illustrated below.

Collaborating among multiple agencies to understand and control potential health implications of nanomaterials in 3D printer emissions. A CPSC-NIST collaboration developed test and analytical methods for detecting the presence of multiwalled carbon nanotubes (MWCNTs) in consumer-grade 3D printing materials and assessing the release of MWCNTs during the printing process. This research provided insights into the factors affecting the number, size distribution, and characteristics of released particles.[170] Complementary and cooperative efforts at NIOSH include an assessment of emissions from recycling of waste plastic from fused filament fabrication,[171] a review of the extent to which safety data sheets for resins used in material jetting and vat photopolymerization additive manufacturing processes adequately report the presence of skin irritants and/or sensitizers,[172] and development and publication of a 3D model for an inexpensive exhaust control device to capture ultrafine particle emissions generated by fused deposition modeling 3D printers.[173] NIOSH also evaluated emissions from different printer and feedstock combinations operating in chamber studies and workplace environments. This knowledge was used to create risk-management recommendations to protect

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[168] https://nij.ojp.gov/funding/fellowships/graduate-research-fellowship-program

[169] https://www.nasa.gov/stem/epscor/home/index.html

[170] For more information, including the NIST final report and a December 2023 CPSC staff statement on this project, see: https://www.cpsc.gov/content/CPSC-Nanotechnology-Program-Project-Report-NIST-2018-3D-Printing.

[171] https://doi.org/10.1016/j.resconrec.2021.105911

[172] https://doi.org/10.1016/j.yrtph.2022.105198

[173] https://3d.nih.gov/entries/3DPX-015467

workers in makerspaces, schools, libraries, and small businesses, which were published in November 2023.[174] Related recent work at EPA includes analysis of filaments, emissions, and products of 3D printing processes[175] and characterization of human exposure to 3D printing processes.[176] NNI agencies are coordinating their research on the implications of 3D printer emissions (including nanoplastics) through an informal interest group.

Developing and distributing information on best practices in safe handling of nanomaterials. NIOSH has a long and distinguished history of conducting research on and developing best practices for controlling worker exposures to nanomaterials, and then disseminating that information through publications and workplace posters.[177] The most recent in this series is *Occupational Exposure Sampling for Engineered Nanomaterials*,[178] which provides guidance in one document for workplace sampling for three engineered nanomaterials with established NIOSH Recommended Exposure Limits, as well as a practical approach to exposure sampling for other engineered nanomaterials that do not have exposure limits. NIOSH has also published the results of its studies in the scientific literature, including the results of a survey of engineered nanomaterial (ENM) health and safety practices at over 600 companies working with nanomaterials,[179] a series of articles on its 3D printer emission research,[180] and a multi-instrument assessment of fine and ultrafine titanium dioxide aerosols.[181]

Creating occupational health training curricula for nanotechnologies. The NIH/NIEHS Superfund Research Program is supporting a major research university to provide professional training through academic curricula, research experiences, and continuing education courses in industrial hygiene and environmental health sciences to graduate students and industrial hygienists in the Southern California region, recruiting diverse undergraduate and graduate students to join the graduate school pursuing master’s and doctoral studies in occupational and environmental health sciences fields. Foci of the program include training on occupational exposures, effects, best practices, and protection guidance regarding engineered nanomaterials and nanotechnology-enabled products, including consumer electronic products and their related waste managed at the generation and disposal stages.[182]

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[174] https://www.cdc.gov/niosh/docs/2024-103/pdfs/2024-103.pdf

[175] e.g., https://doi.org/10.1016/j.chemosphere.2021.130543, https://doi.org/10.1007/s42452-022-05221-7, https://doi.org/10.1016/j.scitotenv.2022.160512

[176] e.g., https://doi.org/10.1016/j.jaerosci.2021.105765, https://doi.org/10.1016/j.scitotenv.2021.152622

[177] https://www.cdc.gov/niosh/topics/nanotech/pubs.html

[178] https://www.cdc.gov/niosh/docs/2022-153/

[179] https://doi.org/10.3390/ijerph19137676

[180] https://doi.org/10.1016/j.yrtph.2022.105198, https://doi.org/10.1080/10937404.2022.2092569, https://doi.org/10.1016/j.resconrec.2021.105911, https://doi.org/10.1021/acs.chas.0c00129, https://doi.org/10.1080/10937404.2021.1936319

[181] https://doi.org/10.1080/15287394.2022.2150730

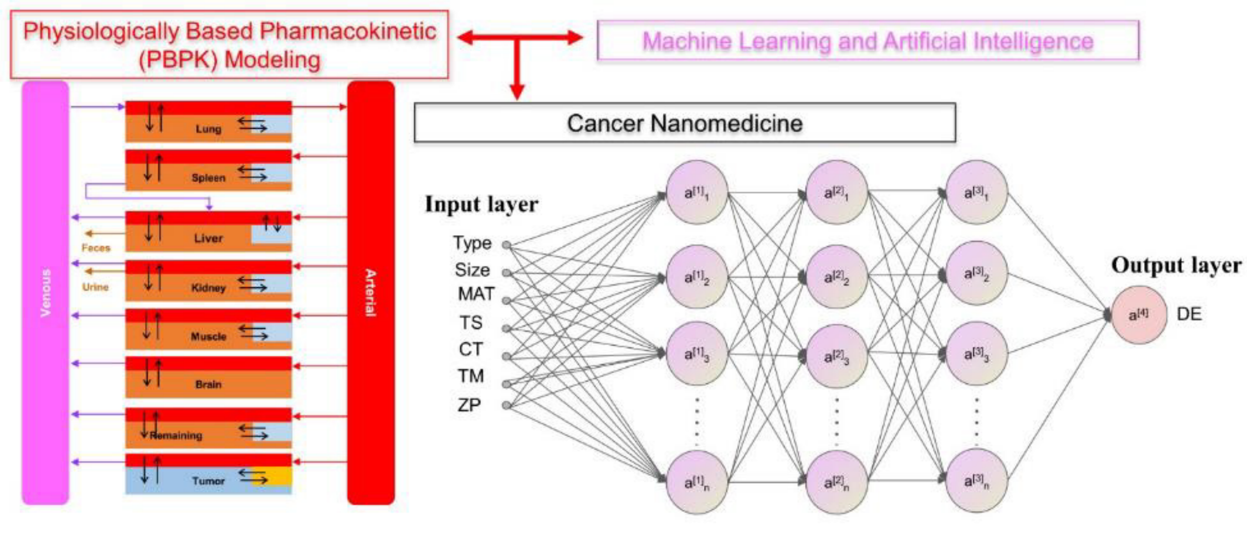
[182] https://reporter.nih.gov/search/I49Tu5DPREGv0dMRD9nXAw/project-details/10485173

Integrating nanotechnology with artificial intelligence and machine learning for nanomedicine discovery and safety assessment

The intersection of artificial intelligence, machine learning, and nanotechnology will require the development of collaborative and integrative approaches across these and other emerging and advanced technologies. One such area is nanomaterial product design and safety assessment, particularly for nanomedicine and drug delivery systems. For example, ML and AI approaches are being developed to predict nanoparticle (NP) delivery to tumors.[183] *NIH/NIBIB-supported research analyzed the roles of NP physicochemical properties, tumor models, and cancer types on NP tumor delivery efficiency using multiple ML and AI methods and data from the Nano-Tumor Database.*

The integration of AI with physiologically based pharmacokinetic (PBPK) modeling advances predictive modeling in cancer nanomedicine, and more broadly, human health assessment of nanomaterial exposure. PBPK models are mathematical descriptions that account for exposure routes and concentrations delivered, biodistribution, metabolism, and elimination of a substance. The model developed by these NIH-supported university researchers can serve as a predictive tool to assist in the design of new NP-based drug formulations for cancer therapy by improving the efficiency of preclinical trial screenings and reducing and refining the use animal studies.

This activity potentially can inform and complement other federal interagency initiatives reported on in previous NNI budget supplement reports, including the review and development of new testing methodologies (e.g., through the efforts of the Interagency Coordinating Committee on the Validation of Alternative Methods, ICCVAM) and efforts to develop interoperable formats for federal nanoEHS databases.[184]



Graphic depiction of the integration of PBPK models and AI to predict the delivery efficiencies of different NPs at different times after intravenous injection in tumor-bearing mice based on the Nano-Tumor Database. The database includes 376 datasets covering a wide range of cancer nanomedicines published from 2005 to 2018. The study evaluated the impact of physicochemical properties (type, size, core material, and zeta potential) and parameters related to the description of tumor studies (tumor model, size, and cancer type) on drug delivery efficiencies. Image credit: *International Journal of Nanomedicine*/Dove Medical Press Limited.

Disseminating data and information to streamline regulatory processes. The FDA Nanotechnology Task Force celebrates National Nanotechnology Day by organizing symposia or workshops. The 2022

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[183] https://doi.org/10.2147/IJN.S344208

[184] See the NNI Supplement to the President's 2023 Budget, p. 63 and p. 66, respectively: https://www.nano.gov/sites/default/files/pub_resource/NNI-FY23-Budget-Supplement.pdf.

FDA NanoDay Symposium[185] was convened to support industry in the development of nanotechnology products regulated by FDA, with speakers from FDA centers who discussed topics related to manufacturing and pre-clinical and clinical data necessary to support regulatory review and commercialization of these products, targeting in particular small businesses that are early in their product development and lack regulatory experience. A major component of the symposium was the presentation of a document finalized in 2022, *Drug Products, Including Biological Products, that Contain Nanomaterials—Guidance for Industry*.[186] Several talks referenced the guidance and how it can be implemented in filings to FDA; three of the speakers were among the authors. Other speakers discussed CFSAN's safety evaluations of food-contact substances that contain nanomaterials, FDA efforts to develop nanomaterial methods and materials standards and how product developers can benefit from these efforts, and the needs and opportunities for advancing continuous manufacturing of drug products containing nanomaterials, with a focus on liposomes and lipid nanoparticles. There were 3,549 total attendees from 97 countries; half of the registrants were from small businesses. The presentations are posted for the benefit of constituents who were unable to attend the event.

The 2023 FDA NanoDay Symposium[187] on continuous manufacturing (CM) of nanomaterials provided an overview of CDER's experience with CM technologies, case-studies of intramural and extramural research in the areas of nanomaterials CM, and a discussion of how industry, academia and other regulatory agencies can collaborate and engage with FDA in advancing the field of nanotechnology and CM.

In complementary work at NIH, NCI supports caNanoLab,[188] a data sharing portal designed to facilitate information sharing across the international biomedical nanotechnology research community and the public to expedite and validate the use of nanotechnology in biomedicine. caNanoLab provides support for the annotation of nanomaterials with characterizations resulting from physico-chemical, *in vitro* and *in vivo* assays, and the sharing of these characterizations and associated nanotechnology protocols in a secure fashion. caNanoLab was developed in a collaboration between two NCI programs: the Alliance for Nanotechnology in Cancer[189] and the Center for Biomedical Informatics and Information Technology.[190] caNanoLab holds large amount of data originating from existing publications and samples and lists several characterization assay protocols.

Using nanomaterials to maximize the efficiency and effectiveness of pesticides. "Nanopesticides" are nanoscale pesticidal active ingredients with the ability to deliver those active ingredients in a controlled and targeted manner. EPA scientists and collaborators from academia and a State government agency conducted a comprehensive analysis (including field trials) of the key properties of nanopesticides in controlling agricultural pests for crop enhancement. They concluded that the efficacy of nanopesticides against target organisms is 32% higher and toxicity to non-target organisms is 43% lower compared to conventional pesticides. They also found a 41% reduction in the premature loss of active ingredients prior to reaching target organisms and a 22% reduction in the leaching of active ingredients into soils. Other benefits noted in the study included enhanced adhesion to foliage,

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[185] https://www.fda.gov/drugs/news-events-human-drugs/fda-nanoday-symposium-2022-10112022

[186] https://www.fda.gov/regulatory-information/search-fda-guidance-documents/drug-products-including-biological-products-contain-nanomaterials-guidance-industry

[187] https://www.fda.gov/drugs/news-events-human-drugs/2023-nanoday-symposium-continuous-manufacturing-nanomaterials-10112023

[188] https://cananolab.cancer.gov/#/

[189] https://www.cancer.gov/nano/research/alliance

[190] https://datascience.cancer.gov/

improved crop yield and quality, and more responsive delivery of active ingredients to mitigate stresses such as heat, drought, and salinity. While calling for further investigations to address uncertainties associated with potential adverse effects of some nanopesticides, the group concluded that nanopesticides are potentially more efficient, sustainable, and resilient, with lower adverse environmental impacts than conventional pesticides, and could promote higher crop yields and contribute to global food security.[191]

Incorporating inclusion, diversity, equity, and access into the NNI's responsible development framework

In 2021, the NNI broadened its responsible development goal (now Goal 5) to incorporate inclusion, diversity, equity, and access as well as the responsible conduct of research (RCR). This change brought RCR and IDEA and traditional ELSI and nanoEHS anchors into the responsible development framework. NNI agencies have supported projects that address these various elements. For example, under its "Empowering Women and Underrepresented Undergraduates with Advanced Technology Research Training in Agriculture and Food Sciences" program, NIFA is providing grants to institutions in Hawaii and South Carolina. In Hawaii, the Advanced Technology Training in Agriculture and Food Science Research and Extension Experiences for Undergraduates[192] *project is providing experiential learning for women and minority undergraduate students in the fields of nanotechnology, space-farming, gene-editing, "omics," as well as advanced techniques in food sciences such as "supercooling." The South Carolina project, "Florece!: Future Leaders Obtaining Research & Extension Career Experiences," seeks to provide undergraduates with world-class research and extension skills that will allow them to tackle food insecurity and barriers to the sustainability of agricultural systems.*[193]

Students in Hawaii participating in NIFA-supported research and extension program for undergraduates. NIFA seeks to develop the local agriculture and food science industry workforce in Hawaii through education and training of women and underrepresented groups. Image credit: University of Hawaiʻi System News.

The NNI's 2023 nanoEHS webinar series is focusing on the questions, challenges, and breakthroughs needed to continue advancing responsible development of nanotechnology. The 2023 theme complements the NNI's effort to refresh its 2011 nanoEHS research strategy. During these webinars, rising experts and diverse early career researchers in nanoEHS are sharing their perspectives on the pressing issues and new questions driving their research.

Panelists in the March 28, 2023, NNI nanoEHS webinar, "What's Next in nanoEHS." The series spotlights early career and rising nanoEHS experts, where diversity among speakers was an important goal. Clockwise from top left: Quinn Spadola (NNCO, moderator), Adeyemi Adeleye, Joana Sipes, and Marissa Giroux. Image credits: NNCO.

Remediating agricultural wastewater using nanostructured wood. University scientists supported by NIFA have developed a technique for using nanostructured wood (NW) decorated with titania (TiO_2)

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[191] https://doi.org/10.1038/s41565-022-01082-8

[192] More information is available on the NIFA Current Research Information System (CRIS): https://cris.nifa.usda.gov/ (search for Project ID HAW05706-G).

[193] More information is available on the CRIS website (search for Project ID SC-2020-09438).

particles to remove and photocatalytically degrade fertilizers and other chemical pollutants in agricultural wastewater into CO_2, water, and low-molecular-weight compounds. The NW is created by the direct carbonization of wood sawdust, and serves not only as a physical absorbent, but also as a porous carbon-rich support bearing graphitic nanostructures for enhanced TiO_2 photocatalysis. TiO_2 decorated on the NW support, deposited by thermal spray coating or grown by co-carbonization, can remove agricultural pollutants under visible light radiation with enhanced photocatalytic efficiency.[194]

Providing ready access to COVID-19 diagnostics in rural communities. The NanoEarth node of the NSF-funded NNCI network has developed a laboratory-based detection assay for the identification of SARS-CoV-2 in samples from various clinical specimens that can be readily deployed in areas where access to testing is limited. This test shows sensitivity, specificity, and inclusivity values comparable to other molecular assays. It also can be reconfigured to meet supply chain shortages, modified for scale-up requirements, and used with several different types of clinical specimens. Test development involved 3D engineering of critical supplies and formulating a stable collection media that allowed samples to be transported for hours over a dispersed rural region without the need for a cold chain. This additional testing capacity is particularly helpful in rural areas that would otherwise be unable to meet testing needs.[195]

Plans for PCA 5. Responsible Development

PCA 5 covers a broad range of activities to ensure responsible development of nanotechnology. Activities include research and development directed at understanding the potential environmental, health, and safety impacts of nanotechnology, and at assessing, managing, and mitigating identified risks. Research addressing the broad implications of nanotechnology for society is also captured in this PCA. Responsible development encompasses efforts to benefit society addressing topics such as social, economic, ethical, and legal considerations, as well as issues related to diversity, equity, inclusion, and access. Research integrity, safety, and reproducibility are also captured in PCA 5.

While PCA 5 investments comprise a small portion of the overall NNI investments, they account for very large percentages (in most cases 100%) of the nanotechnology budgets of key regulatory, environmental, and worker protection agencies. They are also critical to maintaining public confidence in the safety and effectiveness of nanotechnology-enabled applications supported under other PCAs, to establishing regulatory clarity for companies seeking to commercialize nanotechnology products, and to assuring that the benefits of the NNI's nanotechnology investments accrue to the benefit of all Americans.

NNI participating agencies have been collaborating from the beginning of the initiative to promote and coordinate research on nanoEHS implications of nanotechnology, and to shape that research agenda to inform regulatory policies. A series of nanoEHS strategy documents released in 2006 through 2008[196] culminated in the publication of the NNI's first comprehensive EHS research strategy in 2011.[197] Since then, there have been a series of NNI workshops and reports assessing progress on the 2011 strategy.[198] In 2022, the NEHI Working Group embarked on a project to review and refresh the 2011 strategy. Following internal deliberations and literature reviews, NEHI worked with NNCO and OSTP to release a

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[194] https://cris.nifa.usda.gov/cgi-bin/starfinder/37646/crisassist.txt

[195] https://doi.org/10.1038/s41467-021-24552-4

[196] https://www.nano.gov/ehsdocuments

[197] https://www.nano.gov/sites/default/files/pub_resource/nni_2011_ehs_research_strategy.pdf

[198] https://www.nano.gov/ehsdocuments

Request for Information[199] and organized a public meeting[200] to gather external stakeholder input on the new strategy. The updated strategy document is currently under preparation; following public comment, it is expected to be released in calendar year 2024. In addition, the NEHI Working Group is coordinating interagency efforts on micro- and nanoplastics, 3D printing, and informatics and databases through informal interest groups.

In 2024, NSF will continue its funding for nanoEHS research through core programs directed at understanding nano-bio phenomena and processes, as well as methods for reducing the risks of nanotechnology development, and through its Nanoscale Interactions program[201] and sponsorship of the Center for Sustainable Nanotechnology.[202] There will be increased support for diversity and equity by inclusion and access for underrepresented groups, women, and people with disabilities interested in nanoscale science and engineering, and for broad geographical representation in all 50 States. NSF programs with a specific focus on inclusion, diversity, equity, and access reside in the Division of Equity for Excellence in STEM of the Directorate for STEM Education. Many make awards in nanotechnology research, education, and workforce development (e.g., through the CREST program; see above under PCA 4).[203] NSF will also address sustainable semiconductor manufacturing. NSF sponsors an annual Nanoscale Science and Engineering Grantee Conference to assess progress in nanoscience and nanotechnology and facilitate identification of new research directions. The 2022 conference was focused on sustainable society and the 2023 focus was on nano-biotechnology and nanomedicine. The NSF PCA 5 investments also include research directed at identifying and quantifying the broad implications of nanotechnology for society, including social, economic, ethical, and legal implications. NSF's NNCI centers also have extensive diversity and outreach programs.

The nanoEHS efforts of NIH's National Institute of Environmental Health Sciences are designed to gain a fundamental understanding of the molecular and pathological pathways involved in mediating biological responses to engineered nanomaterials. Building on the previous efforts of the Nanotechnology Health Implications Research Consortium, current NIEHS-funded nanoEHS efforts include investigator-initiated research projects such as work focused on understanding how nanoparticle exposure modulates allergic lung disease and skin immune response using animal models. Planned activities in the NIEHS Division of Translational Toxicology include completion of analysis and reporting of studies evaluating immunotoxicity and chronic carcinogenicity of multiwalled carbon nanotubes. The NIEHS Superfund Research Program plans to emphasize research that develops nanotechnology-enabled structures to enhance sustainable remediation and to enable rapid, accurate environmental monitoring. The NIEHS SBIR/STTR program also supports research efforts for developing tools for nanomaterials exposure monitoring, including characterization of toxicity of airborne ENMs using a direct *in vitro* exposure method and development of a third-party verification process for characterizing exposures to products containing ENMs. NIEHS has issued a Notice of Special Interest for extramural research to promote investigations on exposure to and health effects of micro- and nanoplastics; applications will be accepted through 2027.[204]

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[199] https://www.federalregister.gov/documents/2023/05/23/2023-10958/request-for-information-national-nanotechnology-initiative-environmental-health-and-safety-research

[200] https://www.nano.gov/ehsstrategymeeting

[201] https://new.nsf.gov/funding/opportunities/nanoscale-interactions

[202] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2001611

[203] For example, https://www.nsf.gov/awardsearch/showAward?AWD_ID=1914751

[204] https://grants.nih.gov/grants/guide/notice-files/NOT-ES-23-002.html

NIOSH's nanoEHS efforts focus on addressing worker health and safety needs related to nanotechnology, advancing understanding of nanotechnology-related toxicology and workplace exposures, so that effective risk management practices can be implemented during the discovery, development, and commercialization of engineered nanomaterials along their product life cycles. Through strategic planning, research, collaboration with stakeholders, and dissemination, NIOSH develops guidance that supports and promotes the safe and responsible development and commercialization of ENMs.[205] NIOSH will conduct toxicology studies that advance the understanding of potential human health implications of exposure to nanomaterials, evaluate biomarkers of exposure and disease, develop innovative *in vitro* methodologies to better predict *in vivo* outcomes, and evaluate pulmonary and dermal exposure and toxicity, and systemic toxicity, that results from occupational exposures to nanomaterials and nanotechnology-enabled products. NIOSH will advance understanding of nanomaterials impacts by using real-world materials and exposure data to guide toxicology-testing regimens, correlating results with worker health studies, to gain a more realistic view of the impact of nanomaterials in their actual manufactured state. NIOSH plans to develop, test, and evaluate direct-reading instruments capable of detecting and measuring airborne nanoparticles. Additional plans include field tests of the portable aerosol multielement spectrometer developed by NIOSH, as well as efforts in detection of airborne nanoparticles, including in biological systems, to evaluate and predict biological behavior and translocation between organ systems. NIOSH will also explore the feasibility of applying advanced sensing technology and data analytics to biomarkers as a means of evaluating nanomaterial exposure and possible early response.

NIOSH will continue to develop occupational safety and health guidance that can be incorporated into business plans to both protect worker safety and promote safe nanotechnology application development and commercialization. NIOSH will collaborate with the America Makes advanced manufacturing innovation institute, with university partners, and with industry collaborators to promote safe practices in nanotechnology and advanced manufacturing. NIOSH plans to work with industry to develop practical, "real world" evaluation of hazard and risk represented by nanomaterials through their life cycles, focus the NIOSH field research effort on outputs that support sustainable operations, and collaborate with industry to assess the toxicology of carbon-based and metal-based nanomaterials, nanocellulose, and nanoclay materials. NIOSH is collaborating with nongovernmental organizations, trade unions, and industry to evaluate nanotechnology-enabled spray coatings, composites, and other nanomaterials in construction and manufacturing. It will also continue collaborations with ISO and OECD on nanoEHS-related standards and test guidelines.

Ongoing and planned nanoEHS investments at NIST include research on: (1) particle number concentration measurements and development of number concentration reference materials; (2) liposome and mRNA lipid nanoparticles toward development of reference materials; (3) protocols for generating pristine and weathered nanoplastic test materials using cryomilling (in collaboration the European Commission's Joint Research Centre); (4) detection and characterization of airborne plastics; and (5) the use of novel imaging techniques such as optical photothermal infrared spectroscopy to better understand the properties and sources of micro- and nanoplastics particles.

The NIFA nanotechnology program funds EHS assessments of engineered nanoparticles applied in food and agricultural systems, including detection and quantification of engineered nanoparticles, characterization of hazards and exposure levels, and fate and transport of ENMs in foods, agricultural production, and the environment. The program addresses environmental issues and agricultural waste

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[205] https://www.cdc.gov/niosh/topics/nanotech/pubs.html

challenges such as extraction of biopolymers from agricultural byproducts and the design of nanocatalysts for bioprocessing of waste into food, feed, industrial chemicals, biofuels, and energy.

EPA's nanotechnology-related research is conducted as part of the Office of Research and Development (ORD)[206] Chemical Safety for Sustainability and Safe and Sustainable Water Resources national research programs. Research on ENMs is focused on developing, collating, mining, and applying information to inform both exposure and hazard assessments and support risk-based decisions related to the agency's implementation of the Toxic Substances Control Act (TSCA) and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). These efforts are coordinated with the Office of Chemical Safety and Pollution Prevention (OCSPP),[207] which is responsible for implementation of these statutes. EPA's Trash-Free Waters (TFW) program[208] works to reduce the volume of trash entering our waters by collaborating with partners to implement solutions to land-based sources of trash, including micro-/nanoplastics.

In 2024 ORD will conduct intramural research to inform safety assessments of emerging materials that require evaluation of impacts on humans and ecological species, which may include nanopesticides, ENMs, micro-/nanoplastics, and other incidental nanomaterials. In addition, support for implementation of an evaluation framework for nanomaterials under FIFRA is an ongoing need. ORD recently issued an extramural solicitation[209] focused on developing and demonstrating nanosensor technology with functionalized catalysts with potential to degrade contaminants in addition to detecting and monitoring pollutants. ORD's intramural nanoplastics research will include focus on developing analytical methods for the detection of nanoplastics in environmental, cellular, and tissue matrices, which will support health studies and development of standardized methods to assess ecological effects for sensitive species. Pursuant to Section 132 of the Save Our Seas 2.0 Act of 2020,[210] the TFW program and NOAA's Marine Debris Program plan to release a report in 2024 on microfiber pollution on behalf of the Interagency Marine Debris Coordinating Committee. OCSPP is actively engaged in international cooperation efforts with OECD through its Working Group of National Coordinators of the Test Guidelines Programme, and through participation in the OECD Working Party for Manufactured Nanomaterials. OCSPP also participates in the NEHI Working Group, informal NNI interest groups on nanoplastics and nanosensors, and the U.S.-EU nanoEHS Communities of Research.[211] EPA/ORD is also working, through the NEHI Working Group, toward the goal of improving interoperability of nanoEHS data from disparate agency sources. EPA's automated ontological mapping tool (OntoSearcher), which was piloted in 2021 with OSHA and NIOSH datasets, enables mapping of data to an ontology that supports integration of nanoEHS data developed by various NNI participating agencies into a common framework.

FDA/CFSAN is conducting research on nanotechnology-related areas relevant to human food safety, e.g., the potential migration of engineered nanomaterials from nanotechnology-enabled food-contact materials to food, to estimate possible consumer exposure. CFSAN is researching possible incidental presence of nanoparticles in certain food additives to support safety assessments. FDA/NCTR conducts collaborative regulatory science research on characterization, safety, and efficacy assessment of nanomaterials, in cooperation with stakeholders within FDA, other government agencies, and

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[206] https://www.epa.gov/aboutepa/about-office-research-and-development-ord

[207] https://www.epa.gov/aboutepa/about-office-chemical-safety-and-pollution-prevention-ocspp

[208] https://www.epa.gov/trash-free-waters

[209] https://www.epa.gov/research-grants/developing-and-demonstrating-nanosensor-technology-detect-monitor-and-degrade

[210] https://www.congress.gov/bill/116th-congress/senate-bill/1982/text

[211] https://us-eu.org/

academia. NCTR is also a key participant in FDA's research addressing potential implications of micro- and nanoplastics pollution. FDA's Nanotechnology Task Force celebrates National Nanotechnology Day each year by organizing symposia or workshops to improve communications and cooperation with the research and business communities and the general public on the agency's activities in pursuit of the responsible development of nanotechnology.

CPSC's PCA 5 investments focus on determining potential consumer exposures to nanomaterials and the health effects of those exposures. It is working to advance voluntary standards through the development of methods to characterize and quantify the release of nanomaterials from consumer products. Working with other NNI participating agencies, priorities for 2024 include: (1) collaborations with EPA, NIOSH, and NIST to characterize the use/release of nanomaterials during the lifecycle of additive manufacturing systems; (2) a risk assessment of silver nanoparticles; (3) development of a U.S. federal interagency harmonized nanotoxicology database; (4) development of an ISO voluntary standard (TC 229 PWI 5265) for characterizing and quantifying the release of nanomaterials from wood products; and (5) production of a white paper that provides a risk management framework for assessing the safety of products, including evaluations unique to nanoscale properties of materials.

CDC/NCEH and /ATSDR are both engaged in internal research and analysis of existing technical literature on potential environmental and human health implications of micro- and nanoplastics. Although not currently counted in the NNI budget crosscut, NCEH and ATSDR are active participants in the NNI's informal interagency interest group on nanoplastics, and are collaborating with other agencies on this topic, e.g., developing best practices for collection and characterization of environmental micro- and nanoplastics samples and evaluating the readiness for developing standards related to nanoplastics measurements. Examples of recent projects involving staff from both NCEH and ATSDR include a scoping review of microplastics environmental and human exposure data[212] and a study on liver carcinogenicity potential from occupational exposure to polyvinyl chloride microplastics.[213] NCEH, ATSDR, and many other agencies participated in two public webinars reviewing U.S. government nanoplastics activities, on March 22 and June 6, 2023.[214] Ongoing and planned NCEH and ATSDR projects include (1) completing a manuscript of a systematic review on human exposures to microplastics in water and potential health effects, (2) evaluating human exposure from outdoor and indoor emissions, (3) developing an interactive scoping review hub for microplastics literature, (4) conducting a systematic review on micro-and nanoplastics biomonitoring data gaps and needs to estimate human health risks, and (5) assessing the potential for microplastics mitigation in urban constructed wetlands.

DARPA's Coded Visibility program is engaging with the U.S. Army Combat Capabilities Development Command Chemical Biology Center to understand the inhalation effects of different nanomaterials and morphologies to determine health risks of newly developed obscurant materials.

Progress on the Nano4EARTH National Nanotechnology Challenge.

The 2021 NNI Strategic Plan outlines a mechanism for mobilizing and connecting the nanotechnology community to help address critical issues, National Nanotechnology Challenges. Nanotechnology researchers working in these areas will be connected with broader efforts focused on these issues to accelerate solutions that benefit society. The NNI announced a National Nanotechnology Challenge on

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[212] https://doi.org/10.3390/microplastics2010006

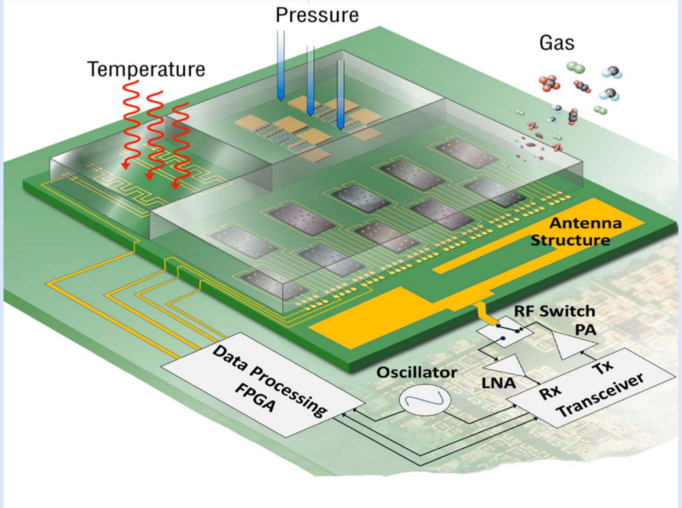
[213] https://doi.org/10.1002/ajim.23540

[214] See https://www.nano.gov/PublicWebinars for archives of the webinars.

climate change, Nano4EARTH, on October 7, 2022.[215] Nano4EARTH recognizes the role nanotechnology will and already plays in: **e**valuating, monitoring, and detecting climate change status and trends; **a**verting future greenhouse gas emissions; **r**emoving existing greenhouse gases; **t**raining and educating a highly skilled workforce to harness nanotechnology solutions; and developing **h**igher resilience to—and mitigation of—climate change-induced pressures for improved societal/economic resilience. NNI funding for Nano4EARTH spans all of the PCAs. As discussed above in the budget summary section of this report, rough estimates for spending by the NNI-participating agencies on activities in support of Nano4EARTH are just under $200 million in 2023 and just over $200 million in the 2024 request. NNI community-wide activities in support of this NNC since its inception are outlined in the sidebar at the end of this section of the report. The following are a just a few examples of the many individual agency activities that have been furthering the goals of the Nano4EARTH NNC.

Directly synthesizing MXenes for energy storage and other applications. Potential applications of 2D transition-metal carbides and nitrides known as MXenes include high-performance lithium-ion and sodium-ion batteries and supercapacitors, but their utility has been limited previously by inefficient synthesis methods. University researchers supported by multiple NSF, AFOSR, and DOE awards (and using NSF- and DOE-funded research infrastructure) have developed a method for direct, scalable, and economical synthesis by chemical vapor deposition growth of MXene carpets and complex microspheres. The microspheres form through buckling and release of MXene carpet to expose fresh surface for further reaction; 2D layers of MXene grow perpendicular to the substrate and then fold into microspherical structures. Directly synthesized Ti_2CCl_2 MXenes showed excellent energy storage capacity for lithium-ion intercalation. The work was featured on the cover of a major scientific journal in March 2023.[216]

Using nanosensors to monitor methane gas released from permafrost



Nanosensor platform for detecting greenhouse gases. Image credit: Mahmooda Sultana/NASA Goddard Space Flight Center.

One quarter of the Earth's terrestrial surface is underlain by permafrost, which contains an estimated 1,672 Pg of carbon and has been warming at approximately 0.5°C per decade, releasing the carbon as methane and carbon dioxide. Much of the permafrost in the interior of Alaska is just below freezing (-1°C), making this large store of carbon vulnerable to thaw, potentially resulting in a runaway problem. Thawing permafrost transforms the entire ecosystem and landscape, with changes in vegetation, deepening of active layers, and changing saturation, and concomitant changes in greenhouse gas fluxes. Scientists at NASA Goddard Spaceflight Center have developed a multifunctional nanosensor platform that includes a suite of high-performing environmental sensors based on different nanomaterials. This small, lightweight, and low-power instrument is currently being used to investigate the methane released from permafrost and identify localized sources of methane.

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[215] https://www.nano.gov/nano4EARTH

[216] https://doi.org/10.1126/science.add9204

Commercializing nanotechnology-enabled polymer batteries for grid storage of renewable energy. Researchers at the Army-supported Institute for Soldier Nanotechnologies have developed a safe, non-lithium-based stationary energy storage system designed specifically for the electrical grid. It is capable of providing flexible, safe power assets that handle peak loads and time shift. A spinoff company is now manufacturing power cells derived from ISN research on nanostructured conductive polymers—organic compounds that can behave like metals—that can respond to both base and peak loads in microseconds, potentially allowing for a variety of uses for the same battery system. Commercial and industrial installations can provide stable, constant power in a wide variety of environmental and weather conditions; utilities can store power during times of low demand to be available during spikes in need; renewable energy providers like solar arrays and wind farms can collect and store energy when conditions are optimal for distribution when the sun is not shining and the wind is not blowing; and large-scale datacenters can use these cells to provide secure and reliable power to critical systems. These polymer batteries, each roughly the size of a soda can, are safer than standard batteries due to their friendlier materials, have lifespans more than twice as long as Li-ion batteries and more than 20 times as long as lead acid batteries, and can operate in a wider range of temperatures than either Li-ion or lead acid batteries. They provide a scalable solution to large and small stationary energy storage requirements, and could help fill a key gap in enabling the renewable energy economy of the future.

Doubling the energy efficiency of semiconductor devices every two years. For decades, the number of transistors in an integrated circuit doubled approximately every two years, as observed by Moore's Law; along with this came steady improvement in the cost and energy efficiency of computing and other microelectronics applications. With the sunsetting of Moore's Law, from 2010 to 2020 energy use by microelectronic devices doubled every three years, and since 2020 has increased to account for more than 10% of global electricity use. Demand is expected to grow even more dramatically in coming decades with the advent of computing-intensive applications such as artificial intelligence. This unsustainable trend has created an urgent need for rapid increases in microelectronics energy efficiency. In 2022 DOE announced the Energy Efficiency Scaling for 2 Decades (EES2) national initiative, with the aim of getting the semiconductor industry back on the path of doubling energy efficiency every two years, thereby also increasing the economic competitiveness of American semiconductor manufacturers and strengthening domestic clean energy supply chains. As of the fall of 2022, over 20 companies and other organizations made commitments to contribute to meeting this challenge.[217] In 2023 DOE's Advanced Materials and Manufacturing Technologies Office announced a call for national laboratory research proposals in support of the EES2 initiative.[218] Because leading-edge semiconductor devices are all manufactured and function at the nanoscale, most of this effort, with public sector R&D leveraging internal industry funding, will involve nanotechnology. This activity is in keeping with the much broader DOE Energy Earthshots Initiative,[219] funding research at both national laboratories and universities, much of which will also involve nanotechnology.

Enabling energy-efficient artificial intelligence through neuromorphic computing. NIST researchers and collaborators from U.S. and international universities and two companies (using facilities at the NIST CNST) have been engaged for several years in a project on Spintronics for Neuromorphic Computing, where information is carried by electronic spin rather than charge. Among the spintronic devices that are being explored are magnetic tunnel junctions (MJTs), which are

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[217] https://www.energy.gov/eere/amo/articles/department-energy-announces-pledges-21-organizations-increase-energy-efficiency

[218] https://www.energy.gov/eere/ammto/fy-2023-microelectronics-lab-call

[219] https://www.energy.gov/energy-earthshots-initiative

particularly suited to implementing novel approaches to computing because they are multifunctional and compatible with standard integrated circuits. When operated near the thermal switching threshold, MJTs exhibit complex stochastic behavior that is reminiscent of some aspects of brain activity. In other configurations they can oscillate when driven by a steady current. The research team is exploring the extent to which these novel functionalities can be applied to computing that emulates the brain,[220] which is known to be far more energy efficient than traditional computing hardware. The team has demonstrated a crossbar array with 30 nm diameter MJTs,[221] a binary neural network implemented on a passive array of MJTs,[222] and energy-efficient stochastic computing with superparamagnetic tunnel junctions,[223] among many other accomplishments.

Understanding the impact of nanomaterials on climate resilience of agriculture. As discussed previously in this report (see p. 41), nanomaterials (NMs) are being developed for precision delivery of pesticides to maximize effectiveness and minimize unwanted side effects and pollution. NMs are also being proposed for use in targeted delivery of fertilizers for similar reasons.[224] However, the prospect of widespread application of NMs in agriculture raises potential concerns about their impacts on microbiome structure and pathogen persistence in soil and irrigation water. NIFA has funded a university research group to address these concerns and fill knowledge gaps using a state-of-the-art multi-omics and ML platform. Mechanisms of NM-induced pathogen evolution and adaption are being explored using multi-omics and ML, involving nanopore whole-genome sequencing, whole-transcriptome sequencing, and metabolomics. The experiments include climate simulation to examine how climate change affects the implications of NMs use in agrifood systems.[225]

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[220] https://www.nist.gov/programs-projects/spintronics-neuromorphic-computing

[221] https://www.nist.gov/image/fig-1-colorized-scanning-electron-micrograph-crossbar-array-30-nm-diameter-magnetic-tunnel

[222] https://www.nist.gov/publications/implementation-binary-neural-network-passive-array-magnetic-tunnel-junctions

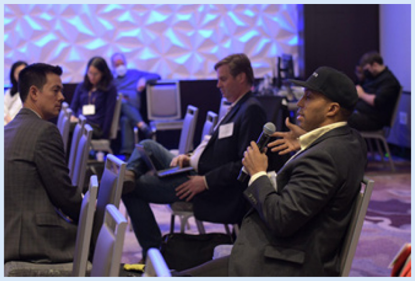
[223] https://www.nist.gov/publications/energy-efficient-stochastic-computing-superparamagnetic-tunnel-junctions

[224] https://doi.org/10.1021/acs.jafc.7b02178

[225] https://cris.nifa.usda.gov/cgi-bin/starfinder/72186/crisassist.txt

Nanotechnologists and climate scientists working together to accelerate solutions for climate change: Selected highlights of NNI community-wide activities implementing Nano4EARTH[226]

In January 2023, the Nano4EARTH kick-off workshop brought together over 400 members of the NNI community—including representatives from academia, K-12 education, government, industry, and philanthropic organizations—to identify nanotechnologies poised to have an impact on climate change in four years or less, in addition to sharing resources available to address barriers to entrepreneurship and technology adoption. Goals and metrics to maintain momentum throughout the challenge were also identified. Some of the themes highlighted included coatings, lubricants, membranes, and other interface technologies; batteries and energy storage; greenhouse gas capture; and catalysis.[227]



Participants in the Nano4EARTH kickoff workshop. Image credit: NNCO.

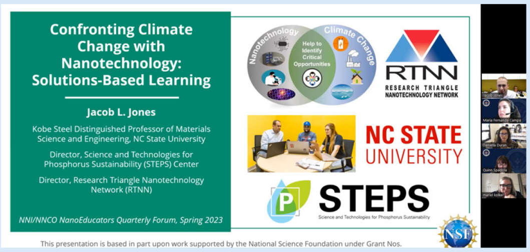
Participants in the July 6, 2023, NNI Nano4EARTH roundtable meeting on coatings and lubricants. Image credit: NNCO.

The NNI is organizing a series of ongoing roundtable discussions on some of the themes highlighted at the workshop. The roundtables each convene about a dozen subject matter experts from academia, national laboratories, industry, and the financial and technology transfer communities. The lively conversations are focusing on identifying the most pressing needs and opportunities and asking the groups to match emerging opportunities to needs. By bringing together groups with diverse backgrounds and expertise, the discussions aim to facilitate creative thought, collaboration between sectors, and serve as a resource for identifying areas of the greatest potential impact.

Community-led events have included a February 2023 meeting organized by the NSF-supported NNCI Research Community for Nanotechnology Convergence to identify Critical Nanotechnology Opportunities for Addressing Climate Change. The goal of the event was to help identify basic research needs related to climate change that could be addressed through the nanotechnology lens. Nano4EARTH also inspired this year's climate change theme for the Nanotechnology Entrepreneurship Challenge organized by the NNCI (see workforce sidebar above for details, Goal 4 section).

NNCO organized a Nano4EARTH session at a professional conference where entrepreneurially minded participants presented their nanotechnology-enabled climate solutions to a panel of commercialization experts from the federal government, national labs, and the private sector. Topics ranged from innovations to decrease the energy demand of computing, decreasing the environmental impacts of electronic components, novel methodologies to make graphene, and precision agriculture.

To help bring nanotechnology and climate change conversations into the classroom, the NanoEducators Quarterly Forum chose climate change as the topic for the Spring 2023 semester. The Forum met twice during the spring 2023 semester and invited a middle school teacher and a college professor to share ideas on how to use nanotechnology to inspire students to create creative solutions for climate change.



Confronting Climate Change with Nanotechnology: Solutions-Based Learning

Jacob L. Jones

Kobe Steel Distinguished Professor of Materials Science and Engineering, NC State University

Director, Science and Technologies for Phosphorus Sustainability (STEPS) Center

Director, Research Triangle Nanotechnology Network (RTNN)

NNI/NNCO NanoEducators Quarterly Forum, Spring 2023

This presentation is based in part upon work supported by the National Science Foundation under Grant Nos.

NanoEducators presentation. Image credit: NC State.

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[226] For additional details and a complete list, see https://www.nano.gov/Nano4EARTH.

[227] https://www.nano.gov/nano4EARTHWorkshop

Appendix A. Contact List

Affiliations are as of November 2023.

OSTP

Dr. Branden Brough
NSET Co-chair, EOP Liaison
Office of Science and Technology Policy
Executive Office of the President

OMB

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

Mr. Thomas Libert
Office of Management and Budget
Executive Office of the President

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

NNCO[228]

Dr. Branden Brough
Director
National Nanotechnology Coordination Office
bbrough@nnco.nano.gov

Dr. Quinn Spadola
Deputy Director
National Nanotechnology Coordination Office
qspadola@nnco.nano.gov

ATSDR

Dr. Custodio Muianga
Environmental Health Scientist
Agency for Toxic Substances and Disease Registry
cmuianga@cdc.gov

BARDA

Dr. Sandeep Patel
Director, Division of Research, Innovation, and Ventures
Biomedical Advanced Research and Development Authority
Department of Health and Human Services
Sandeep.Patel@hhs.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
Program Manager, Chemicals, Nanotechnology and Emerging Materials
Office of Hazard Identification & Reduction
Consumer Product Safety Commission
tthomas@cpsc.gov

DHS

Dr. Laura Parker
Senior Advisor for Sensors
Office of Science & Engineering / Technology Center Division
Science and Technology Directorate
Department of Homeland Security
Laura.Parker@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. Stephanie Hooker
Acting Director, Associate Director for Strategic Outreach
Material Measurement Laboratory
National Institute of Standards and Technology
stephanie.hooker@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. Tariq Hafiz
Director, TC 3600
Patent and Trademark Office
Tariq.Hafiz@uspto.gov

Mr. Matthew W. Such
Group Director, TC 2800
Patent and Trademark Office
Matthew.Such@uspto.gov

DOD

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

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[228] Additional NNCO staff contacts are on p. 56.

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

Mr. Michael Holthe
Director, Platforms & Weapons Technologies
Office of the Under Secretary of Defense for Research and Engineering
Department of Defense
michael.j.holthe2.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. 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

Lt. Col Wooddy Miller
Program Manager, Optoelectronics, THz and Nanotechnology
Directorate of Physics and Electronics
Air Force Office of Scientific Research
wooddy.miller.1@us.af.mil

Dr. Brian D. Pate
Physical Scientist
Basic & Supporting Research Div.
Defense Threat Reduction Agency
brian.pate@dtra.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. Andrew R. Schwartz
NSET Co-chair
Director, Materials Sciences and Engineering Division
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

Dr. Kenneth Nowak
Program Manager, R&D Office
Department of the Interior
U.S. Bureau of Reclamation
knowak@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. Kyle Fox
Science & Technology Research Advisor
Office of Research, Evaluation, and Technology / Technology and Standards Division
Office of Science and Technology
National Institute of Justice
Department of Justice
Kyle.Fox@usdoj.gov

Dr. Greg Dutton
Physical Scientist
Office of Investigative and Forensic Sciences
Office of Science and Technology
National Institute of Justice
Department of Justice
Gregory.Dutton@usdoj.gov

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

DOT

Mr. David Kuehn
Program Manager, Exploratory Advanced Research
Federal Highway Administration
Department of Transportation
Turner-Fairbank Highway Research Center
David.Kuehn@dot.gov

EPA

Mr. Jeffrey L. Dawson
Science Advisor
Office of Chemical Safety and Pollution Prevention
Environmental Protection Agency
dawson.jeff@epa.gov

Dr. Annette Guiseppi-Elie
National Program Director (Acting)
Chemical Safety for Sustainability Research Program
Office of Research and Development
Environmental Protection Agency
guiseppi-elie.annette@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. Emilie J. Siochi
NASA Langley Research Center
Advanced Materials & Processing Branch
emilie.j.siochi@nasa.gov
Dr. Tiffany S. Williams
NASA Glenn Research Center
Materials and Structures Division
Tiffany.S.Williams@nasa.gov

NCEH

Dr. Max Zarate-Bermudez
Environmental Epidemiologist
National Center for Environmental Health
mzaratebermudez@cdc.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

NIH/NIBIB

Dr. David Rampulla
Director
Division of Discovery Science & Technology (Bioengineering)
National Institute of Biomedical Imaging and Bioengineering
National Institutes of Health
david.rampulla@nih.gov

Dr. Luisa Russell
Program Director
Division of Discovery Science and Engineering (Bioengineering)
National Institute of Biomedical Imaging and Bioengineering
National Institutes of Health
luisa.russell@nih.gov

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. Lingamanaidu V. Ravichandran
Program Officer
Exposure, Response, and Technology Branch
Division of Extramural Research & Training
National Institute of Environmental Health Sciences
National Institutes of Health
lingamanaidu.ravichandran@nih.gov

Dr. Nigel Walker
Chief, Systems Toxicology Branch
Division of Translational Toxicology
National Institute of Environmental Health Sciences
National Institutes of Health
walker3@niehs.nih.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. Vladimir V. Murashov
Special Assistant to the Director
Office of the Director
National Institute for Occupational Safety and Health
vladimir.murashov@cdc.hhs.gov

Dr. Jay Vietas
Chief, Emerging Technologies Branch
Division of Science Integration
National Institute for Occupational Safety and Health
qsp2@cdc.gov

NRC

Mr. Steve R. Ruffin
Branch Chief, Office of Research, Division of Engineering
Nuclear Regulatory Commission
Steve.Ruffin@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. Fred Kronz
Program Director, Division of Science, Technology, and Society
Directorate for Social, Behavioral, and Economic Sciences
National Science Foundation
fkronz@nsf.gov

Dr. Richard Nash
Associate Program Director
Division of Electrical, Communications, and Cyber Systems
Directorate for Engineering
National Science Foundation
rnash@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. Birgit Schwenzer
Program Director, Solid State & Materials Chemistry
Division of Materials Research
Directorate for Mathematical and Physical Sciences
National Science Foundation
bschwenz@nsf.gov

State

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

Treasury

Dr. Heather Hill
Bureau of Engraving and Printing
Office of Technology Development
Department of the Treasury
heather.hill@bep.gov

USDA/ARS

Dr. Jonn Foulk
National Program Leader, Product Quality and New Uses
Biorefining, Biofuels, Biobased Products (NP306)
Agricultural Research Service
U.S. Department of Agriculture
Jonn.Foulk@usda.gov

USDA/FS

Dr. Kenneth Zwick
Assistant Director for Research
Forest Products Laboratory
U.S. Forest Service
U.S. Department of Agriculture
kenneth.zwick@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

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

Dr. Jason Delborne
AAAS Science and Technology Policy Fellow
NNCO
jdelborne@nnco.nano.gov

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

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

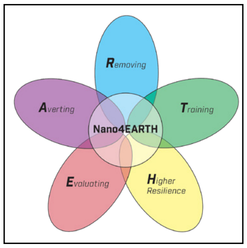
Mr. Mike Kiley
Industry Liaison
NNCO
mkiley@nnco.nano.gov

Dr. Matthew Noor
Staff Scientist
NNCO
mnoor@nnco.nano.gov

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

Convening the NNI Community

Nano4EARTH




Credit: NNCO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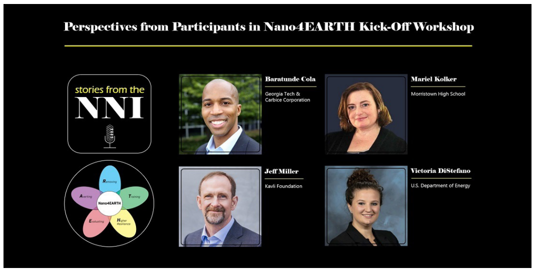
"Stories from the NNI" Podcast


Perspectives from Participants in Nano4EARTH Kick-Off Workshop

stories from the NNI

Baratunde Cola
Georgia Tech & Carbice Corporation

Mariel Kolker
Morristown High School

Jeff Miller
Kavli Foundation

Victoria DiStefano
U.S. Department of Energy


Inspiring Curiosity, Creativity, and Action with Nanotechnology

Matt Pleil
University of New Mexico

Marshall Escamilla
Tumble Science Podcast for Kids

stories from the NNI

Matthew Jackson
Cobb County School District

Student Leaders Conference (held jointly with the TechConnect World Innovation Conference & Expo)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NanoEducators Quarterly Forum


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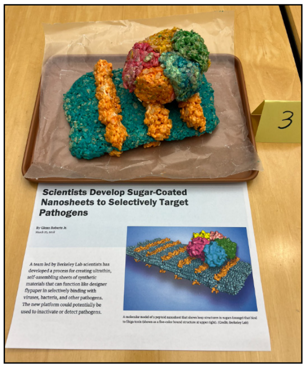
Virtual events to be held in January, April, September, November

Bring your ideas, share your voice, and get involved!

Join the mailing list:
https://tinyurl.com/nanoedforum

Celebration of National Nanotechnology Day (Oct. 9, 2023)

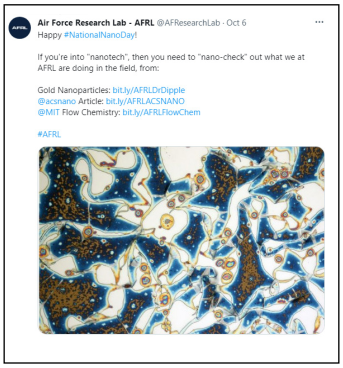


Scientists Develop Sugar-Coated Nanosheets to Selectively Target Pathogens

By Glenn Roberts Jr.
March 25, 2018

A team led by Berkeley Lab scientists has developed a process for creating ultrathin, self-assembling sheets of synthetic materials that can function like designer flypaper in selectively binding with viruses, bacteria, and other pathogens. The new platform could potentially be used to inactivate or detect pathogens.

A molecular model of a peptoid nanosheet that shows loop structures in sugars (orange) that bind to Shiga toxin (shown as a five-color bound structure at upper right). (Credit: Berkeley Lab)

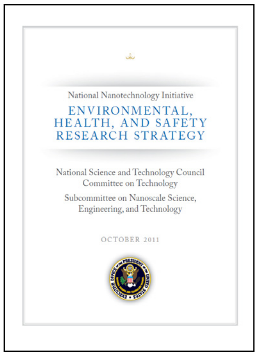

Air Force Research Lab - AFRL @AFResearchLab · Oct 6
Happy #NationalNanoDay!

If you're into "nanotech", then you need to "nano-check" out what we at AFRL are doing in the field, from:

Gold Nanoparticles: bit.ly/AFRLDrDipple
@acsnano Article: bit.ly/AFRLACSNANO
@MIT Flow Chemistry: bit.ly/AFRLFlowChem

#AFRL

Refreshing the NNI's Environmental, Health, and Safety Research Strategy


National Nanotechnology Initiative
ENVIRONMENTAL, HEALTH, AND SAFETY RESEARCH STRATEGY

National Science and Technology Council
Committee on Technology
Subcommittee on Nanoscale Science, Engineering, and Technology

OCTOBER 2011


Credit: NNCO

Nanotechnology Infrastructure Leaders Summit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National Nanotechnology Coordination Office
2415 Eisenhower Avenue, Alexandria, Virginia 22314