THE NATIONAL NANOTECHNOLOGY INITIATIVE SUPPLEMENT TO THE PRESIDENT'S 2025 BUDGET

Product of the

SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

COMMITTEE ON TECHNOLOGY

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

DECEMBER 2024

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The National Science and Technology Council (NSTC) is the principal means by which the executive branch coordinates science and technology policy across the diverse entities that make up the federal research and development enterprise. A primary objective of the NSTC is to ensure that science and technology policy decisions are consistent with the President's stated goals. The NSTC prepares research and development strategies that are coordinated across federal agencies aimed at accomplishing multiple national goals. The work of the NSTC is organized under committees that oversee subcommittees and working groups focused on different aspects of science and technology. More information is available at https://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 2025 Budget request submitted to Congress on March 11, 2024, 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, https://www.nano.gov.

About the cover

Outside Covers: A silicon-on-glass platform of nanostructures that form an ultrathin, flat lens that uses precisely designed and fabricated 50 nm nanostructures to manipulate and focus a broad spectrum of light onto a single focal point is shown. Created with electron beam lithography where a beam of electrons draws a pattern on a material surface, this lens is compact and lightweight for optical components in many applications such as mass production of semiconductor components using photolithography. See https://doi.org/10.1515/nanoph-2024-0150. Image credit: NanoLight/The Pennsylvania State University. **Inside Back Cover:** The inside face of the back cover is a collage of images from a National Nanotechnology Coordination Office (NNCO) symposium on March 5, 2024, celebrating the 20-year anniversary of the authorization of the NNI. Collage content and design is by Kristin Molash of NNCO.

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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
CBET	Chemical, Bioengineering, Environmental and Transport Systems (NSF division)
CDER	Center for Drug Evaluation and Research (FDA)
CFSAN	Center for Food Safety and Applied Nutrition (FDA)
CNC	cellulose nanocrystal
CNMS	Center for Nanophase Materials Sciences (DOE/ORNL)
CNST	Center for Nanoscale Science and Technology (NIST)
CNT	carbon nanotube
CORs	Communities of Research (U.S.-EU)
DAC	direct air capture
DARPA	Defense Advanced Research Projects Agency
DMREF	Designing Materials to Revolutionize and Engineer our Future (NSF)
EFMA	Emerging Frontiers and Multidisciplinary Activities (NSF)
EHS	environment(al), health, and safety
ELSI	ethical, legal, and other social implications
ENG	[Directorate for] Engineering (NSF)
ENM	engineered nanomaterial
EPSCoR	Established Program to Stimulate Competitive Research (program)
ERDC	Engineering Research and Development Center (U.S. Army)
GHG	greenhouse gas
ISN	Institute for Soldier Nanotechnologies (Army)
ISO	International Organization for Standardization
ITAR	International Traffic in Arms Regulations
LNP	lipid nanoparticle
ML	machine learning
MOF	metal-organic framework
mRNA	messenger RNA
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)
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
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
ORNL	Oak Ridge National Laboratory
OSTP	Office of Science and Technology Policy (Executive Office of the President)

[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
PCAST	President's Council of Advisors on Science and Technology
PFAS	per- and polyfluoroalkyl substances
QIS	quantum information science
R&D	research and development
RADx-RAD	Rapid Acceleration of Diagnostics-Radical (NIH initiative)
REU	Research Experiences for Undergraduates (NSF)
SBIR	Small Business Innovation Research program
STEM	science, technology, engineering, and mathematics
STTR	Small Business Technology Transfer Research program
WPMN	Working Party on Manufactured Nanomaterials (OECD)

Executive Summary

The U.S. National Nanotechnology Initiative (NNI) is working to leverage the power of nanotechnology to benefit everyone in America. Nanotechnology encompasses the understanding and control of matter at the level of atoms and molecules where unique phenomena enable novel applications. It has led to revolutions in areas such as aerospace, agriculture, infrastructure, clean energy, water purification, consumer electronics, faster microchips, artificial intelligence, powerful messenger RNA (mRNA) vaccines, and underpins technologies of the future. Nanotechnology plays a role in ensuring America's national and economic security, delivering clean and reliable energy, improving robust health outcomes, clean water access, and food safety and abundance. President Biden's 2025 Budget requests over $2.2 billion for the NNI, with cumulative funding totaling over $45 billion since the inception of the NNI in 2001 when Congress approved increased funding for nanotechnology in fiscal year 2021 appropriations. (References to years in this report are to fiscal years unless otherwise noted. The NNI was formally authorized in the 21st Century Nanotechnology Research and Development Act of 2003.) This highest-ever request reflects the United States' global leadership in the fundamental understanding and control of matter at the nanoscale.) 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 2023 and 2024 and those proposed in 2025 include strong support for broad, fundamental research in nanoscience, and increased funding for the translation of that knowledge into technological breakthrough to the benefit of society. 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.

What is Nanotechnology?

Nanotechnology encompasses science, engineering, and technology that enables understanding, measuring, manipulating, and manufacturing at the atomic, molecular, and supramolecular levels, aimed at creating materials, devices, and systems with fundamentally new molecular organization, properties, and functions.[2] The size regime that researchers can achieve 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 materials and manufacturing. Multidisciplinary collaboration across the field of nanotechnology is ensuring renewed U.S. leadership in the microelectronics industry and in advanced computing and communications. This is fueling progress on many other national priorities, including global security and stability, meeting the challenge of climate change, achieving better health outcomes, and ensuring future economic competitiveness.

Examples of nanotechnology innovations are illustrated below: (a) new method to layer atomically thin materials for artificial intelligence computing chips that improves efficiency and performance; (b) new lipid nanoparticles that can transport treatments directly to the lungs and retina; (c) increasing carbon capture efficiency with nature-inspired atomically precise catalysts; (d) students touring the clean room at the NNCI SENIC site that provides researchers a one-stop shop for nanoscale science and engineering tools; (e) highly sensitive and ultrafast breath sensor using nanoscale silk processing to create hybrid biological transistors; (f) using machine learning to predict material properties based on the molecular structures of polymers.

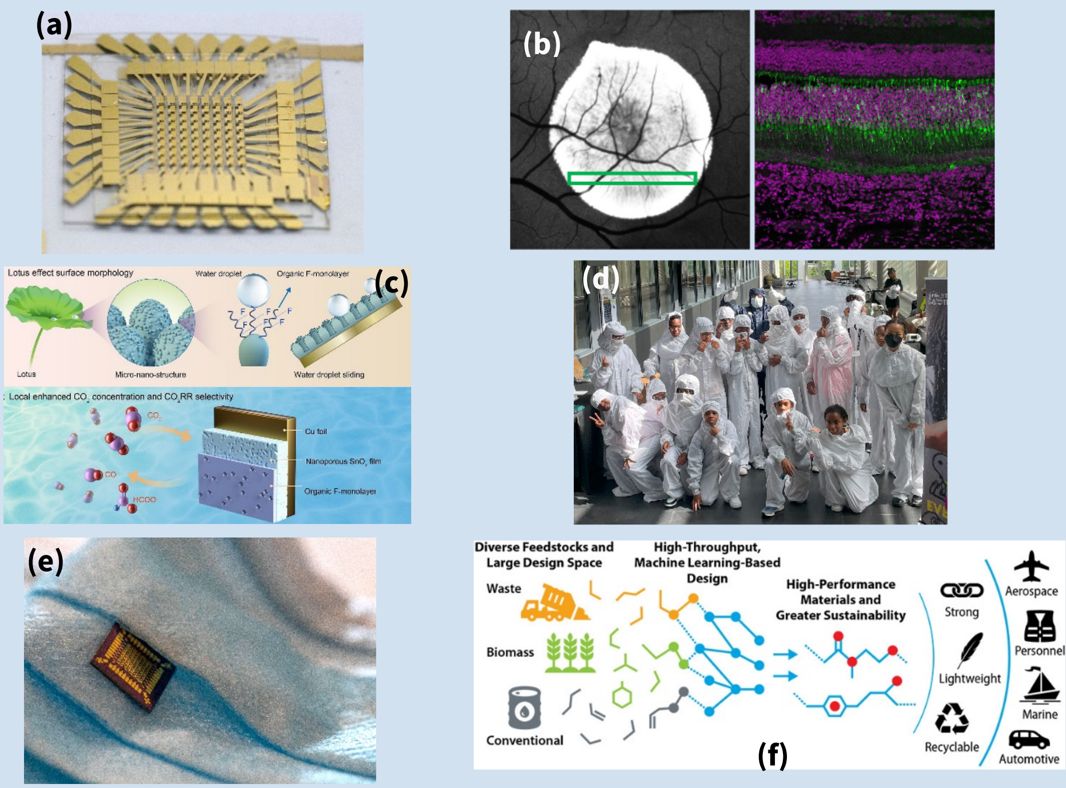

Image credits: (a) Washington University in St. Louis; (b) Oregon State University; (c) University of Central Florida; (d) Georgia Institute of Technology; (e) Tufts University Silklab; (f) National Renewable Energy Laboratory. For more information on nanotechnology benefits and applications, please visit https://www.nano.gov/about-nanotechnology/applications-nanotechnology.

[2] 15 USC §7509 (https://www.govinfo.gov/content/pkg/USCODE-2011-title15/pdf/USCODE-2011-title15-chap102.pdf)

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 creates government efficiency by leveraging resources and 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 Biden-Harris Administration and national priorities.[3] For example, in the areas of artificial intelligence (AI) and autonomous systems, NNI participating agencies are funding research on novel processing hardware for AI computing,[4] and low-power computing devices to increase energy efficiency of AI applications. Nanotechnology also 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 increasing climate resilience through the National Nanotechnology Challenge (NNC), Nano4EARTH, coordinating research across the agencies on interfacial technologies (e.g., for reducing friction), novel energy storage technologies, greenhouse gas capture, and improved catalysis.[5] Meanwhile, NNI funding for nanotechnology health research has reached an all-time high. This funding includes over $900 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 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. All the while, the coordination provided through the NNI has facilitated the proactive responsible development of new technologies, thereby streamlining their adoption.

[3] https://www.whitehouse.gov/wp-content/uploads/2023/08/FY2025-OMB-OSTP-RD-Budget-Priorities-Memo.pdf
[4] https://doi.org/10.1038/s41563-023-01704-z
[5] https://www.nano.gov/nano4EARTH; see examples of Nano4EARTH activities and progress beginning on p. 51.

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)
Countering Weapons of Mass Destruction Office*
Science and Technology Directorate
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)*
Nuclear Regulatory Commission (NRC)†
U.S. National Science Foundation (NSF)*

* 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 nanoscale science. This report highlights 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. 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 potential societal implications are being performed in parallel. In 2024, NNI participating agencies have completed a multi-year effort to update and refresh the 2011 NNI Environmental Health and Safety (EHS) Research Strategy.[6]

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 focused attention of a national initiative, nanotechnology is responsible for over 171,000 jobs across 3,700 U.S. companies that are conducting nanotechnology R&D alone.[7] According to another study, the economic impact of nanotechnology on the U.S. economy was close to a trillion dollars over the past two decades and $67-83 billion in 2022, which does not include major industries that have been enabled by nanotechnology. Including the semiconductor industry alone pushes the 2022 estimate to $268–297 billion.[8] Strategic collaborations, including with public-private partnerships, nongovernmental organizations, and international likeminded allies and partners, help to promote progress in nanoscale science, engineering, and technology; broad and equitable 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] NSET participating agencies 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 and experiential nanotechnology education and workforce development activities. Each year NNI participating agencies review and approve the NNCO budget and contribute to its funding.

[6] https://www.nano.gov/ehsstrategy2024update

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

[8] https://www.nano.gov/node/5669

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

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 significant advances that have occurred under the auspices of the NNI and the maturity and broad relevance of the field. These recommendations are: (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 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 developing plans to implement PCAST's recommendations. With respect to Recommendation 1, NNI re-authorization plans are being considered that would update the 21st Century Nanotechnology Research and Development Act to reflect the current needs of the NNI. The NSET Subcommittee is continuing its leadership of the NNI, as called for in Recommendation 2 and documented in this report. As a first step in addressing Recommendation 3, NNCO is supporting NNI participating agencies in planning an in-person convening in March 2025 to raise awareness of programs and practices in multidisciplinary experiential learning programs across the federal government. The EXperiential And MultidisciPlinary Learning and Education (EXAMPLE) convening's agenda will include panels showcasing the importance of interdisciplinary collaboration, discussing metrics and evaluation, highlighting success stories and professionals who went through multidisciplinary programs, and discussing the role of user facilities in experiential training.

The National Academies of Science, Engineering, and Medicine began its review of the NNI in 2024, also in accordance with the Act. This study is focusing on a review of the composition of the science and engineering community currently being served by the nation's nanotechnology research and development infrastructure, with the goal of identifying barriers for communities that are not fully engaging with this infrastructure.

Outline of this Report

Chapter 2 of this report is an overview of the budgets for nanotechnology R&D for 2023 (actual), 2024 (estimated), and 2025 (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.

[10] https://www.whitehouse.gov/wp-content/uploads/2023/08/PCAST_NNI_Review_August2023.pdf
[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 2025 Budget requests an all-time record of $2.2 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 $45 billion (including the 2025 request); Figure 1 shows the funding trends over time. Table 2 shows total NNI funding by agency for fiscal years 2023 through 2025. 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 2023 and 2024 and those proposed for 2025 reflect a continued emphasis on fundamental research in nanoscience; programs 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 nanotechnology-related investments allocated by each participating agency (the "NNI crosscut"). Each agency determines its budget for programs supporting nanotechnology R&D in coordination with OMB, OSTP, and Congress. However, since nanotechnology is so engrained in the nation's R&D activities, determining what is or is not nanotechnology can be challenging. 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 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.

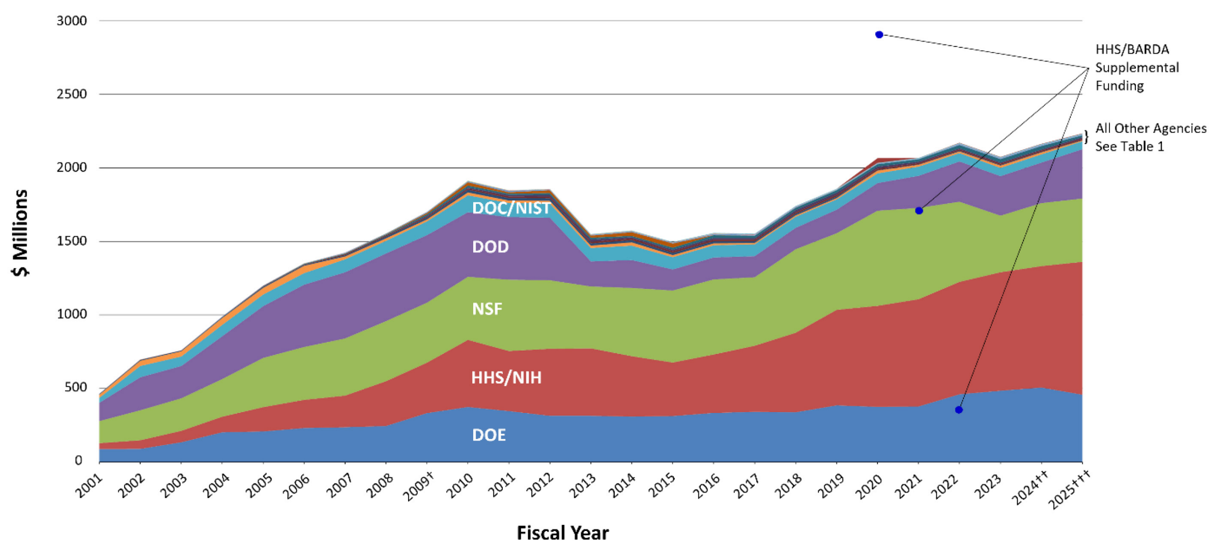

Figure 1. NNI Funding by Agency, 2001–2025.*

* 2021–2024 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.

†† 2024 numbers are based on appropriated levels.

††† 2025 Budget.

Table 2: NNI Budget, by Agency, 2023–2025
(dollars in millions)

Agency	2023 Actual	2024 Estimated*	2025 Proposed
CPSC	0.4	0.05	0.05
DHS/CWMD	0.4	0.5	0.0
DOC/NIST	53.3	53.2	53.6
DOD**	269.7	354.7	335.6
DOE***	441.2	442.7	457.8
DOJ/NIJ	2.2	1.8	1.3
DOT/FHWA	0.6	0.3	0.3
EPA	4.2	4.3	2.8
HHS (total)	876.4	866.2	926.3
BARDA	2.1	2.1	2.1
FDA	10.4	11.9	10.6
NIH	854.7	842.6	903.9
NIOSH	9.2	9.6	9.6
NASA†	14.3	11.5	5.3
NSF	477.7	362.6	430.8
USDA (total)	21.4	20.6	21.6
ARS	5.0	5.0	5.0
FS	4.4	4.6	4.6
NIFA	12.0	11.0	12.0
TOTAL††	**2161.7**	**2118.3**	**2235.2**

* 2024 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, the 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.

† Funding levels for NASA reflect the completion of multiple nanotechnology-related projects.

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

The President's 2025 Budget includes a $2.2 billion request for nanotechnology R&D to support nanoscale science, engineering, and technology R&D at 12 agencies, including multiple departments/offices within several agencies such as DOD, HHS, USDA, and DOE (see Table 2 above and the footnotes for DOD and DOE). The five federal organizations with the largest proposed 2025 investments (representing 98% of the NNI total) are:

- HHS/NIH (nanotechnology-based biomedical research at the intersection of life and physical sciences).
- DOE (fundamental and applied research providing a basis for new and improved energy technologies, and support for nanotechnology research infrastructure).
- NSF (fundamental research and education across all disciplines of science and engineering).
- 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 through 2025, 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 the investment from these agencies on clean energy, energy efficiency, and environmental sustainability totals to roughly 10%. The estimated Nano4EARTH-related funding in the 2025 request is up approximately 10% compared to the 2024 request that was published in the NNI Supplement to the President's 2024 budget.[13]

Breakout of Funding by PCA

Tables 3–5 show the funding for 2023–2025 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[14] and at the beginning of each of the PCA sections of Chapter 3 of this report, below.

Table 3: Actual 2023 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	0.4	0.4
DHS/CWMD	0.0	0.4	0.0	0.0	0.0	0.4
DOC/NIST	14.3	8.5	27.5	0.0	3.0	53.3
DOD	208.4	60.1	0.0	0.2	1.0	269.7
DOE	237.6	39.3	164.3	0.0	0.0	441.2
DOJ/NIJ	0.5	1.6	0.0	0.1	0.0	2.2
DOT/FHWA	0.0	0.6	0.0	0.0	0.0	0.6
EPA	0.0	0.0	0.0	0.0	4.2	4.2
HHS (total)	215.8	610.3	17.8	4.3	28.2	876.4
BARDA	0.0	2.1	0.0	0.0	0.0	2.1
FDA	4.0	5.3	0.0	0.0	1.1	10.4
NIH*	211.8	602.9	17.8	4.3	17.9	854.7
NIOSH	0.0	0.0	0.0	0.0	9.2	9.2
NASA	0.0	14.3	0.0	0.0	0.0	14.3
NSF**	285.5	127.6	26.2	23.3	15.1	477.7
USDA (total)	4.0	16.4	0.0	0.0	1.0	21.4
ARS	0.0	5.0	0.0	0.0	0.0	5.0
FS	0.0	4.4	0.0	0.0	0.0	4.4
NIFA	4.0	7.0	0.0	0.0	1.0	12.0
TOTAL	**966.1**	**879.1**	**235.8**	**27.9**	**52.9**	**2161.7**

* NIH totals include $12 million in supplemental 2023 funding ($10.4 million for PCA 1 and $1.6 million for PCA 2).

** NSF totals include ~$2.4 million in supplemental 2023 funding ($1 million for PCA 1, $1.1 million for PCA 2, $0.2 million for PCA 3, and $0.1 million for PCA 5—rounded to the nearest tenth of a million).

13 https://www.nano.gov/sites/default/files/pub_resource/NNI-FY24-Budget-Supplement.pdf, p. 7

14 https://www.nano.gov/pcadefinitions

Table 4: Estimated 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	0.05	0.05
DHS/CWMD	0.0	0.5	0.0	0.0	0.0	0.5
DOC/NIST	14.9	8.1	27.4	0.0	2.8	53.2
DOD	276.6	70.1	6.7	0.2	1.1	354.7
DOE	238.0	40.2	164.5	0.0	0.0	442.7
DOJ/NIJ	0.5	1.2	0.0	0.1	0.0	1.8
DOT/FHWA	0.0	0.3	0.0	0.0	0.0	0.3
EPA	0.0	0.0	0.0	0.0	4.3	4.3
HHS (total)	208.2	607.2	17.8	4.3	28.7	866.2
BARDA	0.0	2.1	0.0	0.0	0.0	2.1
FDA	5.4	5.3	0.0	0.0	1.2	11.9
NIH**	202.8	599.8	17.8	4.3	17.9	842.6
NIOSH	0.0	0.0	0.0	0.0	9.6	9.6
NASA	0.0	11.5	0.0	0.0	0.0	11.5
NSF	230.9	78.4	21.8	18.0	13.5	362.6
USDA (total)	3.0	16.6	0.0	0.0	1.0	20.6
ARS	0.0	5.0	0.0	0.0	0.0	5.0
FS	0.0	4.6	0.0	0.0	0.0	4.6
NIFA	3.0	7.0	0.0	0.0	1.0	11.0
TOTAL	**972.1**	**834.0**	**238.2**	**22.6**	**51.4**	**2118.3**

Table 5: Proposed 2025 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	0.05	0.05
DOC/NIST	15.3	8.1	27.4	0.0	2.8	53.6
DOD	254.9	67.5	12.6	0.2	0.5	335.6
DOE	235.8	47.0	175.0	0.0	0.0	457.8
DOJ/NIJ	0.0	1.2	0.0	0.1	0.0	1.3
DOT/FHWA	0.0	0.3	0.0	0.0	0.0	0.3
EPA	0.0	0.0	0.0	0.0	2.8	2.8
HHS (total)	232.4	639.9	18.3	4.8	30.9	926.3
BARDA	0.0	2.1	0.0	0.0	0.0	2.1
FDA	4.0	5.5	0.0	0.0	1.2	10.6
NIH	228.4	632.3	18.3	4.8	20.1	903.9
NIOSH	0.0	0.0	0.0	0.0	9.6	9.6
NASA	0.0	5.3	0.0	0.0	0.0	5.3
NSF	258.4	113.1	23.7	20.5	15.1	430.8
USDA (total)	4.0	16.6	0.0	0.0	1.0	21.6
ARS	0.0	5.0	0.0	0.0	0.0	5.0
FS	0.0	4.6	0.0	0.0	0.0	4.6
NIFA	4.0	7.0	0.0	0.0	1.0	12.0
TOTAL	**1000.7**	**898.8**	**257.0**	**25.6**	**53.1**	**2235.2**

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

** NIH totals include $1.5 million in supplemental 2024 funding ($1.3 million for PCA 1 and $0.2 million 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 2023 (nearly $2.2 billion) is significantly higher than the 2023 requested value published in the NNI Supplement to the President’s 2023 Budget (nearly $2.0 billion).

As nanotechnology and its applications mature, investments by some agencies and departments that perform research to facilitate their missions have risen in recent years. Most notably, NIH's investments have more than doubled in ten years—from less than $400 million in 2015 to over $900 million in the 2025 request, even as nanotechnology-specific NIH programs have sunset. FDA’s nanotechnology investments are also up from figures reported previously, from just under $8 million/year[15] to between $10 million and $12 million/year for 2023–2025, as more nanotechnology-enabled medical products are coming to the agency for review. The percentage of total NNI investments in the "applications, devices, and systems" PCAs has risen from under 24% in 2016 to about 40% in 2023–2025. Nanotechnology is proving itself increasingly as a solution contributing to agency mission requirements.

However, even as nanotechnology applications emerge, it is vital to maintain the pipeline of fundamental research investments that will enable the development of future applications. The NNI request for foundational research (PCA 1) for 2025 is sustained at about $1 billion.

Many of the proposed 2025 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 and impacts in artificial intelligence. As called out repeatedly in the March 2024 National Strategy for Microelectronics Research,[16] dramatic improvements in the energy efficiency of semiconductor devices are critical for continued progress in the U.S. microelectronics industry, and this is particularly important for compute-intensive applications such as AI. Nanotechnology is key to addressing this issue, with R&D on new nanoscale hardware-based solutions. The DOE Microelectronics Science Research Centers authorized in the CHIPS and Science Act and funded beginning in 2024[17] 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.[18] 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. NNCO provides leadership and staff support for the NSTC’s Subcommittee on Microelectronics Leadership, and the NNI participating agencies coordinate their nanotechnology investments to maximize the leveraging of existing NNI activities to benefit the Subcommittee on Microelectronics Leadership’s whole-of-government efforts in microelectronics R&D, education, and infrastructure.

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15 As reported in the NNI Supplement to the President’s 2024 Budget, p. 6.

16 https://www.whitehouse.gov/wp-content/uploads/2024/03/National-Strategy-on-Microelectronics-Research-March-2024.pdf

17 https://www.energy.gov/science/articles/department-energy-announces-160-million-research-form-microelectronics-science

18 See the Plans for PCA 2 section below, beginning on p. 25, for details on the new nanotechnology-related investments under the CHIPS and Science Act.

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 2019 through 2022 (2022 is the latest year for which nanotechnology award data researched by agencies and OMB are available). NNI participating agencies have supported nearly $2.5 billion in nanotechnology SBIR and STTR awards (both Phase I and Phase II) since 2004.[19] Total nanotechnology SBIR/STTR investments reached an all-time high of over $250 million in 2022. Even though not all agencies specifically identify nanotechnology in their SBIR/STTR solicitations, their actions are enabling innovations in many nanotechnology-related 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).

Table 6: 2019–2022 Agency SBIR and STTR Awards
(dollars in millions)

	2019			2020			2021			2022		
Agency	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**
DHS	2.0	0.0	2.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
DOC/NIST	1.1	0.0	1.1	1.9	0.0	1.9	1.3	0.0	1.3	3.9	0.0	3.9
DOD	63.5	22.5	86.0	51.5	17.8	69.3	45.5	23.1	68.6	85.5	23.7	109.2
DOE	31.2	3.4	34.6	26.0	3.7	29.7	27.3	8.8	36.0	44.1	13.2	57.3
EPA	0.7	0.0	0.7	0.5	0.0	0.5	0.6	0.0	0.6	0.2	0.0	0.2
HHS/NIH	42.6	5.5	48.1	42.9	5.7	48.6	41.8	6.5	48.3	38.7	7.0	45.7
NASA	7.7	1.6	9.3	6.5	2.8	9.3	9.7	2.0	11.7	8.1	1.3	9.4
NSF	16.2	3.4	19.6	19.0	1.8	20.8	18.0	5.1	23.1	16.7	6.2	22.9
USDA	0.8	0.0	0.8	1.8	0.0	1.8	3.2	0.0	3.2	2.2	0.0	2.2
TOTAL	**165.7**	**36.4**	**202.1**	**151.0**	**31.9**	**182.8**	**147.4**	**45.4**	**192.8**	**199.3**	**51.5**	**250.8**

The following is a small, representative sampling of the hundreds of nanotechnology SBIR and STTR topics funded by NNI participating agencies in 2022 that are supporting the development and application of nanotechnology R&D with potential for commercialization:

- Nano-electro-mechanical systems for non-destructive characterization of thin film materials (NIST).
- Nanoarray integrated microfibers for next generation medical masks (NIST).
- Carbon nanotube enhanced distillation for economic recovery of ethanol in the biofuel industry (NIFA).
- Nanosorbents to capture environmental DNA for aquaculture health monitoring (NIFA).
- Incorporating nanosilicon particles to improve high-energy-density batteries at low cost (DOE).
- Recycling rare earth metals with bimetallic nanocatalysts (DOE).
- Quantum communications for deep space exploration (NASA).
- Compact, high-gain 2D nanomaterial-based mass spectrometers (NASA).
- A cost-effective, portable, and automated platform for microplastics characterization (EPA).
- Nanomaterials-based sensor chips for low-cost handheld sulfur dioxide tester (EPA).

[19] 2004 was the first year that the NNI began collecting SBIR/STTR data.

- Nanopore and solid-state nanomaterials for improved DNA sequencing and for clinical genomics implementation (NIH).
- Nanoscale adsorbent materials in infrared sensors to detect PFAS (NIH).
- A multifunctional lipid nanoparticle delivery system for targeted delivery of vascular RNA therapeutics (NSF).
- A unique aerogel-based separator technology for safe and ultrafast charging of batteries (NSF).
- A protective nanocrystalline coating to enable consistent superlubricity (DOD).
- Metal organic framework sponges for enhanced protection against warfare chemicals (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. This is 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. The examples are intended to be an illustrative sampling, but not a comprehensive list, of relevant federal agency activities. 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 makes important advances in diverse areas of fundamental and applied science. Such coordination also maintains U.S. leadership in nanotechnology R&D, as well as ensures that the United States remains the preferred international partner. Just a few selected examples of NNI progress under Goal 1, including many projects conducted in collaboration with international partners, are highlighted below.

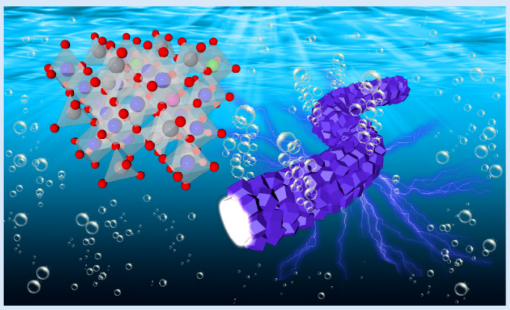
Harnessing the power of lipid nanoparticle mRNA technology to fight cancer. Researchers supported by NIH are designing lipid nanoparticles (LNPs) to increase the effectiveness of cancer immunotherapy by promoting their uptake by antigen-presenting cells, stimulating the maturation of these cells, and modulating the activity of adjuvants. They developed a method for screening LNPs to optimize the type of helper lipid and lipid-component ratios, enhancing the delivery of tumor-antigen-encoding messenger RNA (mRNA) to dendritic cells and increasing immune system antitumor activity. In a mouse model of melanoma, after injection of the LNPs they noted potent antitumor activity triggered by LNPs that elicited strong immune activity in both type-1 and type-2 T helper cells.[20]

In complementary work supported by NIH, NSF, DOD, and private foundations, researchers have invented a novel genetic macrophage-programming nanoparticle design that reprograms tumor-associated macrophages using targeted mRNA nanocarriers.[21] The targeted mRNA nanocarriers deliver transcribed mRNA encoding transcription factors that reprogram macrophages, resulting in a strong anti-tumor response without generating off-target toxicity. The research team has successfully achieved the scale production of good manufacturing practices (GMP)-grade nanoparticles. The team plans to use these nanoparticles in future clinical trials to treat chemotherapy-resistant ovarian cancer.[22]

[20] https://doi.org/10.1038/s41551-023-01131-0
[21] https://doi.org/10.1038/s41467-019-11911-5, https://doi.org/10.1038/s41467-020-19486-2
[22] https://www.fredhutch.org/en/news/spotlight/2022/01/ccg-parayath-naturecomm.html

Advancing the science of nanocatalysis to address national priorities.

NNI participating agencies are pushing the frontiers of catalysis to improve energy efficiency of industrial processes, open new paths to renewable energy conversion, reduce or eliminate the need for critical minerals in catalytic processes, and enhance fundamental understanding and control of chemical processes at the nanoscale. For example, university and DOE National Laboratory scientists using resources of the DOE Nanoscale Science Research Centers and the NSF National Nanotechnology Coordinated Infrastructure developed a new technique that promotes catalyst production and enhances efficient chemical conversion using hydrogenation by catalysts with strong metal support interactions. This technique, using mechanical force to control nanoparticle encapsulation, introduces a new pathway for chemical production that is more energy efficient, easier to control than traditional methods, and has enhanced hydrogenation for industrial uses to transform small molecules into value-added chemicals.[23]



Artistic rendering of anode catalyst reacting in water via electrolysis. Oxygen bubbles evolving from fibrous, interconnected catalyst particles (right) during electrocatalytic reaction with water. Lattice structure for cobalt-based catalyst on left. Image credit: L. Chong et al., ANL.

In another example, DOE-supported researchers using facilities at DOE's Center for Nanoscale Materials (CNM) NSRC and the Advanced Photon Source at Argonne National Laboratory developed an Earth-abundant catalyst that lowers costs for producing clean hydrogen by water electrolysis. They developed a nanofibrous cobalt spinel catalyst doped with La and Mn to replace the expensive iridium-based catalyst presently used for oxygen evolution in water with proton exchange membrane electrolyzers. Such electrolyzers could run with renewable, intermittent energy, such as solar and wind. An electrolyzer with this anode catalyst could produce clean, lower cost hydrogen for use in powering vehicles with fuel cells and as a chemical in industrial processes such as steel making and ammonia production.[24]

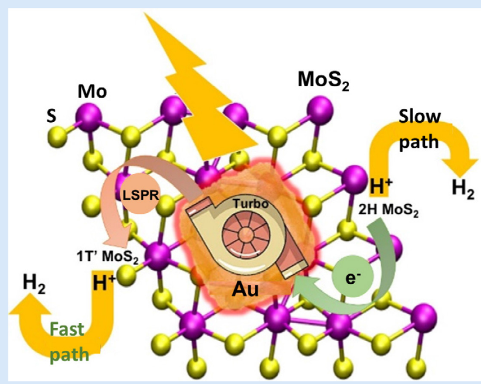


Diagram of gold nanocages with MoS_2 and tuned surface plasmon resonances. Image credit: R. Peng et al., CNM, with permission from the Royal Society of Chemistry.

In complementary work, another team at DOE's CNM used ultrafast pump-probe spectroscopy to reveal the mechanism by which tuning of surface plasmon resonances of gold nanocages can enhance photocatalytic water splitting on MoS_2 *to produce hydrogen at a rate 40X greater than previously possible with bare* MoS_2 *nanosheets. This method for exploiting plasmonic nanomaterials to greatly enhance the activity of photocatalysts presents a new strategy to increase the efficiency of solar energy harvesting and enable practical clean hydrogen production.*[25]

Combining nanoscale additive manufacturing with tissue engineering to address heart disease. Researchers at the NSF-supported Engineering Research Center in Cellular Materials (CELL-MET) have developed technologies for directed multiscale assembly of cellular metamaterials with nanoscale precision, with the 10-year goal of developing a hybrid (nanoscale/additive manufacturing) strategy to develop a centimeter-scale, vascularized cardiac tissue patch. The team is using nanotemplated

23 https://doi.org/10.1021/acscatal.2c05730
24 https://doi.org/10.1126/science.ade1499
25 https://doi.org/10.1039/d3ta01657a

bioblock printing to generate cardiac microbundles that can be assembled into larger structures, with the ultimate goal of implanting fully vascularized cardiac patches into animal models. To enable the vascularization of these patches, the team developed a technique for loading endothelial cells with superparamagnetic iron oxide nanoparticles, which can then be seeded onto magnetized microfiber lattices, serving as the template for the vascular structures. Following encapsulation in a hydrogel, the capillary templating lattice is selectively degraded by a bacterial lipase that does not impact cell viability or function.[26] In employing an integrated engineering approach to achieving its goals, the team has made advances at the intersections of fields such as stem cell biology, nanoscaffold engineering, materials science, bioprinting, mechanobiology, and imaging.

Enabling nanomedicine through understanding interactions between nanoparticles and cells. Researchers from NIST, the Center for Nanophase Materials Sciences (CNMS) NSRC at DOE's Oak Ridge National Laboratory, and international collaborators, with additional support from NSF (using the NSF/NIST Center for High Resolution Neutron Scattering and the DOE Spallation Neutron Source) have determined why cell membranes can push away nanoparticles that approach them. The researchers discovered that this repulsion—which notably affects neutral, uncharged nanoparticles—happens in part because the smaller, charged molecules that the electric field attracts will crowd the membrane and push away the larger nanoparticles. Since many drug treatments are built around proteins and other nanoparticles that target the membrane, the repulsion could play a role in treatment effectiveness, enabling nanomedicine advances.[27]

Combining flow chemistry and additive manufacturing to fabricate low-cost, highly sensitive, field-deployable environmental sensors. Researchers at DOD's Air Force Research Laboratory (AFRL) with additional university collaborators supported by NIH have developed a high-throughput method for fabricating low-cost surface-enhanced Raman spectroscopy (SERS) substrates. They used flow chemistry to prepare a solution of silver nanoparticles and graphene inks followed by aerosol jet printing to deposit the SERS substrates on Kapton polymer-based films. They have demonstrated the ability of these substrates to measure SERS spectra of standard dyes (fluorescein and rhodamine) down to concentrations of 10^{-7} M. Target analytes for these sensors include chemical warfare agents and environmental contaminants such as PFAS. The group has successfully detected SERS spectra from nano- and picomolar concentrations of perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS).[28] The work was conducted in collaboration with the Army and the Centers for Disease Control (CDC). Artificial intelligence and machine learning techniques were used to optimize the fabrication process.

Synthesizing atomically precise graphene nanoribbons (GNRs) to enable advances in nanoelectronics. A DOD/Office of Naval Research (ONR)-supported team of scientists, with additional support from DOE, have succeeded for the first time in synthesizing monodisperse "designer" graphene nanostructures, using bottom-up chemical synthesis techniques in a programmable and deterministic fashion. Graphene nanoribbons have been under investigation for promising applications in nanoelectronics, spintronics, photonics, sensing, quantum information processing, and energy conversion. But a slight change in structure changes the bandgap, so atomic precision is needed to ensure the desired properties of the GNRs. The group has developed a general fabrication method for

[26] https://doi.org/10.1002/adfm.202203715
[27] https://www.nist.gov/news-events/news/2024/01/cells-electric-fields-keep-nanoparticles-bay-scientists-confirm; https://doi.org/10.1021/jacs.3c12348
[28] https://doi.org/10.1021/acsomega.2c07134

preparing monodisperse samples of specific GNR structures with precisely controlled GNR sequence, length, and shape, enabled by an iterative synthesis strategy. This is a significant advance towards the vision of bottom-up, atomic-precision nanofabrication of functioning carbon nanoelectronics.[29]

Expanding synthesis capabilities for quantum material discovery. Two-dimensional (2D) materials continue to be at the forefront of research innovation, with applications in critical and emerging technology areas like quantum information science (QIS) and microelectronics, by harnessing innovations in nanomaterial fabrication and characterization. The NSF MonArk Quantum Foundry, announced in 2022, is part of an active community of university researchers examining nano-optical characterization of 2D materials.[30] Recently two more public universities joined MonArk due to new NSF Established Program to Stimulate Competitive Research (EPSCoR) program supplemental support.[31] For quantum materials development, researchers affiliated with the MonArk Quantum Foundry are developing nano-optical characterization and fabrication methods, using robotic elements, for 2D material systems with high-quality emergent phenomena compatible with current nano-optical techniques. Next steps include expanding to cryogenic and ultrahigh vacuum environments, since most current methods are conducted under ambient conditions.

Plans for PCA 1. Foundational Research

The foundational research under PCA 1 is defined as: (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 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 nearly 45% of the proposed NNI total for 2025. NSF and DOD are the largest contributors to this PCA by dollar amount, followed by DOE and NIH. Below are some illustrative examples across agencies of relevant programmatic activities, but is not a comprehensive list.

Programs in multiple NSF directorates support nanoscale science and engineering research related to PCA 1. About 10% of NSF investments in PCA 1 include foundational research on climate change understanding and mitigation, contributing to the Nano4EARTH NNC.[32] Most of the research is sponsored in individual and small group research across multiple NSF directorates. A subset of Engineering Research Centers,[33] Science and Technology Centers,[34] Centers for Chemical Innovation,[35] AI Institutes,[36] and other

[29] https://doi.org/10.1021/jacs.2c05670
[30] https://doi.org/10.1021/acs.nanolett.2c03373; https://doi.org/10.1063/5.0101819
[31] https://www.monarkfoundry.org/news/uapb-and-sdsmt-is-joining-the-monark-quantum-foundry; https://www.sdsmt.edu/news/releases/quantummaterialsinstitute.html
[32] https://www.nano.gov/nano4EARTH
[33] https://www.nsf.gov/eng/eec/erc.jsp
[34] https://new.nsf.gov/od/oia/ia/stc
[35] https://new.nsf.gov/funding/opportunities/centers-chemical-innovation-cci
[36] https://new.nsf.gov/funding/opportunities/national-artificial-intelligence-research-institutes

centers programs support various aspects of nanoscale science and engineering (NSE). About 60 percent of the Materials Research Science and Engineering Centers[37] pursue NSE-related fundamental research.

NSF invests in understanding nanoscale biological machines (e.g., the nucleus of cells, synapses that can simultaneously process and store information) through core programs in its directorates for Engineering (ENG), Biological Sciences (BIO), and Mathematical and Physical Sciences (MPS). NSF will expand its efforts in 2025 in nanobiotechnology associated with synthetic biology and synthetic cells through a new Dear Colleague Letter (DCL) on Synthetic Cells and Cellular Systems;[38] a new solicitation, Designing Synthetic Cells Beyond the Bounds of Evolution;[39] and a DCL on Sentinel Systems that Detect, Recognize, Actuate, and Mitigate Emergent Biological Threats.[40]

Additional core programs and solicitations contributing to PCA 1 in the ENG Directorate include Advanced Manufacturing;[41] Manufacturing Systems Integration;[42] Mechanics of Materials and Structures;[43] Biomechanics and Mechanobiology;[44] Leading Engineering for America's Prosperity, Health, and Infrastructure;[45] Nanoscale Interactions;[46] Particulate and Multiphase Processes;[47] Electronics, Photonics and Magnetic Devices;[48] Communications, Circuits, and Sensing-Systems;[49] Industry-University Cooperative Research Centers (IUCRCs);[50] and Emerging Frontiers and Multidisciplinary Activities (EFMA).[51] Contributing core programs in the MPS Directorate include most of the programs within the Division of Chemistry;[52] Topical Materials Research Programs;[53] Partnerships for Research and Education in Materials;[54] Materials Innovation Platforms;[55] and some programs within the Division of Mathematical Sciences and the Division of Physics. Contributing programs in the Directorate for Computer Information Science and Engineering include the Foundations of Emerging Technologies program,[56] the Software and Hardware Foundations program,[57] and the Computing Systems Research program.[58]

Programs cutting across multiple NSF directorates that make awards related to PCA 1 include Predictive Intelligence for Pandemic Prevention centers,[59] Future Manufacturing,[60] Growing Convergence

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37 https://new.nsf.gov/funding/opportunities/materials-research-science-engineering-centers
38 https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf24112
39 https://new.nsf.gov/funding/opportunities/designing-synthetic-cells-beyond-bounds-evolution/nsf24-505/solicitation
40 https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf22077
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42 https://new.nsf.gov/funding/opportunities/manufacturing-systems-integration-msi
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44 https://new.nsf.gov/funding/opportunities/biomechanics-mechanobiology-bmmb
45 https://new.nsf.gov/funding/opportunities/leading-engineering-americas-prosperity-health
46 https://new.nsf.gov/funding/opportunities/nanoscale-interactions
47 https://new.nsf.gov/funding/opportunities/particulate-multiphase-processes/505700/pd20-1415
48 https://new.nsf.gov/funding/opportunities/electronics-photonics-magnetic-devices-epmd
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57 https://new.nsf.gov/funding/opportunities/shf-ccf-software-hardware-foundations
58 https://new.nsf.gov/funding/opportunities/csr-cns-computer-systems-research
59 https://new.nsf.gov/funding/opportunities/predictive-intelligence-pandemic-prevention-phase/nsf23-608/solicitation
60 https://new.nsf.gov/funding/opportunities/future-manufacturing-fm

Research,[61] Research Coordination Networks,[62] and Designing Materials to Revolutionize and Engineer our Future (DMREF, with participation also from DOD, DOE, and NIST).[63] National priorities addressed by NSF programs that include support for foundational nanotechnology research include semiconductors and microelectronics,[64] QIS,[65] AI,[66] biotechnology,[67] clean energy,[68] sustainability/climate change,[69] and advanced manufacturing.[70]

DOD supports foundational nanotechnology research both through extramural funding from agencies such as the Air Force Office of Scientific Research (AFOSR),[71] the ONR,[72] and the Army Research Office (ARO),[73] as well as through intramural research at in-house DOD laboratories—e.g., the Air Force Research Laboratory, the Naval Research Laboratory (NRL), and the Army Research Laboratory (ARL).[74] In addition, foundational nanotechnology research is funded by the Defense Advanced Research Projects Agency (DARPA), the Defense Threat Reduction Agency (DTRA), the Chemical and Biological Defense program, and the Office of the Undersecretary of Defense for Research and Engineering (OUSD/R&E).[75]

For example, DTRA 2023–2025 funding supports eight projects under the Interactions of Ionizing Radiation with Matter University Research Alliance[76] and Materials Science in Extreme Environments University Research Alliance,[77] which include foundational nanotechnology research. The ONR Nanoelectronics program encourages innovative research and breakthrough scientific discoveries at the nanoscale that will inform the development of future computing technologies. In 2025, there will be an increased focus on basic research in the emerging area of probabilistic computing, which (like quantum computing) has the potential to solve some of the hardest computational tasks in the DOD. The fundamental unit in probabilistic computing is the probabilistic bit, or p-bit. A key priority is to support new projects developing complementary types of p-bits. These projects will augment the concurrent ONR MURI project “OptNet: Optimization with p-bit Networks” that began in September 2023. NRL’s Institute for Nanoscience research program includes fundamental discovery-phase research, with a focus on interdisciplinary nanoscience. NRL funding supports ~17 concurrent projects (each spanning approximately 4 years in duration), including topics such as low-power, high-speed electronics;

61 https://new.nsf.gov/funding/opportunities/growing-convergence-research-gcr
62 https://new.nsf.gov/funding/opportunities/research-coordination-networks
63 https://new.nsf.gov/funding/opportunities/designing-materials-revolutionize-engineer-our
64 https://new.nsf.gov/funding/opportunities/future-semiconductors-fuse2/nsf24-521/solicitation, https://www.nsf.gov/pubs/2022/nsf22113/nsf22113.jsp, https://www.nsf.gov/pubs/2022/nsf22076/nsf22076.jsp, https://www.nsf.gov/pubs/2024/nsf24038/nsf24038.jsp, https://www.nsf.gov/pubs/2024/nsf24041/nsf24041.jsp
65 https://new.nsf.gov/funding/opportunities/expanding-capacity-quantum-information-science/nsf24-523/solicitation, https://new.nsf.gov/funding/opportunities/quantum-manufacturing, https://www.nsf.gov/pubs/2024/nsf24042/nsf24042.jsp
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67 https://www.nsf.gov/pubs/2024/nsf24040/nsf24040.jsp
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69 https://new.nsf.gov/funding/opportunities/critical-aspects-sustainability-cas, https://www.nsf.gov/pubs/2021/nsf21124/nsf21124.jsp, https://www.nsf.gov/pubs/2022/nsf22111/nsf22111.jsp, https://www.nsf.gov/pubs/2024/nsf24045/nsf24045.jsp
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77 https://hemi.jhu.edu/mseeura/

photonics, plasmonics, and polaritonics; complex magnetism; nanoscale energy generation, conversion, and storage; 2D materials for sensing and information processing; bio/inorganic hybrids; and neuroelectronics and signaling processes. AFRL's Air Force Crystal Growth Center conducts exploratory synthesis of new materials for evaluation by DOD and academic collaborators, with new capabilities to fully characterize the fundamental magnetic, optical, structural, and thermal properties of these materials, for applications ranging from artificial neural networks to next-generation electronic device architectures and advanced manipulation of light. Other AFRL projects falling under PCA 1 include development of soft materials for electronics and sensing and research on synthesis and properties of nanoceramics for aerospace applications. This includes collaborations with Argonne and Oak Ridge national laboratories as well as multiple universities.

DOE's Office of Science supports fundamental nanotechnology R&D through PCA 1. Contributing programs in the Office of Basic Energy Sciences that support nanoscience include core research in the Chemical Sciences, Geosciences, and Biosciences Division, including Fundamental Interactions, Photochemistry and Biochemistry, and Chemical Transformations;[78] core research in the Materials Sciences and Engineering Division, including Condensed Matter and Materials Physics, Materials Design Discovery and Synthesis, and Scattering and Instrumentation Sciences;[79] research conducted at the Nanoscale Science Research Centers within the Scientific User Facilities Division[80] (where infrastructure investments are reported under PCA 3); Energy Frontier Research Centers;[81] Energy Innovation Hubs (including Fuels from Sunlight and Batteries and Energy Storage);[82] Computational Materials and Chemical Sciences;[83] and National Quantum Information Science Centers.[84]

DOE priorities for 2025 include the Energy Earthshot Initiative, announced in 2021. In 2023, the Office of Science initiated two funding opportunities in support of the Energy Earthshot Initiative: Energy Earthshot Research Centers and Science Foundations for Energy Earthshots, which funded 18 university teams and 8 national laboratory centers. Many of these include considerable nanoscience components.

The DOE Office of Nuclear Energy also invests in PCA 1 through the Nuclear Science User Facilities program,[85] which funds competitively awarded nuclear fuel and materials research projects that include some topics focused on nanoscale science.

The National Institutes of Health PCA 1 investments include research supported by the National Cancer Institute (NCI), the National Institute of Biomedical Imaging and Bioengineering (NIBIB), the National Human Genome Research Institute (NHGRI), and the National Institute of Dental and Craniofacial Research (NIDCR).

NCI provides support for basic, applied, and translational research in cancer nanotechnology. In particular, the funding opportunity, Innovative Research in Cancer Nanotechnology (IRCN, PAR-23-246 for 2024 and subsequent years),[86] covers mechanistic studies contributing to fundamental understanding of nanoparticle design rules and mechanisms behind their *in vivo* interactions.

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78 https://science.osti.gov/bes/csgb
79 https://science.osti.gov/bes/mse
80 https://science.osti.gov/bes/suf
81 https://science.osti.gov/bes/efrc/
82 https://science.osti.gov/bes/Research/DOE-Energy-Innovation-Hubs
83 https://science.osti.gov/bes/Research/Computational-Materials-and-Chemical-Sciences-CMS-CCS
84 https://science.osti.gov/Initiatives/QIS/QIS-Centers
85 https://nsuf.inl.gov
86 https://grants.nih.gov/grants/guide/pa-files/PAR-23-246.html

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 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 NHGRI is producing fundamental discoveries toward improving existing technologies for direct single-molecule RNA, DNA, and protein 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 and solid-state 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 conductors to determine individual base incorporations. Many of these novel approaches and technologies are supported by NHGRI's Genome Technology program.[87] Funding opportunities are focused on the early stages of novel technologies that will enable improved DNA sequencing and direct RNA sequencing.[88]

The NIDCR Strategic Plan for 2021-2026 prioritizes research to transform material and biomaterial products through innovations in engineering, chemistry, and biophysics, including building interdisciplinary expertise in nanotechnology. Additionally, due to the shortage of robust diagnostic tests to address the coronavirus pandemic, research on nanosensors continues to receive increased attention by the scientific community interested in developing biodevices for screening, monitoring, and diagnosis of oral and overall health. Some of this research builds on previous funding under the 2021–2023 NIDCR initiative on Enabling Technologies to Accelerate Development of Oral Biodevices,[89] which supported research on functional biodevices making use of enabling technologies such as nanomaterials or nanoscale biodevices for use in detection, diagnosis, and treatment of oral and systemic disease. Projects supported include real-time monitoring of saliva for levels of drugs such as anti-epileptic seizure medication for precision medicine and advancing optimal dosing. Other research builds on work funded during the COVID pandemic under the Rapid Acceleration of Diagnostics-Radical (RADx-RAD) initiative[90] on exploring the use of nanotechnology to identify biomarkers emanating from skin or the oral cavity in patients with symptomatic and asymptomatic COVID-19.

NIST's foundational nanotechnology research portfolio includes the development of cutting-edge approaches to design and accurately measure the size, shape, quantity, and physico-chemical complexity of nanoparticles, nanostructured films, and nanocomposites in a variety of environments. It also includes development of optical metasurface technologies (with potential applications in ultrafast and nonlinear optics, as well as advanced imaging and photonic sensing) and photonic interfaces to atomic-scale quantum systems. NIST is developing best practices and disseminating new measurement methods and data analysis techniques to determine the thermodynamics of DNA nanostructure assembly that will inform predictive models of nucleic acid systems and drug development. NIST PCA 1 investments also include foundational research related to semiconductors and microelectronics, consistent with the CHIPS and Science Act of 2022 (see PCA 2 section below for additional details).

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87 https://www.genome.gov/Funded-Programs-Projects/Genome-Technology-Program
88 https://grants.nih.gov/grants/guide/notice-files/NOT-HG-24-012.html
89 https://grants.nih.gov/grants/guide/pa-files/PAR-20-233.html
90 https://grants.nih.gov/grants/guide/rfa-files/RFA-OD-20-020.html, https://grants.nih.gov/grants/guide/rfa-files/rfa-od-20-021.html

FDA's Center for Food Safety and Applied Nutrition (CFSAN) has been conducting research on nanotechnology relevant to human food safety, e.g., understanding the potential migration of engineered nanomaterials from nanotechnology-enabled food contact materials to food to estimate possible consumer exposure. This improves CFSAN's ability to review future submissions to its programs and advise manufacturers interested in this emerging technology. CFSAN is also actively conducting research on possible incidental presence of nanoparticles in certain food additives to ensure current data and information are available to support safety assessments. Furthermore, CFSAN is involved in R&D on nanotechnology-enabled sensors for contaminants, biological toxins, and pathogens in food products, which helps improve FDA's ability to respond rapidly to foodborne disease outbreaks and other emerging threats to human and animal health.

The FDA Office of Regulatory Affairs (ORA), Office of Regulatory Science (ORS) continues to work with FDA product centers to conduct collaborative research to develop analytical methods for the characterization of nanomaterials in FDA-regulated products. Such methods will enable FDA to identify potential risks associated with such products through pre- and post-market oversight and determine problems that can affect product safety and provide guidance to sponsors/reviewers for the future approval of products. ORS collaborates with FDA's Center for Drug Evaluation and Research (CDER) in developing and validating analytical methods for characterization of complex liposomal drug formulations. ORA recruits and trains research fellows in the development and validation of advanced analytical methods based on standardized testing for the FDA, the United States Pharmacopeia (USP), and the International Council for Harmonization of Technical Requirements to characterize nanomaterial constituents in FDA-regulated products.

FDA's National Center for Toxicological Research (NCTR) conducts collaborative regulatory science research on characterization, safety, and efficacy assessment of nanomaterials, and documentary standards development with stakeholders within FDA, other government agencies, and academia. NCTR's Nanocore has developed a base line reference dataset of the most common polymers present in the environment that would serve towards the development of a collaborative, global, comprehensive, and curated public database for the identification and quantitation of various micro-/nanoplastics and their mixtures.[91] Ongoing research projects include the investigation into antimicrobial effectiveness of novel nanomaterials and nanostructures, including determination of their cytotoxicity and genotoxicity; and *in vitro* epigenetic evaluation of TiO_2 nanoparticles to study DNA methylation patterns, global histone modifications, and microRNA expression.[92] In order to fill knowledge gaps associated with complex drug nanocrystals, an ongoing study is investigating their effects on gastrointestinal-tract microbiome and function to compare and contrast with the parent active pharmaceutical ingredient.[93]

USDA/NIFA funds foundational nanotechnology research through its Agriculture and Food Research Initiative (AFRI)—Foundational and Applied Science Program,[94] which includes a program on Nanotechnology for Agricultural and Food Systems.[95] Priorities under PCA 1 include discovery and characterization of nanoscale phenomena, processes, and structures relevant and important to agriculture and food. A wide range of research topics are supported, e.g., investigation of plant virus nanoparticle technology for use as plant vaccines, synthesis of few-layer graphene-encapsulated iron nanoparticles from agricultural wastes, exploration of cellulose nanocrystals for detection of allergens

91 https://pubmed.ncbi.nlm.nih.gov/37196807/
92 https://pubmed.ncbi.nlm.nih.gov/32031460/
93 https://pubmed.ncbi.nlm.nih.gov/38146991/
94 https://www.nifa.usda.gov/grants/funding-opportunities/agriculture-food-research-initiative-foundational-applied-science
95 https://www.nifa.usda.gov/grants/programs/food-science-technology-programs/nanotechnology-program

and emerging contaminants, and use of multiscale modeling and machine learning for design and characterization of chitosan-based nanocomposites.

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 liaise with industry who conducts outreach, shares best practices, and supports collaborations as appropriate. A few examples of progress on Goal 2 are shown below.

Creating new generations of nanotechnology-enabled biosensors for detecting disease. Results from the 2021–2023 NIDCR biosensor initiative on Enabling Technologies to Accelerate Development of Oral Biodevices are beginning to emerge. This funding opportunity has been supporting projects that incorporate transformative engineering solutions to technical challenges associated with new development, substantial optimization of existing technologies, and clinical translation of intraoral biodevices. These functional biodevices make use of enabling technologies such as nanomaterials or nanodevices for detection, diagnosis, and treatment of oral and systemic disease. Projects supported include real-time monitoring of saliva for levels of drugs such as anti-epileptic seizure medication for precision medicine and advancing optimal dosing. NIH-supported researchers have developed a frequency-locked loop based multimodal readout integrated circuit for interfacing with off-chip temperature, electrochemical, and pH sensors[96] and a body-heat-powered, multi-sensor system-on-a chip supporting readout from multiple chemical and biological sensors.[97]

This research complements earlier work done during the COVID-19 pandemic on use of nanotechnology for rapid and affordable detection of infectious diseases, where NIDCR led an emergency initiative to support advanced development of novel, non-traditional, nanotechnology-based approaches for detection of the SARS-CoV-2 virus and biomarkers of the COVID-19 disease for use in outbreaks of COVID-19 and to address future health emergencies. SBIR and STTR projects funded through the RADx-RAD initiative[98] have used nanotechnology and nanomaterial approaches to identify biomarkers emanating from skin or the oral cavity in patients with symptomatic and asymptomatic COVID-19. This initiative is (1) advancing novel biosensing technologies that are innovative, safe, and effective; and (2) incorporating such technologies into devices with integrated AI systems for the detection, diagnosis, prediction, prognosis, and monitoring of COVID-19 in clinical, community, and everyday settings. A variety of nanotechnology-based designs target detection of volatile organic compounds (VOCs, i.e., scents or odors) emanating from skin and exhaled breath in a passive and noninvasive manner. In addition, other oral biosensing technologies are targeting a wealth of biological, chemical, and physical biosignatures representative of SARS-CoV-2 virus and/or COVID-19 disease sampled from exhaled breath/droplets, saliva, and tissues in the oral cavity using unique designs for sampling, detection, and analytical interpretation. Projects supported under this initiative include use of single-walled CNT corona phase for viral sensing applications,[99] development of a five-minute magnetic nanoparticle spectroscopy-based

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96 https://pubmed.ncbi.nlm.nih.gov/37347623/
97 https://pubmed.ncbi.nlm.nih.gov/37318975/
98 https://grants.nih.gov/grants/guide/rfa-files/RFA-OD-20-020.html, https://grants.nih.gov/grants/guide/rfa-files/RFA-OD-20-021.html
99 https://doi.org/10.1021/acs.jpcc.2c06434

bioassay for ultrafast detection of SARS-CoV-2 spike protein,[100] and a nanoparticle clustering-based magnetic particle spectroscopy bioassay method for detection of SARS-CoV-2 spike and nucleocapsid proteins in the liquid phase.[101]

Supporting commercialization of nanotechnology-enabled medical products through development and validation of standards. Previous NNI budget supplements have reported on efforts by FDA and other NNI participating agencies to promote the development of continuous manufacturing processes for reducing the cost and improving the quality of nanotechnology-enabled medical products.[102] Another key factor in promoting commercialization of such products is the development and validation of standards that streamline and clarify regulatory approvals. In previous years, FDA scientists worked with ASTM International and the International Organization for Standardization (ISO) to develop several such standards, including three standard test methods for lipid quantitation in liposomal formulations. In 2023, FDA/NCTR scientists completed three interlaboratory studies to determine the precision and bias of those published standard test methods, collaborating with academic researchers and industry to prepare liposomal samples for analysis. In all, 66 laboratories in 13 countries participated in these studies.[103]

Revolutionizing metallurgy and aerospace propulsion with nanotechnology-enabled additive manufacturing. NASA has developed a three-dimensional (3D)-printable alloy strengthened by nanoparticulate dispersants, GRX-810, that has attracted the interest of the metallurgy and rocket propulsion communities because of its light weight and high mechanical durability at extreme high temperatures. The invention led to an R&D 100 award in 2023 for GRX-810 3D Printable Alloy Designed for Extreme Environments.[104] A key element of the alloy formulation is nanoscale particles of yttria, yielding an oxide-dispersion-strengthened alloy. GRX-810 has been licensed to four American companies, which will be using the material to make sturdier, more resilient aircraft and spacecraft components.[105] The alloy is fabricated using additive manufacturing and incorporates nanoscale yttria particles throughout its microstructure, which provides a doubling of tensile strength and oxidation resistance and 1,000-fold better creep properties compared to traditional nickel-based superalloys. The material has already been successfully hot-fire tested in injectors and nozzles for a liquid oxygen/liquid methane rocket engine. It can also be used in preburners, turbines, and other hot-section components, which must withstand temperatures up to 1100°C.[106]

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100 https://www.ncbi.nlm.nih.gov/pmc/articles/9762417

101 https://www.ncbi.nlm.nih.gov/pmc/articles/8442556

102 e.g., lipid nanoparticles used in mRNA vaccines; see the NNI Supplement to the President’s 2024 Budget (https://www.nano.gov/sites/default/files/pub_resource/NNI-FY24-Budget-Supplement.pdf), p. 20.

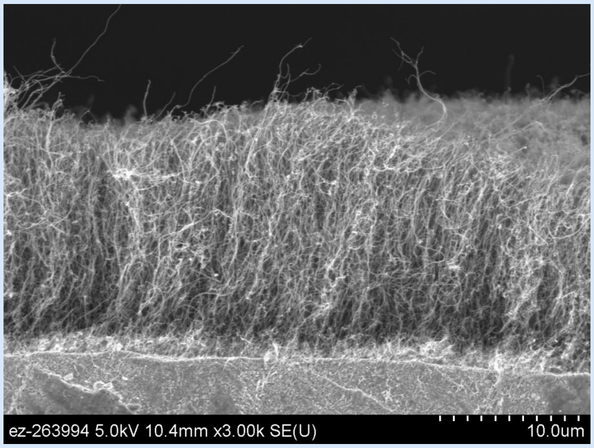
103 https://www.astm.org/products-services/standards-and-publications/standards/workitem-wk85363; https://www.astm.org/products-services/standards-and-publications/standards/workitem-wk85365; https://www.astm.org/products-services/standards-and-publications/standards/workitem-wk85364

104 https://www.nasa.gov/newsletters/aerospace-frontiers/nasa-glenn-earns-rd-100-award/

105 https://www.metaltechnews.com/story/2024/05/15/tech-bytes/grx-810-licensed-to-four-us-companies/1763.html

106 https://www.metal-am.com/nasas-grx-810-alloy-undergoes-successful-hot-fire-testing-for-liquid-rocket-engines/

Mitigating climate change at interfaces: Achieving superlubricity and heat management with nanotechnology



ORNL's vertically aligned carbon nanotubes reduce friction to nearly zero to improve energy efficiency. Credit: Chanaka Kumara/ORNL, U.S. Dept. of Energy.

Addressing inefficiencies at interfaces would help reduce energy consumption and greenhouse gas emissions of many industries. Through friction alone, the United States loses more than $1 trillion annually, equivalent to around 5% of the U.S. gross domestic product. The Nano4EARTH community has identified the reduction of energy losses at interfaces through nanotechnology-enabled advancements in coatings, lubricants, membranes, and other interface technologies as one promising area for mitigating climate change.

To reduce friction at interfaces, a team of scientists at DOE's Oak Ridge National Laboratory developed a novel coating made of carbon nanotubes, providing superlubricity at ambient conditions. While typical oil lubricants provide coefficients of friction of around 0.1, this coating has demonstrated superlubricity, defined as coefficients of friction of less than 0.01, which translates to virtually no resistance when parts slide on each other. This coating has achieved coefficients of friction as low as 0.001.

This new coating covers the treated surface with vertical carbon nanotubes and an oil. When another surface passes over it, the carbon nanotubes fracture and are then deposited on both contact surfaces, forming a graphene film that is responsible for the nearly zero coefficient of friction. This stable graphene film can withstand more than 500,000 rubbing cycles without the need of speciality environments, making superlubricity feasible in common applications.

Lubrication is not the only way to address inefficiencies at interfaces. Carbon nanotubes are versatile and can also be harnessed as a thermal interface material. Thermal management of heat is another way to increase energy efficiency of a system. Aligned carbon nanotubes can achieve this by managing thermal conductivity and resistance. A company that has received support from DARPA, NASA, NSF, and the SBIR program has developed a thermal management system based on aligned carbon nanotubes that combines the benefits of solid and liquid thermal interface materials. The company's products are commercially available and have been used in NASA satellites, data centers, and electric vehicles.[107]

Using nanoparticles to enable smaller, less expensive, and portable magnetic resonance imaging (MRI) systems. NIST researchers and collaborators from industry and an international university have discovered that nanoparticles can boost image quality in low-field MRI scans. The researchers found that iron oxide nanoparticles outperformed gadolinium contrast agents used in conventional MRI machines. At low magnetic field strength, the nanoparticles provided good contrast using a concentration of only about one-ninth that of the gadolinium particles. This could enable new, portable MRI machines that use lower-strength magnetic fields, which could expand the ways in which MRI is used, e.g., in ambulances and other mobile settings. They could cost much less, promising to make MRI more widely available, including in underserved communities and developing nations. Other

[107] https://www.ornl.gov/news/superlubricity-coating-could-reduce-economic-losses-friction-wear; https://doi.org/10.1016/j.mtnano.2022.100297; https://carbice.com

advantages of this innovation include that iron oxide nanoparticles are broken down by the human body, vs. gadolinium, which may accumulate in tissues, and this could reduce dependence on gadolinium, a rare-earth element, for medical imaging.[108]

Enhancing efficient semiconductor capabilities for microelectronics. Building on research funded by NSF, a startup company was founded by a former graduate student based on NSF-supported research at a public land-grant research university that resulted in breakthrough development of hierarchical manufacturing approaches for the scalable assembly of densely aligned, semiconducting nanotubes. These assembly advances have enabled CNT-based field-effect transistors that outperform silicon analogues with higher electrical current density, increasing speed, and decreasing power usage for digital and wireless devices. The startup was awarded an NSF STTR Phase I award in 2023 to support commercialization of these novel technologies. Silicon replaced with smaller and more densely packed CNTs outperforms silicon-based analogues, enabling more high-performance and data-intensive applications at a lower power usage. An important step in manufacturing is failure testing, and a company supported by DOE's SBIR program developed a process for high-throughput, high-quality production of tungsten tips for nanoprobes that can be used for both scanning tunneling microscopy and semiconductor nanoprobing and failure analysis. Other nanoprobe research funded by DOE at a public research university focused on power control electronics; the research ended in 2021 but continues to yield new patents[109] and publications.[110] These examples highlight how close partnership and support from federal agencies allow researchers to create and scale small businesses that find solutions for state-of-the-art microelectronics challenges.

Looking to future advances toward monolithic electronics, researchers at the DOD-supported Institute for Soldier Nanotechnologies (ISN), working with researchers from DOE's Oak Ridge National Laboratory and industry, have developed a new low-temperature process that allows for the rapid growth of atomically thin semiconductor transistors to be grown directly on top of silicon chips, facilitating the radical increase in density of computing power needed for advanced applications.[111]

Increasing infrastructure durability by improving concrete properties. Concrete remains critical to our nation's infrastructure needs. Improving durability and performance of materials reduces the overall use of virgin materials and energy required to build and maintain the U.S. highway system. Supplementary cementitious materials can reduce the amount of cement used in concrete, reducing greenhouse gas emissions without compromising performance or safety. DOT's FHWA, in coordination with DOC/NIST and DOD/Army's Engineering Research and Development Center (ERDC), continues identifying and assessing the performance of supplementary cementitious materials for highway structures and pavements[112] and also developing and testing chemistry models to study the compatibility of waste plastics in asphalt binders. This complements ongoing work by the USDA's Forest Service, which continues studying cellulose nanocrystal-enhanced cement. Results from a Forest Service field demonstration have been published,[113] while experiments continue to follow the aging and weathering to ensure long-term performance. The concept is being extended in 2024 to a spillway dam project.

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108 https://www.nist.gov/news-events/news/2023/07/new-nist-measurements-aim-advance-and-validate-portable-mri-technology; https://doi.org/10.1038/s41598-023-38222-6
109 U.S. Patent No: 11,852,654 B2; Patent Date: December 26, 2023
110 https://doi.org/10.1016/j.mechatronics.2024.103165
111 https://doi.org/10.1038/s41565-023-01375-6
112 https://doi.org/10.21949/1521984
113 https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/51738464

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

PCA 2 covers research and development that applies the principles of NSE to create novel devices and systems, or to improve existing ones. It includes the 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. NNI PCA 2 investments have grown in recent years, from under 24% of the total in 2016 to over 40% in the 2025 request.

PCA 2 is the largest category in the NIH NNI investment portfolio, accounting for nearly 70% of its 2025 request, up from just under 68% in the 2024 request.[114] Other agencies contributing to PCA 2 in the 2025 budget (in descending order of dollar amount of investments) include NSF, DOD, DOE, NIST, NIFA, FDA, NASA, ARS, FS, BARDA, DOJ, and FHWA.

Several of the NIH/NCI-funded efforts have applied focus and are dedicated to developing new and improved diagnostics and therapeutics. The former primarily prioritizes high sensitivity and the capacity for multiplexed detection. The latter, in addition to nanotechnology-based chemotherapeutics, are increasingly exploring gene therapies and immunotherapies. The Toward Translation of Nanotechnology Cancer Interventions[115] funding opportunity facilitates late preclinical evaluations, enhancing the integration of nanotechnology cancer interventions into mainstream translational and clinical programs.

NIH’s National Institute of Allergy and Infectious Diseases (NIAID) is supporting the development of nanotechnology-enabled approaches to diagnose, treat, and prevent infectious diseases. For example, scientists are developing an mRNA-lipid nanoparticle vaccine against mpox and vaccinia viruses, and a single-component nanoparticle vaccine to block malaria transmission. To provide stronger and longer-lasting protection against SARS-CoV-2, NIAID-funded scientists are developing an extended-release vaccine strategy that encapsulates protein nanoparticle vaccines with a biodegradable polymer. This modular design could have broader applicability towards the development of vaccines for other infectious pathogens. NIAID-funded scientists are also using nanotechnology to improve diagnostic testing. For example, a point-of-care test for drug-resistant tuberculosis (TB) based on nanoreactor bead chemistry and a protein-based nanopore biosensor assay to diagnose active TB using serum biomarkers are in development. Through its Advancing Vaccine Adjuvant Research for Tuberculosis (AVAR-T) program,[116] NIAID is funding the development of preventive, including post-exposure, TB vaccines through side-by-side comparisons of adjuvants. This development will allow scientists to investigate distinct immune profiles associated with nanomaterial-based adjuvants. NIAID continues its efforts to develop “universal” flu vaccines that display portions of influenza viruses on the exterior of a nanoparticle. These vaccines could provide immunity against a broad range of influenza viruses and would not need to be reformulated and administered on a yearly basis. Several clinical trials for a ferritin nanoparticle-based influenza vaccine candidate have demonstrated that this vaccine platform is safe and stimulates immune responses against multiple influenza subtypes. Scientists are also assessing an investigational mosaic nanoparticle vaccine designed to provide consistent protection for multiple seasons in clinical trials. Additionally, scientists are developing a tandem helix-A nanoparticle, a novel design that could open opportunities for the development of nanoparticles with broad coverage over many diverse influenza subtypes.

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[114] See https://www.nano.gov/sites/default/files/pub_resource/NNI-FY23-Budget-Supplement.pdf, p. 12.
[115] https://grants.nih.gov/grants/guide/pa-files/PAR-22-071.html
[116] https://www.niaid.nih.gov/research/advancing-vaccine-adjuvant-research-tuberculosis-avar-t

NIH/NIBIB serves as the engineering hub of NIH, supporting diverse research on engineered nanotechnology for crosscutting biomedical applications. Examples include nanoscale voltage generators for biomacromolecule delivery, theranostic nanoparticles for image-guided drug delivery, nucleic acid nanoparticles designed to mimic monoclonal antibodies, and nanostructured degradable bone cement.

NIH/NIBIB is establishing a Biomaterials Network Technology Development Coordinating Center, which is now funded and in the early buildout stages, with the aim to accelerate innovation, development, and early dissemination of biomaterials-based technologies, including nanoscale technologies, and overcome challenges to clinical translation.

NIH/NIDCR support for the Dental, Oral and Craniofacial Tissue Regeneration Consortium (DOCTRC)[117] will extend until 2025. DOCTRC is facilitating the advancement of promising technologies, including 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. Translational projects supported include stem cell-based therapies for bone regeneration, immunomodulatory strategies to treat periodontal disease, and remineralization treatments using nanoparticles. These projects have begun to demonstrate tangible FDA regulatory successes in 2024, including a successful Investigational New Drug filing, and several teams poised for 510(k) submission by late 2024. Product development for several of these projects is also supported through synergistic STTR/SBIR funding. A new concept, Accelerating Product Excellence in Innovation and for Clinical Adoption,[118] will expand on the success of DOCTRC, with the goal of continuing to power the engine to accelerate preclinical product development through innovation, commercialization, and clinical adoption.

In 2025, NIH/NHGRI will fund a new Technology Development Coordinating Center,[119] which is responsible for enhancing integration between components of the NHGRI Genome Technology program by facilitating opportunities for collaborations. The center also disseminates program advances, develops resources and outreach strategies for engaging the broader biomedical research community, and manages an Opportunity Funds program to rapidly fund and support promising small-scale work that advances development of innovative genomic technologies.

NSF supports nanotechnology commercialization through the development of spin-off companies from projects funded by core programs such as Advanced Manufacturing, Future Manufacturing, and Engineering Research Centers. These companies can take advantage of resources provided by NSF-funded infrastructure programs such as the National Nanotechnology Coordinated Infrastructure. Industry partnerships are fostered through programs such as IUCRC and Grant Opportunities for Academic Liaison with Industry,[120] and through NSF collaboration with Manufacturing USA institutes.[121] The Technology, Innovation and Partnerships (TIP) Directorate has the mission to support use-inspired research and translation of research results to the market and society. Authorized by the CHIPS and Science Act of 2022, TIP focus areas include laying the foundation for the American industrial innovation base through investment in regional innovation ecosystems, accelerating technology development and

[117] https://doctrc.org/

[118] https://www.nidcr.nih.gov/grants-funding/funding-priorities/future-research-initiatives-concept-clearances/accelerating-product-excellence-innovation-clinical-adoption-apex

[119] https://grants.nih.gov/grants/guide/rfa-files/RFA-HG-24-006.html

[120] https://www.nsf.gov/eng/eec/goali.jsp

[121] https://www.nsf.gov/pubs/2024/nsf24014/nsf24014.jsp

translation, and growing a workforce at all levels leveraging all Americans. TIP activities that involve support for nanotechnology applications, devices, and systems research include the NSF SBIR and STTR programs[122] and the Partnerships for Innovation,[123] Accelerating Research Translation,[124] NSF Convergence Accelerator,[125] NSF Regional Innovation Engines,[126] and NSF Innovation Corps (NSF I-Corps™) programs.[127] Commercialization of nanotechnology is also aided by NSF workforce development programs such as Non-Academic Research Internships for Graduate Students,[128] and through the training of undergraduate and graduate students supported by NSF-funded research projects—providing a pipeline of talented people who are available for U.S. companies to hire (see PCA 4 section below).

DOD supports nanotechnology applications, devices, and systems research (PCA 2) through extramural and intramural funding from the Air Force (AFOSR/AFRL), Navy (ONR/NRL), Army (ARO/ARL), DARPA, DTRA, the Office of the Under Secretary of Defense for Research and Engineering, and the Chem/Bio program. For example, DARPA supports the development of nanotechnology-enabled functional materials and devices under the SynQuaNon program,[129] which is developing novel classes of superconducting metamaterials for new capabilities in QIS, and is shifting from exploration to development in 2025. DARPA has also been supporting nanomaterials development under the Coded Visibility program, [130] which is nearing completion in 2024. AFRL is conducting research on 2D nanomaterials (e.g., transition metal dichalcogenides, MXenes, 2D covalent organic frameworks) and advanced processing technologies (e.g., liquid phase exfoliation, vapor phase growth, 3D printing, laser manufacturing, composites) to develop applications and devices such as multifunctional structural coatings, optical coatings, and electronics and sensors. The ONR Power Electronics program[131] is supporting the development of nanotechnology-enabled wide-bandgap semiconductor materials (e.g., SiC) for power electronics power distribution system applications, including high power and pulsed power required in the modern Navy systems. It is also supporting research on additive manufacturing of ferrites for ultra-high-frequency megawatt-class magnetic devices, tunable paramagnetic and superparamagnetic materials development for hybrid core inductors for shipboard power (in cooperation with Sandia National Laboratory), and boundary-engineered nanocomposites as high-frequency inductors for shipboard and airborne Navy power systems. DTRA is supporting research under PCA 2 on radiation-hardening of nanoscale microelectronics and characterization of nanoscale defects and interfaces in microelectronics.

DOE support for R&D on nanotechnology-enabled applications, devices, and systems includes the microelectronics Energy Efficiency Scaling for 2 Decades (EES2) initiative, supported by the Advanced Materials & Manufacturing Technologies Office (AMMTO) within the Office of Energy Efficiency and Renewable Energy (EERE). DOE is partnering with multiple organizations nationwide to develop an EES2 R&D roadmap, which will include ~55 high-impact technologies, many of which incorporate

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122 https://new.nsf.gov/funding/opportunities/nsf-small-business-innovation-research-small-0/nsf24-579/solicitation
123 https://new.nsf.gov/funding/initiatives/pfi
124 https://new.nsf.gov/funding/opportunities/accelerating-research-translation-art
125 https://new.nsf.gov/funding/opportunities/nsf-convergence-accelerator-phases-1-2-2023-cohort
126 https://new.nsf.gov/funding/initiatives/regional-innovation-engines
127 https://new.nsf.gov/funding/initiatives/i-corps
128 https://www.nsf.gov/eng/eec/intern.jsp
129 https://www.darpa.mil/program/synthetic-quantum-nanostructures
130 https://www.darpa.mil/program/coded-visibility
131 https://www.nre.navy.mil/organization/departments/code-33/power-and-energy-focus-area/power-electronics-and-electromagnetism

nanotechnology (e.g., CNT devices), and which will inform funding opportunity announcements (FOAs) at AMMTO, other DOE offices, and other U.S. government agencies.[132] EES2 lab call projects funded in 2023[133] are expected to continue through 2025–2026. In August 2024, DOE issued an RFI soliciting feedback from stakeholders on the EES2 initiative and the draft roadmap.[134] Other DOE activities related to PCA 2 include the January 2024 AMMTO Battery Manufacturing Platform Technologies FOA, which includes a subtopic on Scalable Manufacturing of Nanolayered Films for Energy Storage.[135] The DOE Office of Nuclear Energy invests in PCA 2 through the Advanced Sensor and Instrumentations program,[136] which funds research activities on the development and demonstration of sensors for advanced reactors and irradiation testing. Activities considered here are based on additive manufacturing processes that include of nanoscale precursor materials.

NIST PCA 2 investments include research on quantum materials design and characterization. NIST is conducting research on nanoscale devices and systems for applications such as microelectronics, coatings, and pharmaceutical products. A major new thrust at NIST is microelectronics, semiconductor, and electronic packaging R&D funded under the CHIPS and Science Act of 2022, including the National Semiconductor Technology Center,[137] the National Advanced Packaging Manufacturing Program,[138] the CHIPS Metrology program,[139] and the CHIPS Manufacturing USA institute.[140] This is in addition to long-standing and continuing research in the Microsystems and Nanotechnology Division,[141] the NanoFab at the Center for Nanoscale Science and Technology[142] in Gaithersburg, MD (which also serves as a user facility, see PCA 3 section below), and at the NIST Boulder Microfabrication Facility.[143]

Other NIST research areas falling under PCA 2 include nanopore biosensors, work with FDA on nanoparticle tracking methods and microfluidic measurement devices to characterize complex liposomal products, development of standards and calibrations for super-resolution optical microscopy, single- and multi-organ microphysiological systems that mimic the human body to evaluate efficacy and toxicity of new drugs, and self-assembled DNA nanostructures for adaptable biomarker sensing.

NIFA/AFRI priorities under PCA 2 include R&D on novel uses and high-value-added products of nano-biomaterials from agricultural and forest origins for food and non-food applications; nanotechnology-enabled smart sensors for accurate, reliable, and cost-effective early and rapid detection of targets of interest in agricultural production and food safety; cost-effective distributed sensing networks for intelligent and precise application of agricultural inputs; and monitoring physiological biomarkers for optimal crop or animal productivity and health. Examples of supported projects include fate, transport, and efficacy of nanofertilizers, nanopore-based sensing for rapid detection of microbial foodborne pathogens, and nanotechnology-enabled adjuvants for poultry vaccines.

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132 https://www.energy.gov/eere/ammto/articles/what-do-microelectronics-have-do-emissions-reductions
133 https://www.energy.gov/eere/ammto/fy-2023-microelectronics-lab-call
134 https://www.energy.gov/eere/ammto/articles/doe-seeks-input-dramatically-increase-energy-efficiency-semiconductor
135 https://www.energy.gov/eere/ammto/ammto-releases-157-million-funding-opportunity-advance-domestic-manufacturing-next
136 https://asi.inl.gov
137 https://www.nist.gov/chips/research-development-programs/national-semiconductor-technology-center
138 https://www.nist.gov/chips/research-development-programs/national-advanced-packaging-manufacturing-program
139 https://www.nist.gov/chips/research-development-programs/metrology-program
140 https://www.nist.gov/chips/research-development-programs/chips-manufacturing-usa-institute
141 https://www.nist.gov/pml/microsystems-and-nanotechnology-division
142 https://www.nist.gov/cnst
143 https://www.nist.gov/programs-projects/boulder-microfabrication-facility

A key element of FDA research falling under PCA 2 is contributing to the development of voluntary consensus standards, which provide clear regulatory expectations, streamline premarket review, and facilitate markets for safe and effective products, as well as promoting international harmonization. This includes research to inform the development of these standards, as well as the conduct of international interlaboratory studies to evaluate test method standards for precision and bias. FDA's Center for Biologics Evaluation and Research (CBER) Office of Vaccines Research and Review conducts research to evaluate the safety and effectiveness of preventative vaccines against infectious diseases, e.g., the LNP-encapsulated COVID-19 mRNA vaccine. Current and ongoing activities include evaluating the effectiveness of this class of vaccine against a wide variety of other infectious disease agents, including influenza virus, respiratory syncytial virus (RSV), Nipah virus, human immunodeficiency virus (HIV), Zika virus, TB, human cytomegalovirus, and malaria, and also some cancer vaccines.

At NASA, nanotechnology is used to accomplish mission needs and objectives through experimental and theoretical research. NASA's research portfolio for nanotechnology enabled applications, devices, and systems covers a range of application areas, from lightweight materials and structures for aircraft and space exploration; to energy storage, power, and propulsion; nanosensors; spacecraft water sustainability; multifunctional textiles; and advanced instrumentation to enable deep space exploration. For example, NASA is supporting nanotechnology-enabled SBIR and STTR projects on miniaturized contaminant detection systems for potable water and wastewater; advanced textiles for intravehicular and extravehicular crew garments, including nanolayer-coated flame-retardant fabrics for space crew clothing; and Lunar and Martian regolith control (see above in the SBIR/STTR section of Chapter 2 for additional SBIR/STTR examples). Plans for 2025 include continued support for the Super-lightweight Aerospace Composites Project under the Game Changing Development Program in the Space Technology Mission Directorate, which is advancing manufacturability of structural aerospace nanocomposites to realize weight savings through nanocomposite propellant tanks for nuclear thermal propulsion systems; future activities will feature prototype carbon nanotube-reinforced composite article fabrication and testing. Concluding in 2024 is the Game Changing Development Project, Refractory Alloy Additive Manufacture Build Optimization, which included the addition of nanodispersants to feedstocks to improve mechanical performance of additive manufactured parts. NASA is working with NIH on nanosensor-enabled diagnostic platforms to allow rapid characterization of pathogens associated with pelvic and gynecologic infections; bacterial identification is enabled through nanoparticle structures functionalized to be sensitive to genetic sequences of interest.

The USDA/ARS Western Regional Research Center is conducting research on: (1) biomass from hemp pulped nanofibers (in water-soluble films for packaging); (2) thermoplastic starch blends of cellulose nanocrystals/nanofibrils (extruded mix and film blowing for packaging); and (3) straw residue, bagasse, and grasses as feedstocks for production of commercially viable nanoparticles for nanocomposites. Nanotechnology projects at the ARS National Center for Agricultural Utilization Research cover: (1) application of phospholipid/polysaccharide nanoparticles to enhance/deliver bioactives into food and cosmetics; (2) use of agricultural wastes to produce commercial nanoscale cellulases and hemicelluloses; (3) development of protein nanocapsules for food ingredients to reduce chronic disease form vitamin E deficiencies; and (4) production of nanocellulose films and gels from sorghum stover for paints and 3D printing feedstocks. The Southern Regional Research Center is conducting research on a variety of nanomaterials incorporated into cotton fibers: (1) silver nanoparticles for antimicrobial activity, thermal insulation, flame retardancy, and hydrophobicity; (2) iron oxide nanoparticles for magnetic applications; and (3) copper ion nanoparticles for purification of air and water. All three centers have multiple cooperative research and development agreements (CRADAs) with industry. In addition, ARS is supporting research at a public land-grant research university on manufacturing and applications of nanocellulose fiber molded products. With additional support from NIFA and the Forest Service, the university has developed a pilot-scale (2000 lb./day) nanocellulose production facility and a large 3D printer.

The USDA Forest Service supports nanotechnology research under PCA 2 to contribute to conservation and productivity of U.S. forest resources, sustaining forests, the economy, and quality of life. Plans and priorities for 2025 include: (1) development of a biorefinery to make cellulose nanomaterials from biomass, exploring the organosolv process to make cellulose nanocrystals (CNCs) directly from Western U.S. forest thinnings (a collaborative project between the USDA Forest Products Laboratory—FPL and a university); (2) collaborative research with a number of universities and FPL on renewable packaging (e.g., molded paper with a cellulose nanomaterial coating to replace PFAS, cellulose nanomaterial fruit coatings to preserve freshness; (3) CNC filters to remove PFAS from water; (4) nanocellulose-coated paper substrates for printed sensors and electronics; (5) development of a rapid and robust instrument for CNC size distribution measurement; and (6) CNC-enhanced cement. In the latter project, FPL and the U.S. Endowment for Forestry and Communities[144] will conduct a needs assessment for CNC commercialization in the cement industry and will sponsor a CNC-enhanced cement application for spillways in restoration of a natural area. Some of these projects include funding from NIFA.

BARDA continues to provide funding under PCA 2 for infectious disease diagnostics and vaccine research, complementary to efforts at NIH/NIAID and FDA reported elsewhere in this document.

PCA 2 investments from DOJ/NIJ's Forensic Science Research and Development program[145] fund projects that apply nanotechnology toward the sensitive and selective detection and identification of trace chemical and biological materials collected as forensic evidence.

Under PCA 2, DOT's FHWA will continue its work to understand and control the performance of supplementary cementitious materials at the nanoscale, including identifying and assessing performance of alternative materials for highway structures and pavements and providing evidence for mix designs, testing methods, and standards for these materials. FHWA is also supporting research through its SBIR program on vehicle communications via nanotechnology-enabled inductive paint, investigating mechanisms for communication between infrastructure and vehicles using road markings.

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. USPTO has been providing information and analysis on nanotechnology patenting trends to NSET and NNCO, as a way to pinpoint emerging applications and as a metric for commercialization activity. Work is ongoing to identify nanotechnology-related patent classification symbols[146] and track patenting trends in those topic areas.

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.

[144] https://www.usendowment.org/
[145] https://nij.ojp.gov/topics/forensics/forensic-science-research-and-development
[146] https://www.uspto.gov/web/patents/classification/cpc/html/cpc.html

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 often 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.

DOE NSRCs furthering sustainability and energy security. A hallmark of DOE's Nanoscale Science Research Center user facilities is the combination of cutting-edge instrumentation and highly-trained staff scientists that can advance priority research areas. An example is recent progress towards cost-effective catalysts for hydrogen production using earth-abundant materials. Domestic demand for clean hydrogen has the potential to increase more than tenfold by 2030[147] for use in the industrial, chemical, and heavy-duty transportation sectors. Critical to this scale up are catalysts for producing hydrogen via electrolysis and materials to replace expensive iridium-based catalysts. Researchers across three national laboratories used the NSRC Center for Nanoscale Materials and Advanced Photon Source at Argonne National Laboratory to study a new catalyst material, a nanofibrous cobalt spinel doped with lanthanum and manganese, that demonstrated excellent electrical properties and low degradation.[148] Another example is the cross-fertilization between Oak Ridge National Laboratory's NSRC Center for Nanophase Materials Sciences and USDA/NIFA. NIFA planned its annual project director's meeting on nanotechnology for agriculture and food systems adjacent to the CNMS user meeting, as done previously with Lawrence Berkeley National Laboratory's NSRC Molecular Foundry and Los Alamos National Laboratory that successfully led to new research collaborations. This allowed NIFA-funded scientists to attend to discuss and plan future experiments with user facility scientists, invite researchers from CNMS and NIFA to present at each other's respective meetings, and led to further invitations for collaboration and deepening of professional contacts.

Cementing links between NNCI and DOD Microelectronics Common Hubs. NSF-supported NNCI comprises 16 unique sites across 16 states with 13 partners providing 71 facilities and over 2000 tools to researchers from all areas of science and engineering; about 40% of those researchers each year are new users. Year 8 saw 594 small businesses with over 1400 users at NNCI facilities. In September 2023, NNCI held the Nanotechnology Infrastructure of the Future workshop and released an accompanying report.[149] Also in September 2023, under the CHIPS and Science Act, DOD announced[150] its eight regional innovation hubs as part of the Microelectronics Commons; each hub has an NSF-funded NNCI partner site as a member. Initial Commons funding was awarded to establish infrastructure and workforce development programs across critical areas like 5G/6G wireless technology, AI and hardware, commercial leap-ahead technologies, electromagnetic warfare, secure edge/Internet of Things (IoT) computing, and quantum technology. NNCI infrastructure, both facilities and open-source software,

147 https://liftoff.energy.gov/clean-hydrogen/
148 https://doi.org/10.1126/science.ade1499
149 https://nnci.net/sites/default/files/inline-files/2023_FutureNanotechnologyInfrastructure_WhitePaper_FINAL.pdf
150 https://www.defense.gov/News/News-Stories/Article/Article/3532338/dod-names-8-locations-to-serve-as-new-microelectronics-commons-hubs/

has supported DOD critical technology areas like microelectronics[151] and will continue to do so through these innovative partnerships to ensure an acceleration from R&D to scaling up production and manufacturing of products and applications arising from domestic R&D.

Using nanostructures to enable novel scientific instrumentation. Specialized physical tools are essential for continuing to push the frontiers of nanotechnology R&D. Building on earlier work on the use of superconducting nanowires as single photon detectors,[152] researchers from NIST and NASA's Jet Propulsion Laboratory, with support from DARPA, have built a superconducting camera containing 400,000 pixels—400 times more than any other device of its type. Superconducting cameras allow scientists to capture very weak light signals, whether from distant objects in space or parts of the human brain. The camera is made up of grids of superconducting nanowires, cooled to near absolute zero, in which current moves with no resistance until a wire is struck by a photon. An image is created from the combination of photon locations and intensities. The team plans to improve the sensitivity of the prototype camera so that it can capture virtually every incoming photon, this new tool would support applications such as imaging faint galaxies or planets that lie beyond the solar system, measuring light in photon-based quantum computers, and using near-infrared light to peer into human tissue.[153]

Another NIST team has developed an instrument called Thermal Magnetic Imaging and Control (Thermal MagIC), which uses nanospheres to enable precise 3D mapping of temperatures within an object. The instrument measures the magnetic responses of nanometer-sized spheres embedded in the object whose temperature is being measured. Thermal MagIC consists of two systems working together. The first part consists of the sensors themselves: nanometer-sized spheres whose magnetic signals change with temperature. The second part is the instrument that excites the tiny spheres magnetically and then reads out their signal. With this system, the team has been able to measure temperature differences to within 500 millikelvin in a volume of just 63 nanoliters. This technology could enable non-invasive temperature measurements inside living systems, or even the temperature inside a Kevlar vest as a bullet penetrates it.[154]

Leveraging cancer nanotechnology expertise for the COVID-19 pandemic. NIH/NCI, in collaboration with NIST and FDA, established the Nanotechnology Characterization Laboratory (NCL) to perform preclinical characterization of nanomaterials being proposed for use in cancer diagnostics and therapeutics. Notably, 23 collaborators of NCL reached clinical trials with the aid of data produced at the facility. Over its 20 years of operation, NCL has characterized more than 550 different nanomaterials, established over 89 standardized protocols for various nanoparticle assays, and published over 250 peer-reviewed publications covering nanoparticle characterization, immunotoxicity, and safety. As the only outward-facing federally funded resource for medical applications of nanotechnology, NCL continues to make substantial progress on cancer nanotechnologies, and is now harnessing that expertise and materials characterization infrastructure in response to the global COVID-19 pandemic.

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151 https://doi.org/10.1038/s41467-022-35446-4

152 See the back cover of the NNI Supplement to the President's 2021 Budget: https://www.nano.gov/sites/default/files/pub_resource/NNI-FY21-Budget-Supplement.pdf

153 https://www.nist.gov/news-events/news/2023/10/nist-team-develops-highest-resolution-single-photon-superconducting-camera; https://doi.org/10.1038/s41586-023-06550-2

154 https://www.nist.gov/news-events/news/2023/09/working-their-thermal-magic-digging-details-ambitious-new-thermometry; https://doi.org/10.1038/s41598-023-42620-1

Carbon management at scale: Direct air capture demonstration facilities

Carbon management, particularly direct air capture (DAC), is another promising area identified by Nano4EARTH participants where nanotechnology advancements can accelerate climate mitigation impacts. DOE's National Energy Technology Laboratory (NETL) DAC Center is a new facility that supports the rapid development of DAC technologies as part of the solution to achieve net-zero emissions by 2050. The facility supports testing at three different scales: lab-scale to test long-term stability of materials, bench-scale modules to examine flow dynamics, and small pilot-scale for testing prototypes. The NETL DAC Center supports testing, development, and commercialization pathways for emerging technologies projects from innovators in industry, academia, and government that have achieved proof-of-concept but not yet full pilot scale (technology readiness levels 3 to 6) under a broad range of climate conditions.

NETL researchers are studying how to increase the lifetimes and effectiveness of sorbents used in direct air capture technologies to remove CO_2 from the air. Image credit: NETL.

The NETL DAC Center's advanced testing capabilities are currently investigating the degradation mechanism of various sorbents used in the DAC technologies.[155] *Sorbent materials are susceptible to thermal and oxidative degradation over their lifecycles. Therefore, the DAC Center is working toward the design, testing, and validation of an accelerated aging test that will help predict the longevity and cost-effectiveness of these sorbent materials. This center will help innovators' research and development of new sorbent materials and designs to last longer in the field ensuring safe, efficient, and cost-effective deployment at scale.*[156]

AFRL making strides in beamline capabilities and harnessing AI/ML. The Air Force Research Laboratory Materials Solutions Network at CHESS (MSN-C) is a synchrotron x-ray resource to address design, manufacturing, and materials challenges facing the DOD tri-service and industry through collaborative research across nanotechnology, additive manufacturing, AI/machine learning (ML), and hypersonics with potential for biotechnology, space, and quantum sciences. MSN-C provides significant staff support to users from machining to software development, including visualization and AI/ML analysis using novel algorithms optimized for graphics processing units (GPUs) providing significant improvements in computational speed. NIST worked with MSN-C to develop autonomous experimentation towards nanoparticle synthesis and measurement of complex liquid mixtures to create robust data sets for further development of ML techniques for soft materials.[157] MSN-C is supported through a partner funding model, with multiple organizations supporting its core facility and two beamlines providing measurement and characterization tools for nanotechnology R&D: the Structural Materials Beamline and Functional Materials Beamline (FMB).[158] Advances have also been made with users on synthesis of quantum dots,[159] wafer-scale organic electronic materials,[160] and polymers for 3D printing with real-time analysis of the morphology.[161] U.S. Army DEVCOM is taking

155 https://netl.doe.gov/node/13754
156 https://netl.doe.gov/node/13754
157 https://doi.org/10.1021/acs.chemmater.2c03118
158 https://doi.org/10.1080/08940886.2023.2202578
159 https://doi.org/10.1021/acsami.3c17623
160 https://doi.org/10.1039/D3NR05798D
161 https://doi.org/10.1021/acs.macromol.3c02327

advantage of FMB's ability to support International Traffic in Arms Regulations (ITAR) and export-controlled materials to perform studies that could not be done at other facilities. In 2023, FMB supported users across the DOD industrial base and services, including ARL, NRL, and NIST. AFRL MSN-C has also supported four public college summer undergraduate researchers and three interns.

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 Materials Genome Initiative. PCA 3 accounts for 38% of the DOE investment, and over 51% of the NIST investment, in the 2025 NNI budget request. Key NNI infrastructure investments include the DOE NSRCs, the NSF NNCI, the NIST CNST and Boulder Microfabrication Facility, and the NIH/NCI NCL. The largest PCA 3 investment in the 2025 NNI budget request is from DOE, followed by NIST, NSF, NIH, and DOD. Interagency coordination and leveraging across the NNI-supported infrastructure ecosystem will continue in 2025, following from and building on the September 2023 NNCO-initiated Nanotechnology Infrastructure Leadership Summit.[162]

The five NSRCs[163] are the core of the DOE nanotechnology research infrastructure investments. Each center has a particular focus: synthesis and characterization (the Center for Functional Nanomaterials at Brookhaven National Laboratory[164]); electronics/photonics and soft/hybrid materials assembly (Center for Integrated Nanotechnologies at Sandia National Laboratory and Los Alamos National Laboratory[165]); interfaces, interactions, and nanoscale assembly (the Center for Nanoscale Materials at Argonne National Laboratory[166]); materials science and quantum information science (the Center for Nanophase Materials Sciences at Oak Ridge National Laboratory[167]); and soft matter synthesis/functionality and energy conversion/storage (the Molecular Foundry at Lawrence Berkeley National Laboratory[168]). These are complemented by other DOE Office of Basic Energy Sciences scientific user facilities across the nation that offer cutting-edge instrumentation and highly trained staff scientists. All of these facilities are available through a competitive peer-reviewed proposal process. For 2025 and beyond, DOE is planning an NSRC recapitalization effort that will involve acquiring and installing 17 new instruments across the network of NSRCs, including advanced microscopes, lithography and deposition equipment, robotics and multimodal tools, novel sample

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162 https://www.whitehouse.gov/ostp/news-updates/2023/10/06/readout-of-the-nanotechnology-infrastructure-leaders-summit/

163 https://nsrcportal.sandia.gov/. See the individual NSRC websites for details, or the NNI Supplement to the President's 2024 Budget, p. 32: https://www.nano.gov/sites/default/files/pub_resource/NNI-FY24-Budget-Supplement.pdf.

164 https://www.bnl.gov/cfn/

165 https://cint.lanl.gov/

166 https://www.anl.gov/cnm

167 https://www.ornl.gov/facility/cnms

168 https://foundry.lbl.gov/

environments, and time-resolved tools. With an estimated completion date of January 2026, this NSRC recapitalization effort will add state-of-the-art capabilities in three important areas: (1) decoding nanoscale dynamics and heterogeneity, (2) expanding the limits of nanofabrication, and (3) accelerating nanomaterial discovery and design. In addition to the recapitalization project, NSRCs devote a portion of their operating budgets to updating their capabilities. For example, the Center for Functional Nanomaterials at Brookhaven National Laboratory will be investing in a cryo x-ray photoemission electron microscope and CNMS at Oak Ridge National Laboratory will acquire a milli-Kelvin scanning tunneling microscope. These and other NSRC activities going forward will be informed by the May 2024 DOE Basic Energy Sciences Advisory Committee report, *New and Upgraded National User Facilities in Basic Energy Sciences*.[169]

NIST is sustaining its PCA 3 research infrastructure investments at the Center for Nanoscale Science and Technology[170] and Center for Neutron Research (NCNR)[171] user facilities on the NIST Gaithersburg campus, the NIST Boulder Microfabrication Facility, and NIST capabilities at the National Synchrotron Light Source II (NSLS-II).[172] CNST provides important contributions to NIST's support for semiconductor and microelectronics R&D in implementing the CHIPS and Science Act of 2022. NCNR is conducting an extensive repair, maintenance, and upgrade project that is expected to be complete in 2026. NIST's Synchrotron Science Group, stationed at the NSLS-II facility at Brookhaven National Laboratory, develops state of-the-art synchrotron x-ray measurement technology around a core-competency in x-ray absorbance spectroscopy. New NIST nanotechnology-related infrastructure investments funded under the CHIPS and Science Act include the National Semiconductor Technology Center and the CHIPS Manufacturing USA institute.

NSF support for the NNCI[173] user facilities and the NNCI coordination office will continue through 2025. (See above in the Goal 3 section for additional details.) Support for NNCI comes from almost all NSF directorates and the Office of International Science and Engineering in the Office of the Director. NNCI supports users from all areas of science and engineering, and also constitutes one of NSF's major contributions to infrastructure in support of the implementation of the CHIPS and Science Act of 2022. In addition to support for the semiconductor industry and advanced manufacturing more broadly, it supports other industries and technologies of the future such as quantum information science, biomedicine, biotechnology, and advanced wireless technologies. A key component of the NNCI program is education and outreach activities such as participation in the Research Experiences for Undergraduates (REU)[174] and Veterans Research Supplement[175] programs. NNCI plans for 2025 include continued engagement with the broader nanotechnology infrastructure ecosystem, following from the September 2023 NNCO-run Nanotechnology Infrastructure Leaders Summit, organizing a "Nano Internet of Things" research community workshop, support for a Science Outside the Lab event in the summer of 2025,[176] and continuing innovation and entrepreneurship programs, such as the spring 2025 NNCI-wide Nanotechnology Entrepreneurship Challenge.[177]

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169 https://science.osti.gov/-/media/bes/besac/pdf/Reports/Report-to-BESAC-on-New-and-Upgraded-National-User-Facilities-2024-05-28Final.pdf

170 https://www.nist.gov/cnst

171 https://www.nist.gov/ncnr

172 https://www.nist.gov/mml/mmsd/synchrotron-science-group

173 https://nnci.net/

174 https://new.nsf.gov/funding/opportunities/research-experiences-undergraduates-reu

175 https://www.nsf.gov/pubs/2023/nsf23161/nsf23161.jsp

176 https://nnci.net/science-outside-lab

177 https://nnci.net/nanotechnology-entrepreneurship-challenge-ntec

Additional NSF nanotechnology-related infrastructure investments include national facilities that provide specialized instrumentation and unique research capabilities such as the National High Magnetic Field Laboratory,[178] the Center for High Energy X-ray Sciences at a university high energy synchrotron source (CHESS, in collaboration with DOD—see below and also above in the Goal 3 section for details),[179] and the Materials Innovation Platforms,[180] all supported by the Division of Materials Research (DMR) within the MPS Directorate. DMR also leads in a collaboration with NIST to jointly support the Center for High Resolution Neutron Scattering.[181] MPS's Division of Chemistry leads in supporting the ChemMatCARS beamline[182] at the Advanced Photon Source, Argonne National Laboratory.

NIH/NCI continues its steadfast support for the NCL, which specializes in characterizing nanomaterial formulations for imaging and therapeutic applications developed by researchers spanning academia, industry, and government sectors. Through its Assay Cascade program, NCL receives a diverse array of nanomedicine technologies, and has experience with virtually all nanoparticle platforms, therapeutic agents, and applications aimed at advancing cancer diagnostics and treatments. NCL has expanded its focus to include the evaluation of nanomedicine bioequivalence, as well as the assessment of personalized vaccine strategies and immunotherapies. In addition, NCL has initiated evaluations of nanotechnology-based strategies for the diagnosis and treatment of COVID-19, demonstrating its adaptability and commitment to addressing emerging health challenges.

NIH/NIAID is committed to advancing capacities to develop and manufacture nanoparticle vaccines around the world. The NIAID Vaccine Research Center collaborates with a biotechnology company based in Cape Town, South Africa, to exchange scientific expertise to advance development and manufacture of mRNA LNP vaccines. A team of vaccine production experts from South Africa has trained at NIH in Maryland as part of this global mRNA vaccine collaboration. This exchange will support efforts to produce large amounts of DNA, *in vitro* mRNA transcription, and lipid nanoparticle formulations, as well as create a foundation for additional research on next-generation mRNA-based vaccines for HIV, TB, malaria, influenza, cancer-associated viruses such as HPV, and other important diseases.

DOD support for nanotechnology research infrastructure includes the Institute for Nanoscience at the Naval Research Laboratory and the AFRL Materials Solutions Network at CHESS. NRL maintains research facilities at Stennis, MS, Key West, FL, Monterey, CA, and Washington, DC, where the Institute for Nanoscience is located. The Institute for Nanoscience and its companion, the Institute for Quantum Science, support DOD nanotechnology research in seven focus areas for fundamental and applied research, including electromagnetic and undersea warfare, battlespace environments, information technology and electronics, materials and chemistry, and space research and technology. Facilities at the Institute for Nanoscience include a 5,000 ft^2 class 100 clean room; ultra-quiet environmentally controlled lab modules; electron-beam, optical, direct-write, and 3D lithography systems; multiple deposition, etch, and ion mill systems; a plasma-enhanced atomic layer deposition system; and scanning electron, scanning tunneling, and atomic force microscopes. Recent and planned capital equipment investments include a 200 mm wafer handling capability and electron beam lithography capable of 7 nm minimum feature sizes.

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178 https://physics.fsu.edu/research/national-high-magnetic-field-laboratory
179 https://www.chess.cornell.edu/partners/chexs
180 https://new.nsf.gov/funding/opportunities/materials-innovation-platforms-mip
181 https://www.nist.gov/ncnr/chrns
182 https://chemmatcars.uchicago.edu/

DOD's AFRL, in partnership with CHESS (funded by NSF),[183] continues to support the Materials Solutions Network at CHESS, which is transforming synchrotron x-ray techniques to engineering tools with standards, automation, and mature workflows through service lab–industry–academia collaborative research. One of the facility's unique capabilities is the ability to work on materials and processes that are restricted under ITAR or national security export controls. (See above in the Goal 3 section for additional details.) Discussions with NIST about additional partnership opportunities are underway in 2024. Plans for 2025 include establishing a user consortium with membership fees and the development of measurement tools for extreme environments. AIM Photonics, NextFlex, and other Manufacturing USA institutes[184] also constitute major DOD contributions to the nanotechnology research infrastructure.

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.[185] Just a few examples of NNI progress in Goal 4 are featured below.

NSF's NNCI education and outreach activities reach more than 40,000 people. Network events included the Nano Summer Institute for Middle School Teachers, involving 10 NNCI sites with over 100 teachers from around 15 states, and the annual REU Convocation, involving 87 students across 12 NNCI sites. Summer internship programs for undergraduates and veterans continued through the REU and Veterans Research Supplement programs. One REU program conducted in partnership between two public universities focused on developing skills in arctic geoscience research by integrating studies of bedrock geology with records of environmental change. Four REU students conducted fieldwork in Greenland then brought their samples to the NanoEarth NNCI facility for analysis and shared their experiences at the REU Convocation. NNCI sites also continue to provide meaningful learning opportunities for advanced degrees with students earning 671 doctorates, 578 masters, and 257 BS/BA degrees, between 2022 and 2024.

[183] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1946998
[184] https://www.manufacturingusa.com/institutes
[185] 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.

Expanding the clean energy and nanotechnology workforce

Education, training, and workforce development are key component areas of the Nano4EARTH National Nanotechnology Challenge. To scale and implement nanotechnology-enabled solutions to climate change, the community needs to expand and train the future clean energy and nanotechnology workforce.

Next-generation batteries will provide energy storage solutions that minimize or eliminate the reliance on lithium and other critical materials. Next-generation battery manufacturing provides an employment opportunity as the country expands its investments to on-shore manufacturing capabilities. Through a DOE grant, a company producing nanocomposite silicon-lithium batteries for vehicles and other applications is developing an innovative education program to train the future battery workforce in Moses Lake, Washington. The company is developing batteries using less critical materials without compromising performance, due to their silicon-based nanocomposite anodes, and was a prior NSF SBIR awardee.

The company is partnering with local education hubs in Moses Lake, WA. As part of this program students will receive the interdisciplinary experiential learning in mechanical, electrical, and software engineering needed for successful employment at the nanocomposite silicon anode manufacturing plant the company is currently building in Moses Lake. Through the DOE grant, the company will provide equipment and curriculum development for each school and will also facilitate internships and scholarships for students. Students who participate in the program will receive a certificate for manufacturing competency. At full capacity, this plant will produce enough batteries for 1 million electric vehicles and employ over 500 people.[186]

Sila announced its new plan for workforce development in Moses Lake, Washington, WA at a community roundtable at Sila's Moses Lake plant featuring Governor Jay Inslee, U.S. Secretary of Energy Jennifer Granholm, and Senator Maria Cantwell. Image credit: Sila.

NIFA creating opportunities for the next generation of students and faculty. NIFA continues providing opportunities through nanotechnology R&D and education to support the development of workforce for the growing research fields at the nanotechnology-agriculture-food nexus. Postdoctoral fellowships are provided through the AFRI Education and Workforce development program.[187] These fellowships are designed to be transferable across institutions, so recipients can apply for and begin faculty positions with their own funding sources. In 2024, two prior awardees are starting new faculty positions and are successfully negotiating their start dates as they begin their independent research careers. In June 2024, NIFA supported the Nanoscale Science and Engineering for Agriculture and Food Systems Gordon Research Conference that included NNCO participation. Attendees came together to discuss impactful nanotechnology applications for sustainable food production; this was preceded by student-led sessions. Lastly, a faculty member from a public university was recognized with a distinguished faculty lectureship for sustained excellence in teaching, scholarship, and service. That faculty member's public lecture focused on nanotechnology innovations for shared sustainability,

[186] https://www.silanano.com/press/press-releases/sila-launches-new-educational-programs-in-moses-lake-investing-2-million-in-local-workforce-development

[187] https://www.nifa.usda.gov/grants/programs/agriculture-food-research-initiative/afri-education-workforce-development

including research supported by NIFA and NSF examining nanotechnology-enabled phosphorus use efficiency for sustainable agriculture practices.

Gaining regulatory expertise through FDA internships. FDA/CFSAN uses the Joint Institute for Food Safety and Applied Nutrition internship program, which is administered jointly by FDA and a public land-grant university, to allow undergraduate students to participate in research, including on nanotechnology-related regulatory science projects, at FDA facilities. Undergraduate students from minority and underserved communities participate in CFSAN nanotechnology research under the direction of staff scientists through the DOE's Minority Educational Institution Student Partnership Program. Finally, through its cooperative agreement with the Institute of Food Safety and Health, CFSAN offers graduate students at a private research university training opportunities in several of CFSAN's nanotechnology research programs. These students have gone on to enroll in PhD programs and full-time industry jobs.

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. In response to this recommendation, NNCO will convene a public meeting on EXperiential And MultidisciPlinary Learning and Education (EXAMPLE), including representatives of NNI participating agencies and the education community, to raise awareness of programs and practices in multidisciplinary experiential learning programs across the federal government. (See above in Chapter 1 for details.) NNCO will develop a matrix of federally funded multidisciplinary experiential learning programs (including K-12, community college, undergraduate, and graduate programs) that agencies can use as a reference and resource for themselves and their grantees. Participating agencies include DOD, DOE, DOL, NASA, NSF, and USDA. The event is tentatively scheduled for early in calendar year 2025.

Many NNI R&D and infrastructure programs support education and workforce development, therefore even agencies that do not report funding to PCA 4 are contributing to the NNI's education and workforce development efforts. NSF accounts for the majority of NNI funding reported to PCA 4, followed by NIH, DOD, and DOJ. A sampling of current and planned NNI agency activities related to PCA 4 is summarized below.

Educational curriculum development and activities are among the priorities established by the Nano4EARTH planning group for the upcoming fiscal year. The group is establishing a formal collaboration with teachers from the Environmental and Climate Change Literacy Projects and the NanoEducators Quarterly Forum to develop classroom material based on the Nano4EARTH roundtable discussions.

NSF programs that support nanotechnology education and workforce development include REUs;[188] Research Experiences for Teachers (RET) in Engineering and Computer Science;[189] RET in the Biological Sciences;[190] Advanced Technological Education (ATE);[191] Historically Black Colleges and Universities (HBCU) – Undergraduate;[192] Centers of Research Excellence in Science and Technology (CREST) centers;[193] Louis Stokes Alliances for Minority Participation (LSAMP);[194] Research Traineeship;[195] Scholarships in Science, Technology, Engineering, and Mathematics;[196] Tribal Colleges and Universities;[197] and NSF Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science (INCLUDES).[198] Examples of the kinds of awards funded under these programs include RET awards to NNCI sites to provide high school and community college faculty with opportunities to engage in high-quality, hands-on nanotechnology research in state-of-the-art NNCI facilities;[199] REU awards, also to NNCI sites, to provide undergraduates with cutting-edge research experience on hybrid perovskite systems for solar cells, lighting, and lasers;[200] and an LSAMP award to an HBCU to collaborate with a community college and a public university to use nanotechnology and its many applications as a conduit for engaging and inspiring talented students from traditionally under-represented minority populations.[201]

At NASA, nanotechnology-related internship opportunities are available from high school through graduate levels that offer students an opportunity to gain practical work experience while working side-by-side with mentors. Internships may be full-time or part-time. Under NASA's EPSCoR program, designed to strengthen the research capability of jurisdictions that have not in the past participated equitably in competitive aerospace research activities, students are participating in research projects on AI-enabled electrospinning of nanofiber membranes towards in-space manufacturing, improving space solar power with photon-concentrating devices, and an assessment of the impact of temperature cycles and outgassing on fiber-packaged silicon photonic transceivers (a project under NASA's EPSCoR International Space Station Flight Opportunity program).[202] NASA has a variety of academic research programs, including Space Technology Research Institutes, Early Career Faculty, and Early-Stage Innovations programs, that support nanotechnology workforce development by partnering with academia and engaging a range of students and early-career technologists. For example, the Institute for Ultra-Strong Composites by Computational Design[203] (a Space Technology Research Institute, continuing through 2024) is training postdoctoral researchers as well as students at the undergraduate, master's and PhD levels across multiple universities. Student development opportunities are also

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188 https://new.nsf.gov/funding/opportunities/research-experiences-undergraduates-reu
189 https://new.nsf.gov/funding/opportunities/research-experiences-teachers-engineering-computer
190 https://new.nsf.gov/funding/opportunities/research-experience-teachers-ret-funding-0
191 https://new.nsf.gov/funding/opportunities/advanced-technological-education-ate
192 https://new.nsf.gov/funding/opportunities/historically-black-colleges-universities-1
193 https://new.nsf.gov/funding/opportunities/centers-research-excellence-science-technology-1
194 https://new.nsf.gov/funding/opportunities/louis-stokes-alliances-minority-participation
195 https://new.nsf.gov/funding/opportunities/us-national-science-foundation-research
196 https://new.nsf.gov/funding/opportunities/nsf-scholarships-science-technology-engineering
197 https://new.nsf.gov/funding/opportunities/tribal-colleges-universities-program-tcup
198 https://www.nsf.gov/news/special_reports/big_ideas/includes.jsp, https://new.nsf.gov/funding/opportunities/nsfs-eddie-bernice-johnson-inclusion-across-nation/nsf22-622/solicitation
199 e.g., https://www.nsf.gov/awardsearch/showAward?AWD_ID=1953418
200 e.g., https://www.nsf.gov/awardsearch/showAward?AWD_ID=2050841
201 https://www.nsf.gov/awardsearch/showAward?AWD_ID=1826735
202 https://www.nasa.gov/learning-resources/established-program-to-stimulate-competitive-research/awards/
203 https://www.nasa.gov/directorates/stmd/space-tech-research-grants/the-institute-for-ultra-strong-composites-by-computational-design-us-comp/

provided in NASA's Space Technology Graduate Research Opportunities program; it supports students pursuing master's or doctoral degrees in topic areas aligned with the NASA Space Technology Mission Directorate Strategic Framework (many of which are nanotechnology-related).[204] Each student is matched with a technically relevant and community-engaged NASA subject matter expert who serves as the student's research collaborator. Additional programs that may support nanotechnology topics for 2025 include annual funding opportunities open to universities (e.g., University SmallSat Technology Partnerships,[205] NASA Innovative Advanced Concepts,[206] and Lunar Surface Technology Research Opportunities[207]) and funding opportunities open to the public (e.g., NASA Tournament Lab,[208] which uses crowdsourcing to tackle NASA challenges, and prizes and challenges).[209]

A key USDA/NIFA program that supports nanotechnology education and workforce development is the AFRI Education and Workforce Development program,[210] which includes program areas on professional development for agricultural literacy, agricultural workforce training at community colleges, food and agricultural non-formal education, research and extension experiences for undergraduates, and predoctoral and postdoctoral fellowships. Examples of nanotechnology projects funded under this program include research on plant virus nanoparticle technology for plant vaccines and on plant-derived nanovesicles for nucleic acid delivery for control of microbial pathogens. NIFA-supported researchers participate in NNI public webinars that provide educational content for both the research community and the general public, including the February 2024 webinar on Nanometrology for Food, Agriculture and the Environment.[211] NIFA also continues to support the bi-annual Gordon Research Conference on Nanoscale Science and Engineering for Agriculture and Food Systems,[212] which plays an educational role in disseminating and exchanging information on nanotechnology applications for sustainable food production.

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 other social implications (ELSI) and nanotechnology-related environmental, health, and safety (nanoEHS) implications of nanotechnology development, as well as inclusion, diversity, equity, access, 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, all of which speeds laboratory discoveries to market. Just a few examples of these efforts are illustrated below.

Expanding and strengthening responsible development in the NNI. In July 2024, NNCO convened a public workshop[213] with social science experts working in areas that intersect with the responsible development of nanotechnology. The highly interdisciplinary participants exchanged flash talks on

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204 https://www.nasa.gov/nasa-space-technology-graduate-research-opportunities-nstgro/
205 https://www.nasa.gov/smallspacecraft/university-smallsat-technology-partnership-initiative/
206 https://www.nasa.gov/stmd-the-nasa-innovative-advanced-concepts-niac/
207 https://www.nasa.gov/lunar-surface-technology-research-lustr/
208 https://www.nasa.gov/general/nasa-tournament-lab/
209 https://www.nasa.gov/prizes-challenges-and-crowdsourcing/
210 https://www.nifa.usda.gov/grants/funding-opportunities/agriculture-food-research-initiative-education-workforce-development
211 https://www.nano.gov/NanometrologyWebinarSeries
212 https://www.grc.org/nanoscale-science-and-engineering-for-agriculture-and-food-systems-conference/
213 https://www.nano.gov/socialscienceworkshop

their areas of specialty, heard perspectives from the European Union and OSTP,[214] and engaged in dialogues on specific case studies inspired by current activities in federal agencies. Together, federal scientists and social scientists explored potential intersections between social science approaches and nanotechnology R&D. The NNCO is producing a report summarizing the workshop and providing an outlook for next steps, lessons learned, and actions to operationalize ideas generated at the workshop to reinvigorate networks and ensure integration of social science concepts in future visions of interdisciplinary nanotechnology research, development, and training.

Working together to address 3D printing products of common interest. CPSC, EPA, NIOSH and NIST collaborative work, leveraging respective agency strengths, continues to evaluate emissions, factors influencing emissions, and the potential toxicity from exposure to emissions from 3D printers, including the release and accumulation of nanoplastics as well as the potential release of engineered nanomaterials (e.g., CNTs) from 3D-printed products. This interagency work has expanded to new types of 3D printers that are becoming more affordable to small businesses and the public, with an emphasis starting in 2023 on potential exposures to children. In 2023 and 2024 four technical reports were received, two on early work on 3D printer emission characterization (NIST) and emission toxic effects (NIOSH). Both reports are under final review at CPSC and will be posted when cleared for public release. In addition to these technical reports, five papers were published in 2023–2024 on 3D printer studies, and the group led a special session on 3D printing at the Organisation for Economic Co-operation and Development (OECD) Working Party on Manufactured Nanomaterials (WPMN) annual meeting. NIOSH continues its toxicology studies on the potential hazards of the printer emissions. In contrast to results from an *in vitro* study published in 2022, the 2024 studies on whole body inhalation exposure to a low concentration of polycarbonate filament emissions induced no significant pulmonary toxicity,[215] but similar exposures resulted in neuroendocrine system effects.[216] EPA 3D printer studies include investigating the presence of environmentally persistent free radicals on total particulate matter released from 3D printers using ABS filaments,[217] and they come to similar conclusions as the recently released NIOSH guide on safe 3D printing,[218] that wearing gloves and washing hands may adequately reduce metal exposure risks for brittle feedstock. Lastly, work performed by a public research university under CPSC contract developed a best practice white paper that serves to assist staff in applying current thinking regarding nanotoxicology when assessing the safety of products. That report is also under final review at CPSC. NIOSH celebrated the 20th anniversary of its Nanotechnology Research Center (NTRC) in October 2024 with a NIOSH NTRC Nanotechnology Health and Safety Summit, also hosted by the university.[219]

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214 https://www.whitehouse.gov/wp-content/uploads/2024/05/Blueprint-for-the-Use-of-Social-and-Behavioral-Science-to-Advance-Evidence-Based-Policymaking.pdf

215 https://doi.org/10.1080/15287394.2024.2311170

216 https://doi.org/10.1080%2F15287394.2023.2226198

217 https://doi.org/10.1016/j.cej.2023.148158; https://link.springer.com/article/10.1007/s42452-022-05221-7; https://doi.org/10.1016/j.scitotenv.2023.166538

218 https://www.cdc.gov/niosh/docs/2024-103/default.html

219 https://med.uc.edu/depart/eh/centers/erc/erc-blog/erc-blog/2024/10/31/2024-niosh-nanotechnology-health-and-safety-summit

Responsible development of nanotechnology to address sustainability of energy materials

There are concerns the transition to clean energy technologies will increase the demand for rare earth metals and other critical minerals. Developing alternatives for rare earth metals and more efficient/sustainable ways of extracting and refining them are two pillars of the DOE's Critical Minerals and Materials Strategy.[220] *Nanotechnology may provide solutions and has begun to impact the sustainable energy landscape.*[221] *For example, the use of carbon nanomaterials to replace or supplement energy- and resource-intensive metals could impact the overall demand for extraction and processing of primary materials.*[222]

Photo of critical metal neodymium produced using a novel electrolysis process developed with funding from DOE. Neodymium is essential for producing magnets, key to clean energy and defense applications. Neodymium production using the process can enable a resilient domestic mine-to-magnet supply chain. Image credit: Case Western Reserve University.

Nanotechnology is also being used to develop more efficient and environmentally sustainable ways of extracting critical minerals from ores and recycled products. With support from DOE, researchers from a private research university with collaborators from mulitiple national laboratories have improved a high-temperature electrochemical process called electrowinning by using a nanometer-scale coating of ruthenium dioxide on graphite as the anode in the process for refining neodymium metal, resulting in greatly reduced CO_2 *and perfluorocarbon greenhouse gas (GHG) emissions compared to conventional processing methods.*[223] *In another example, work funded by DOE and EPA several years ago on the recovery of metals from recycled products using CNT-enabled filters*[224] *is now being commercialized by a startup company that recently received funding from DOE/AMMTO, a major heavy equipment manufacturer, and other investors.*[225]

Nanomaterials are also being used to develop new battery chemistries and architectures to minimize the dependence on critical materials with supply chain issues, such as lithium and cobalt. Environmental, health and safety research and life cycle assessment are the building blocks for identifying and engineering more sustainable or efficient replacements consistent with responsible technological innovation.[226] *The Nano4EARTH National Nanotechnology Challenge has created a national focal point for U.S. efforts to leverage the responsible development of nanotechnology to tackle climate change.*[227]

Coordinating on micro- and nanoplastics priorities. In July 2024, the White House released its strategy to tackle plastic pollution, *Mobilizing Federal Action on Plastic Pollution: Progress, Principles, and Priorities*,[228] including recommended actions specific to micro- and nanoplastics. Federal agencies are well positioned to build on their ongoing work to better understand and address the impact of plastic pollution, and some examples are outlined below, including leveraging of interagency nanoEHS expertise. NNI agencies have collaborated on nanoEHS research through interagency agreements, data sharing, and joint planning of research priorities facilitated by discussions in the NSET Subcommittee's

220 https://www.energy.gov/cmm/critical-minerals-materials-program
221 https://doi.org/10.1021/acsenergylett.3c01303
222 https://doi.org/10.1016/j.jclepro.2017.04.048
223 https://doi.org/10.1021/acssuschemeng.3c07720
224 https://doi.org/10.1039/C7EW00187H
225 https://nthcycle.com/
226 https://doi.org/10.1038/s41578-023-00611-8
227 https://www.nano.gov/nano4EARTH
228 https://www.whitehouse.gov/wp-content/uploads/2024/07/Mobilizing-Federal-Action-on-Plastic-Pollution-Progress-Principles-and-Priorities-July-2024.pdf

NEHI Working Group. For example, the NIH/National Institute of Environmental Health Sciences (NIEHS) Division of Translational Toxicology is collaborating with FDA/NCTR to support development of standards and analytical approaches for characterization and quantitation of nanomaterials, including characterization of real-world samples containing nanoplastics. These studies will facilitate appropriate planning for studies to assess the potential human health impact of exposure to nanoplastics.

CDC/NCEH and CDC/ATSDR published open source reviews on micro and nanoplastics with estimated exposures from each of three routes of exposures.[229] Major exposure sources are found to be inhalation and ingestion from diet, packaging materials, and other day-to-day consumer products. NCEH studied an optical imaging technique specific to nanoplastics with high chemical specificity[230] and conducted a systematic review of micro- and nanoplastics in water and potential health effects.[231] FDA recently published a perspective article on the analysis of micro and nanoplastics in human food[232] to inform the basic research community about the regulatory science ecosystem so future micro- and nanoplastics studies are more consistent in the application of methodology, enabling better cross-study comparisons to support science-based policy and decision making.[233] The USGS Water Resources Mission Area supported work to establish a micro- and nanoplastic strategic science vision report[234] prioritizing research relevant to the mission, expertise, and capabilities of the agency. Tracking the growing literature is an ongoing challenge, but ATSDR has developed “Hubs of Interactive Literature” to provide an interactive, searchable, user-friendly companion to traditional review articles.[235] This platform helps members of the public and research communities to better access and understand the expanding literature and help facilitate decision making on these complicated topics.

Building on prior work, EPA’s Trash Free Waters (TFW) program released a report in April 2023[236] summarizing challenges and opportunities related to addressing tire wear particle pollution, a significant category of microplastics found in waterways, following two roundtables involving stakeholders from national, state, Tribal, and local governments, along with industry, academia, and non-governmental organizations. To address the growing concerns over tire pollution, EPA researchers led an effort to investigate the life cycle of tires and their impacts on the environment,[237] providing a holistic examination and data synthesis on tires as complex pollutants across three levels: their whole state (e.g., tire production or disposal in landfills), as particulates (e.g., as they are worn down), and as a mixture of “chemical cocktails.” In addition, in July 2024, the TFW program and NOAA’s Marine Debris Program released *Interagency Marine Debris Coordinating Committee Report on Microfiber Pollution*,[238] as called for in the Save our Seas 2.0 Act.

Classifying chemicals for regulatory evaluation. DOD is advancing the science on chemical classes[239] and how to group chemicals for evaluation or regulation, complementary to ongoing work at EPA

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229 https://doi.org/10.3390/microplastics2010006; https://doi.org/10.1016%2Fj.scitotenv.2020.144010
230 https://doi.org/10.1073/pnas.2300582121
231 https://www.nejm.org/doi/full/10.1056/NEJMoa2309822
232 https://pubmed.ncbi.nlm.nih.gov/38452774/
233 https://doi.org/10.1021/acs.analchem.3c05408
234 https://doi.org/10.3133/cir1521
235 https://public.tableau.com/app/profile/katie.stallings/viz/ReviewofMPsandNPsinIndoorandOutdoorAir-HIL/Contents
236 https://www.epa.gov/trash-free-waters/science-case-studies#Tire
237 https://doi.org/10.1016/j.scitotenv.2024.171153
238 https://marine-debris-site-s3fs.s3.us-west-1.amazonaws.com/s3fs-public/publications-files/2022%20NOAA%20Report%20IMDCC%20Microfiber%20Pollution_Final.pdf
239 https://doi.org/10.1186/s12940-022-00919-y

including on PFAS.[240] One difficulty is that some groups, including those of high interest like PFAS and nanomaterials, still lack unified definitions within the research community, let alone within regulatory bodies. Along with publishing, DOD maintains active communication with toxicologists within the services and across the federal government. This ongoing push is especially timely to streamline assessment and regulation of these chemicals due to the number of them on the market and their complexity.

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 some 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.

The NNI participating agencies with dedicated funding in PCA 5 (in order of amount of funding requested for 2025) are NIH, followed by NSF, NIOSH, EPA, NIST, FDA, NIFA, DOD, and CPSC (see Table 5 on p. 8 for details). PCA 5 funding at NIH has increased from $12.5 million in the 2024 request published in the NNI Supplement to the President's 2024 Budget[241] (and $17.9 million in estimated 2024 funding published in this year's budget) to $20.1 million in the 2025 request. The total NNI funding request for PCA 5 increased from $51.9 million in 2024 to $53.1 million in the proposed 2025 budget.

Research on incidental nanomaterials of particular potential environmental and human health concern (e.g., micro- and nanoplastics and 3D printer emissions) is an area of emphasis in NNI nanoEHS investments for 2024–2025. Agency activities in these areas are coordinated by informal interagency interest groups, with support from NNCO. These are among several new topics that are addressed in the NNI's updated EHS research strategy, which was published in December 2024.[242] The updated strategy is based in part on extensive public outreach, including a Request for Information,[243] a public meeting,[244] and a draft posted for public comment in June 2024,[245] in addition to extensive internal discussion and review by the participating agencies and the Executive Office of the President.

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240 https://www.sciencedirect.com/science/article/pii/S246811132400029X?via%3Dihub
241 https://www.nano.gov/2024BudgetSupplement, p. 8.
242 https://www.nano.gov/ehsstrategy2024update
243 https://www.federalregister.gov/documents/2023/05/23/2023-10958/request-for-information-national-nanotechnology-initiative-environmental-health-and-safety-research
244 https://www.nano.gov/ehsstrategymeeting
245 https://www.federalregister.gov/documents/2024/06/13/2024-13031/notice-of-availability-and-request-for-comments-national-nanotechnology-initiative-environmental

NNCO also supports the U.S.-EU nanoEHS Communities of Research (CORs),[246] which provide a platform for scientists in Europe, the United States, and other regions of the world to collaboratively identify and address key research needs through community-led activities such as telecons, webinars, publications, and annual in-person meetings. There are currently seven CORs addressing questions about the potential EHS implications of nanomaterials and work is being done to expand this effort, particularly beyond the EU. Each COR has one U.S.-based co-chair and one EU-based co-chair. The CORs hold an annual workshop, typically rotating between being located in the United States and European Union; the most recent workshop took place on October 16, 2024, in Switzerland.[247]

Many of the agencies participating in the NEHI Working Group coordinate on nanoEHS database and informatics efforts through an informal interagency interest group. The group continues building off of the NNI 2023 Nanoinformatics Conference and associated publication of the meeting's proceedings[248] on issues including nanoinformatics infrastructure and interoperability. NNCO co-hosted the conference and participated in preparation of the manuscript, which was led by EPA members of the interest group.

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,[249] current NIEHS-funded nanoEHS efforts include investigator-initiated projects, e.g., research focused on understanding how nanoparticle exposure modulates allergic lung disease using animal models. Planned activities in the NIH/NIEHS Division of Translational Toxicology include completion of analysis and reporting of studies evaluating immunotoxicity and chronic carcinogenicity of multiwalled nanotubes. The NIEHS Superfund Research Program[250] plans to emphasize research that develops nanotechnology-enabled structures to enhance sustainable remediation and to enable rapid, accurate environmental monitoring, as well as occupational health training curriculum for nanotechnologies. The NIEHS SBIR/STTR program also supports research efforts for developing tools for nanomaterials exposure monitoring, including characterization of toxicity of airborne engineered nanomaterials using a direct *in vitro* exposure method and development of a third-party verification process for characterizing exposures to products containing engineered nanomaterials. NIEHS will continue to accept applications through 2027 from its Notice of Special Interest for extramural research to promote investigations on exposure to and health effects of micro- and nanoplastics.[251] To gain more insight into nanoplastics, NIEHS-funded researchers modified an imaging technique called stimulated Raman scattering microscopy to rapidly detect micro- and nanoplastics in bottled drinking water.[252] This technique holds promise for analyzing micro- and nanoplastics in complicated environmental and biological samples such as tap water, indoor and outdoor air samples, and biological tissues.

NanoEHS-related research at NSF in support of nanomaterials characterization, interfacial nanoscale phenomena, and exposure is performed in NSF's core programs. For example, the Nanoscale Interactions program[253] in the ENG Directorate's Division of Chemical, Bioengineering, Environmental

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[246] https://us-eu.org/
[247] https://us-eu.org/eu-u-s-nanoehs-communities-of-research-workshop-oct-16-2024/
[248] https://doi.org/10.1016/j.comtox.2024.100316
[249] https://www.niehs.nih.gov/research/supported/exposure/nanohealth
[250] https://www.niehs.nih.gov/research/supported/centers/srp
[251] https://grants.nih.gov/grants/guide/notice-files/NOT-ES-23-002.html
[252] https://pubmed.ncbi.nlm.nih.gov/38190543/
[253] https://new.nsf.gov/funding/opportunities/nanoscale-interactions

and Transport Systems (CBET) supports research to advance fundamental and quantitative understanding of the interactions of nanomaterials and nanosystems with biological and environmental media. Examples of awards that have been funded from core programs supporting nanoEHS research include the use of machine learning to predict nano-bio interactions in the protein corona for nanoparticles that may be used in medicine, materials, and agriculture, to aid in understanding the potential human health effects of those particles; and biophysical mechanisms of interactions between micro-/nanoplastics and natural pulmonary surfactants. ENG is also supporting award supplements to support U.S.-Africa collaboration on nanotechnology convergence for sustainable development, including sponsoring the Third Nanotechnology Convergence for Sustainable Energy, Environment, Climate Change and Health: A US-Africa Conference, held in July 2024 in Casablanca, Morocco.[254] The MPS Directorate continues to support the Center for Sustainable Nanotechnology at a public land-grant university.[255] NSF also supports research on EHS implications of micro- and nanoplastics through core programs in multiple directorates, coordinated through a DCL on Critical Aspects of Sustainability: Micro- and Nanoplastics.[256] Research on prevention of plastic waste through the development of recyclable, upcyclable, and/or biodegradable polymers (enabled in part by nanotechnology) is supported by a new initiative and research solicitation in partnership with industry on Sustainable Polymers Enabled by Emerging Data Analytics.[257] The Eco Manufacturing thrust area in the Future Manufacturing program also supports research on recycling, upcycling, repurposing, repairing, and reusing not only polymers but all material systems.[258]

NSF’s Directorate for Social, Behavioral and Economic Sciences funds research on ethical, legal, and other social implications related to nanotechnology. A major component of the NSF activity in this area is support for ELSI and broader responsible development activities at the NNCI centers. Examples include surveying and examining the career paths of former NNCI research facility users, surveying and interviewing scholars to understand how societal and economic implications issues can make their way into classrooms, running a faculty “Science Outside the Lab” program to train nanoscience faculty from across the country in how science policy impacts their work and vice versa, and raising public awareness of nanoscience through a “nanojournalism” initiative.

CDC/NIOSH is a leader in federal government research on understanding the potential human health and safety implications of nanotechnology, with a specific focus on addressing worker health and safety needs related to nanotechnology by developing and deploying effective solutions with industry. NIOSH research advances the 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, collaborating with stakeholders, and dissemination, NIOSH develops guidance that supports and promotes the safe and responsible development and commercialization of engineered nanomaterials.

NIOSH conducts toxicology studies that advance the understanding of potential human health implications of exposure to nanomaterials. These studies assist in determining the biological mechanisms of toxic effects and how the key chemical and physical factors of engineered nanomaterials may influence these mechanisms. NIOSH is advancing a realistic view of the impact of

254 https://engconf.us/conferences/civil-and-environmental-engineering/nanotechnology-convergence-for-sustainable-energy-environment-climae-change-and-health/
255 https://susnano.wisc.edu/, https://www.nsf.gov/awardsearch/showAward?AWD_ID=2001611
256 https://www.nsf.gov/pubs/2020/nsf20050/nsf20050.jsp?WT.mc_id=USNSF_25&WT.mc_ev=click
257 https://new.nsf.gov/funding/opportunities/molecular-foundations-sustainability-sustainable/nsf24-567/solicitation
258 https://www.nsf.gov/awardsearch/simpleSearchResult?queryText=nanoplastics&ActiveAwards=true

nanomaterials along the life cycle by using real-world materials and exposure data to guide toxicology testing regimens. These results are correlated with health studies conducted among workers at facilities where activities with these materials are performed, in order to gain a realistic view of the impact of nanomaterials in their actual manufactured state. NIOSH plans to develop novel laboratory-based analytical methods that provide accurate workplace exposure estimates and determine representative particle characteristics. Additional plans include characterizing workplace exposures and determining relevant facility and worker characteristics.

NIOSH will develop occupational safety and health guidance that can be incorporated into business plans to both protect worker safety and promote safe application development and commercialization. It will also recruit companies that produce or handle CNTs to participate in a Carbon Nanotube Registry, a long-term research effort dedicated to understanding workplace health risks associated with CNTs.

NIOSH will collaborate with the America Makes Manufacturing USA institute, including universities and industry, to promote safe practices in nanotechnology and advanced manufacturing. It will 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, metal-based, nanocellulose, and nanoclay-enabled materials.

NIOSH collaborates with a nonprofit construction research and training center, trade unions, and industrial partners to evaluate nanotechnology-enabled spray coatings, composites, and other nanotechnology-enabled materials in construction and manufacturing. It will also continue its work with ISO/TC 229, Nanotechnologies, OECD/WPMN, as well as the ASTM International Technical Committee E56 on Nanotechnology.

EPA engagement in nanotechnology occurs in both the research and regulatory domains. EPA's nanotechnology-related research is conducted as part of the Chemical Safety for Sustainability and Safe and Sustainable Water Resources National Research Programs within the Office of Research and Development (ORD). Research on engineered nanomaterials 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 Toxics 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), which is responsible for implementation of these statutes. EPA's Trash-Free Waters Program works to reduce the volume of trash entering U.S. waters by collaborating with partners to implement solutions to land-based sources of trash, including microplastics. Additionally, ORD's research is used broadly by multiple stakeholders.

To inform plans and priorities for PCA 5, ORD will conduct research to inform safety assessments of emerging materials, which require evaluation of the environmental impacts of emerging materials on humans and ecological species. Emerging materials of relevance and interest may include nanopesticides and micro-/nanoplastics as well as other engineered and incidental nanomaterials. Investigation of the human and environmental health effects of nanoplastics will include a focus on developing analytical methods for the detection of nanoplastics in environmental, cellular, and tissue matrices. These data will support health studies, and standardizing methods to assess ecological effects of nanoplastics for sensitive species. In addition, support for implementation of an evaluation framework for nanomaterials under FIFRA is an ongoing need.

OCSPP is actively engaged in international cooperation efforts with OECD, including with new projects, guidance documents, and test guidelines through OECD's Working Group of National Coordinators of the Test Guidelines Programme, and through participation in OECD/WPMN. Additionally, OCSPP participates in multiple working groups, including the U.S.-EU nanoEHS CORs, the NNI's nanoplastics and nanosensors interest groups, and the NEHI Working Group. The Department of State also coordinates U.S. participation in the OECD Working Party for Biotechnology, Nanotechnology, and Converging Technologies.

NIST will continue its research and development of reference and test materials for particle number concentration measurements, liposome and mRNA lipid nanoparticles, and pristine and weathered nanoplastics. There are three categories of NIST activities in support of micro- and nanoplastics research: (1) collecting and characterizing of real-world environmental samples, e.g., at the Center for Marine Debris Research, a joint institute between NIST and a university;[259] (2) generating laboratory models and methods inside of established protocols; and (3) conducting research at the frontiers of physical measurement—developing new capabilities and methods that advance and elevate the quality of the measurements and data on micro- and nanoplastics pollution.[260] Environmental sampling activities include collecting micro- and nanoplastics from beach and ocean sediments and other types of environment samples and filtering and fractionating those samples and the particles that are obtained from them in the laboratory environment. Laboratory models and testing activities include accelerated aging/weathering to simulate degradation in aquatic environments, developing milling protocols for making test materials, and developing a cell-based model of the intestinal tract to assess uptake of particles. Advanced measurement research includes the application of new instrumentation capabilities to micro-/nanoplastics research and building a new laboratory for nanoplastics in liquid media. NIST also is pursuing important work in developing and validating micro- and nanoplastics reference materials and standards, such as producing research-grade test materials through cryo-milling of commercial plastic samples, collecting environmental specimens and converting them into reference materials, and producing high-precision micro- and nanoscale arrays for calibrating imaging tools. NIST is producing and offering a number of plastic polymer Standard Reference Materials with relevance to the study of plastic pollution.[261]

EHS considerations are also an important component of NIST's investments in research under the CHIPS and Science Act. One of the early R&D programs announced under the National Semiconductor Technology Center will address issues associated with the use of PFAS in semiconductor manufacturing.[262]

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 study the behavior of nanomaterials in biological systems and their effects on both human and animal health. FDA scientists are actively involved in collaborative consensus standards development, and in organizing meetings and symposia related to nanotechnology. These investments and activities support FDA's mission to protect and promote public health and to help foster the responsible development of nanotechnology. FDA's Nanotechnology Task Force facilitates communication and cooperation across the agency on

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259 https://www.nist.gov/mml/csd/biochemical-and-exposure-science-group/center-marine-debris-research

260 See: https://www.nist.gov/mml/mmsd/primary-focus-areas/micro-and-nano-plastics

261 https://www.nist.gov/programs-projects/reference-materials-plastic-pollution-measurement-science

262 https://www.semiconductors.org/chips-rd-programs/. See elsewhere in this report, and in the NNI Supplement to the President's 2022 Budget (p. 41) for information on potential nanotechnology-enabled solutions to issues associated with PFAS, as well as additional information in the NNI supplements to the President's 2023 and 2024 budgets, https://www.nano.gov/budgetsupplements.

nanotechnology research, and with national and international stakeholders. It provides the overall coordination of FDA's nanotechnology research efforts in: (1) scientific staff development and professional training, (2) laboratory and product-testing capacity, and (3) collaborative and interdisciplinary nanotechnology research.

NIFA invests in PCA 5 to support EHS assessments of engineered nanoparticles applied in food and agricultural systems, including detection and quantification of engineered nanoparticles and the characterization of their potential hazards, exposure levels, transport, and fate in foods, agricultural production, and the environment. NIFA support for research on distributed sensing networks for precise application of agricultural inputs is also relevant to nanoEHS. NIFA supports research on social, ethical, cultural, legal, and other potential impacts of nanotechnology through AFRI's Social Implications of Food and Agriculture Technologies priority area[263] within the Agriculture Economics and Rural Communities program.[264] This research engages a range of individuals including scientists, legal scholars, bioethicists, social scientists, and researchers from the humanities, the public, and other stakeholders to assess the technology's merits and risks and/or examine issues and modes of communication.

DOD supports a modest amount of nanoEHS research within the broad context of its Chemical Material Risk Management Program,[265] managed by the Office of the Assistant Secretary of Defense for Energy, Installations, and Environment, which has the mission to protect readiness, people, and the environment by identifying and managing risks associated with the chemicals and materials DOD uses. Additional nanoEHS research and management activities are conducted by individual DOD services and agencies as their interests and activities dictate.

CPSC's mission is to reduce unreasonable risks of injury associated with consumer products. In order to determine whether nanotechnology-enabled consumer products are hazardous to consumers, CPSC engages with federal partners and contractors in projects to characterize and quantify exposures to engineered nanomaterials released from products, develop methods and frameworks to assess such releases, and develop toxicity databases from published literature. CPSC, EPA, NIOSH, and NIST will continue collaborating on evaluating 3D printer emissions (including nanoplastics and engineered nanomaterials) and their potential toxicity. For 2025 and beyond, this work is expanding to evaluation of a broader array of 3D printer technologies, and is emphasizing potential exposures to children. Information collected from these efforts to characterize exposure have resulted in the development of best practices for product use; refinements will continue as the interagency research progresses. Staff and partners are engaged in voluntary standards activities to create validated methods for quantifying and characterizing exposures from products. Reports and publications from contract studies support the development of voluntary standards, risk assessment and management frameworks, and continued evaluations of the release and exposure to nanomaterials. In addition, CPSC plays a key role in developing and sustaining the NNI and international nanoEHS research communities; a CPSC staff member has been co-chairing the NEHI Working Group, and CPSC staff plays leading roles in supporting the U.S.-EU nanoEHS CORs and in developing the updated NNI EHS research strategy.

Several other NNI participating agencies that do not report funding specifically to PCA 5 also make important contributions to the NNI nanoEHS enterprise. For example, within the CDC, ATSDR and NCEH have convened a Microplastics and Human Health Working Group focusing on microplastics, including

[263] https://www.nifa.usda.gov/social-implications-food-agriculture-technologies

[264] https://www.nifa.usda.gov/grants/programs/agriculture-food-research-initiative-afri/agriculture-economics-rural-communities-program-area

[265] https://www.denix.osd.mil/cmrmp/

nanoplastics and other nanomaterials, aimed at better understanding the occurrence of microplastics in the environment, routes of exposures, and potential health effects. The group meets monthly to discuss project updates, presentations, and participation in scientific events of interest that are internal or external to the U.S. government. Priorities and plans for 2025 include finalizing and publishing a number of manuscripts reviewing and analyzing the scientific literature on potential human and environmental health effects of micro-/nanoplastics, and updating the working group's strategic plan. Both ATSDR and NCEH are active participants in the NNI's nanoplastics interagency interest group and have ongoing collaborations with the California Water Resources Control Board Microplastics Monitoring Subcommittee; additional collaborations are planned with the a California-based nonprofit that advances sustainable stormwater management.

The USGS Environmental Health Program (EHP) conducts research in nanotechnology and environmental effects of micro- and nanoscale particles, including plastics. For example, the USGS EHP at Columbia Environmental Research Center[266] is developing analytical capabilities for evaluating the fate, transport, and effects of microplastics. USGS continues research on the use of nanoparticles for environmental sensing. A recent publication in biosensors describes a collaboration with the U.S. Army Engineer Research and Development Center and academic partners.[267]

The USGS Water Resources Mission Area (WMA) has two projects supporting microplastics research: (1) The WMA Next-Generation Water Observing Systems program partners universities with USGS scientists to design and implement innovating technologies for monitoring water resources. Through this program, funds are distributed to the USGS New York Water Science Center and a university for development and deployment of an *in-situ* microplastics analyzer that uses a built-in flow-through cell and vortex separator, machine-learning and imagery, and infrared spectroscopy to determine particle morphology and polymer type. (2) Through the WMA Urban Waters directed Cooperative Matching Funds program, funds have been allocated for developing a standardized method for collecting representative microplastics samples in urban streams; this project is in its third year and involves four USGS Water Science Centers. In addition, WMA has provided funding for the creation of a microplastic Strategic Science Vision report.[268] WMA is also supporting Water Science Center staff to participate in an International Joint Commission workgroup tasked with developing recommendations for a microplastics monitoring strategy for the Great Lakes Basin.

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 climate change, Nano4EARTH, on October 7, 2022.[269] Nano4EARTH recognizes the role nanotechnology will and already plays in: Evaluating, monitoring, and detecting climate change status and trends; Averting future greenhouse gas emissions; Removing existing greenhouse gases; Training and educating a highly skilled workforce to harness nanotechnology solutions; and developing Higher resilience to—and mitigation of—climate change-induced pressures for improved societal/economic resilience. NNI funding for Nano4EARTH spans all of the PCAs. NNI community-wide activities in support

266 https://www.usgs.gov/centers/columbia-environmental-research-center
267 https://doi.org/10.3390/bios14060288
268 https://doi.org/10.3133/cir1521
269 https://www.nano.gov/nano4EARTH

of this NNC since its inception are outlined in the sidebar at the end of this section of the report. The following are select examples of the many individual agency activities that have been furthering the goals of the Nano4EARTH NNC.

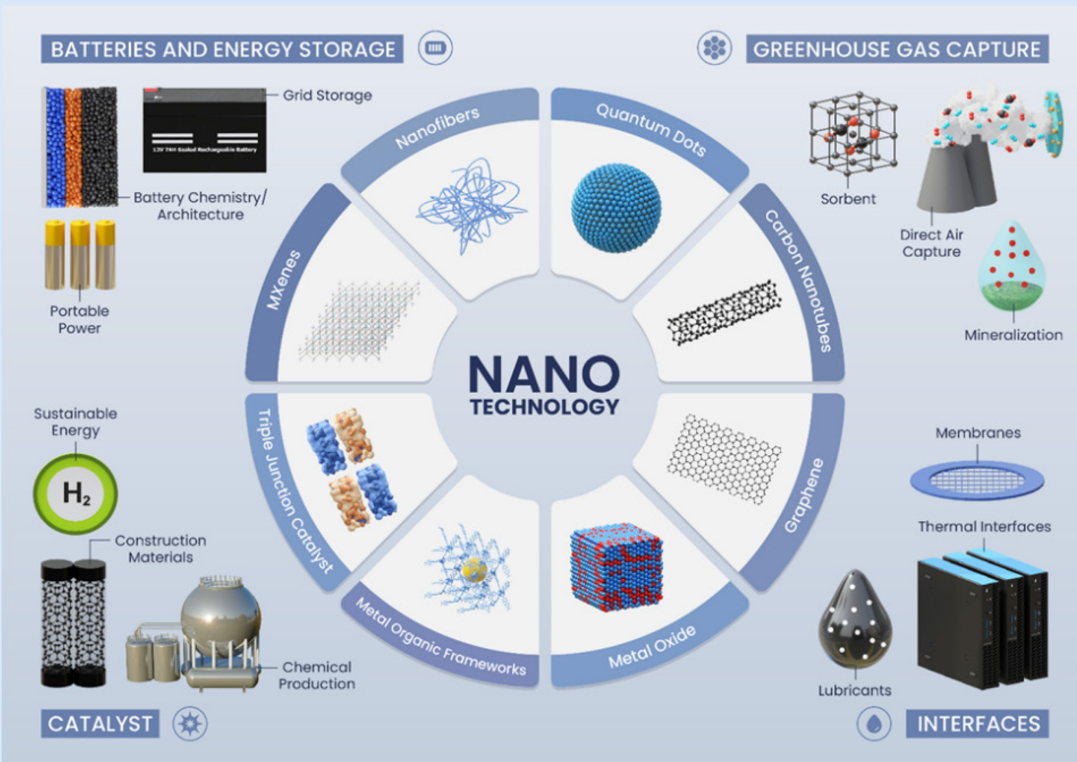
Setting standards for accountability and verification. With new legislative incentives from the Bipartisan Infrastructure Law and Inflation Reduction Act, there is significant momentum for clean energy deployment. These efforts need to involve meaningful community engagement in order to implement solutions to increase energy security and climate resilience while also maximizing benefits for workers and communities. Part of developing trust and accountability is establishing standards and being able to accurately quantify the impact of climate solutions. For example, in carbon management, the Inflation Reduction Act's 45Q tax credit enhancement provides stronger economic incentives for carbon capture technologies, while the DOE carbon negative Earthshot sets ambitious targets for permanent and cost-effective sequestration. Along with materials research, NIST is working to ensure traceability of GHG measurements, ensuring data quality and standardization, through the entire life cycle. NIST, in coordination with the DOE DAC facilities, is developing a series of DAC benchmark materials as research-grade test materials, with industry feedback on priority materials to support timely, effective, and scalable implementation.[270] NIST also convenes the low-carbon cements and concretes consortium,[271] in coordination with the Council on Environmental Quality within the Executive Office of the President, DOE, EPA, and DOT, to engage with industry, academia, and standards developing organizations to facilitate development of voluntary consensus standards and inter-laboratory comparisons.

Integrating synthesis, experiment, modeling, and theory to accelerate discovery of materials for carbon capture. The development of new materials and technologies that enable cost-effective carbon capture is a component of a many-pronged approach to combatting climate change. NSF-supported university researchers and industry are developing new materials for selective adsorption of CO_2 versus nitrogen in the presence of water. The main thrust of the work is to develop integrated simulation, theoretical, and experimental methods for understanding the effect of water on CO_2/N_2 separations in metal-organic frameworks (MOFs) and to use these tools to speed up the discovery of new materials for carbon capture. They developed a high-throughput screening procedure to screen a MOF database to identify top-performing materials for carbon capture from high-humidity flue gases. Another university research group, supported by DOE, is looking at MOFs for direct-air capture of CO_2, assessing their stability, carbon capture mechanisms, capture-release cycling behavior, and potential for scaled-up synthesis, addressing barriers for these MOFs to go from the research laboratory to implementation in DAC devices on a global scale.[272] In a third example, university scientists supported by four different NSF awards from three NSF divisions have laid out a pathway for the development of multi-dimensional designer catalysts for negative emissions science that bridges the gap between synthesis, simulations, and analysis. Their review paper assesses a number of different approaches to electrocatalytic and/or photocatalytic CO_2 reduction, including a variety of catalytic materials (e.g., Chevrel phases, metal chalcogenides, metal halide perovskites, and 2D MOFs) and processes that are under investigation for carbon sequestration applications. They conclude that successful development of these technologies will require multidisciplinary teams of experts engaged in targeted and accelerated design of materials, advanced instrumentation, theory, simulations, and data science.[273] (See the sidebar in the Goal 1 section above (p. 13) for additional examples of catalysis using nanoscale materials for carbon capture.)

270 https://doi.org/10.1557/s43577-022-00320-7
271 https://www.nist.gov/programs-projects/low-carbon-cements-and-concretes-consortium
272 https://doi.org/10.1002/adfm.202307478
273 https://doi.org/10.1016/j.isci.2021.103700

Nano4EARTH Accomplishments: Perspective on nanotechnology solutions to climate change

As part of the interagency collaboration and activities organized under the National Nanotechnology Challenge on Climate Change, Nano4EARTH, a multi-stakeholder group of experts from across the U.S. government (AFRL, ARL, DOE, EPA, NIST, NNCO, NSF, and the U.S. Army Corps of Engineers), a private foundation, and a nanotechnology company have published a peer-reviewed journal article outlining how nanotechnology can help accelerate progress towards addressing climate change. In particular, four promising nanotechnologies were identified: advanced environmentally friendly batteries and energy storage solutions; "green" nanoscale catalysts; sustainable and more effective membranes, lubricants, and interfaces; and scalable materials that capture greenhouse gases. These advancements could be applied to hard-to-abate power, transportation, industrial, and building sectors to reach 2030 global decarbonization goals. Through this article the authors provide a framework for the nanotechnology community to accelerate the development of climate solutions.



Examples of nanotechnology-enabled solutions for climate intensive processes. The examples shown illustrate nanomaterials and technologies for (1) batteries and energy storage; (2) greenhouse gas capture; (3) interfaces; and (4) catalysis. The inside of the circle highlights nanomaterials that are being used to enable climate solutions; the outer circle are examples of specific technologies. Image Credit: *Nature Nanotechnology.*

Continuing momentum on DOE Energy Earthshots™. DOE Energy Earthshots™ provide targets to inspire ambitious progress in developing and implementing innovative technologies. The most recent of these is the industrial heat shot, setting a goal to reduce industrial GHG emissions 85% by 2035. Nanoscience R&D can play a key role in finding low- or no-heat process technologies for industrial decarbonization, such as design and discovery of nanomaterials for electrolysis to produce clean hydrogen, which is especially critical to decarbonize hard-to-abate sectors like steel and cement. The Industrial Heat Summit,[274] held in October 2023, convened key stakeholders to discuss workforce

[274] https://www.energy.gov/eere/iedo/events/industrial-heat-shot-summit

development, community engagement, and industry needs followed by award selections announced in January 2024 from DOE's Industrial Efficiency and Decarbonization funding opportunity announcement.[275] Earlier sidebars in this report highlight several other DOE accomplishments.

Using nanomaterials and quantum sensing to understand and address climate impacts. NASA research related to Nano4EARTH spans climate research, aeronautics, clean energy, and environmental monitoring. The transformative aeronautics concepts program supported work studying innovative nanomaterials for high-voltage aerospace insulation and cables to enable electrified aircraft propulsion, such as through using copper-carbon nanotube fibers for lightweight power transmission.[276] NASA's new Quantum Pathways Space Technology Research Institute[277] is focused on the development of a high-sensitivity quantum-gravity gradiometer that is being designed to provide an advanced capability for Earth-observing satellites. Data obtained using the technology could help improve understanding of climate by measuring changes taking place in Earth's ice masses, oceans, and land water.

Plans for the Nano4EARTH National Nanotechnology Challenge

As discussed above in the budget summary section of this report, NNI participating agencies are reporting total estimated funding for the Nano4EARTH NNC of just over 10% of the total 2025 NNI request, up roughly 10% from the estimated Nano4EARTH funding request reported in the NNI Supplement to the President's 2024 budget.[278] DOE, NSF, NASA, ARS, and NIST are reporting funding for Nano4EARTH, in descending order of estimated funding amounts. In addition, EPA, DOD, NRC, and NCEH participate in the planning activities, in keeping with their respective missions. The following is a sampling of planned activities for 2025 and beyond for some of the participating agencies.

NNCO will help the agencies plan and organize activities for the next three years of the challenge that can be executed within existing authorizations and budgets, to build on and use the information gathered in the January 2023 kickoff meeting[279] and subsequent roundtable meetings on interfaces, energy storage, GHG capture, and catalyst technologies,[280] and other related events.[281] These activities range from interagency opportunities to public-facing events and collaborative activities, and are grouped into six main categories: (1) convening agency representatives to develop an integrated communications plan identifying top-priority messages and their targeted audiences, (2) selecting approximately six nanomaterials to focus on in order to help accelerate Nano4EARTH goals, (3) identifying agency subject matter experts who could serve as proposal reviewers for Nano4EARTH-related funding solicitations, and/or be available for details to other agencies, (4) developing gap analyses for each Nano4EARTH roundtable summary with language that agencies can use as reference for funding solicitations, (5) adapting the roundtable summaries into classroom curricula and other educational materials, and (6) mapping Nano4EARTH-related capabilities across the nation to identify regional ecosystems that can help accelerate the achievement of the NNC's goals. Some of these activities (e.g., communications plan, material co-development, gap analyses, and curriculum development) are already underway; others are in the planning stages.

275 https://www.energy.gov/eere/iedo/industrial-efficiency-and-decarbonization-funding-opportunity-announcement
276 https://doi.org/10.3390/c9020043
277 https://www.nasa.gov/news-release/nasa-awards-advance-3d-printing-quantum-tech-for-climate-research/
278 Per the NNI Supplement to the President's 2024 Budget, p. 7: https://www.nano.gov/sites/default/files/pub_resource/NNI-FY24-Budget-Supplement.pdf
279 https://www.nano.gov/nano4EARTHWorkshop
280 See the summaries of the roundtable meetings posted at https://www.nano.gov/nano4EARTH.
281 https://www.nano.gov/n4erelatedevents

DOE's activities in support of Nano4EARTH cover two of the five NNC themes: (2) averting future greenhouse gas emissions, where EERE has related applied research programs, and the Office of Science supports underlying fundamental research; and (3) removing existing greenhouse gases, where the Office of Fossil Energy and Carbon Management has related programs, again with support from the Office of Science's fundamental research activities. Nanotechnology is expected to make significant contributions to achieving the goals of the DOE Energy Earthshots, including the Carbon Negative Shot, the Clean Fuels & Products Shot, the Enhanced Geothermal Shot, the Floating Offshore Wind Shot, the Hydrogen Shot, the Industrial Heat Shot, the Long Duration Storage Shot, and the Affordable Home Energy Shot.[282] For example, nanotechnology may contribute to advancing the challenges of the Hydrogen Shot by helping research at the National Energy Technology Laboratory on developing hydrogen internal combustion processes that meet environmental standards for low emissions of nitrogen oxide pollutants. Another significant intersection between DOE priorities and Nano4EARTH is the Semiconductor Industry Energy Efficiency Scaling initiative, managed by EERE/AMMTO, which seeks to increase energy efficiency of semiconductors/microelectronics by at least 1,000x in the next 20 years. Many of the potential technology approaches to achieving this goal will involve nanotechnology, since all cutting-edge semiconductor devices today are fabricated and operate at the nanoscale. In August 2024, DOE issued an RFI seeking public and stakeholder on the goals, objectives, and next steps in the initiative,[283] which will inform a forthcoming EES2 roadmap.[284]

Many programs and solicitations across multiple NSF directorates support research related to Nano4EARTH. For example, ENG's Electrochemical Systems program[285] and MPS's Solid State and Materials Chemistry and Ceramics programs[286] support research in the area of energy storage, as do cross-cutting programs supported by several directorates, e.g., Designing Materials to Revolutionize and Engineer our Future[287] and the DCL on Clean Energy Technologies.[288] DMREF supports catalysis research, as do catalysis programs in both ENG and MPS.[289] Research on nanotechnology at interfaces, including coatings, lubricants, thermal interface materials, and membranes, is supported by ENG's Nanoscale Interactions program[290] and MPS's Solid State and Materials Chemistry and Polymers programs.[291] TIP's SBIR/STTR programs support research on topics such as energy storage, catalysts, greenhouse gas removal.[292] For 2025 and beyond, in addition to the programs listed above, research related to Nano4EARTH may be funded by other core programs such as IUCRCs, Engineering Research Centers, and EFMA in ENG (see PCA 1 section above), as well as Electronics, Photonics and Magnetic Devices[293] and Communications, Circuits, and Sensing-Systems[294] (for energy-efficient

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282 See details of each of these Earthshots at https://www.energy.gov/energy-earthshots-initiative.
283 https://www.energy.gov/eere/ammto/articles/doe-seeks-input-dramatically-increase-energy-efficiency-semiconductor
284 https://www.nist.gov/publications/energy-efficiency-scaling-2-decades-ees2-roadmap-computing
285 https://new.nsf.gov/funding/opportunities/electrochemical-systems
286 https://new.nsf.gov/funding/opportunities/solid-state-materials-chemistry, https://new.nsf.gov/funding/opportunities/ceramics
287 https://new.nsf.gov/funding/opportunities/designing-materials-revolutionize-engineer-our
288 https://www.nsf.gov/pubs/2023/nsf23109/nsf23109.jsp
289 https://new.nsf.gov/funding/opportunities/catalysis, https://new.nsf.gov/funding/opportunities/chemical-catalysis-cat
290 https://new.nsf.gov/funding/opportunities/nanoscale-interactions
291 https://new.nsf.gov/funding/opportunities/solid-state-materials-chemistry, https://new.nsf.gov/funding/opportunities/polymers
292 https://new.nsf.gov/funding/opportunities/nsf-small-business-innovation-research-small-0
293 https://new.nsf.gov/funding/opportunities/electronics-photonics-magnetic-devices-epmd
294 https://new.nsf.gov/funding/opportunities/communications-circuits-sensing-systems-ccss

microelectronics), and several additional programs in the Chemical Process Systems cluster[295] within the CBET Division. Some programs within MPS's Division of Physics[296] have a minor focus on climate change-related research, as do the Atmospheric and Geospace Sciences, Earth Sciences, and Ocean Sciences divisions in the Directorate for Geosciences.[297] There is also a cross-directorate DCL on Critical Aspects of Sustainability: Innovative Solutions to Climate Change,[298] and a DCL on Funding Opportunities for Engineering Research to Achieve Net-Zero Climate Goals by 2050.[299]

NASA has activities that support three of the Nano4EARTH themes: (1) evaluating, monitoring, and detecting climate change status and trends; (2) averting future greenhouse gas emissions; and (3) training and educating a highly skilled workforce to harness nanotechnology solutions. NASA's technology portfolio relevant to Nano4EARTH includes climate research, aeronautics, clean energy, and environmental monitoring. New nanotechnology research activities to address climate change under theme (1) above include a Quantum Pathways Space Technology Research Institute led by a public research university (see above in the section on Progress on Nano4EARTH for details). Under theme (2), NASA's Transformative Aeronautics Concepts program[300] is supporting the development of boron nitride and copper-CNT composite nanomaterials to enable electrified aircraft propulsion. Nanotechnology plays an important role in realizing the potential of solid-state batteries, including the use of functionalized holey graphene to achieve high-specific-energy-density, wide-operating-temperature, lithium–sulfur batteries for electrified aircraft propulsion. See the PCA 2 section above for information on the Super-lightweight Aerospace Composites Project, which is aimed at reducing fuel consumption as well as improving overall performance of aerospace vehicles. See the PCA 4 section of this report for examples of NASA educational activities in support of Nano4EARTH theme (4).

The NIST climate research portfolio,[301] which has some intersections with nanotechnology, includes climate measurements and monitoring, decarbonization of the economy, and adaptation and resilience, as well as life cycle analysis and carbon accounting. Under Nano4EARTH theme (3), removing existing greenhouse gases, NIST direct air capture research includes benchmarking nanomaterials such as zeolites, MOFs, and covalent organic frameworks (COFs) as CO_2 adsorbents. NIST is also using nanotechnology instrumentation technologies to make fundamental measurements for its DAC research. NIST reference materials support industry development of next-generation batteries and supercapacitors, carbon capture and storage (adsorbents, flue gas membranes), lightweighting materials, smart grid technologies, and advanced solar cells.

DOD research at the Institute for Soldier Nanotechnologies contributing to the Nano4EARTH NNC includes the development of nanomaterials for improved thermophotovoltaic cells; a photonics-enhanced electronic network interface card for faster, more efficient computing; and stabilized electrode/electrolyte interfaces for safer and higher storage capacity solid-state batteries to avert future greenhouse gas emissions. The Institute for Soldier Nanotechnologies is also developing an improved solar cell simulator to allow fine tuning of layer thickness and materials properties for more efficient solar cells, and is researching the use of gold nanoparticles and nanoporous gold for high-surface-area catalyst supports. ARL is conducting research on generating hydrogen fuel from

[295] https://new.nsf.gov/funding/opportunities/chemical-process-systems-cluster
[296] https://www.nsf.gov/funding/programs.jsp?org=PHY
[297] https://www.nsf.gov/funding/programs.jsp?org=GEO
[298] https://new.nsf.gov/funding/opportunities/critical-aspects-sustainability-cas-innovative
[299] https://www.nsf.gov/pubs/2024/nsf24045/nsf24045.jsp
[300] https://www.nasa.gov/directorates/armd/tacp/
[301] https://www.nist.gov/climate

nanostructured metals, polymer/nanomaterial-additive composites for daytime passive radiative cooling, 2D polymer battery membranes, high-performance MXene batteries, and CNT lubricants.

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Celebrating the NNI

To celebrate 20 years of U.S. leadership in nanotechnology since the passing of the 21st Century Nanotechnology Research and Development Act, over 400 members of the NNI community gathered for a day-long symposium at the National Academies of Sciences, Engineering, and Medicine. The event featured Arati Prabhakar, Assistant to the President for Science and Technology and Director of the White House Office of Science and Technology Policy; Ron Wyden, U.S. Senator from Oregon and author of the legislation; NASA astronaut Kathleen Rubins; and Chad Mirkin, Northwestern professor. At the symposium, leaders from academia, government, and industry spoke about U.S. success in nanotechnology and future directions in this field, while dozens of students from around the country presented posters on their work. President Joe Biden, as well as former President Bill Clinton and his assistant for science and technology, Neal Lane, also submitted words of support.

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