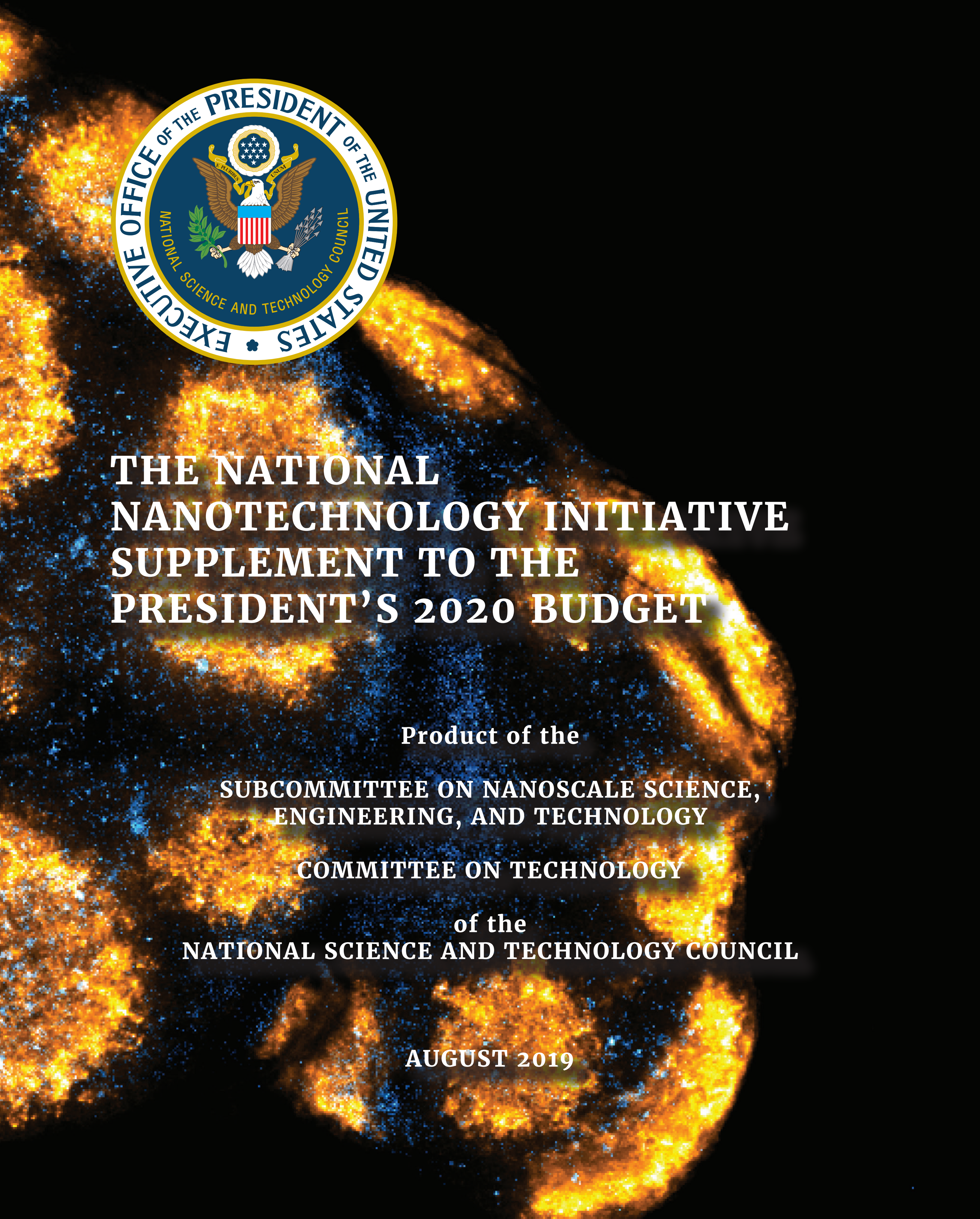

THE NATIONAL NANOTECHNOLOGY INITIATIVE SUPPLEMENT TO THE PRESIDENT’S 2020 BUDGET

Product of the

SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

COMMITTEE ON TECHNOLOGY

of the
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

AUGUST 2019

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

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About this document

This document is a supplement to the President's 2020 Budget request submitted to Congress on March 11, 2019, and serves as the Annual Report for the National Nanotechnology Initiative called for under the provisions of the 21st Century Nanotechnology Research and Development Act (15 USC §7501). The report also addresses the requirement for Department of Defense reporting on its nanotechnology investments (10 USC §2358). Additional information regarding the NNI is available on the NNI website at www.nano.gov.

About the cover

Outer Covers: Inside lymph nodes lie germinal centers, tiny biological factories where antibody-producing B cells generate a coordinated immune response against infectious diseases. The Lab of Darrell Irvine at the Koch Institute for Integrative Cancer Research at the Massachusetts Institute of Technology (MIT) develops nanoparticle vaccines that target specific cell types to jump-start this process. This image was taken to see if the nanoparticles (blue) would home in on follicular dendritic cells (orange), which orchestrate B cell proliferation and antibody production in germinal centers. While this particular vaccine takes aim at HIV, targeted delivery of nanoparticles within the lymph nodes could combat many other diseases as well, including cancer. This image was acquired using a Nikon A1R Ultra-Fast Spectral Scanning Confocal Microscope. The work was supported by the National Institutes of Health (National Institute of Allergy and Infectious Diseases and National Cancer Institute), the Koch Foundation, the Ragon Institute, the Howard Hughes Medical Institute, and the International AIDS Vaccine Initiative. Image credit: Jason Y.H. Chang, Tyson Moyer, and Darrell Irvine, Koch Institute for Integrative Cancer Research at MIT.

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

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Executive Summary

The President's 2020 Budget requests over $1.4 billion for the National Nanotechnology Initiative (NNI), a continued investment in basic research, early-stage applied research, and technology transfer efforts that are leading to the breakthroughs of the future. Cumulatively totaling nearly $29 billion since the inception of the NNI in 2001 (including the 2020 request), this support reflects the continued importance of investments that advance our fundamental understanding of and ability to control matter at the nanoscale, as well as the translation of that knowledge into technological breakthroughs that benefit the American people. Past research and development activities have led to nanotechnology-enabled applications in areas as diverse as electronics, medicine, transportation and infrastructure, water purification and monitoring, energy, aerospace, apparel and textiles, sporting goods, and agriculture and food safety. The nanotechnology R&D underway today will provide the foundation for future applications enabling entirely new capabilities and products. The NNI investments in 2018 and 2019 and those proposed for 2020 reflect a sustained emphasis on broad, fundamental research in nanoscience. Through this sustained support, the President's Budget includes nanotechnology investments that will further the progress of the NNI to strengthen the national security innovation base, transform health care, modernize America's infrastructure, advance manufacturing, educate a future-focused workforce, and lead to job growth and economic prosperity. This document 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).

What is Nanotechnology?

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

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

For example, nanotechnology innovations enable: (a) materials and devices for quantum encryption and computing; (b) fabric that regulates the amount of heat that passes through it depending on conditions; (c) sensors for interplanetary missions; (d) flexible electronics on non-silicon materials; (e) novel semiconductor manufacturing technologies; (f) low-temperature, energy-saving, solar-powered catalysts; (g) bandages that speed up healing; and (h) wearable artificial kidneys.

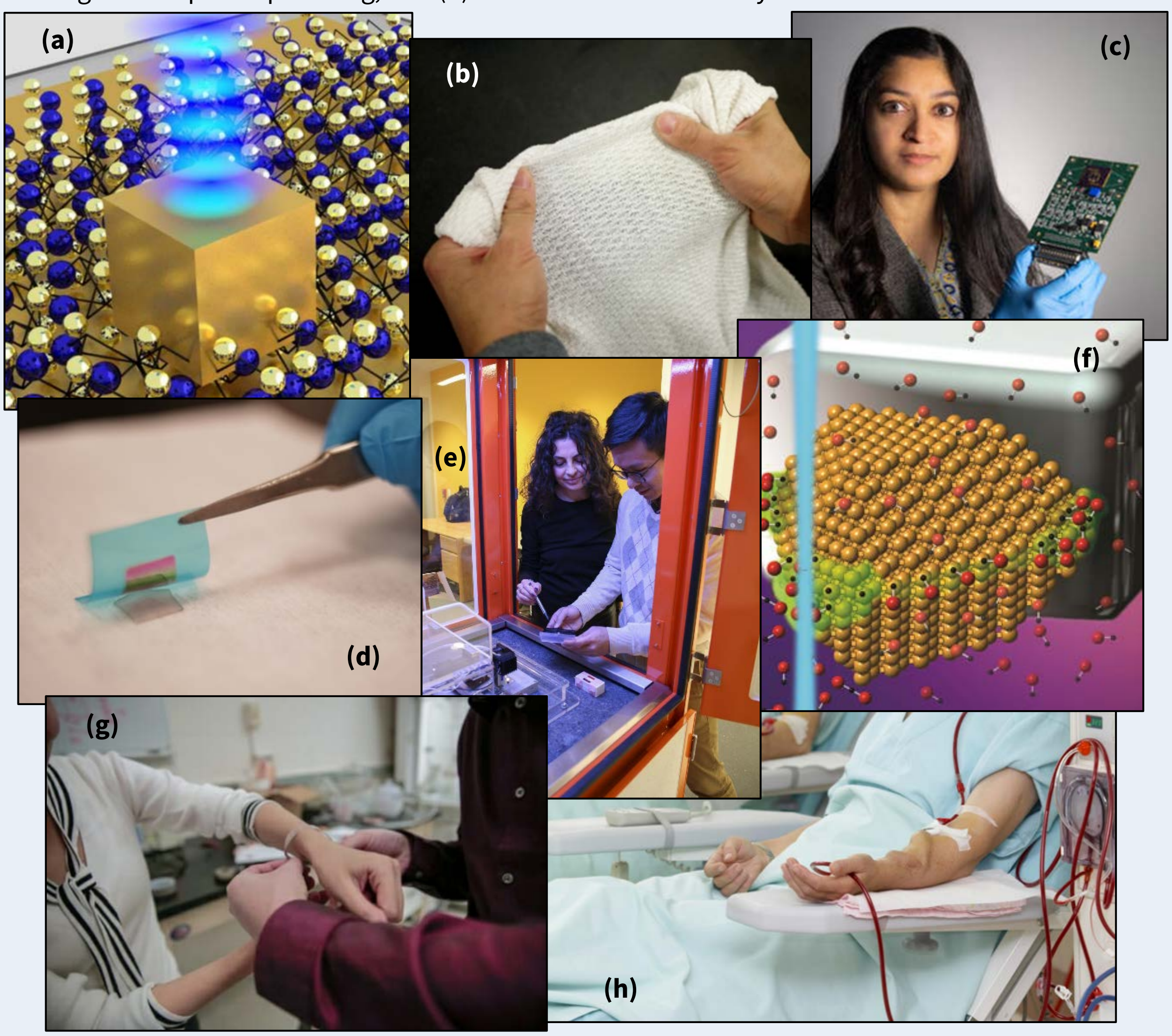

Image credits: (a) Stevens Institute of Technology; (b) University of Maryland; (c) NASA; (d) Massachusetts Institute of Technology; (e) New York University; (f) NIST; (g) University of Wisconsin, Madison; (h) Shutterstock. For more information on nanotechnology benefits and applications, please visit www.nano.gov/you/nanotechnology-benefits.

1. INTRODUCTION

The National Nanotechnology Initiative (NNI), established in 2001[1] and authorized in 2003 by the 21st Century Nanotechnology Research and Development Act,[2] is a U.S. Government research and development (R&D) initiative. Twenty Federal departments, independent agencies, and commissions[3] work together toward the shared vision of *a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society*.[4] The NNI maximizes interagency coordination of nanotechnology R&D, enables agencies to avoid duplicative efforts, and establishes shared goals, priorities, and strategies that complement agency-specific missions and activities. Table 1 lists the agencies currently participating in the NNI. More information about the structure, goals, and priorities of the NNI can be found on Nano.gov.

Understanding and controlling matter at the nanoscale enables a host of unique physical, chemical, and biological properties with broad applications across disciplines and industrial sectors. Past research and development activities have led to nanotechnology-enabled applications in areas as diverse as electronics, medicine, transportation and infrastructure, water purification and monitoring, energy, aerospace, apparel and textiles, sporting goods, and agriculture and food safety. The nanotechnology R&D underway today will provide the foundation for future applications enabling entirely new capabilities and products. From temperature-regulating fabrics to bandages that speed up healing, nanotechnology has much more to offer. For example, nanotechnology research will enable advances in future electronics to ensure the continued strength of the U.S. semiconductor industry. Through sustained support of basic and early-stage applied research, the President's Budget includes nanotechnology investments that will further the progress of the NNI to strengthen the national security innovation base, transform health care, modernize America's infrastructure, advance manufacturing, educate a future-focused workforce, and lead to job growth and economic prosperity.

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

Nanotechnology is a focus of R&D efforts around the globe. The NNI actively engages with like-minded regions to advance America's values at home and abroad. For example, the National Nanotechnology Coordination Office (NNCO) facilitates communities of research to share scientific information regarding nanotechnology environmental, health, and safety issues and to promote science-based regulation.

Chapter 2 of this NNI budget supplement presents budget information and highlights of agency plans and priorities by Program Component Area (PCA). Chapter 3 includes examples of progress toward the four NNI goals. Additional information regarding agency priorities for nanotechnology is provided in Appendix A and on the budget pages of Nano.gov. Appendix B provides a list of abbreviations and acronyms used throughout this document, and contact information for NNI participants is included in Appendix C.

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

[2] 15 U.S.C. §7501: https://www.govinfo.gov/app/details/USCODE-2016-title15/USCODE-2016-title15-chap101-sec7501/

[3] Hereafter within this document the Federal departments, independent agencies, and commissions participating in the NNI are referred to collectively as "agencies."

[4] www.nano.gov/2016strategicplan, p. 3

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

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

No external reviews of the NNI have been completed since the release of the Supplement to the President's 2019 Budget. The National Academies, however, has initiated its quadrennial review of the NNI.[5] The panel is tasked with analyzing the relative international position of the United States with respect to nanotechnology R&D (including identification of critical research areas where the United States should be world leader) and assessing the current state of nanoscience and nanotechnology resulting from the NNI. Based on this assessment, the panel is further tasked with considering if and how the NNI should continue. If continuation is suggested, recommendations to improve the program are also solicited.

[5] https://www8.nationalacademies.org/pa/projectview.aspx?key=51396

2. NNI Budget and Program Plans

Budget Summary

The President's 2020 Budget requests over $1.4 billion for the NNI, a continued investment in basic research, early-stage applied research, and technology transfer efforts that are leading to the breakthroughs of the future. Cumulatively totaling nearly $29 billion since the inception of the NNI in 2001 (including the 2020 request), this support reflects the continued importance of investments that advance our fundamental understanding of and ability to control matter at the nanoscale, as well as the translation of that knowledge into technological breakthroughs that benefit the American people. The NNI investments in 2018 and 2019 and those proposed for 2020 reflect a sustained emphasis on broad, fundamental research in nanoscience. The NNI budget represents the sum of the nanotechnology-related investments allocated by each of the participating agencies (the "NNI budget crosscut"). Each agency determines its budget for nanotechnology R&D in coordination with OMB, OSTP, and Congress. NNI agencies collaborate closely—facilitated through the NSET Subcommittee, its working group and coordinators, and NNCO—to create an integrated R&D program that leverages resources to advance NNI goals and meet individual agency mission needs and objectives.

The NNI leverages efforts to yield impacts greater than individual agency activities alone and supports cross-disciplinary teams to uncover new and innovative solutions to difficult problems. The NNI exemplifies the interagency coordination and cross-disciplinary collaboration called for in the 2020 Administration Research and Development Budget Priorities Memorandum.[6] Agencies continue to prioritize investments in nanotechnology to meet their mission needs, including homeland security and defense, medicine, advanced manufacturing, nanoelectronics and future computing, and agriculture. Nanotechnology is critical to advances in a wide range of industries and will continue to impact American prosperity, create new industries, generate new jobs, and increase workforce productivity. The NNI supports significant investments in research infrastructure, developing new research tools, and making these tools available through user facilities. The NNI also supports science, technology, engineering, and mathematics (STEM) education to ensure a continued source of inspirational discoveries and transformative technological advances.

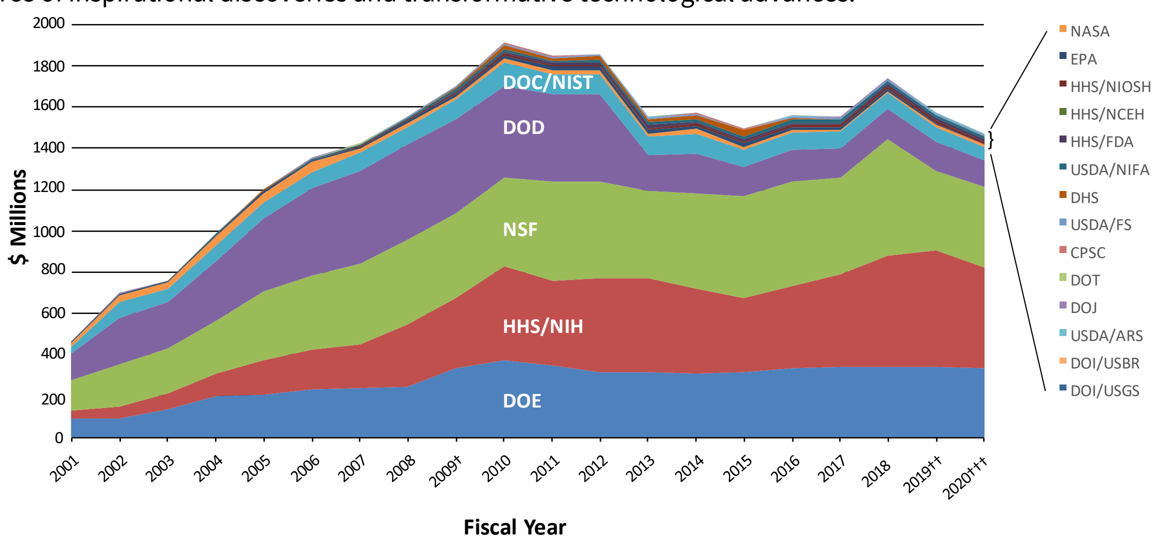

Figure 1. NNI Funding by Agency, 2001–2020.

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

†† 2019 numbers are based on appropriated levels.

††† 2020 Budget.

[6] https://www.whitehouse.gov/wp-content/uploads/2018/07/M-18-22.pdf

Table 2: Actual 2018 Agency Investments by Program Component Area
(dollars in millions)*

Agency	1. Nanotechnology Signature Initiatives (NSIs) and Grand Challenge (GC)**	1a. Nanomanufacturing NSI	1b. Nanoelectronics NSI	1c. NKI NSI	1d. Sensors NSI	1e. Water NSI	1f. Future Computing GC	2. Foundational Research	3. Nanotechnology-Enabled Applications, Devices, and Systems	4. Research Infrastructure and Instrumentation	5. Environment, Health, and Safety	NNI Total
CPSC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
DHS	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.2
DOC/NIST	22.3	3.7	10.0	0.9	0.8	0.3	6.6	11.4	4.6	34.1	2.8	75.1
DOD	33.8	0.4	22.9	1.3	1.0	2.3	5.9	85.4	21.1	2.1	3.5	145.9
DOE	1.5	0.0	0.0	0.0	1.5	0.0	0.0	181.2	18.6	137.1	0.0	338.4
DOI/USGS	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1
DOJ/NIJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.1	0.0	2.2
DOT/FHWA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.3
EPA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.6	10.6
HHS (total)	29.3	0.0	0.4	1.8	27.1	0.0	0.0	100.3	365.3	23.4	47.3	565.6
FDA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.2	15.2
NIH	29.3	0.0	0.4	1.8	27.1	0.0	0.0	100.3	365.3	23.4	22.0	540.3
NIOSH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.1	10.1
NASA	2.5	0.4	1.3	0.0	0.8	0.0	0.0	4.3	2.5	0.0	0.1	9.4
NSF	167.7	35.9	74.5	20.2	14.2	11.6	11.4	292.3	49.9	45.6	12.5	568.0
USDA (total)	10.3	6.3	0.0	0.0	3.0	1.0	0.0	2.2	8.3	1.0	2.3	24.1
ARS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.0	0.0	3.3
FS	4.8	4.8	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.3	5.3
NIFA	5.5	1.5	0.0	0.0	3.0	1.0	0.0	2.0	5.0	1.0	2.0	15.5
TOTAL* **	**267.6**	**46.7**	**109.0**	**24.2**	**48.6**	**15.1**	**24.0**	**677.1**	**472.7**	**243.3**	**80.1**	**1740.9**

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

The President's 2020 Budget supports nanoscale science, engineering, and technology R&D at 11 agencies. The five Federal organizations with the largest investments (representing 96% of the total) are:

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

Other agencies and agency components investing in mission-related nanotechnology research in the 2020 Budget are CPSC, HHS/FDA, HHS/NIOSH, DOJ, DOT/FHWA, EPA, NASA, USDA/ARS, USDA/FS, and USDA/NIFA.[7]

[7] See Table 1 (p. 2) or Appendix B for explanations of the agency abbreviations used throughout this report.

Table 3: Estimated 2019 Agency Investments by Program Component Area

Agency	1.	1a.	1b.	1c.	1d.	1e.	1f.	2.	3.	4.	5.	Total
CPSC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.9
DHS	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3
DOC/NIST	22.4	3.7	10.0	0.9	0.8	0.3	6.8	11.4	4.6	33.4	2.8	74.5
DOD	43.3	0.4	32.3	0.9	0.7	2.2	6.8	67.0	18.7	3.5	3.4	135.9
DOE	1.9	0.0	0.0	0.0	1.9	0.0	0.0	183.5	15.6	142.1	0.0	343.1
DOI/USBR	0.2	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.2
DOJ/NIJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.3	0.0	2.1
DOT/FHWA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	1.5
EPA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.6	9.6
HHS (total)	30.3	0.0	0.4	1.9	28.0	0.0	0.0	103.0	378.8	24.2	44.1	580.4
FDA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.2	11.2
NCEH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
NIH	30.3	0.0	0.4	1.9	28.0	0.0	0.0	103.0	378.8	24.2	22.7	559.0
NIOSH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.1	10.1
NASA	2.4	0.4	1.3	0.0	0.7	0.0	0.0	4.4	3.0	0.0	0.1	9.8
NSF	109.0	28.0	32.0	19.5	7.5	11.0	11.0	188.9	38.1	43.7	10.9	390.6
USDA (total)	9.3	4.3	0.0	0.0	3.0	2.0	0.0	2.3	8.4	1.0	2.1	23.1
ARS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.0	0.0	3.3
FS	3.3	3.3	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.1	3.7
NIFA	6.0	1.0	0.0	0.0	3.0	2.0	0.0	2.0	5.1	1.0	2.0	16.1
TOTAL	**219.1**	**36.8**	**75.9**	**23.2**	**43.0**	**15.6**	**24.6**	**560.5**	**470.5**	**248.2**	**73.8**	**1572.1**

Table 4: Proposed 2020 Agency Investments by Program Component Area

Agency	1.	1a.	1b.	1c.*	1d.	1e.	1f.	2.	3.	4.	5.	Total
CPSC	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.9
DOC/NIST	23.2	3.7	9.4	-	0.8	0.3	9.1	8.6	4.4	28.5	2.0	66.7
DOD	38.1	0.3	28.0	-	0.4	1.1	8.3	71.1	18.5	1.7	0.3	129.7
DOE	1.9	0.0	0.0	-	1.9	0.0	0.0	187.5	11.4	133.9	0.0	334.7
DOJ/NIJ	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	1.8	0.3	0.0	2.1
DOT/FHWA	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.5
EPA	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	3.5	3.5
HHS (total)	24.9	0.0	0.3	-	24.6	0.0	0.0	91.6	327.9	21.2	41.7	507.3
FDA	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	10.6	10.6
NIH	24.9	0.0	0.3	-	24.6	0.0	0.0	91.6	327.9	21.2	21.0	486.6
NIOSH	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	10.1	10.1
NASA	2.4	0.4	1.3	-	0.7	0.0	0.0	4.5	2.9	0.0	0.1	9.8
NSF	91.5	28.0	32.0	-	7.5	11.0	13.0	207.5	37.9	42.0	10.6	389.4
USDA (total)	9.3	4.3	0.0	-	3.0	2.0	0.0	2.3	9.4	1.0	2.1	24.1
ARS	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	3.3	0.0	0.0	3.3
FS	3.3	3.3	0.0	-	0.0	0.0	0.0	0.3	0.0	0.0	0.1	3.7
NIFA	6.0	1.0	0.0	-	3.0	2.0	0.0	2.0	6.1	1.0	2.0	17.1
TOTAL	**191.3**	**36.7**	**71.0**	-	**38.9**	**14.3**	**30.4**	**573.0**	**414.7**	**228.6**	**61.1**	**1468.7**

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

Table 5: NNI Budget, by Agency, 2018–2020
(dollars in millions)

Agency	2018 Actual	2019 Estimated*	2020 Proposed
CPSC	1.0	0.9	0.9
DHS	0.2	0.3	0.0
DOC/NIST	75.1	74.5	66.7
DOD	145.9	135.9	129.7
DOE**	338.4	343.1	334.7
DOI (total)	0.1	0.2	0.0
USBR	0.0	0.2	0.0
USGS	0.1	0.0	0.0
DOJ/NIJ	2.2	2.1	2.1
DOT/FHWA	0.3	1.5	0.5
EPA	10.6	9.6	3.5
HHS (total)	565.6	580.4	507.3
FDA	15.2	11.2	10.6
NCEH	0.0	0.1	0.0
NIH	540.3	559.0	486.6
NIOSH	10.1	10.1	10.1
NASA	9.4	9.8	9.8
NSF	568.0	390.6	389.4
USDA (total)	24.1	23.1	24.1
ARS	3.3	3.3	3.3
FS	5.3	3.7	3.7
NIFA	15.5	16.1	17.1
TOTAL	1740.9	1572.1	1468.7

* 2019 numbers are based on appropriated levels.

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

With a significant proportion of agencies' nanotechnology investments now coming from "core" R&D programs, where the high success rate of nanotechnology-related proposals cannot be anticipated in advance, the actual NNI investments are often higher than the estimated and requested levels. For example, the actual NNI investments being reported by the participating agencies for 2018 ($1.74 billion) are significantly larger than 2018 estimated investments previously published in the 2019 Budget ($1.48 billion) and 2018 requested investments published in the 2018 Budget ($1.21 billion).

Programmatic Plans and Changes by PCA

The budget details presented in this document encompass a broad array of NNI R&D activities. This section highlights examples of agency plans corresponding to the investments in each NNI Program Component Area for 2020. Additional details and examples can be found at Nano.gov. The formal definition of each PCA can be found at www.nano.gov/about-nni/what/vision-goals.

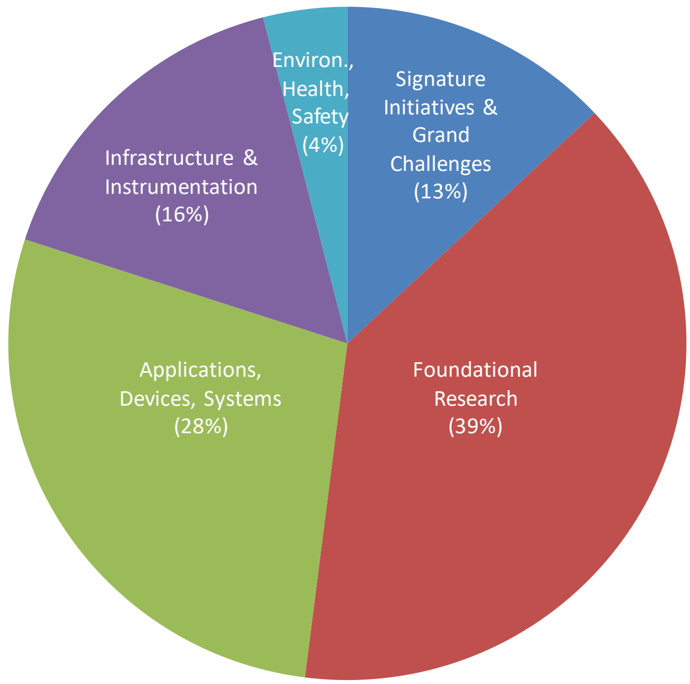

Figure 2. Breakout of NNI Funding by Program Component Area in the 2020 Budget.

PCA 1. Nanotechnology Signature Initiatives and Grand Challenges

The NNI agencies, collectively and individually, utilize a variety of mechanisms to accelerate nanotechnology research and development on topics related to the Nanotechnology Signature Initiatives (NSIs) and the Nanotechnology-Inspired Grand Challenge for Future Computing. Representatives of agencies participating in the NSIs join regular teleconferences to discuss technical challenges and accomplishments, share information on agency plans and activities, and plan collaborative activities.

The NSI portfolio is intended to be dynamic. A vibrant community has embraced the concepts identified in the Nanotechnology Knowledge Infrastructure signature initiative, and the NNI agencies have recognized that this area will continue to advance without the spotlight afforded by the NSI mechanism. Agencies have reported investments for 2018 and 2019, but funding will not be reported for this NSI moving forward.

In 2020, the *Nanotechnology for Sensors and Sensors for Nanotechnology* signature initiative (Sensors NSI) will prioritize cross-agency discussions of technical challenges related to nanotechnology-enabled sensors, with one area of emphasis on wearable and implantable sensors. Representatives participating in the NSI will also pursue mechanisms, such as a public webinar series and presentations at technical conferences, to build and strengthen connections with the broader nanosensors research community. Agency-specific activities in support of this NSI will include development of sensor technologies to identify biological and chemical species for applications in human and robotic space exploration by NASA. NIST scientists will conduct simulations of nanoporous membranes with potential applications in lead ion detection. NSF's dedicated programs on biosensing and biophotonics will support fundamental research on sensing technologies.

Several institutes within NIH plan to research biomedical and clinical opportunities that could benefit from the use of *in vitro* and *in vivo* imaging and sensing devices. Examples include technologies that would provide mechanistic understanding of disease progression, monitor therapeutic response, and advance other medical device applications. Therefore, NIH plans to leverage the technical developments from the Sensors NSI workshops and interagency collaborations such as the NSF-NIH Smart and Connected Health program.

The NIH Enabling Technologies to Accelerate Development of Oral Biodevices initiative[8] supports research on multifunctional oral biodevices, including those incorporating nanotechnology, to evaluate, monitor, and manage oral and overall health. The long-term goal is to accelerate technical development and clinical translation of innovative oral biodevices that are highly sensitive and specific and to facilitate incorporation of precision medicine approaches into clinical practice.

DOD has interests in sensing technologies to monitor the warfighter's health, performance, and physical environment, and invests in sensors R&D across the department. For instance, DOD will investigate nanosensor platforms for detecting the cellular signals that control wound healing. NIFA will maintain its support for R&D on nanobiosensors to detect pathogens, toxins, and contaminants in food, and to monitor physiological biomarkers for optimizing crop and animal productivity and health. NIFA will also support development of distributed sensor networks for precision agriculture. DOE is supporting basic and applied R&D on improved sensors and controls technologies for fossil-based electric power generation. Real-time, multipoint, distributed sensing at the nanoscale will enable energy process optimization and component health prediction, thereby enhancing the flexibility, reliability, and efficiency of both existing and new fossil power plants.

Agencies participating in the *Water Sustainability through Nanotechnology* signature initiative (Water NSI) will continue to discuss technologies to monitor and improve water availability and quality. Planned activities include an in-person technical meeting on nanotechnology-enabled water treatment technologies and an embedded technical session in a major conference. Agency-specific activities in support of this NSI include NIFA efforts aimed at developing novel detection and treatment technologies as part of new smart irrigation systems, including for small and mid-size farms. The goal is to significantly improve agricultural water quality and use efficiency, and to increase the use of alternative water sources for irrigation of fresh produce, decreasing freshwater withdrawals and closing water use gaps. Nanotechnology research that supports the goals of the Water NSI is supported by the NSF Innovations at the Nexus of Food, Energy and Water Systems initiative.[9] In addition to NSF's core nanoscience-related programs on water filtration and applications, the Nanosystems Engineering Research Center for Nanotechnology Enabled Water Treatment Systems (NEWT), funded through 2020, aims to develop high-performance water treatment systems that will broaden access to clean drinking water from a variety of unconventional sources, and to enable industrial wastewater reuse at remote locations such as oil and gas fields.[10] The NASA Johnson Space Center is interested in nanophotocatalysts, membrane nanotechnology, and nano-adsorbents currently under development by NEWT researchers for their potential applications in spacecraft water treatment and recovery for long-duration human space exploration.

In support of the *Sustainable Nanomanufacturing* signature initiative, the 2019 *Advancing Commercialization of Nanocellulose: Critical Challenges Workshop*[11] was organized by an industry consortium in collaboration with USDA Forest Service and NNCO. The event built on key findings from the 2014 *Cellulose Nanomaterials: A Path Towards Commercialization Workshop*.[12] In support of this NSI, the establishment of a nanomanufacturing U.S.-EU Community of Research (COR) is under consideration. This collaboration would add to existing topics under the COR mechanism and may address precompetitive issues such as standards and environmental, health, and safety (EHS) considerations.

[8] https://www.nidcr.nih.gov/grants-funding/funding-priorities/future-research-initiatives/enabling-technologies-accelerate-development-oral-biodevices
[9] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505241
[10] http://www.newtcenter.org/
[11] https://www.appti.org/2019-workshop.html
[12] https://www.nano.gov/ncworkshop

Advances in nanomanufacturing continue to be made with support from individual agencies under a variety of programs and activities. NSF investments include a Dear Colleague Letter, Supporting Fundamental Research to Enable Innovation in Advanced Manufacturing at Manufacturing USA Institutes.[13] It solicits proposals addressing fundamental research needs in advanced manufacturing, including nanomanufacturing and manufacturing across length scales. Activities related to engineering biology at the nanoscale for advanced manufacturing are being organized in several NSF directorates. The Nanomanufacturing Node of nanoHUB[14] was launched in 2017 with a lifetime of five years and a focus on modeling and simulation of manufacturing processes. Exploratory research directions at NSF include manufacturing of nanomachines and nanobiostructures, cellular nanobiomanufacturing, atomically precise manufacturing, and nanomanufacturing for quantum devices and sensors. DOE's Advanced Manufacturing Office (AMO) exploratory research includes atomically precise manufacturing and nanomanufacturing efforts related to graphene and metals. DOE's Office of Energy Efficiency and Renewable Energy has projects related to nanocellulose across several of its offices, including AMO.

NIST will conduct research on graphene and transition metal dichalcogenides (TMDs), single atomic layers of crystalline materials that exhibit unusual electronic and quantum characteristics and that hold promise for high-performance devices of the future. In 2020, NIST plans to develop testing techniques that allow the application of operational stresses such as temperature and mechanical forces to TMDs while they are observed in a scanning electron microscope. DOD is developing polymer matrix composites with embedded nanosensors. Optically active nanoparticles are being added to these composites for real-time monitoring of key parameters during processing. The goal is to significantly reduce costs associated with resin cure cycle development, manufacturing flaws, and nondestructive evaluation.

Forest Service investments are in the development and manufacture of cellulosic nanomaterials. Through a public-private partnership, investments will support previously funded projects that industry experts believe have commercialization potential.

The *Nanoelectronics for 2020 and Beyond* signature initiative and the *Nanotechnology-Inspired Grand Challenge for Future Computing* share a complementary focus on research and development activities on next-generation computing technologies. These technologies are critical for national security and economic well-being, and agencies continue to support efforts that advance nanoelectronics research. Agency-specific investments will include DOD efforts to investigate photonic approaches to quantum information processing. NIST will develop and apply *in situ* diagnostics and process control methods for chemical vapor and atomic layer deposition to improve production yields of electronic devices and facilitate production processes for next-generation ultra-thin films.

NSF plans ongoing collaboration with other agencies in activities such as the Energy-Efficient Computing: from Devices to Architectures (E2CDA) program,[15] and the Semiconductor Synthetic Biology for Information Processing and Storage Technologies (SemiSynBio) program.[16] NSF will increase coordinated research on its Quantum Leap[17] and Future of Work at the Human-Technology Frontier[18] "Big Ideas" priority areas. The Defense Advanced Research Projects Agency (DARPA) and its industry partners are supporting six new research centers under its Joint University Microelectronics Program (JUMP).[19] JUMP will push fundamental technology research and also establish long-range microelectronic research themes with greater emphasis on end-application and systems-level computation. In 2019, for example, the Applications and Systems-

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[13] https://www.nsf.gov/pubs/2017/nsf17088/nsf17088.jsp

[14] https://nanohub.org/

[15] https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf17531

[16] https://www.nsf.gov/pubs/2017/nsf17557/nsf17557.htm

[17] https://www.nsf.gov/news/special_reports/big_ideas/quantum.jsp

[18] https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf19541

[19] https://www.darpa.mil/program/joint-university-microelectronics-program

Driven Center for Energy-Efficient Integrated Nanotechnologies (ASCENT) is exploring vertical complementary metal–oxide semiconductor (CMOS) transistors for novel memory-logic co-integration circuits, beyond-CMOS spintronics for brain-inspired computing, and in/near-memory hardware demonstrations for machine-learning workloads. ASCENT is addressing both device materials and the architectures required to use them.

The Future Computing Grand Challenge will be advanced with support from several agencies. Planned NSF research topics include "Brain-Like Computing" and "Intelligent Cognitive Assistants" (ICAs), with active centers in this area. NSF plans to continue including ICAs in 2019 and 2020 as part of program announcements for two NSF Big Ideas: "The Future of Work at the Human-Technology Frontier" and "Growing Convergence Research." Further collaboration is planned with industry groups developing hardware (with a focus on "beyond Moore" system architectures and corresponding devices), software (with a focus on artificial intelligence), and implementation in various applications. The research will be conducted in collaboration with other agencies and public-private consortia.

DOD plans to initiate an effort in nanophotonic-based reservoir computing. Institute for Soldier Nanotechnologies (ISN) researchers have proposed a revolutionary new nanostructured nanophotonic architecture for a fully-optical neural network that, using unique advantages of optics, can result in a computational speed enhancement of at least two orders of magnitude—and three orders of magnitude in power efficiency—compared to the current state of the art for conventional learning tasks. The DARPA/industry JUMP program will include research on the stochastic-spiking networks algorithm and theory development for future artificial intelligence computing workloads.

NIST has intramural and extramural activities that support advances in computing technologies, including a public-private partnership to identify and implement revolutionary solutions to break through the bottleneck of energy-constrained computational performance. This effort has launched two university-based research consortia: (1) NEW LIMITS (for NEW materials for LogIc, Memory, and InTerconnectS) focuses on new materials to enable novel computing and storage paradigms beyond the capabilities of conventional CMOS; and (2) Spintronic Materials in Advanced Information Technologies (SMART) accelerates the development of beyond-CMOS building blocks with advanced spintronic materials and devices. These centers are funded through the Nanoelectronics Computing Research (nCORE) consortium,[20] established by NIST and industry.

PCA 2. Foundational Research

Foundational research continues to be the largest PCA, accounting for over 39% of total NNI investments in the 2020 Budget. Three agencies (DOE, DOD, and NSF) are requesting over 50% of their total NNI investments in PCA 2, and NASA is requesting just over 45%. Those four agencies also account for over 80% of the total PCA 2 investments. This investment is consistent with the focus in the President's 2020 Budget on supporting early-stage R&D that will lead to the innovations of the future, and with the traditional role of those four agencies in funding basic research. Many other NNI agencies also have broad foundational nanotechnology research portfolios, as briefly outlined below.

The DOE Office of Basic Energy Sciences (BES) supports fundamental nanoscience research in the fields of materials science, chemical science, geoscience, and bioscience, with the goal of understanding, predicting, and ultimately controlling matter and energy at the level of electrons, atoms, and molecules. This work is carried out primarily at universities and DOE national laboratories through single-investigator and small group projects, as well as larger centers such as the Energy Frontier Research Centers and Energy Innovation Hubs. This diverse research provides the foundation for future new energy technologies and supports the DOE mission. As part of a $218 million DOE investment in the emerging field of quantum information science

[20] https://www.src.org/program/ncore/

(QIS), BES announced seven awards totaling $30 million over three years to develop QIS infrastructure and support QIS research at the five Nanoscale Science Research Centers (NSRCs).[21]

NSF supports a wide range of foundational research programs. The NSF investment includes discovery and development of fundamental knowledge pertaining to new nanoscale phenomena in the physical, biological, and engineering sciences; research aiming to understand scientific and engineering principles related to nanoscale systems, structures, processes, and mechanisms; discovery and synthesis of novel nanoscale and nanostructured materials, including biomaterials and modular structures; and research directed at identifying and quantifying the broad implications of nanotechnology for society. A special area of focus has been nanostructure assembly in synthetic cells that is a part of the NSF Big Idea, "Understanding the Rules of Life."

DOD recognizes the need for strong efforts in foundational nanoscience research as part of its overall nanotechnology investment portfolio, to meet the needs of warfighters in future military missions. PCA 2 investments by DOD agencies cover the full spectrum of fundamental nanotechnology R&D, including research on novel nanomaterials with potential structural, electronic, and biological applications; nano-electronics, -photonics, and –magnetics; nanobiotechnology; and catalysis. DOD will continue to support nanobiotechnology research, with emphases on fabrication techniques for hierarchical, biologically based materials with defined properties, DNA nanotechnology, synthesis and patterning of materials by microorganisms, and design and fabrication of bio-inspired and biomimetic materials and devices. DOD will support R&D on nanoscale processing and electrically assisted manufacturing of high-performance, lightweight metal alloys and ceramics, and on understanding the scientific phenomena that define the unique properties of structural and multifunctional nanomaterials. DOD nanoelectronics efforts will support development of reliable and cost-effective means to synthesize and fabricate electronic circuitry at atomic resolution. DOD plans include efforts in phonon-polariton lattices, controlling magnetism in metamagnetic nanostructures, enhanced optical properties in hybrid nanostructures, and bio-inspired quantum-coherent networks in DNA origami structures. DOD is supporting research on optofluidics, a relatively new research field that focuses on the intersection of optics and microfluidics, exploring the precise control of optically active colloidal nano- and microdroplets. This technology shows promise as a platform for novel optoelectronic applications such as reconfigurable filters and electrically dimmable eyewear. DOD has initiated new basic research focused on use of nanomaterials to modify polymers and coating systems for controlled optoelectronic properties.

NIH investments in foundational research reflect the discovery and understanding of scientific principles in medical research. For example, the Innovative Research in Cancer Nanotechnology program is focused on revealing and enhancing fundamental understanding of mechanisms behind *in vivo* delivery of nanoparticles and operation of *in vitro* nanodevices. NIH leverages its investments on the promise of nanotechnology as an invaluable tool to produce novel structures that induce regeneration and repair of biological tissues, deliver biomolecules to tissues with pre-defined kinetics, and control tissue infection and inflammation, among other uses. NIH's support for the development of new nanomaterial-based dental composites will continue at least until 2021 as part of a new initiative on Advancing Imaging, Device Production, and Clinical Capabilities in Digital Dentistry. NIH's Dental, Oral and Craniofacial Tissue Regeneration Consortium will also extend over an additional 6 years.

NIST's foundational nanotechnology research portfolio includes efforts to measure and advance the understanding of functional nanostructured materials, nanoscale imaging, and nanomechanical properties of materials. NIST staff members are developing advances in spectroscopy of low-dimensional nanoscale materials and measurement science of colloidal nanomaterials. In 2020, NIST plans to develop, validate, and apply new and improved measurement science for the characterization of soft nanomaterials, particularly

[21] https://www.energy.gov/articles/department-energy-announces-218-million-quantum-information-science

materials designed to detect, diagnose, and treat human disease. Insights from this work will inform proposed international standards on liposome characterization, a project that is also led by FDA.

NIFA's foundational nanotechnology research includes discovery and characterization of novel nanoscale phenomena, processes, and properties relevant and important to agriculture and food, hybrid bioinorganic systems, systems biology, and additive manufacturing technology. NIFA also supports research on the social, ethical, legal, and other implications that nanotechnology and other emerging technology applications may pose for society, agricultural markets, and consumer preferences.

The Ultra-Strong Composites by Design (US-COMP) NASA Space Technology Research Institute is a collaboration between investigators at eleven universities, industry, NASA, and DOD. This five-year, $15 million institute is focused on fundamental research to inform the design of carbon nanotube (CNT) reinforcements and composites with significantly improved mechanical properties relative to state-of-the-art aerospace-grade carbon fiber reinforced composites. To meet this goal, US-COMP is exploring optimized CNT material synthesis techniques, advanced composite processing methods, computational tools, and test methods.

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

The agencies participating in the NNI support R&D on nanotechnology-enabled devices and systems across a wide variety of applications, including flame-retardant cotton materials; medical devices; and smart, autonomous devices and systems. Nanotechnology-enabled applications, devices, and systems is the largest PCA in the NIH NNI investment portfolio. NIH funds nanotechnology-related proposals covering all the major diseases (e.g., cardiac, cancer, diabetes, kidney, etc.). Programs and projects in PCA 3 include medical devices, nanotherapeutics, drug-delivery systems, and novel radiotherapeutics supported through several funding opportunity announcements renewed or ongoing in 2018–2020. For example, NIH is investing in capacity-building initiatives, emerging/innovative technologies, and acceleration platforms to expedite HIV vaccine manufacturing, including cell line development platforms, upstream and downstream purification approaches, and nanoparticle-based immunogen and adjuvant codelivery systems. Other ongoing activities and plans for 2020 focus on building an armamentarium of particulated adjuvants for preclinical and clinical studies. This includes manufacturing a liposomal adjuvant for antigen-adjuvant comparison clinical study, alum adjuvants to support various HIV immunogen/protein clinical trials, and a polysaccharide particle adjuvant for codelivery with HIV immunogens.

NIH-supported research in nanotechnology includes the development of oral biodevice technologies for the evaluation, monitoring, and management of oral and overall health, and the development of high-performing dental materials for the restoration, repair, and replacement of dental, oral, and craniofacial tissues. The trans-NIH effort (led by the National Center for Advancing Translational Sciences), "Microphysiological Systems for Disease Modeling and Efficacy Testing," will continue until 2022. This initiative supports studies to develop micro- and nanoscale *in vitro* microphysiological system platforms (also known as tissue chips), and to validate these platforms for their ability to mimic physiological functions of human tissues and organs. This effort, executed in partnership with DOD, FDA, and pharmaceutical industry partners, supports studies to demonstrate the functional utility of tissue chips.

Core programs in several NSF directorates support development of new principles, design methods, and constructive solutions for nanodevices. A special focus is on smart, autonomous nanoscale-based devices and systems. FHWA is pursuing advances in performance, durability, and resiliency of transportation infrastructure materials. Prior innovations in nanoscale characterization techniques and modeling material interactions at multiple scales are being leveraged to enable increased use of recycled or waste materials in infrastructure applications.

ARS is pursuing R&D aimed at enabling novel commercial processes for the development and production of new commercial cotton products, including cotton-containing nonwoven materials for the production of durable antimicrobial wound dressings; nanoscale metal particles inside cotton fibers providing increased flame retardant and moisture control properties; and cotton-based body-contacting materials for use in biomedical, biosensor, and hygienic applications. Other research includes using nanoparticles in new *in vitro* and *ex vivo* approaches for cellular and tissue biophotonic imaging and for tracking pathogens to address bacterial abundance and persistence related to livestock well-being, and the development of nanobiosensors for pathogen detection in food animals and plants and their derived products.

NIFA nanotechnology efforts support innovative and applied research to develop nanotechnology-enabled applications, devices, and systems for a wide range of national priorities. Applications of interest include food safety and security, animal health and wellness, development of novel bio-based products, and protection of agricultural ecosystems, with the objective of creating new discoveries, products, markets, and jobs.

NIST measurement science programs to support PCA 3 include efforts for photonic circuits, nanoscale coatings, atom-based devices, and nanoelectronics. NIST will continue to develop new methods to advance the development of single-photon detectors to harness the unique properties of graphene and to develop improved reference standards. NIST will also continue research efforts to advance the use of scanning probe microscopies to evaluate nanoscale properties of materials and to develop measurement and characterization methods that can drive advances in atomically thin two-dimensional devices for use in microelectronics. In 2020, NIST expects to demonstrate manipulation, initialization, and readout of single- and two-qubit systems made from precisely placed phosphorus dopants in silicon.

DOD will develop new approaches to interface with and control biological systems. These approaches include the development of "protonic" devices for actuating cells and self-assembled nanoscale transducers that can wirelessly control living cells. DOD is funding research on nanoclay-based insulating materials for electric propulsion motors and generators with game-changing torque density to address increasing demands for electrical energy on ships—and with potential commercial applications including in electric vehicles. DOD will continue applied research programs focused on the use of advanced materials, including nanotechnology, to support requirements for advanced force protection systems. DOD will collaborate with university researchers to investigate nanomaterial additions to construction materials such as asphalt and composites to improve mechanical properties and durability, and to study controlled optoelectronic properties for a variety of future sensing and coating applications. Planned research at ISN includes functional fibers and fabric networks; quantum dot UV tagging and communications; ultra-sensitive IED sensing; nanoparticle-enhanced obfuscation; health monitoring and treatment; and nano-optoelectronics research related to portable power, communications, and signal processing and detection.

NASA ongoing and planned PCA 3 investments include collaboration with a university to develop and prototype a compact, high-resolution spectrometer based on a quantum dot array. This array will be suitable for small satellite missions for a range of science applications including detecting composition of atmosphere or surfaces of planetary bodies, as well as Earth observations such as chemical analysis for homeland and national security applications. Other investments include work with NSF-funded university researchers on three-dimensional (3D) micro- and nanoscale printing of wireless temperature and pressure sensors, and work on manufacturing of flexible substrate printed nanosensors for chemical, biological, and radiation detection. These sensors will be used for planetary science missions and for monitoring crew cabin environments. NASA Ames researchers are developing nanoscale vacuum channel transistors (NVCTs) for use on future Europa missions. Work in 2019 involves assembling functional circuits based on NVCTs. In 2020, application demonstrations and redesigns for reliability and long lifetime will be undertaken.

PCA 4. Research Infrastructure and Instrumentation

NNI infrastructure investments will continue to support physical and cyber resources, as well as workforce development. The majority of agency investments in this category are devoted to user facilities and equipment. For example, the 2020 NSF request includes continued support for the National Nanotechnology Coordinated Infrastructure (NNCI), a network of university-based user facilities. A five-year renewal of NNCI is planned for 2020, and NSF will increase coordinated research on its Mid-Scale Research Infrastructure priority area. DOE/BES operates NSRCs, user facilities for interdisciplinary R&D at the nanoscale that encompasses new science, new tools, and new computing capabilities. The NSRCs contain cleanrooms, nanofabrication resources, one-of-a-kind signature instruments, state-of-the-art electron microscopy, and other instruments not generally available except at major user facilities. The facilities are made available through external peer review of academic, industry, and government user proposals. Operating funds enable scientific staff to perform cutting-edge research and provide technical support to external users. The NSRCs provide training for graduate students and postdoctoral researchers in interdisciplinary nanoscale science, engineering, and technology research.

In 2020, a currently operating NIST beamline, based on “hard” x-rays, will be joined by two NIST beamlines with “softer” x-rays at the National Synchrotron Light Source II (NSLS-II), located at DOE’s Brookhaven National Laboratory. Nine end stations will take advantage of the unique broad and brilliant spectrum at NSLS-II to provide a world-leading suite of tools to measure the atomic, molecular, and electronic structure of materials. A unique aspect of the NIST beamlines is the ability to measure samples with multiple beams, enabling the measurement of more diverse and complex structures such as in polymer-metal composites. The NIST Center for Neutron Research (NCNR) and the Center for Nanoscale Science and Technology (CNST) provide scientists from academia and industry with unique world-class capabilities.

Several agencies also fund centers that provide resources for the nanotechnology community. Relevant NSF centers are Science and Technology Centers (STCs), Engineering Research Centers (ERCs), Centers for Chemical Innovation (CCIs), and Materials Research Science and Engineering Centers (MRSECs). Examples include two ERCs, one each on nanobiotechnology and cell technology, and a CCI that investigates the fundamental molecular mechanisms by which nanoparticles interact with biological systems. NIH provides funds for resource centers in cardiac, cancer, dental, and other clinical research areas. NIH also has a long-standing practice of addressing infrastructure needs, such as information technology R&D, computing-enabled communications, and educational resources, through research funding mechanisms. NIH institutes also support training through networks and centers funded to achieve their mission-specific goals, e.g., the six National Cancer Institute (NCI) Centers in Cancer Nanotechnology Excellence (CCNEs), sixteen Innovative Research in Cancer Nanotechnology projects, and six Cancer Nanotechnology Training Centers. NCI also supports the Nanotechnology Characterization Laboratory (NCL), located in the Frederick National Laboratory for Cancer Research. NCL is an intramural laboratory serving as a centralized resource to characterize nanomaterials. NCL collaborates closely with FDA to be informed on regulatory aspects of nanotechnology and benefits from the expertise of NIST concerning nanomaterial standardization.

An ongoing interagency agreement between NIH and NIST supports development of performance-based, clinically-relevant standards for dental materials, including nanomaterials, for applications in the oral environment, and the design of new analytical instrumentation for characterization of nanomaterial-based dental composite restorative systems. In this collaboration, NIST is developing measurement strategies, standard methods, and reference materials, and NIH is providing funding support and expert scientific and clinical advice. NIH efforts to promote development of clinically relevant standards for dental materials will continue through 2020.

Workforce development remains an area of interest for NNI agencies. NSF continues to sponsor nanotechnology education and related activities, such as disseminating the video series developed with a media company and NNCO, *Nanotechnology: Super Small Science*. NSF also sponsors the “Generation Nano” competition for high school students with assistance from NNCO, and the “Quantum Matters” competition for undergraduate and graduate students, both nationwide, with the participation of a science museum.[22] An industrial internship program ("INTERN") in emerging technologies, including nanotechnology, has been expanded.[23]

NIFA support for nanotechnology education includes its competitive grants to universities for developing nanotechnology food and agricultural science curricula and its education and workforce development programs,[24] which focus on building institutional capacity and enhancing the pipeline for producing more STEM graduates to meet the projected shortfall in agriculture-related fields. NIFA's support for university-based nanotechnology R&D will train a cohort of transdisciplinary graduate and undergraduate students.[25]

PCA 5. Environment, Health, and Safety

A collaborative community of researchers—encompassing government, academic, and industry representatives—is required to ensure the responsible development of nanotechnology. NNI agencies individually and collectively support this community through a variety of activities that include fundamental research on the potential EHS implications of nanomaterials; development of resources such as databases, standard operating procedures, and guidance documents; participation in standards developing organizations; and sharing knowledge gains and safe practices with researchers and industry. Agencies and NNCO use a variety of mechanisms to share information on nanotechnology-related environmental, health, and safety (nanoEHS) research findings, including a public webinar series, presentations at technical conferences, and publications.

Several agencies will fund or conduct fundamental research to expand the nanoEHS knowledge base. NSF's requests for research are primarily directed at understanding nano-bio phenomena and processes, as well as EHS implications and methods for reducing the potential risks of nanotechnology development. NSF continues to sponsor a Center for Environmental Implications of Nanotechnology. The NSF nanoEHS program has been renamed Biological and Environmental Interactions of Nanoscale Materials.[26]

NIOSH will continue to conduct toxicology studies to evaluate biomarkers of exposure and disease using proteomic, metabolomic, and bioinformatic approaches. NIOSH will also continue developing innovative *in vitro* methodology to better predict *in vivo* outcomes, and evaluating pulmonary and dermal exposure and toxicity, and systemic toxicity that results from occupational exposures.

FDA's investments span several FDA centers. Select highlights include Center for Drug Evaluation and Research (CDER) research on quality considerations for complex drug products, bioequivalence of drug products containing nanomaterials, and advanced and emerging characterization methods; Center for Devices and Radiological Health (CDRH) efforts to better understand the complex interactions that occur between the body's physiological processes and various types of nanoengineered surfaces; and National Center for Toxicological Research and Office of Regulatory Affairs investments in advanced tools, safety assessments, staff training, standard methods, and methodology development.

EPA's nanoEHS research is focused on developing and applying information on engineered nanomaterials to inform both exposure and hazard assessments and support risk-based decisions related to the agency's implementation of the Toxics Substances Control Act and the Federal Insecticide, Fungicide, and Rodenticide Act. For example, the agency is conducting research to characterize the transport, transformation, fate, and environmental impacts of nanotechnology-enabled pesticides.

[22] https://www.mos.org/quantum-matters-competition
[23] https://www.nsf.gov/pubs/2018/nsf18102/nsf18102.jsp
[24] https://nifa.usda.gov/program/afri-education-workforce-development
[25] https://nifa.usda.gov/funding-opportunity/agriculture-and-food-research-initiative-foundational-applied-science-program
[26] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505553

NIH nanoEHS research efforts are designed to gain a fundamental understanding of the molecular and pathological pathways involved in mediating biological responses to engineered nanomaterials (ENMs). To continue the success achieved with a small library of ENMs, the Nanotechnology Health Implications Research (NHIR) consortium centers will continue to be funded through 2021. The centers will continue their efforts to gain understanding on ENM-biological interactions using diverse *in vitro*, tissue-on-chip, and *in vivo* models, and will expand their efforts to include additional emerging anisotropic ENMs. Collaborative efforts with FDA under the National Toxicology Program will also continue. This research complements exposure assessment of nanomaterial manufacturing facilities conducted in collaboration with NIOSH.

NIST EHS research continues at a modest level, leveraging cooperative efforts with other NNI agencies and international partners. For example, NIST researchers are working with CPSC under an interagency agreement to develop protocols to screen, collect, and detect ENMs in house dust. NIST and the European Commission Joint Research Centre intend to continue a collaborative effort to address the need for proven methods, standards, and reference materials to expedite the testing and regulatory approval of nanotechnology-enabled medical products. Two pilot programs focused on liposomal drug formulations are under development. Key partners in this effort include FDA, NCI/NCL, National Physical Laboratory (UK), and members of the EU's Nanomedicine Characterisation Laboratory.

As the use of 3D printers and additive manufacturing expands, agencies are working to ensure the responsible development of these technologies. CPSC and NIOSH will continue to investigate potential emissions, human exposures, and health implications of human exposure to ultrafine particles and bioactive compounds from 3D printers. EPA is planning complementary research to characterize the filaments, emissions, and products of 3D printing processes, and the resulting human exposures. DOD is characterizing emissions of nanoparticle additives and volatile organic compounds from fused deposition modeling 3D printers and stereolithography 3D printers, respectively; a future collaboration with NIOSH is anticipated.

NIFA support for EHS research relevant to agricultural production and food applications includes EHS assessments of engineered nanoparticles applied in food and agricultural systems; characterization of hazards, exposure levels, and transport and fate of engineered nanoparticles or nanomaterials in crops, soils (and soil biota), livestock, and production environments; as well as research on transport and fate of engineered nanoparticles in digestive pathways.

NIOSH plans to continue collaborations with other agencies and with industry, including its field research team visits to industry, and its work with trade unions and industrial partners to evaluate nanotechnology-enabled spray coatings, composites, and other nanotechnology-enabled materials in construction and manufacturing.

Use of SBIR and STTR Programs to Advance Nanotechnology

As called for by the 21st Century Nanotechnology Research and Development Act, this report includes information on use of the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs to support nanotechnology development, as well as highlights of agency SBIR and STTR topics and other programs and activities that directly support the accelerated deployment and application of nanotechnology R&D in the private sector.

Five NNI agencies—DOD, DOE, NASA, NIH, and NSF—have both SBIR and STTR programs. In addition, DHS, EPA, NIST, and USDA have SBIR programs that include funding for nanotechnology. Table 6 shows agency funding for SBIR and STTR awards for nanotechnology R&D from 2014 through 2017 (the latest year for which data are available).

Some NNI agencies (e.g., NSF, NASA, and DOE) have included nanotechnology-specific topics in their SBIR and STTR solicitations. The NSF SBIR program has an ongoing nanotechnology topic with subtopics for nanomaterials, nanomanufacturing, nanotechnology solutions for grand challenges, and other nanotechnology topics. DOE has had nanotechnology-related SBIR topics for more than a decade—most recently focused on atomically precise manufacturing. Some agencies have had applications-oriented solicitations for which many awardees have proposed nanotechnology-based innovations. SBIR/STTR data for 2004 through 2017 indicate that the NNI agencies have cumulatively funded nearly $1.5 billion of nanotechnology-related SBIR and STTR awards during this period.

Table 6 illustrates the steady increase in recent years in the level of nanotechnology-related SBIR and STTR funding, with 2017 at a record high of $180 million. Even though few agencies specifically call out nanotechnology in their SBIR/STTR solicitations, it is enabling innovations in many R&D application areas.

Table 6: 2014–2017 Agency SBIR and STTR Awards
(dollars in millions)

	2014			2015			2016			2017		
Agency	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**
DHS	0.3	0.0	0.3	4.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0
DOC/NIST	0.7	0.0	0.7	0.2	0.0	0.2	0.3	0.0	0.3	0.7	0.0	0.7
DOD	11.1	6.5	17.6	24.6	2.8	27.4	41.9	7.3	49.2	61.5	14.5	76.0
DOE	15.1	2.5	17.5	20.5	4.0	24.5	26.2	4.7	30.9	25.1	5.4	30.5
EPA	0.9	0.0	0.9	0.9	0.0	0.9	1.7	0.0	1.7	0.3	0.0	0.3
HHS/NIH	26.9	3.2	30.1	21.8	3.2	24.9	18.2	5.7	24.0	27.2	7.1	34.3
NASA	2.1	1.9	4.0	3.3	0.9	4.2	3.5	1.1	4.6	12.2	2.6	14.8
NSF	22.1	3.6	25.8	19.6	3.8	23.4	22.9	3.5	26.5	18.2	5.5	23.7
USDA	0.1	0.0	0.1	1.5	0.0	1.5	0.0	0.0	0.0	0.3	0.0	0.3
TOTAL	**79.3**	**17.7**	**97.0**	**96.4**	**14.7**	**111.0**	**114.8**	**22.4**	**137.2**	**145.5**	**35.2**	**180.7**

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

- Developing next-generation organ-on-a-chip microfluidic systems for sensing the presence of nanoparticulates in biological matrices (DOD).
- A new high-temperature (up to 1,800 °C) ceramic nanosensor platform (DOE).
- Sensors for measuring mass flow rates of high-temperature processes for fossil energy systems with dense particle flows (DOE).
- Atomically precise catalysts and membranes (DOE).
- Nanophotonic capillary-based water recovery systems (NASA).
- Effective targeted delivery of RNA-based vaccines and therapeutics (NIH).
- Novel optical dental imaging technology utilizing targeted upconversion nanoparticles for noninvasive detection of dental caries (NIH).
- Customized nanotechnology-based treatment of oral cancer (NIH).
- Use of ultra-small nanoparticles for intra-operative imaging and delineation of lymph nodes in surgery (NIH).
- Novel strategies for synergistic delivery of antigens and adjuvants in nanotechnology-enabled immunotherapies (NIH).
- Use of nanodevices for single-cell analysis to discern response to immunotherapies (NIH).
- Measuring the concentration of host-cell proteins in biomanufacturing (NIST).
- Design of sub-100-nm polystyrene particles with a low coefficient of variation in size (NIST).
- Nanosilver-embedded filters for affordable point-of-use water disinfection (NSF).
- Metal organic frameworks for recovery of natural gas during oil and gas production (NSF).
- Low-friction and high-durability nanoparticle composite coatings for bearings (NSF).

- Paper/nanotechnology-based sensors for rapid detection of pesticides in food and water (USDA).
- Manufacturing of ultra-efficient and robust nano-array-based lean NO_x trapping devices (EPA).

Other activities contributing to nanotechnology commercialization include the NSF Industry/University Cooperative Research Centers (I/UCRC),[27] Partnerships for Innovation (PFI),[28] and Advanced Manufacturing[29] programs, the NIST Return on Investment Initiative,[30] the NIH Integrated Preclinical/Clinical AIDS Vaccine Development Program,[31] and several public-private partnerships aimed at accelerating progress in the semiconductor industry[32] and cellulosic nanomaterials derived from trees and other natural sources.[33] Examples of nanotechnology-related topics supported under Innovation Corps (I-Corps™) funding include nanoparticle polymeric antibiotics for drug-resistant infections and interconnect-based nanoscale computing technology for future digital integrated circuits. Additional programs aimed at unleashing American innovation, including NSF's Convergence Accelerators[34] and focused Lab-to-Market efforts, will further support the transition of nanotechnology research advancements into commercial products.

[27] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5501
[28] https://www.nsf.gov/pubs/2019/nsf19506/nsf19506.htm
[29] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505572
[30] https://www.nist.gov/tpo/return-investment-roi-initiative
[31] https://grants.nih.gov/grants/guide/pa-files/PAR-15-330.html
[32] For example, the DARPA JUMP program, the NSF E2CDA program, and the NIST NEW LIMITS and SMART programs.
[33] P3Nano, a partnership between the USDA Forest Service and the U.S. Endowment for Forestry and Communities, Inc. (https://www.usendowment.org/what-we-do/innovation/p3nano-advancing-commercialization-of-cellulosic-nanomaterials/).
[34] https://www.nsf.gov/od/oia/convergence-accelerator/index.jsp

3. Progress towards the NNI Goals

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

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

Nanotechnology research and development activities are taking place all over the world, and NNI participating agencies are committed to supporting basic and early-stage applied research at the leading edge to keep the United States at the forefront of this important area. Continued Federal investments will enable future discoveries that build upon and expand the body of knowledge already developed under the auspices of the NNI to ensure that the United States realizes the benefits to our national and economic security. Meanwhile, research results from past NNI investments are being broadly applied by the private sector in new commercial products, in applications as diverse as automobiles and health care.

Research and development activities in the areas of nanoelectronics, nanomanufacturing, sensors, and water are closely coordinated through the Nanotechnology Signature Initiative[35] mechanism to enhance interagency collaboration and better leverage knowledge and resources.

The following highlights exemplify NNI research expanding the boundaries of scientific understanding in nanoscience and nanotechnology.

Combating pathogens. Researchers at DOE's Molecular Foundry have developed a process for creating ultrathin, self-assembling sheets of synthetic materials that selectively bind with viruses, bacteria, and other pathogens. This is the first time nanostructures have been engineered with such sophistication that they approach the structural precision and complexity found in nature.[36] These nanosheets could find use in biosensors, therapeutics, or the bioremediation of threat agents. Foodborne pathogens increasingly exhibit antibiotic resistance. ARS, in collaboration with university researchers, tested the antimicrobial properties of silver magnetic nanoparticles (Ag-MNPs) against *Escherichia coli* and *Salmonella*. The results indicated that the antimicrobial effects of Ag-MNP are likely exerted through protein changes affecting critical bacterial functions. These proteins can serve as novel biomarkers to further target bacterial contamination, with potential impacts in livestock production.

Exciting cells to treat the brain. DOD has significant interest in new technologies to stimulate electrically excitable cells such as neurons or muscle cells for new diagnostics and therapeutics. DOD scientists, in collaboration with university neuroscientists, have developed technology to interface gold nanoparticles (NPs) with the plasma membrane of neurons. Upon photoactivation of the membrane-tethered NPs, modest local heating of the plasma membrane bilayer opens ion channels that induce action potentials, the basis of neuron activation and communication in the brain. Given the established biocompatibility of gold NPs in the clinic, this novel technology opens the possibility of new, noninvasive therapies for the treatment of traumatic brain injury, post-traumatic stress disorder, and depression.

Understanding and healing wounds. Curing severe blast-induced wounds will require a thorough understanding of the damaged tissue environment. It has recently been postulated that cells secrete nanovesicles called exosomes to help guide the wound healing process, but these vesicles have proven exceedingly difficult to detect. DOD scientists have invented novel nanosensors, comprised of gold-capped nanopillars, which enable single exosome detection in a massively parallel format for the first time. ARS

[35] http://nano.gov/signatureinitiatives
[36] https://science.osti.gov/bes/highlights/2018/bes-2018-07-b/

researchers have prepared cotton-based nanocellulosic aerogels that can be interfaced with chronic wound dressings to sense harmful proteins. Additionally, ARS researchers have developed hemostatic wound dressings using cotton nanocellulose that accelerates clotting and contains protease biosensors that stimulate healing.

University researchers supported by NIH developed an efficient electrical bandage to accelerate wound healing. This bandage uses a wearable nanogenerator to convert skin movements into electricity. Studies demonstrated closure of a full-thickness skin wound within 3 days, compared to the 12 days typical in contraction-based healing. This self-powered electric-dressing modality could provide a therapeutic strategy for non-healing skin wound treatment.[37] DOD-supported researchers at ISN have developed novel nanocomposites for improved hemostasis in wounds, resulting in reduced clotting times or minimal blood loss.

Improving drug delivery. University researchers funded by NIH have developed a method to enhance delivery of nanocarriers to organs by adsorbing the particles onto red blood cells (RBCs). Selective intravascular injection of the RBCs then leads to transfer of the absorbed nanocarriers into the first downstream organ. For example, intravenous injection results in a 40-fold increase in nanocarrier delivery to the lungs, the first downstream organ, relative to injection of free nanocarriers. Injection of RBCs into the carotid artery results in a 10-fold increase in delivery to the brain relative to free nanocarriers. This technology has the potential to enhance drug delivery in diseases such as acute lung injury and stroke while reducing off-target toxicity.[38] Another NIH-funded project has explored the use of lipid nanoparticle (LNP)-mediated delivery of mRNA. This technique has the potential to provide effective treatment for a spectrum of diseases, but efficacy is limited by predominant uptake of LNPs in the liver. Conjugation of mRNA LNPs with antibodies specific to a vascular adhesion molecule resulted in a 200-fold inhibition of liver uptake and a 25-fold increase in mRNA uptake and protein expression in lungs relative to non-targeted LNPs.[39] ARS researchers have developed a soybean oil-base nanolipid that loads and delivers multi-drug-resistant anti-breast cancer drugs.

Visualizing living cells. Researchers at the NSF-funded Center for Sustainable Nanotechnology have developed a high-throughput technique to create biocompatible carbon dots with tunable sizes and emission wavelengths, enabling a significant advance in the ability to visualize living cells using a super-resolution fluorescent microscopy technique.[40]

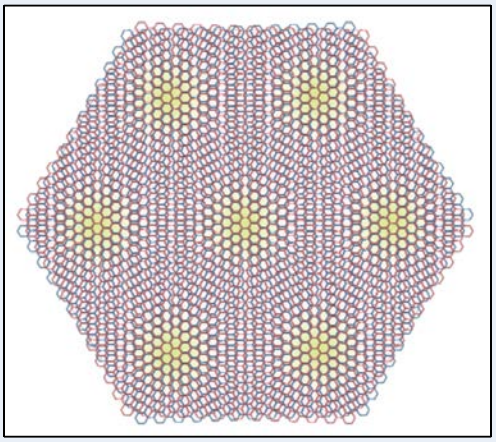
Advancing nanoelectronics. NIST researchers collaborated with university scientists to discover a method to induce structural transitions in resistive random access memory (RRAM) devices. RRAM programming voltages are tunable by controlling the thickness of MoTe-based nanofilms. These findings demonstrate controlled electrical state switching in two-dimensional (2D) materials and highlight the potential of TMD nanomaterials for memory applications.[41] Another group of NIST researchers developed a chemical modification method for controllable and wide-ranging doping of monolayer TMDs. This method can be used to make CMOS transistors for low-energy electronics.

Understanding and creating new electronic states. Scientists at NIST have determined the electronic band alignment of technologically important 2D monolayer layered heterojunctions. This information is used to design and fabricate novel 2D tunnel field effect transistors. In another advancement, NIST researchers have discovered that excitons bound to a single CNT are accompanied by "intertube excitons" that involve tunneling to closely interacting nanotubes. This newly observed quantum tunneling action could impact energy

[37] https://pubs.acs.org/doi/abs/10.1021/acsnano.8b07038
[38] https://www.ncbi.nlm.nih.gov/pubmed/29992966
[39] https://www.ncbi.nlm.nih.gov/pubmed/30336167
[40] https://pubs.acs.org/doi/abs/10.1021/acsnano.8b01619
[41] https://www.nature.com/articles/s41563-018-0234-y

distribution in CNT networks, with implications for light-emitting films and light-harvesting applications. DOD scientists have fabricated a novel bilayer structure comprised of two different monolayer materials to create a new electronic state called an "interlayer exciton" formed between the two layers. These results provide fundamental insight into emerging semiconductor materials, and will enable use of heterostructures for a wide range of technologies, including novel optoelectronic devices such as nanolasers and photodetectors.

"Magic angle" bilayer graphene behaves like a high-temperature superconductor



Moiré pattern formed by twisting two layers of graphene by a small angle. Image credit: Pablo Jarillo-Herrero group, MIT.

University researchers funded by NSF, AFOSR, ARO, and a private foundation have demonstrated that two layers of graphene laid on top of each other at a "magic angle" of precisely 1.1 degrees exhibit superconductivity at high temperature. This research, which was awarded the Physics World "breakthrough of the year award" for 2018, provides new insights into the physics underlying this two-dimensional material's intriguing properties, as well as into the physics of high-temperature superconductivity more generally. Follow-on work published in early 2019 by another university-led team (funded by NSF, ARO, DOE, and a private foundation) has developed a new method to finely tune twisted bilayer graphene to induce superconductivity by applying pressure. The new work confirms the 2018 findings and also demonstrates that squeezing the layers has the same effect as twisting them. Researchers are now twisting and squeezing a variety of atomically thin materials in the hopes of finding superconductivity emerging in other 2D systems. Potential applications include quantum computing and other information technologies, and ultrasensitive photodetectors.

Inventing an artificial synapse. A DOD-sponsored university research group has invented a CNT-based artificial synapse. The CNT-based synaptic resistor (or "synstor") emulates the analog convolutional signal processing, correlative learning, and nonvolatile memory functions of neurobiological synapses. A synstor crossbar circuit was demonstrated to concurrently process and learn from the signals in parallel analog mode with an energy efficiency of 10^{15} floating-point operations per second per watt.

Improving membranes. NSF-funded university researchers have developed a sequence-designed polymer that acts as molecular code to build programmable artificial nanopores that could be used to improve water desalination, biosensing, and energy conversion. Another group supported by NSF has developed block copolymer membranes in a hollow fiber configuration for metal ion capture.[42] Scientists at NIST performed simulations of a new nanoporous membrane, demonstrating that ion flow through the nanopores is highly sensitive to membrane stretching. Potential applications of these membranes include salinity control of solutions, nanoscale mechanical sensing, and a platform for studying ionic solvation.

Making invisible glass. DOE-supported researchers have shown that nanotextured glass surfaces can reduce light reflections to less than 0.2 percent across all visible and infrared light wavelengths—even at large viewing angles. These ultra-transparent windows could change cell phones, solar cells, and lasers and enhance the user experience for consumer devices such as smart phones and televisions. Silicon solar cells encapsulated with "invisible glass" virtually eliminate reflection losses and outperform conventional devices.[43]

[42] https://onlinelibrary.wiley.com/doi/abs/10.1002/app.47038
[43] https://science.osti.gov/bes/highlights/2018/bes-2018-06-a/

Producing large single-crystal-like graphene films. DOE researchers produced large, single-crystal-like graphene films more than a foot long using a new method that relies on harnessing a “survival of the fittest” competition among graphene crystals.[44]

Discovering nanocrystal glue. DOE researchers have discovered that the internal structure of all-inorganic perovskite nanoparticles is different than bulk formulations of the same material. In fact, the phase that has highly desirable optical absorption properties becomes more stable at the nanoscale than the phase typically found in larger crystals. The team built on this discovery and developed a “glue” that locks the nanocrystals together into conductive arrays that retain the nanocrystals’ excellent properties.[45]

Advancing properties of nanocomposites. Scientists at NASA collaborated with industry researchers to produce, at a large scale, CNT reinforcements with nearly three times the specific tensile strength of state-of-the-art CNT fibers and utilized them to fabricate polymeric composites with more than double the specific tensile strength of today’s CNT-reinforced composites. The goal of this work is to incorporate these advanced composites into cryogenic propellant tanks and other components for use in nuclear thermal propulsion systems for future NASA space exploration missions.

A DOD-university team has developed novel thermoset nanocomposites with toughness values greater than any previously known materials. The work is of high relevance to next-generation Air Force platforms that require bonding of dissimilar materials and addresses the need for higher-temperature and lighter composites with complex interlaminar bonding for future jet engines with improved range and fuel economy. In another DOD project, researchers have developed new approaches for the synthesis of hybrid polymer nanocomposites using a combination of functionalized CNTs, graphene, and graphene oxide. These hybrid systems enable improved tensile strength by up to six times along with increases in toughness for Nylon 6 polymer-based nanocomposites.

Developing shape-shifting materials. A DOD team developed liquid crystal elastomers (LCEs) that exhibit anisotropic mechanical, thermal, and optical properties. The researchers prepared nanocomposites in which both the orientation of the LCEs and single-walled carbon nanotubes (SWCNTs) are locally and arbitrarily oriented. The addition of SWCNTs increases the stiffness of the LCE in the orientation direction, yielding a material with a 5:1 directional modulus contrast. The team demonstrated that localized orientation of the LCE and SWCNT allows complex 3D shape transformations to be electrically triggered. Scientists at ISN have developed novel nanostructured functional inks and an accompanying 3D printing platform that can enable both the modeling and design of complex, magnetically actuated devices. While these transformations occur on the macroscale, other DOD researchers have developed a low-energy technique to reshape plasmonic particles on the nanoscale. The nanoparticle reshaping approach works for large-area patterned plasmonic nanocomposites. Films with a distribution of plasmonic properties enable technologies including colorimetric sensors, filters, and gradient refractive index elements. The chemistry-based reshaping occurs >100x faster (seconds) than previously demonstrated using a surface diffusion mechanism (days).

Fabricating nanostructured ceramics. DOD scientists have developed a rapid and scalable process for the fabrication of nanostructured silicon carbide-based ceramics displaying mechanical metamaterial properties. These novel mesoporous structures are achieved through patterning at the nanoscale via block copolymer self-assembly and do not require the typical annealing steps. *In-situ* nanomechanical compression testing reveals ductile-like deformation, complete strain recovery up to 14% strain, and enhanced energy absorption over bulk ceramics. The confluence of rapid self-assembly, affordability, and mechanical metamaterial properties offered by this system solve typical production challenges.

[44] https://science.osti.gov/bes/highlights/2018/bes-2018-08-f/

[45] https://science.osti.gov/bes/highlights/2018/bes-2018-02-m/

Customizing wetting states. DOD- and NSF-funded university researchers have demonstrated a patterning strategy to create functional nanostructured surfaces that enable tunable wetting states with reversible transitions. By stretching and reshrinking polymer nanoridges, structural features could be controlled, and different wetting transitions were achievable in a programmable manner. This parallel, lithography-free technique can rapidly prototype surfaces for diverse applications in advanced water collection, self-cleaning systems, and directed water transport.[46]

Sensing biomarkers, neurochemicals, and drugs. Researchers supported by DOD have developed a small, conformal radio frequency sensor that can be mounted on a tooth and continuously transmit information about analytes of interest in the oral cavity. Multiplexed sensing can be achieved by integrating multiple sensing layers, and potential applications include tracking nutrient intake and monitoring biomarkers found in saliva indicative of disease, inflammation, stress, or fatigue.[47] University researchers supported by NSF have developed graphene sensors for *in vitro* detection of dopamine and serotonin molecules. The approach achieved reproducible fabrication of miniaturized sensors with extraordinary sensitivity relative to conventional materials and laid the foundation for new graphene-based integrated electrochemical sensor arrays.[48] NSF also funded researchers to develop a chip with unique plasmonic nanostructures for on-site drug sensing. The chip could be integrated into a handheld, portable device for detecting drugs in biological samples such as blood, breath, urine, or spit.[49]

Protecting pilots and passengers. DOD scientists have developed a novel CNT-based isopropyl alcohol (IPA) gas sensor to monitor oxygen provided to aircraft pilots and passengers from engine bleed air. IPA has been hypothesized to be a key contaminant causing air sickness. The sensor can discriminate IPA from other air contaminants more selectively than a state-of-the-art commercial volatile organic compound sensor.

Sensing water quality. NIFA-funded university researchers have developed next-generation water quality sensors using tailored nanostructured polymer composite materials. The materials were incorporated as electrodes in an electrochemical cell to make a portable sensor for arsenic in water samples. These sensors harvest energy from the local environment so that battery replacement or charging is not needed.

Building better batteries. A research team supported by DOD reported that crumpled paper-ball-like graphene particles can readily be assembled to yield a battery electrode scaffold with scalable Li loading up to 10 mA hr cm^{-2} within tolerable volume fluctuation. High coulombic efficiency of 97.5% over 750 cycles (1,500 hr) was achieved. Dendritic growth was not observed with plating/stripping Li up to 12 mA hr cm^{-2} on crumpled graphene scaffolds, which points to a solution to a long-standing problem plaguing Li-ion batteries.[50]

Nanostructuring for nuclear energy applications. The DOE Office of Nuclear Energy has supported a variety of projects that investigate nanostructural behavior in materials relevant to nuclear energy applications. Research includes irradiation-resistant nanostructured thermoelectric materials and devices for in-pile power harvesting and sensing, nanodispersion-strengthened metallic composites with enhanced neutron irradiation tolerance, and a nanostructured bulk thermoelectric generator for self-powered sensor networks.

Reducing soldiers' loads. Scientists at ISN have dramatically improved the efficiency of thermophotovoltaic devices using nanostructured photonic crystals. The team demonstrated a nanophotonics-enabled ultra-high-energy-density wearable power source technology for the first time. It has potential to reduce a soldier's battery load by more than 75 percent in a 72-hour dismounted mission. The entire device (including fuel) will be roughly water-bottle sized, safe to handle, and have no moving parts.

[46] https://onlinelibrary.wiley.com/doi/full/10.1002/adma.201706657
[47] https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201703257
[48] https://onlinelibrary.wiley.com/doi/10.1002/adma.201805752
[49] https://onlinelibrary.wiley.com/doi/full/10.1002/smtd.201800045
[50] https://www.cell.com/joule/fulltext/S2542-4351(17)30148-4

Eliminating friction. ISN researchers have demonstrated near-zero friction (superlubricity) between stainless steel and diamond-like-carbon with densely functionalized graphene displaying dynamic intersheet linkages that mechanically transform into stable tribolayers. The macroscopic lubricity evolves through the formation of a thin film of an interconnected graphene matrix on the stainless-steel surface. This approach to reducing friction has broad implications for manufacturing, transportation, and aerospace.

Making cotton flame retardant. ARS researchers have developed low-cost, simple approaches that confer flame retardant and moisture control properties to semidurable cotton textiles through a layer-by-layer (LbL) coating technique that uses nanoscale clay particles as a dispersing matrix. These clay treatments provide a variety of physical and chemical properties to cotton including moisture management, strength, and absorptivity. By treating the cotton fabric with nanocoatings composed of phosphorous-nitrogen-rich polymers prepared via LbL, the fabric can also be rendered anti-flammable. This novel approach would provide excellent thermal protection for medical, military, and large-scale emergency materials where a low-cost, semi-durable product is desired. These same researchers developed a “green” antimicrobial nanosilver cotton fabric that reduces odor-forming bacteria.

Advancing quantum science and technology. A source that emits a regular stream of single photons is a critical component in a wide range of nascent quantum-based technologies, including secure communications, sensing, and computation. Scientists at the DOE Center for Integrated Nanotechnologies and their colleagues chemically modified CNTs, resulting in the first material to emit single photons at room temperature and at telecom wavelengths.[51] DOD scientists have developed a way to directly write quantum light sources into monolayer semiconductors such as tungsten diselenide.

In collaboration with DOE, industry, and academia, the NIST single-atom device project has made single-atom transistors using single phosphorus dopant atoms deterministically placed with near-atomic precision in silicon and aligned with gates and leads also fabricated with single-atom placement. Characterization of the device operation as a single-electron transistor shows clear transport of electrons one-by-one, is stable for long periods of time, and is resistant to typical forms of noise because of the strong quantization provided by individual atoms.

Researchers at NIST have used magnetic fields to confine groups of electrons to a series of concentric rings within graphene. This tiered “wedding cake” experimentally confirms how electrons interact in a tightly confined space according to long-untested rules of quantum mechanics. These findings could also have practical applications in quantum computing.[52]

Scientists and engineers at DOD have incorporated pairs of coupled quantum dots into micromechanical resonators and shown that they are sensitive to motion. Quantum sensing of motion will enable sensitive accelerometry for applications including inertial navigation and gravitational detection of massive objects. These results can also be used to better control quantum systems, couple multiple quantum bits, and access the quantum limits of motion.

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

There are thousands of products on the market resulting from Federal investments in nanotechnology R&D, including sound dampening foams in use by a U.S. automaker, vibrant displays incorporating quantum dots, consumer electronics, myriad coatings and films, and nanomedicines, to name just a few. While nanotechnology is in products throughout the marketplace, there remains significant potential for nanotechnology to enable and inspire entirely new devices and systems in a broad array of applications,

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[51] https://science.osti.gov/bes/highlights/2018/bes-2018-02-j/, https://science.osti.gov/bes/highlights/2018/bes-2018-08-c/
[52] https://www.nist.gov/news-events/news/2018/08/novel-graphene-quantum-dot-structure-takes-cake

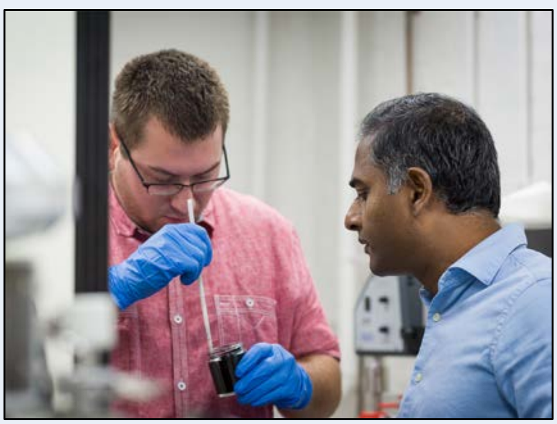
from quantum computing to the treatment of disease. To realize this potential, the focus of Goal 2 is to facilitate the transfer of nanotechnology research and development breakthroughs into applications that the private sector can bring to market. The NNI fosters commercialization through activities such as sharing information, promoting access to user facilities, leveraging resources through public-private partnerships, and participating in international standards activities that are critical to commercialization. In addition to these mechanisms, NNCO has a devoted industry liaison who supports the industry ecosystem by conducting outreach, sharing best practices, and suggesting collaborations as appropriate.

The examples below highlight efforts to support the transfer of technologies into application for public benefit.

Fostering the entrepreneurial ecosystem. NSF's industrial internship program ("INTERN") in emerging technologies, including nanotechnology, has been expanded. NSF continues its contributions to translational innovation programs, including Grant Opportunities for Academic Liaison with Industry (GOALI); Industry/University Cooperative Research Centers (I/UCRC); the NSF Innovation Corps (I-Corps™) program; and within the Partnerships for Innovation (PFI) program, the Technology Translation (PFI-TT) and Research Partnerships (PFI-RP) tracks. The NSF SBIR program has ongoing nanotechnology topics. Examples of recent nanotechnology-related I-Corps awards include research on nanocatalysts for automobile and fuel cell applications,[53] chip-based nano-optofluidic biosensors,[54] novel greases containing carbon nanoparticles,[55] and nanoparticle polymeric antibiotics for drug-resistant infections.[56]

Nanotechnology-enabled carbon fiber composites for the aerospace market

A small business leveraged Federal resources to create a new class of advanced materials that attracted millions of dollars in private sector capital as well as investment from the aerospace industry for more widespread adoption. With support from the Air Force, NASA, and NSF SBIR and STTR programs, the company developed carbon nanotube-based carbon fiber (CF) composites with increased metallic properties compared to conventional CF composites. These materials are designed to reduce weight and enable significant improvement in protecting aircraft and spacecraft from electromagnetic interference and lightning. Throughout the project, the company worked with the Air Force Research Laboratory's Materials and Manufacturing Directorate and used additional support from the Air Force SBIR/STTR Commercialization Readiness Program to partner with a Fortune 50 company. This partnership helped convert the early-stage materials technology into scalable systems, which are now in various stages of evaluation for aerospace production. As a result, the small business is quadrupling the size of its manufacturing facility, investing in new capital equipment, and creating jobs. According to the company, sales in the most recent fiscal year increased five-fold over the previous year and its employee roster is expected to triple, to more than 20 people, within 18 months.



Engineers evaluate conductive nanomaterials for aerospace and defense applications.
Image credit: Veelo Technologies, LLC.

Collaborating to accelerate nanotechnology in aerospace and automotive markets. Collaboration between DOD and a major aerospace company, and support by beamline scientists at Brookhaven National Laboratory, has led to new insights in the complex crosslink reactions of thermosetting resins by using

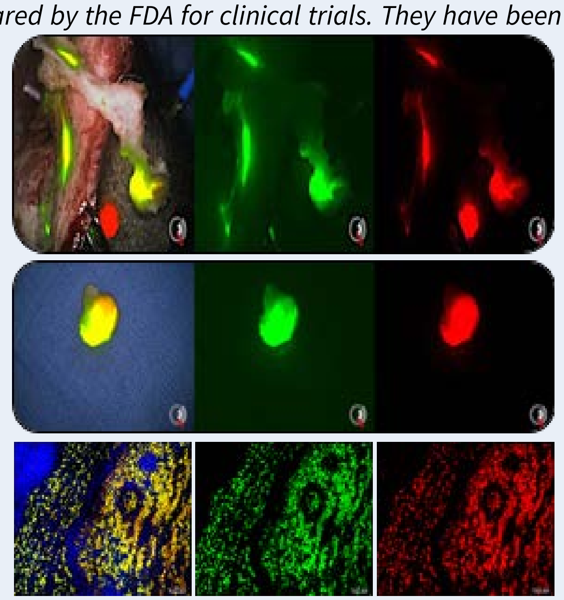
[53] https://nsf.gov/awardsearch/showAward?AWD_ID=1838369&HistoricalAwards=false
[54] https://nsf.gov/awardsearch/showAward?AWD_ID=1824872&HistoricalAwards=false
[55] https://nsf.gov/awardsearch/showAward?AWD_ID=1806034&HistoricalAwards=false
[56] https://nsf.gov/awardsearch/showAward?AWD_ID=1761711&HistoricalAwards=false

nanoparticle probes in x-ray photon correlation spectroscopy experiments. Optimizing the processing steps leads to improved mechanical properties, thermal stability, and overall life-cycle performance, and will ultimately reduce scrap rates in polymer matrix composite production. A NASA team developed a gold nanoparticle catalyst system to oxidize carbon monoxide for use in emergency response respirators on the international space station (ISS) and in future human exploration missions. This catalyst can oxidize carbon monoxide at rates more than ten times faster than state-of-the-art catalysts. This system has been certified for use on the ISS and is slated for future use in the Orion spacecraft.

Translating nanotechnology from bench to bedside. NIH is advancing development of multiple nanotechnology-based HIV vaccine platforms and products for clinical studies. It is fostering innovative and promising nanotechnology platforms by providing funding/seed investment to principal investigators and biotechnology companies. NIH is developing broadly effective HIV vaccine candidates using lipid nanoparticles; this is coupled with development of methods for mass producing the vaccines in compliance with FDA Current Good Manufacturing Practices, and the development of a nasal spray delivery mechanism. NCI-funded CCNEs have established several start-up companies that are translating and commercializing technologies developed in academia with NCI funding. These companies have entered over 20 clinical trials associated with nanotechnology-based cancer treatments. An example is shown in the sidebar below.

Silica nanoparticles for intraoperative sentinel lymph node mapping and radiotherapy

University and hospital researchers funded by NIH have developed highly fluorescent and versatile ultrasmall silica nanoparticles, Cornell prime dots or "C'-dots," for real-time image-guided visualization and treatment of disease. Intraoperatively, this platform provides visual cues to the surgeon to efficiently guide his/her approach, reduce tissue dissection, and precisely localize the first lymph nodes to receive tumor cells from the primary tumor site, sentinel lymph nodes (SLNs). As an ultrabright imaging platform, C' dots can identify SLNs several centimeters deep. They have also been used for targeted therapeutic delivery of radiotherapies and small molecule drugs. These particles have been cleared by the FDA for clinical trials. They have been used to successfully encapsulate a variety of optically distinct dye molecules for concurrent detection of multiple cancer signatures in larger-animal models. The group has further modified C' dots to target tumor cells for high-resolution (<50 micrometer) detection of lymph node micrometastases using clinical fluorescence-guided surgery. Such enhanced intraoperative detection capabilities enable more accurate removal of tumor-bearing SLNs and better patient outcomes. FDA has approved (1) an advanced (Phase 2) clinical trial for SLN mapping in head and neck cancer patients and (2) a Phase 1 trial in malignant brain tumor patients using new ^{89}Zr-labeled, integrin-targeting C'-dots for "pre-therapeutic" planning. A breakthrough designation is currently in progress to accelerate product approval for image-guided SLN mapping.



Green and red dyes indicate unique cancer markers in a large-animal model (top row), in tumors that have been excised (middle row), and in tissue samples of the excised tumors (bottom row). The images in yellow show where the green and red dyes overlap. For further information on this work, see the podcast interview with Michelle Bradbury on the NNI's "Nanotube" site (https://www.youtube.com/channel/UCwO7o2ZT-ATkbl0KrJXXhdA). Image credit: Michelle Bradbury, Memorial Sloan Kettering Cancer Center, and Ulrich Wiesner, Cornell University, Professors & Co-Directors, MSK-Cornell Center for Translation of Cancer Nanomedicines (an NCI CCNE).

Grantees funded by NIH made significant progress in optimizing the nanoscale properties of candidate dental composites by implementing strategic feedback on product development and regulatory requirements, based on interactions with FDA and industry experts. The newly developed dental materials have shown unique features such as self-healing and anti-microbial properties. Additionally, investigators have demonstrated improvements in mechanical performance, biocompatibility, ease of clinical handling, and durability of dental resins combined with nanoparticle-based materials. Several groups are pursuing commercialization strategies via partnerships with industry, product licensing, or startup ventures, and several patents have been issued.

NIH's Dental, Oral and Craniofacial (DOC) Tissue Regeneration Consortium is facilitating the advancement of promising technologies, including nanotechnology-based approaches for regeneration and reconstruction of DOC tissues, to Phase 1 clinical trials. Examples of products and devices include tissue regeneration-enhancing scaffolds and drug and cell delivery systems. Accomplishments under an ongoing NIH-NIST collaboration include advances towards the development of a nanoscale carbonated apatite material mimicking human dental enamel that may find use as a Standard Reference Material. Additionally, NIST researchers have reported successful preparation of nanoscale carbonated hydroxyapatite to prototype a material with comparable composition, porosity, and mechanical properties to those of human enamel.

FDA has worked to understand the properties of nanomaterials as they are used in drug products. This work informs and ensures the development of a regulatory framework that appropriately assesses the impact of nanomaterials on the quality, safety, and efficacy of new and generic drug products. FDA recently published two guidance documents for developers of nanotechnology-enabled drug products: Guidance for Industry: Liposome Drug Products,[57] and the Product-Specific Guidance for Doxorubicin HCL Liposome Injection.

ISN researchers have created a new class of adjuvant nanoparticles composed of lipids, immunostimulatory glycolipids, and cholesterol that self-assemble into well-defined nanoparticles. These particles are designed to efficiently traffic to lymph nodes and stimulate multiple innate immunity pathways to promote vaccine responses. The team discovered that these nanoparticles can elicit a 75-fold increase in antibody titers relative to a model diphtheria vaccine compared to standard adjuvants.

Working with standards developing organizations. Voluntary consensus standards critically support the commercialization and adoption of nanotechnologies, and NNI agencies actively participate and lead in standards efforts through organizations such as ASTM International, the International Electrotechnical Commission, and the International Organization for Standardization (ISO). For example, NIST chairs the U.S. Technical Advisory Group (TAG) to the nanotechnology technical committee of ISO Technical Committee (TC) 229 on Nanotechnologies. The TAG includes representatives of other Federal agencies and private sector organizations, formulates positions and proposals, and provides delegates and experts who represent the United States in ISO groups. Projects led by NIST experts relating to revision of terminology for nanomanufacturing and a new technical specification on particle size and shape distribution characterization using scanning electron microscopy are nearing final publication as Technical Specifications from ISO TC 229. Forest Service experts are involved in ISO groups that are developing reports, technical specifications, and characterization protocols for cellulosic nanomaterials, and reviewing and revising existing standards to incorporate cellulosic nanomaterials. NIST also chairs ASTM International Committee E56 (Nanotechnology). FDA nanotechnology research resulted in contributions to ASTM and ISO standards. FDA recently added four ASTM E56 standards to its list of recognized consensus standards for nanotechnology, bringing the total number of standards adopted for the use of nanotechnology in medical devices to eight. The NNI Standards Coordinator from NIST facilitates sharing of information among the agencies.

Advancing technologies for energy and infrastructure. The SBIR program at the DOE Office of Fossil Energy supported two small businesses that are developing sensors built on nanoscale phenomena. One

[57] https://www.fda.gov/downloads/drugs/guidances/ucm070570.pdf

company has developed a new high-temperature (up to 1,800 °C) ceramic sensing platform that was competitively selected for additional testing by DOD.[58]

DOD researchers collaborated with a university to study the use of nanocellulose additives for concrete and polymer composites. This work focused on functionalization approaches and composite synthesis methods to generate improvements in mechanical properties. The Forest Service is also working to accelerate a concrete bridge demonstration project incorporating cellulose nanocrystals. The Forest Service has stepped up its coordination with a university and the locality that is planning to construct the bridge.

Researchers at a DOD laboratory developed a nanogalvanic aluminum alloy powder. When this power is mixed with any liquid that contains water (e.g., tap water, waste water, energy drink, urine), large volumes of hydrogen gas are generated, representing a breakthrough in the ability to generate power at the point of need. These patent-pending powders produce hydrogen at one of the fastest rates reported in the literature for aluminum + water reactions, and without hazardous or costly materials. The generated hydrogen gas can be used in a fuel cell and/or an internal combustion engine. This material is being evaluated for use in hydrogen vehicles. DOD has cooperative research and development agreements with numerous companies for evaluating this material and is in negotiations for licensing the technology to industry.

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

To advance a world-class nanotechnology research and development program (Goal 1) and foster the transfer of these new discoveries into useful applications (Goal 2), a strong ecosystem must exist that leverages the physical, cyber, and human infrastructure. The NNI continues to support the cyber and physical infrastructure for nanotechnology through its extensive network of research centers and user facilities that provide access to instrumentation for fabrication and characterization, as well as modeling and simulation tools and data. Developing a future-focused workforce is a major objective of the NNI. Efforts focus on students at the community college, undergraduate, graduate, or post-doctoral levels, and on the development of resources for and outreach to K-12 teachers and students.

The following examples illustrate activities that support the NNI physical, cyber, and human infrastructure.

Developing tools and instrumentation for nanotechnology. NNI agencies invest in the development of next-generation tools that will enable the discoveries of the future. For example, NIST researchers have made advances in tool development that push the boundaries of nanomaterial characterization and analysis. Highlights include a variation of atomic force microscopy that can measure physical properties of fragile substances such as biomaterials, ultrathin films, and other nanoscale structures. In partnership with industry, scientists at NIST developed a user-programmable detector for a scanning electron microscope. The instrument can measure atomically thin materials, and the low energy of this microscope allows for precise determination of atomic structure and chemical composition. Working in partnership with industry and academia, a team at NIST made dramatic improvements to the atom probe tomography technique by using extreme ultraviolet photoionization to enable accurate, high-resolution measurements of chemical composition in a wide variety of nanoscale solids.

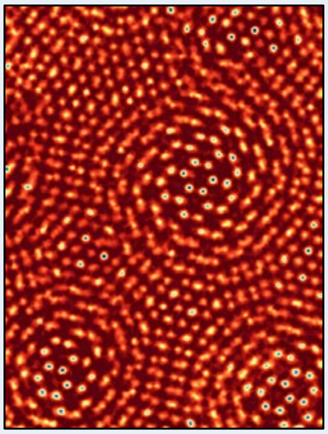
Scientists at ISN have developed a laser-induced particle impact test to investigate the dynamic behavior of nanomaterials under extreme loading. Individual microparticles are accelerated to supersonic velocities through a laser ablation process. The team recorded images of a 14-micrometer silica particle launched at about 500 m/s as it impacted a 3D nanotruss metallic glass sample. Following impact, 75% of the particle's incident kinetic energy had been absorbed and the nanotruss sample was damaged and delaminated from

[58] http://www.sporian.com/

the substrate. The critical aim of this research was to optimize energy absorption performance and to develop fundamental understanding of the mitigation mechanisms.

A Guinness world record: The highest-resolution microscope

Progress in nanotechnology is enabled by the ability to measure and manipulate matter at the nanometer scale and below. Advances in tools such as electron microscopy facilitate a deeper understanding of nanomaterials, and ultimately the development of novel materials based on that understanding. University researchers supported by DOE, NSF, Air Force, and a private foundation have combined a scanning transmission electron microscope image reconstruction method with a new type of pixelated electron detector to obtain the highest resolution images ever seen, clearly showing features as small 0.039 nm. The new method is more than a factor of two better in resolution for energies that can safely image ultra-thin samples than the previous state of the art, offers sharp atomic details, and provides a clear path to even higher-resolution imaging.



In this new approach, researchers generated the image (left) by passing electrons through a molybdenum disulfide sample to produce two-dimensional diffraction patterns and then, using computer algorithms with indirect scattering data, to image the molybdenum and sulfur atoms. The technique could lead to ultra-precise data about atoms in thin sheets. Further, it eventually could provide a way to obtain images of the bonds between every single atom without destroying the sample.

Individual atoms are revealed when two single-layer sheets of molybdenum disulfide are placed on top of one another with a lattice misalignment. Image credit: Cornell University.

Providing research infrastructure and educational resources. Federal user facilities across the country are a cornerstone of the nanotechnology research infrastructure. The NSF-funded NNCI is a network of university-based user facilities.[59] The 16 NNCI sites (and 13 affiliated partners) provide researchers from academia, industry, and government with access to leading-edge fabrication and characterization tools, instrumentation, and expertise. NNCI provides access to 69 facilities with more than 2,000 fabrication and characterization tools. During the third year of the program, 13,110 users accumulated over a million tool hours and 5,000 new users were trained.

In addition to the university-based user facilities, the five NSRCs are DOE's premier user centers for interdisciplinary research at the nanoscale.[60] Each center has expertise and capabilities in selected theme areas, such as synthesis and characterization of nanomaterials; catalysis; theory, modeling, and simulation; electronic materials; nanoscale photonics; soft and biological materials; imaging and spectroscopy; and nanoscale integration. The NIST CNST has continued to provide companies with access to state-of-the-art nanofabrication resources. The NSF-funded Network for Computational Nanotechnology provides a national resource for nanotechnology theory, modeling, and simulation.[61]

NASA continues to support the professional development of graduate students and faculty. For example, the Space Technology Graduate Fellowship program gives students the opportunity to collaborate with NASA scientists and engineers and to utilize NASA facilities. Other highlights include an activity in which NASA and NEWT researchers jointly mentored a group of summer students, and the NASA Space Technology Early Career Faculty program, which enables faculty to explore ideas and approaches to making space travel and exploration more effective, affordable, and sustainable.

[59] http://www.nnci.net/

[60] https://nsrcportal.sandia.gov/

[61] https://nanohub.org/groups/ncn

Many NNI agencies support infrastructure and education needs through existing mechanisms. For example, DOD efforts have developed research and testing facilities and advanced manufacturing capabilities for nanomaterials. Many NIH institutes support training through networks and centers. NNCO supports and amplifies the NNI agencies' education and outreach efforts. Select highlights are on the inside back cover of this report.

Goal 4. Support Responsible Development of Nanotechnology

The responsible development of nanotechnology has been a primary goal of the NNI since its inception. This includes addressing both nanoEHS issues and potential ethical, legal, and societal implications (ELSI) of nanotechnology. An understanding of the behavior of nanomaterials with respect to nanoEHS considerations is essential for protecting workers, consumers, and the environment, and for establishing public confidence and regulatory certainty so companies can readily bring nanotechnology products to market. Considering the applicability of nanotechnology to a wide variety of market segments, well-coordinated nanoEHS research is vital to American innovation and to advancing manufacturing and economic competitiveness.

The following highlights showcase NNI activities supporting the responsible development of nanotechnology.

Understanding and mitigating potential impacts in the workplace. As nanomaterials and nanotechnology-enabled products make their way into commerce, NIOSH has worked to understand the potential health and safety impacts of nanotechnology in occupational settings. NIOSH researchers develop hazard and safety assessments using key classes of engineered nanomaterials that are already in commerce or likely to enter commercial use. NIOSH has used its research findings to develop guidance documents to protect workers. Recently NIOSH provided a second draft of its *Current Intelligence Bulletin on Occupational Exposure to Silver Nanomaterials*[62] for public review and held an open public meeting to solicit comment. It published three workplace design solutions to provide options to companies for controlling possible nanomaterial exposure of their workers. NIOSH also released *Continuing to Protect the Nanotechnology Workforce: Nanotechnology Research Plan for 2018–2025* in January 2019.[63]

NIOSH collaborates with industry to conduct voluntary assessments of workplace processes, and develops methods to identify and quantify worker nanomaterial exposure. NIOSH field research teams visit nanomaterials producers and users, including additive manufacturing and 3D printing facilities. During 2018, NIOSH collaborated with 14 companies and completed 10 field assessments.

The National Institute of Justice administers the Compliance Testing Program (CTP), a voluntary conformity assessment program for the testing and certification of body armor used by law enforcement. In 2018, the NIJ CTP published program requirements for ballistic-resistant and stab-resistant body armor submitted to the program for testing that contain carbon nanotubes or other nanomaterials. These requirements focus on protecting the health of workers involved in the manufacturing, testing, handling, and wearing of body armor submitted to NIJ's program who may be exposed to nanomaterials.

Developing methodologies and standards to support nanoEHS research. Over the past three years, NHIR consortium researchers funded by NIH have studied 26 ENMs of diverse physicochemical properties. The focus has been to generate biological response profiles for the emerging 2D and 3D ENMs (graphene, graphene oxide, nanocellulose, and other anisotropic materials). The NIH National Toxicology Program has been collaborating with FDA to understand the health hazards of nanomaterials and to develop novel methods and approaches for detection of nanomaterials in FDA-regulated products. This includes physicochemical characterization and standards development processes.

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[62] https://www.cdc.gov/niosh/docket/review/docket260a/pdfs/260-A-Draft-Silver-NM-CIB_8-24-18_1.pdf
[63] https://www.cdc.gov/niosh/docs/2019-116/default.html

NIST researchers working in conjunction with FDA have studied the effect of cutting, washing, and scratching nanosilver-containing materials to determine if these common consumer practices initiate or impact nanoparticle release into the environment or into food. The studies showed that while bits of matrix polymer were released by the various methods of abrading the surface, no free silver nanoparticles were observed.[64] NIST and CPSC are collaborating to develop testing and measurement protocols to evaluate the quantities and properties of engineered nanoparticles released from floor coatings and paints by abrasion and/or weathering. Knowledge gained from these efforts contributed to the ongoing development of ISO Technical Report 22293, "Evaluation of methods for assessing the release of nanomaterials from commercial, nanomaterial-containing polymer composites."

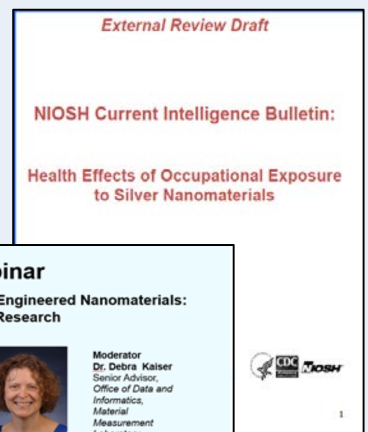
FDA is conducting regulatory science research on the advanced characterization, safety, and biodistribution of nanomaterials in FDA-regulated products. The scientific data and information generated through this research helps FDA to ensure the safety of FDA-regulated products containing nanomaterials.

Developing and disseminating information. As knowledge is created to support the responsible development of nanotechnology, the NNI agencies employ a variety of means to disseminate and incorporate this information into practice. For instance, NNCO hosts a webinar series (archived on Nano.gov) to share information on nanoEHS research advancements and available resources. Examples of resources include the NIOSH documents referenced above, FDA guidance documents, and a joint DOD-CPSC knowledge document on a risk prioritization framework and tool to group different nanomaterials in consumer products.[65]

Applying and communicating nanoEHS knowledge and best practices

The extensive body of nanoEHS knowledge developed under the NNI is being actively applied to ensure the safe and responsible development of nanotechnology. NNI agencies incorporate nanoEHS findings in the development of guidance documents, regulations, technical methods, and other key work products. For example, documents such as NIOSH's Current Intelligence Bulletin on nanosilver[66] and "Approaches to Safe Nanotechnology"[67] and FDA's "Drug Products, Including Biological Products, that Contain Nanomaterials - Guidance for Industry"[68] provide robust recommendations grounded in science.

NNI agencies and NNCO use a variety of mechanisms to disseminate information on key findings and best practices to support the use of nanoEHS information. NNI-sponsored meetings such as the Quantifying Exposure to Engineered Nanomaterials in Manufactured Products workshops (2015 and 2018) brought U.S. and international scientists, regulators, and industry together to communicate findings on the effects of exposure to ENMs. The NanoEHS Public Webinars have been used by NNI agencies to share information on intramural and extramural nanoEHS research. The academic and private sectors also use nanoEHS information when developing nanomaterials and nanotechnology-enabled products to promote lab, workplace, and product safety.



[64] www.nist.gov/news-events/news/2018/11/do-kitchen-items-shed-antimicrobial-nanoparticles-after-use
[65] https://pubs.rsc.org/en/content/articlelanding/2018/en/c8en00848e/unauth#!divAbstract
[66] https://www.regulations.gov/document?D=CDC-2016-0001-0026
[67] https://www.cdc.gov/niosh/docs/2009-125/pdfs/2009-125.pdf
[68] https://www.fda.gov/media/109910/download

FDA collaborates with domestic and international regulatory and research agencies to share information on the state of science, guidance documents, and regulatory research experience. For example, the Indian government released a draft guidance document on "Guidelines for Evaluation of Nanopharmaceuticals in India" following a 2018 workshop in which FDA shared guidance documents, research, and regulatory perspective on medical products containing nanomaterials.

The second Quantifying Exposure to Engineered Nanomaterials from Manufactured Products (QEEN II) workshop was held in October 2018[69] to determine the state of the science and the tools and methods available to characterize and quantify exposure to engineered nanomaterials from consumer products. This event was sponsored by CPSC and co-hosted by OSHA and the NNI. The workshop highlighted progress in: (1) metrology to bring hazard testing in alignment with likely exposures; (2) understanding exposure scenarios for complex nanomaterials; and (3) the development of effective workplace exposure control measures.

[69] https://www.nano.gov/qeen2

Appendix A. Overview of Nanotechnology R&D by Agency

This appendix summarizes nanotechnology R&D activities at individual participating agencies.

Consumer Product Safety Commission (CPSC)

The CPSC staff engages in a range of activities to understand the commercialization of nanotechnology-enabled products (NEPs) and strategies to adequately address potential implications of these product applications. Other emerging technologies such as wearable technology and 3D printing (or additive manufacturing) are expected to be significant users of nanomaterials, and 3D printing is expected to emerge as a significant producer of NEPs over the next few years. Given the convergence of these technologies, the CPSC staff is supporting research with other Federal agencies, academic institutions, and the private sector to better understand the exposures to nanomaterials incorporated into and produced by new technologies across the life cycle. Studies conducted with NIST and NIOSH will identify releases of material during 3D printing and the accumulation of these materials in the indoor environment from production and use of finished products. Staff and partners are engaged in voluntary standards activities to create validated methods for quantifying and characterizing exposures from products. The staff will also develop and validate *in vitro* methods to test existing and emerging nanomaterials that are used in consumer products.

Department of Commerce (DOC)

National Institute of Standards and Technology (NIST). Advancing nanoscale measurement science, standards, and technology is an important component of NIST's mission to promote U.S. innovation and industrial competitiveness. From leading cutting-edge research, to providing world-class facilities, to coordinating the development of standards that promote trade, NIST's intramural nanotechnology research program directly impacts the Nation's economy and well-being. The nanotechnology research conducted in NIST's laboratories and user facilities results in measurements, standards, and data crucial to a wide range of industries and Federal agencies, from new measurement and fabrication methods for advanced manufacturing to reference materials and data needed to inform the responsible development and use of nanotechnology. NIST further supports the U.S. nanotechnology enterprise through its user facilities, including the NIST Center for Neutron Research and the Center for Nanoscale Science and Technology. The NCNR provides access to a range of world-class neutron scattering tools for characterizing the atomic and nanometer-scale structure and dynamics of materials. The CNST provides rapid access to state-of-the-art tools needed to make and measure nanostructures. NIST staff members contribute unique technical expertise and leadership in nanotechnology-related standards development and international cooperation activities. NIST's world-class expertise in measurement, characterization, and standards development helps ensure that the resulting international standards reflect the state of technology, are unbiased, and facilitate innovation and commercialization and user confidence in the safety of nanotechnology. Interagency coordination and information sharing related to these activities is facilitated through the NSET Subcommittee.

Department of Defense (DOD)

DOD recognizes the importance of nanotechnology and nanomaterials to the ongoing modernization of the current force, and also recognizes the revolutionary changes that these technologies may bring to our future warfighting capabilities. The department is committed to maintaining a broad base of foundational nanoscience research across the department's laboratories, and will continue to collaborate with other

Federal agencies in this arena. The department will continue to emphasize the transition of evolving nanotechnologies into the DOD industrial base through the use of DOD ManTech (Manufacturing Technology), Defense Production Act Title III, Defense Innovation Unit Experimental, Manufacturing USA institutes, and SBIR programs.

Department of Energy (DOE)

DOE supports a broad portfolio of pioneering research and development in nanoscale science and engineering to promote scientific and technological innovation and to advance the agency's mission in energy, economic, and the national security of the United States. The majority of DOE NNI funding is managed by DOE's Office of Science, with additional funding from the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy, and the Office of Nuclear Energy. DOE supports nanoscale science and engineering research activities in academia, DOE national laboratories, and industry (including small businesses). For example, in support of its overall early-stage nuclear energy research mission and objectives, the Office of Nuclear Energy invests in nanotechnology-related research and experiments, executed primarily via competitive Nuclear Science User Facilities Consolidated Innovative Nuclear Research facility access awards and Rapid Turnaround Experiment awards to researchers at U.S. universities and national laboratories. In addition, the Office of Science operates five Nanoscale Science Research Centers, user facilities that provide open access to leading-edge synthesis, characterization, and computational tools and scientific expertise for interdisciplinary research at the nanoscale. Nanotechnology plays a vitally important role in addressing the Nation's energy, environmental, and national security challenges. DOE maintains a strong commitment to the NNI, which has served as an effective and valuable way to spotlight needs and target resources in this critical area of science and technology.

Department of Health and Human Services (HHS)

Food and Drug Administration (FDA). FDA invests in nanotechnology research to help address questions related to the safety, effectiveness, quality, and/or regulatory status of products that contain ENMs or otherwise involve the use of nanotechnology; develop models for safety and efficacy assessment; and study the behavior of nanomaterials in biological systems and their effects on both human or non-human animal health. These investments continue to support FDA's mission to protect and promote public health, and to help support the responsible development of nanotechnology. The FDA Office of the Commissioner, in partnership with the FDA Nanotechnology Task Force, facilitates communication and cooperation on nanotechnology research, both within FDA and with other national and international stakeholders. FDA's nanotechnology research efforts include: (1) scientific staff development and professional training; (2) laboratory and product-testing capacity; and (3) collaborative and interdisciplinary nanotechnology research. FDA continues to foster and develop collaborative relationships with other Federal agencies through participation in the NNI and the NSET Subcommittee, as well as with regulatory agencies, healthcare professionals, industry, consumers, and other stakeholders. Recently FDA has increased its international outreach, with the goal of strengthening global regulatory research efforts aimed at the development of novel characterization/measurement tools and consensus standards. These collaborations allow information to be exchanged efficiently and serve to identify research needs related to the use of ENMs in FDA-regulated products.

National Institute for Occupational Safety and Health (NIOSH). NIOSH provides national and world leadership in conducting research on the causes and prevention of work-related illness and injury. NIOSH is a leader in the Federal Government research initiative on understanding the potential health and safety implications of nanotechnology, and in addressing worker health and safety needs related to nanotechnology. NIOSH research advances the understanding of nanotechnology-related toxicology and workplace exposures, so that appropriate 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 making information widely available, NIOSH develops guidance that supports and promotes the safe and responsible development of nanomaterials.

National Institutes of Health (NIH). NIH advances creative, fundamental discoveries and translational nanotechnology research and development to ultimately enhance health, lengthen life, and reduce illness and disability through a variety of mechanisms and approaches. The NIH nanotechnology investment portfolio encompasses both basic and clinical research funded primarily through grants. Current research efforts focus on advancing new medical diagnostics, therapeutics, and vaccines; supporting nanotechnology-related environmental, health, and safety research; developing nanotechnology information resources; and training a new generation of nanotechnology researchers. Due to the successful integration of nanotechnology-based R&D into broad areas of biomedical applications, scientists can propose ideas via non-nanotechnology-specific research opportunity announcements supported by a large number of NIH institutes.

Department of Homeland Security (DHS)

DHS interest in nanoscience is primarily focused on the application of nanoscale materials and devices that provide enhancements in component technology performance for homeland security applications. Applications of interest include threat detection for enhanced security for aviation, mass transit, and first responders. R&D topics include nanomaterials for novel sensing structures and arrays, high-performance nanoscale preconcentrators for use in next-generation detection systems, and development of manufacturing techniques for low-cost nanoscale sensor platforms and wearable sensing technologies.

Department of the Interior (DOI)

U.S. Geological Survey (USGS). USGS nanotechnology R&D is primarily focused on developing improved methods for estimating organic, metal, and biogenic chemicals (including nanomaterials) in the field in natural systems. Future methods for sensing contaminants may include adapting alternative animal bioassays (cell, invertebrate) to assess rapidly contaminants in field-collected samples, which could provide information on unknown contaminant stressors, mixtures, and site-specific data.

Department of Justice (DOJ)

National Institute of Justice (NIJ). The NIJ investment in nanotechnology furthers DOJ's mission through the sponsorship of research that provides objective, independent, evidence-based knowledge and tools to meet the challenges of crime and justice. New projects are awarded on a competitive basis; therefore, total investment may change each fiscal year. However, NIJ continues to view nanotechnology as an integral component of its R&D portfolio as applicable to criminal justice needs.

Department of Transportation (DOT)

Federal Highway Administration (FHWA). FHWA is pursuing nanotechnology-enabled solutions to improve the safety and performance of the Nation's transportation system. Innovative technologies and approaches to modernizing and renewing our transportation infrastructure are paramount to ensuring mobility, accessibility, and economic productivity for all Americans. Development and deployment of high-performance nanomaterials shows great promise for improving the durability, resilience, and long-term performance of extant and future transportation infrastructure.

Environmental Protection Agency (EPA)

EPA's engineered nanomaterials research is conducted as part of the Chemical Safety for Sustainability National Research Program within the Office of Research and Development (ORD). This research is focused on developing, collating, mining, and applying information on engineered nanomaterials to inform both exposure and hazard assessments and support risk-based decisions related to the agency's implementation of the Toxic Substances Control Act (TSCA) and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). EPA's research activities have two objectives: (1) evaluate the environmental release of, and assess human and ecological exposures to, engineered nanomaterials; and (2) integrate information and develop a user interface for ORD's existing nanomaterials database, NaKnowBase, which captures the chemical and physical parameters materials tested by EPA, the assays in which they were tested, and measured results.

National Aeronautics and Space Administration (NASA)

The National Aeronautics and Space Administration is supporting research and development in nanotechnology to address NASA mission needs in aeronautics and space exploration. Nanotechnology R&D efforts include a combination of in-house activities, grants, and contracts that are focused in areas such as the development of advanced lightweight and multifunctional materials to reduce vehicle mass and improve performance; new materials to improve the performance of power generation and storage systems; advanced catalysts and membranes for more efficient air and water purification systems for long-duration human exploration missions; and new materials and manufacturing methods to produce low-power and compact sensors to detect chemical and biological species for astronaut health management and robotic exploration. Such efforts include a combination of theoretical and experimental research. NASA also supports the education and training of the next generation of scientists and engineers through a variety of programs, ranging from internships for undergraduates and high school students, graduate fellowships such as the Space Technology Research Fellowships, and postdoctoral fellowships, as well as the continued development of faculty through Space Technology Early Career Awards and other activities.

National Science Foundation (NSF)

NSF supports fundamental nanoscale science and engineering in and across all disciplines. NSF's nanotechnology research is supported primarily through grants to individuals, teams, and centers at U.S. academic and small-business institutions. The team and center projects are particularly fruitful because nanoscale research and education are inherently interdisciplinary, and some have translational pursuits, often combining elements of materials science, engineering, chemistry, physics, biology, and neuroscience. Several new directions planned for 2019 are nanotechnology for quantum systems and the human-technology frontier, including highly energy-efficient systems and intelligent cognitive assistants; nanobiomanufacturing and nanobiomedicine, including cell technology; chromatin and epigenetic engineering and its nanoscale environment; semiconductor synthetic biology for information processing and storage technologies; food-energy-water processes such as nanostructured membranes and point-of-use nanofiltration; nanomodular materials and systems by design, including hierarchical 3D nanoscale materials; and emerging aspects of nanoelectronics, photonics, use of artificial intelligence for smart materials and systems, papertronics (paper-based electronics), nanoplastics in the environment, and neuroscience. In 2020 NSF will increase its focus on convergence research and education activities in confluence with other interagency initiatives and NSF priority areas (e.g., the National Quantum Initiative, artificial intelligence, and NSF's 10 Big Ideas). NSF will continue its sponsorship of student contests (e.g., the Generation NANO competition for high school students and the Quantum Matters communication competition for undergraduate and graduate students), and its support for the National Nanotechnology Coordinated Infrastructure. Contributions to nanotechnology innovation and translation will continue through programs such as GOALI; I/UCRC; I-Corps™; Partnerships for Innovation, and SBIR. An emerging technologies industrial internship program, INTERN, will be expanded. The 2020 budget reflects the fact that NSF has mainstreamed nanotechnology-related research, education, and infrastructure in core programs in several directorates.

U.S. Department of Agriculture (USDA)

Agricultural Research Service (ARS). The USDA Agricultural Research Service has a limited program addressing research in nanotechnology or related sciences. For example, projects address the development of new commercial cotton-based nonwoven products; chemical modification of cotton for value-added applications; application of novel imaging methodologies for livestock production research; phytochemical intervention of foodborne pathogens utilizing nanoemulsions; production of bioproducts from agricultural feedstocks; development of rapid optical detection methods for food hazards; development of functional bio-based particles using renewable agricultural byproducts; development of new sustainable processing technologies to produce healthy, value-added foods from specialty crops; and addition of value to plant-based waste material through the development of novel, healthy ingredients and functional foods.

Forest Service (FS). Forest Service nanotechnology research supports departmental and agency priorities to facilitate rural prosperity and economic development, ensure productive and sustainable use of our National Forest System lands, and strengthen the stewardship of private lands through research and development. The primary focus of Forest Service nanotechnology research is on producing cellulose nanomaterials from wood and developing the science and technology for the application of cellulose nanomaterials in a broad range of industrial applications. Other nanotechnology research in the Forest Service includes understanding the nanostructure of wood and wood properties and wood-water interactions with nanotechnology techniques.

National Institute of Food and Agriculture (NIFA). The NIFA nanotechnology portfolio will continue providing national leadership and investments in research, education, and extension activities through its extramural funding instruments. NIFA advances nanoscience and nanotechnology for addressing significant societal issues such as sustainable agricultural production, food and nutrition security, food safety and biosecurity, bio-based economy, water and other natural resources, and environmental and ecological systems. The program also supports risk assessment and management, public engagement, and communication about nanotechnology and nanotechnology-enabled products.

APPENDIX B. ABBREVIATIONS AND ACRONYMS[70]

2D two-dimensional

3D three-dimensional

BES [Office of] Basic Energy Sciences (DOE)

BIS Bureau of Industry and Security (DOC)

CCNE Centers in Cancer Nanotechnology Excellence (NIH/NCI)

CMOS complementary metal–oxide semiconductor

CNST Center for Nanoscale Science and Technology (NIST)

CNT carbon nanotube

COR Community of Research (U.S.-EU)

DARPA Defense Advanced Research Projects Agency

E2CDA Energy-Efficient Computing: from Devices to Architectures (NSF)

ENM engineered nanomaterial

EHS environment(al), health, and safety

ENM engineered nanomaterial

EU European Union

GC grand challenge

GOALI Grant Opportunities for Academic Liaison with Industry (NSF)

I-Corps Innovation Corps (NSF and other agencies)

ISN Institute for Soldier Nanotechnologies (DOD)

ISO International Organization for Standardization

I/UCRC Industry/University Cooperative Research Centers (NSF)

JUMP Joint University Microelectronics Program (DARPA/industry)

nanoEHS nanotechnology environment, health, and safety (research, etc.)

NCI National Cancer Institute (HHS/NIH)

NCL Nanotechnology Characterization Laboratory (NIH/NCI)

NCNR NIST Center for Neutron Research

NEHI Nanotechnology Environmental and Health Implications Working Group of the NSET Subcommittee

NEW LIMITS NEW materials for LogIc, Memory, and InTerconnectS (NIST)

NEWT Nanotechnology Enabled Water Treatment Systems Engineering Research Center (NSF)

NHIR Nanotechnology Health Implications Research consortium (NIH/NIEHS)

NIEHS National Institute of Environmental Health Sciences (HHS/NIH)

NKI Nanotechnology Knowledge Infrastructure (Nanotechnology Signature Initiative)

NNCI National Nanotechnology Coordinated Infrastructure (NSF)

NNCO National Nanotechnology Coordination Office

NNI National Nanotechnology Initiative

NSET Nanoscale Science, Engineering, and Technology Subcommittee of the NSTC

NSI Nanotechnology Signature Initiative

NSRC Nanoscale Science Research Center (DOE)

NSTC National Science and Technology Council

OMB Office of Management and Budget (Executive Office of the President)

OSTP Office of Science and Technology Policy (Executive Office of the President)

PCA Program Component Area of the National Nanotechnology Initiative

SBIR Small Business Innovation Research Program

SMART Spintronic Materials in Advanced Information Technologies (NIST)

STEM science, technology, engineering, and mathematics

STTR Small Business Technology Transfer Research Program

TMD transition metal dichalcogenide

UK United Kingdom

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

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

Tech Pathways Podcasts

Clockwise from top left

- Stories from the NNI podcasts highlighting the 15-year anniversary of the authorization of the NNI (www.nano.gov/15nni).

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- National Nanotechnology Day on October 9 (www.nano.gov/nationalnanotechnologyday).
- Animated videos featured on the NNI's YouTube channel, Nanotube (www.youtube.com/channel/UCwO7o2ZT-ATkbl0KrJXXhdA).
- NextTech Student Network (www.nexttechnetwork.org).
- Conferences, workshops, and professional society collaborations, including the National Science Teachers Association, TechConnect, U.S.-EU, and QEEN II (www.acs.org/content/acs/en/acs-webinars/technology-innovation/nanotech.html) (www.nsta.org) (www.techconnect.org) (www.us-eu.org/communities-of-research/overview) (www.nano.gov/qeen2).
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