THE NATIONAL NANOTECHNOLOGY INITIATIVE SUPPLEMENT TO THE PRESIDENT'S 2019 BUDGET

Product of the

SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

COMMITTEE ON TECHNOLOGY

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

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About the National Science and Technology Council

The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the Federal research and development enterprise. A primary objective of the NSTC is to ensure 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 2019 Budget request submitted to Congress on February 12, 2018, 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 of 2003 (Public Law 108-153, 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: An atomically thin two-dimensional membrane has been decorated with a nanoscale periodic pattern of "disclinations," i.e., topological defects in the ring structure of an otherwise hexagonal bond network. The disclinations formed by pentagonal rings define the apices of conical structures that have two stable states: upward "mountains" or downward "valleys." Mechanical interactions between these conical structures cause them to assume a near-random pattern of up and down, thus leading to a membrane with an intriguing combination of regularity and disorder. This membrane can assume millions of distinct shapes, retaining a memory of each. The image is color-coded by the height of the membrane. This work was supported by the National Science Foundation (NSF) as part of the Two Dimensional Crystal Consortium, a Materials Innovation Platform (NSF Award #1539916), with additional contributions from the CoMET NSF Research Traineeship program (NSF Award #1449785). Image credit: Benjamin Katz and Vincent Crespi, Pennsylvania State University.

Inside Back Cover: The inside face of the back cover includes a collage of images illustrating examples of NNI educational outreach activities. See captions under the collage for additional information. Collage content and design by Quinn Spadola and Kristin Roy of the National Nanotechnology Coordination Office (NNCO).

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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 is affecting all aspects of life through innovations that enable, for example (some with images shown below): (a) strong, lightweight materials for aerospace applications; (b) clean, accessible drinking water around the world; (c) superfast computers with vast amounts of storage; (d) self-cleaning surfaces; (e) wearable sensors and health monitors; (f) safer food through packaging and monitoring; (g) regrowth of skin, bone, and nerve cells for better medical outcomes; (h) smart windows that lighten or darken to conserve energy; and (i) nanotechnology-enabled concrete that dries more quickly and has sensors to detect stress or corrosion in roads, bridges, and buildings.

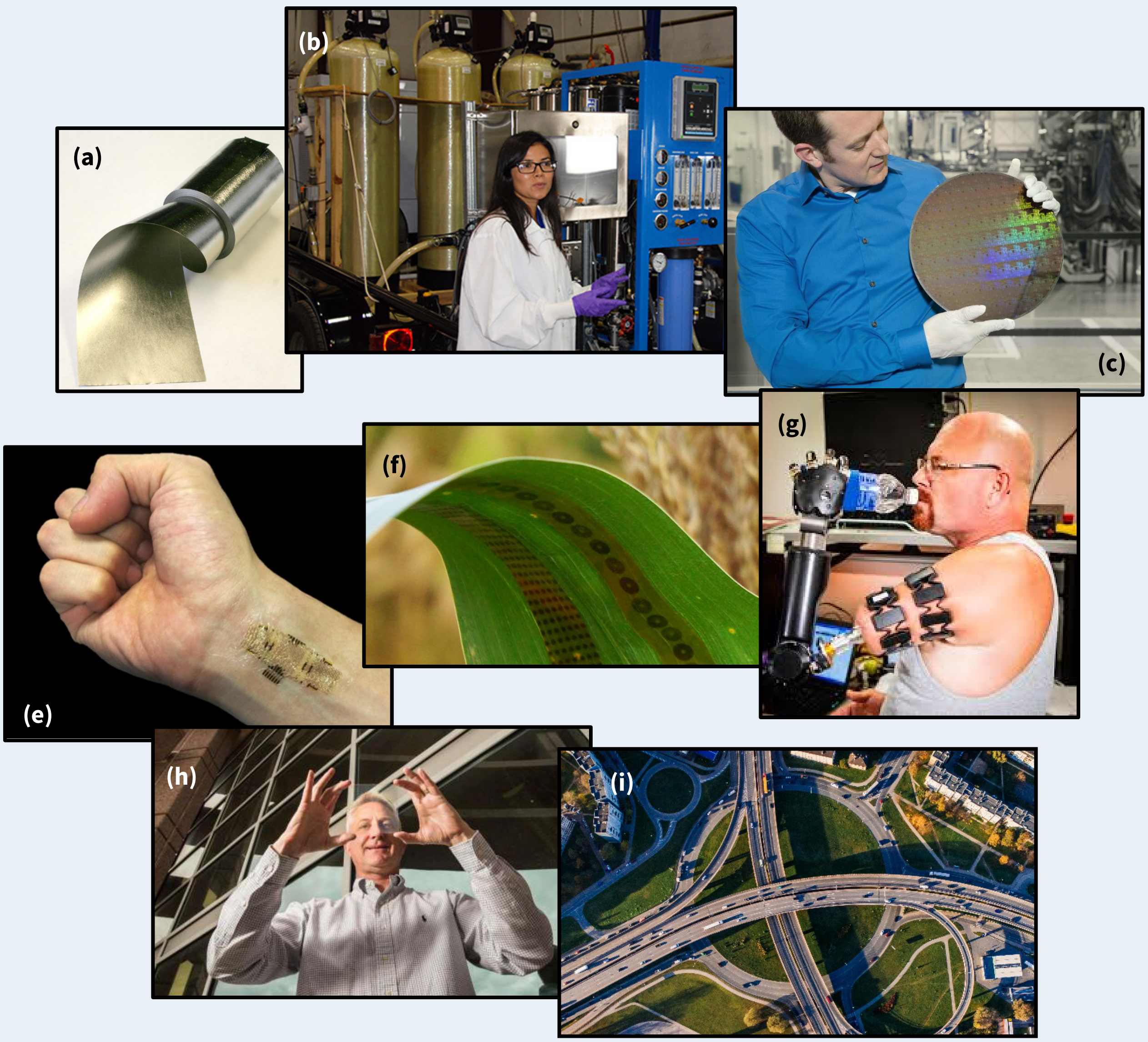

Image credits: (a) National Aeronautics and Space Administration; (b) Rob DeDeaux, U.S. Army Engineer Research and Development Center; (c) IBM; (e) Woon-Hong Yeo, Georgia Institute of Technology; (f) Liang Dong, Iowa State University; (g) Johns Hopkins University Applied Physics Laboratory; (h) Randy Montoya, Sandia National Laboratory; (i) Pexels.com. 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 in 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] Table 1 lists the agencies currently participating in the NNI.

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. These nanotechnology-enabled applications are providing new capabilities to areas as diverse as consumer 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 artificial muscles that heal themselves to transparent wood that can stop a bullet, nanotechnology has much more to offer. Through sustained support of basic and early-stage applied research, the President's budget for nanotechnology 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 operates within the framework of the National Science and Technology Council (NSTC), the Cabinet-level council by which the President coordinates science and technology policy across the Federal Government. The NSTC's Nanoscale Science, Engineering, and Technology (NSET) Subcommittee, composed of representatives from the agencies participating in the NNI and from the Executive Office of the President, 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. More information about the structure, goals, and priorities of the NNI can be found on Nano.gov.

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 the Office of Management and Budget (OMB), the Office of Science and Technology Policy (OSTP), and Congress. NNI agencies collaborate closely—facilitated through the NSET Subcommittee, its working group and coordinators, and the National Nanotechnology Coordination Office (NNCO)—to create an integrated R&D program that leverages resources, including equipment and other infrastructure, and knowledge to advance NNI goals and meet individual agency mission needs and objectives.

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

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[1] General note: In conformance with Office of Management and Budget style, references to years in this report are to fiscal years unless otherwise noted.

[2] 15 U.S.C. §7501(c)(4), P.L. 108-153: www.gpo.gov/fdsys/pkg/PLAW-108publ153/html/PLAW-108publ153.htm

[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

this document, and contact information for representatives from the participating agencies, OSTP, OMB, and NNCO is listed in Appendix C.

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)
National Institute of Standards and Technology (NIST)*
Patent and Trademark Office (USPTO)
Department of Defense (DOD)*
Department of Education (DOEd)
Department of Energy (DOE)*
Department of Health and Human Services (HHS)
Agency for Toxic Substances and Disease Registry (ATSDR)/National Center for Environmental Health (NCEH)
Food and Drug Administration (FDA)*
National Institute for Occupational Safety and Health (NIOSH)*
National Institutes of Health (NIH)*
Department of Homeland Security (DHS)*
Department of the Interior (DOI)
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 (DOTreas)
Environmental Protection Agency (EPA)*
Intelligence Community (IC)
National Reconnaissance Office (NRO)
Office of the Director of National Intelligence (ODNI)
International Trade Commission (USITC)†
National Aeronautics and Space Administration (NASA)*
National Science Foundation (NSF)*
Nuclear Regulatory Commission (NRC)†

* Denotes agencies (or organizations within agencies) with budgets dedicated to nanotechnology research and development

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

There have been no external reviews of the NNI since the release of the Supplement to the President's 2018 Budget.[5]

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[5] Based on the recent statutory changes enacted in the American Innovation and Competitiveness Act of 2017, the quadrennial reviews of the National Nanotechnology Advisory Panel (designated as the President's Council of Advisors on Science and Technology, PCAST) and the National Academies will alternate every two years. See P.L. 114–329, title II, §204(b)(1), Jan. 6, 2017, 130 Stat. 2999: www.gpo.gov/fdsys/pkg/PLAW-114publ329/html/PLAW-114publ329.htm.

2. NNI BUDGET AND PROGRAM PLANS

Budget Summary

The President's 2019 Budget requests nearly $1.4 billion for the NNI, a continued investment in basic research, early-stage applied research, and technology transfer efforts that will lead to the breakthroughs of the future. Cumulatively totaling almost $27 billion since the inception of the NNI in 2001 (including the 2019 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 2017 and 2018 and those proposed for 2019 reflect a sustained emphasis on broad, fundamental research in nanoscience to provide a continuing pipeline of new discoveries that will enable future transformative commercial products and services.

The NNI is a prime exemplar of the interagency coordination emphasized in the 2019 Administration Research and Development Budget Priorities Memorandum,[6] leveraging efforts and avoiding duplication to yield greater impacts than individual agency activities alone. Guided by this memorandum, agencies continue to prioritize investments in nanotechnology to meet their mission needs, including homeland security and defense; innovation in life sciences, medicine, and neuroscience aimed to prevent, treat, and defeat diseases; advanced manufacturing; nanoelectronics and future computing; and energy conversion and storage. Nanotechnology has such a broad impact because it is one of several emerging "general-purpose technologies" that—like the steam engine, electricity, and the Internet—will have a universal impact on American prosperity, with the ability to create entirely new industries, generate new jobs, and increase workforce productivity. The NNI also supports significant investments in research infrastructure and in science, technology, engineering, and mathematics (STEM) education, supporting the Administration's emphasis on a future-focused workforce and the unique capabilities needed to conduct world-leading research.

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 higher than the estimated and requested levels. For example, the actual NNI investments being reported by the participating agencies for 2017 ($1.55 billion) are significantly larger than 2017 estimated investments previously published in the 2018 Budget ($1.47 billion) and 2017 requested investments published in the 2017 Budget ($1.44 billion).

The President's 2019 Budget supports nanoscale science, engineering, and technology R&D at 12 agencies. The five Federal organizations with the largest investments (representing 95% 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).

[6] https://www.whitehouse.gov/sites/whitehouse.gov/files/ostp/fy2019-administration-research-development-budget-priorities.pdf

- 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 are CPSC, HHS/FDA, HHS/NIOSH, DHS, DOJ, DOT/FHWA, EPA, NASA, USDA/ARS, USDA/FS, and USDA/NIFA.[7]

Table 2 presents NNI investments for 2017 through 2019 for Federal agencies with budgets and investments for nanotechnology R&D. Tables 3–5 list the investments by agency and by NNI Program Component Area for 2017 through 2019. Table 6 shows the NNI investments within Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs for 2013 through 2016. Figure 1 shows NNI annual funding by agency since the inception of the NNI in 2001. Figure 2 shows the breakdown of funding by PCA in the 2019 Budget.

Table 2: NNI Budget, by Agency, 2017–2019
(dollars in millions)

Agency	2017 Actual	2018 Estimated*	2019 Proposed
CPSC	1.9	1.0	1.0
DHS	0.4	0.4	0.3
DOC/NIST	80.7	70.1	57.9
DOD	143.3	143.7	125.9
DOE**	341.2	327.2	324.1
DOI/USGS	0.1	0.1	0.0
DOJ/NIJ	2.0	1.7	1.7
DOT/FHWA	0.3	1.5	1.5
EPA	10.7	10.7	4.5
HHS (total)	472.3	469.1	464.3
FDA	11.6	12.5	12.5
NIH	449.6	445.5	440.7
NIOSH	11.1	11.1	11.1
NASA	9.5	7.8	6.0
NSF	465.7	420.8	387.7
USDA (total)	24.2	23.3	20.7
ARS	3.0	3.0	2.0
FS	6.2	5.3	3.7
NIFA	15.0	15.0	15.0
TOTAL***	1552.3	1477.4	1395.6

* 2018 numbers are based on annualized 2018 continuing resolution levels and are subject to change based on final appropriations and operating plans.

** 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, the Office of Nuclear Energy, and the Advanced Research Projects Agency for Energy.

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

[7] See Table 1 (p. 2) or Appendix B for explanations of the agency abbreviations used on this page and throughout the remainder of this report. DOI/USGS is also reporting investments in nanotechnology, but for 2017 and 2018 only.

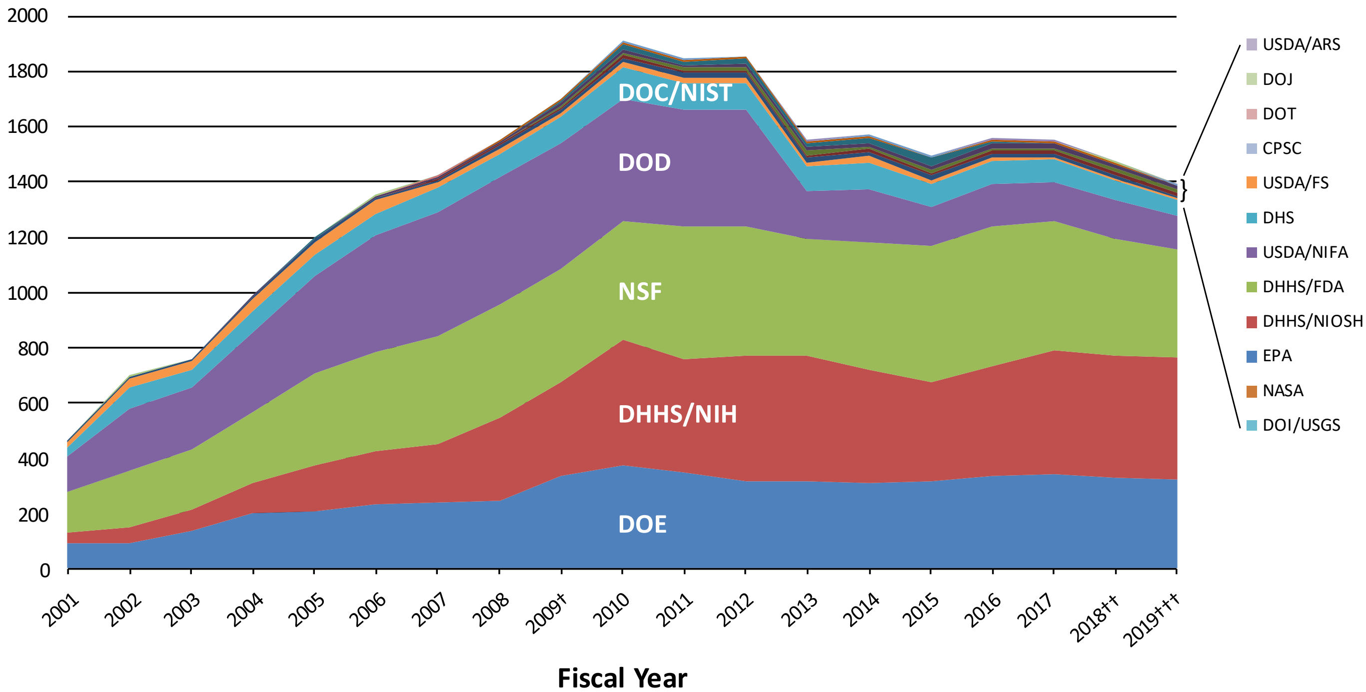

Figure 1. NNI Funding by Agency, 2001–2019.

† 2009 figures do not include American Recovery and Reinvestment Act funds for DOE ($293 million), NSF ($101 million), NIH ($73 million), and NIST ($43 million).

†† 2018 estimated funding is based on annualized 2018 continuing resolution levels and subject to change based on final appropriations and operating plans.

††† 2019 Budget.

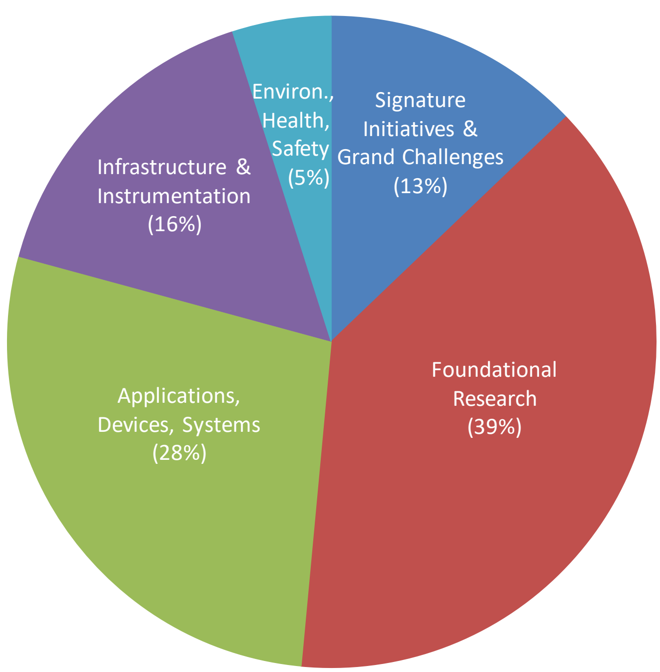

Figure 2. Breakout of NNI Funding by Program Component Area in the 2019 Budget.

Table 3: Actual 2017 Agency Investments by Program Component Area
(dollars in millions)

Agency	1. Nanotechnology Signature Initiatives (NSIs) and Grand Challenges (GCs)*	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	1.9	1.9
DHS	0.4	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.4
DOC/NIST	24.8	4.5	9.2	1.3	0.5	0.3	9.0	11.0	4.7	35.8	4.4	80.7
DOD	24.3	0.8	18.2	1.1	0.9	2.3	1.0	88.4	25.4	1.8	3.4	143.3
DOE	0.3	0.0	0.0	0.0	0.3	0.0	0.0	193.2	11.5	136.2	0.0	341.2
DOI/USGS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
DOJ/NIJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.5	0.2	0.0	2.0
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	10.7	10.7
HHS (total)	14.5	0.0	0.0	1.7	12.8	0.0	0.0	93.4	300.4	23.6	40.4	472.3
FDA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6	11.6
NIH	14.5	0.0	0.0	1.7	12.8	0.0	0.0	93.4	300.4	23.6	17.7	449.6
NIOSH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.1	11.1
NASA	1.7	0.4	0.5	0.0	0.8	0.0	0.0	4.5	3.2	0.0	0.1	9.5
NSF	165.6	39.6	43.5	22.5	14.6	16.0	29.4	184.4	43.1	52.6	20.0	465.7
USDA (total)	9.8	5.6	0.1	0.0	3.0	1.1	0.0	3.0	8.0	1.0	2.4	24.2
ARS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	3.0
FS	4.8	4.6	0.1	0.0	0.0	0.1	0.0	1.0	0.0	0.0	0.4	6.2
NIFA	5.0	1.0	0.0	0.0	3.0	1.0	0.0	2.0	5.0	1.0	2.0	15.0
TOTAL	**241.3**	**50.9**	**71.5**	**26.6**	**33.3**	**19.7**	**39.4**	**578.3**	**398.0**	**251.3**	**83.4**	**1552.3**

* Abbreviated titles for the Nanotechnology Signature Initiatives and Nanotechnology-Inspired Grand Challenges are used in Tables 3–5. See Nano.gov for full titles.

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 2019. The formal definition of each PCA can be found at www.nano.gov/about-nni/what/vision-goals.

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.

Table 4: Estimated 2018 Agency Investments by Program Component Area (dollars in millions)												
Agency	**1. Nanotechnology Signature Initiatives (NSIs) and Grand Challenges (GCs)**	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	0.4	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.4
DOC/NIST	22.3	3.7	10.0	0.9	0.8	0.3	6.6	11.4	4.6	29.1	2.8	70.1
DOD	23.1	0.5	16.2	1.1	0.9	2.3	2.1	87.6	27.9	1.6	3.5	143.7
DOE	0.5	0.0	0.0	0.0	0.5	0.0	0.0	183.9	10.2	132.6	0.0	327.2
DOI/USGS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
DOJ/NIJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.5	0.0	1.7
DOT/FHWA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	1.5
EPA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.7	10.7
HHS (total)	14.3	0.0	0.0	1.7	12.5	0.0	0.0	92.9	297.0	23.7	41.2	469.1
FDA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.5	12.5
NIH	14.3	0.0	0.0	1.7	12.5	0.0	0.0	92.9	297.0	23.7	17.6	445.5
NIOSH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.1	11.1
NASA	2.0	0.0	0.9	0.0	1.1	0.0	0.0	4.0	1.7	0.0	0.1	7.8
NSF	151.4	32.8	35.3	25.0	11.8	11.4	35.1	172.5	36.6	42.9	17.5	420.8
USDA (total)	9.8	5.8	0.0	0.0	3.0	1.0	0.0	2.2	8.0	1.0	2.3	23.3
ARS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	3.0
FS	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	5.0	1.0	0.0	0.0	3.0	1.0	0.0	2.0	5.0	1.0	2.0	15.0
TOTAL	**223.7**	**42.8**	**62.3**	**28.7**	**31.0**	**15.0**	**43.9**	**554.6**	**388.6**	**231.3**	**79.2**	**1477.4**

In 2019, the *Nanotechnology for Sensors and Sensors for Nanotechnology* signature initiative will emphasize cross-agency discussions of technical challenges related to wearable, portable, and implantable sensors, an area of particular interest across many agencies. Agency-specific activities in support of this NSI will include DOD investments in chemical sensors for monitoring wound healing, "smart" molecular sensing machines that can function inside living systems, and quantum sensors. NSF has a dedicated program on nanobiosensors and biophotonics. In addition to a planned collaboration with NSF on nanobiosensing, NIFA will support development of nanobiosensors for more sensitive, specific, and robust detection of pathogens, toxins, and various contaminants in food to ensure food safety and biosecurity. This program also supports research in monitoring physiological biomarkers for optimal crop or animal productivity and health, and the development of cost-effective, distributed sensing networks for intelligent and precise applications of agricultural inputs.

Table 5: Proposed 2019 Agency Investments by Program Component Area
(dollars in millions)

Agency	1. Nanotechnology Signature Initiatives (NSIs) and Grand Challenges (GCs)	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	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3
DOC/NIST	19.0	3.7	10.0	0.9	0.8	0.3	3.3	11.4	4.6	20.7	2.3	57.9
DOD	22.5	0.5	15.7	1.1	0.9	2.2	2.1	72.7	26.5	0.7	3.5	125.9
DOE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	182.1	9.2	132.9	0.0	324.1
DOI/USGS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DOJ/NIJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.5	0.0	1.7
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	4.5	4.5
HHS (total)	14.4	0.0	0.0	1.7	12.7	0.0	0.0	91.8	294.7	22.8	40.5	464.3
FDA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.5	12.5
NIH	14.4	0.0	0.0	1.7	12.7	0.0	0.0	91.8	294.7	22.8	16.9	440.7
NIOSH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.1	11.1
NASA	1.3	0.0	0.8	0.0	0.5	0.0	0.0	3.4	1.2	0.0	0.0	6.0
NSF	111.2	28.0	32.0	19.5	7.5	11.0	13.2	185.4	38.0	42.6	10.6	387.7
USDA (total)	8.3	4.3	0.0	0.0	3.0	1.0	0.0	2.3	7.0	1.0	2.1	20.7
ARS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	2.0
FS	3.3	3.3	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.1	3.7
NIFA	5.0	1.0	0.0	0.0	3.0	1.0	0.0	2.0	5.0	1.0	2.0	15.0
TOTAL	**177.0**	**36.5**	**58.5**	**23.2**	**25.8**	**14.5**	**18.6**	**549.0**	**383.9**	**221.3**	**64.4**	**1395.6**

An example of ongoing NIH nanosensors funding is National Institute of Dental and Craniofacial Research (NIDCR) support for research on biosensors in the oral cavity, with awards funded in 2017 for 2–5 years in duration.[8] This work leverages recent progress in wireless technologies; dissolvable nanotechnology-based electronics, microfabrication, and nanofabrication; as well as improved sensing and drug delivery, among other advances. Research will target the development of new or adaptation of existing biosensors for noninvasive, dynamic, real-time monitoring of physiological processes in the human body using the oral cavity as the sensing site, including preclinical safety testing to facilitate the translation of the oral biosensors into clinical practice.

The DOE Office of Fossil Energy is supporting basic and applied R&D on improved sensors and controls technologies for fossil-based electric power generation, including the use of nanostructured materials and novel architectures (e.g., nanowires and nanotubes), advanced manufacturing and fabrication techniques, integrated device design, packaging, high-temperature electronics, and signal processing. Real-time, multi-

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[8] https://grants.nih.gov/grants/guide/rfa-files/RFA-DE-17-004.html

point, distributed sensing at the nanoscale will improve fundamental understanding of energy processes, and will have a large impact on sensors and controls technologies, with potential breakthrough applications in the power plant industry.

Representatives of agencies participating in the *Water Sustainability through Nanotechnology* signature initiative will consider additional case studies to benchmark key technologies described in the 2016 white paper.[9] Agency-specific activities may include NIFA support for research using systems approaches for addressing water challenges in U.S. agricultural and food production, integrating technologies (including nanotechnology) to develop drought- and flood-tolerant cultivars, intensify food production, improve crop and livestock health, or reduce overall water use. In addition to core nanoscience-related programs on water filtration and applications, NSF will continue to support the Nanotechnology Engineering Research Center (ERC) for Nanotechnology-Enabled Water Treatment Systems.[10]

Building on the successful *Technology Development Pathways* workshop[11] and a follow-on conference session in 2018, the *Sustainable Nanomanufacturing* signature initiative will explore case studies of companies that have successfully transitioned a product from research to commercialization, with particular attention given to how these companies have overcome key technical barriers such as quality control and scale up. Forest Service nanotechnology R&D investments focus on cellulose nanomaterials. The priorities are in technologies for manufacturing different types of cellulose nanomaterials and in developing the science and technologies to facilitate new product development. Ongoing projects include development of concrete strength enhancers, green packaging material, and aerogels for oil-spill cleanup. NIFA's sustainable nanomanufacturing effort will focus on nanobiomaterials derived from crops, woods, and other biomass-based agricultural by-products, including novel uses and high-value-added products for food and non-food applications. Ongoing research efforts include synthesis of carbon-based nanomaterials, development of cost-effective production methods, functionalization and characterization of nanobiomaterials, and applications of nanocellulose.

Under a Space Technology Mission Directorate Tipping Point Project, NASA is collaborating with an industry partner to investigate the vibration-damping capability of carbon nanotube composites in aerospace structures. Application of these composites in self-damping structures would eliminate or reduce the need for added vibration-damping systems to protect spacecraft during launch and would significantly reduce the parasitic weight associated with these systems. NSF plans support for advanced manufacturing research to address basic research enabling innovation at Manufacturing USA institutes,[12] and for research on engineering biology at the nanoscale for advanced manufacturing activities. A new direction is manufacturing of nanomachines and nanobiostructures.

The nanotechnology research community increasingly has embraced a proactive attitude toward nanoinformatics, and a vibrant international community has emerged that is developing and implementing a cohesive nanoinformatics approach. These conversations are taking place through a variety of forums, including the National Cancer Informatics Program Nanotechnology Working Group and the Data Management Working Group of the European Nanosafety Cluster. The international nanoinformatics community has also developed the *EU-U.S. Nanoinformatics Roadmap 2030*.[13] While much of the activity has moved into the community, agency-specific activities in support of the *Nanotechnology Knowledge Infrastructure (NKI)* signature initiative include NSF funding for the Network for Computational Nanotechnology (NCN). Program solicitations on cyber-enabled discovery and innovation and software

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[9] www.nano.gov/node/1580

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

[11] www.nano.gov/TechPathwaysWorkshop

[12] https://www.nsf.gov/pubs/2017/nsf17030/nsf17030.jsp

[13] https://www.nanosafetycluster.eu/Nanoinformatics2030.html

infrastructure for sustained innovation will contribute to data infrastructure, software advances, and high-throughput computation. NSF will increase coordinated research on its Harnessing the Data Revolution priority area. NIH will continue to develop strategies to enhance healthcare research through greater data collection, sharing, and tool development.

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 in support of next-generation computing technologies. Agency-specific investments for the signature initiative will include DOD support for photonic approaches to quantum information processing and spintronics, as well as nanophotonic-based reservoir computing. NSF plans ongoing collaboration with the semiconductor industry and other agencies in activities such as the Energy-Efficient Computing: from Devices to Architectures (E2CDA) program,[14] which kicked off its second phase in March 2018, and the Semiconductor Synthetic Biology for Information Processing and Storage Technologies program,[15] with a focus on energy-efficient devices, systems, and architectures. NSF will increase coordinated research on its Quantum Leap and Future of Work at the Human-Technology Frontier "Big Ideas" priority areas.[16] The Defense Advanced Research Projects Agency (DARPA) collaborative effort with industry—the Joint University Microelectronics Program (JUMP)[17]—will also continue to support the goals of the signature initiative and the Future Computing Grand Challenge.

The Future Computing Grand Challenge will be advanced with support from several agencies, including NSF support of research on brain-like computing and intelligent cognitive assistants (ICAs).[18] NSF plans to sponsor ICA research 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 and other agencies in developing hardware (with a focus on a "beyond Moore" system architecture and corresponding devices) and software (with a focus on artificial intelligence).

PCA 2. Foundational Research

Foundational research continues to be the largest PCA, accounting for over 39% of total NNI investments in the 2019 Budget. Three agencies (DOE, DOD, and NASA) are requesting over 55% of their total NNI investments in PCA 2, and NSF is requesting just under 50%. 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 2019 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 broad and diverse research provides the foundation for future new energy technologies and supports the DOE mission in energy, environment, and national security.

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

[14] https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf17531
[15] https://www.nsf.gov/pubs/2017/nsf17557/nsf17557.htm
[16] https://www.nsf.gov/about/congress/reports/nsf_big_ideas.pdf
[17] https://www.darpa.mil/about-us/timeline/jump
[18] https://www.nsf.gov/crssprgm/nano/reports/ICA2_Workshop_Report_2018.pdf

nanoscale and nanostructured materials, including biomaterials and modular structures; and research directed at identifying and quantifying the broad implications of nanotechnology for society.

The investments by NIH reflect the discovery and understanding of scientific principles in biomedical research supported throughout the NIH institutes. NIH funds nanotechnology-related research proposals covering all the major diseases (e.g., cardiac, cancer, diabetes, kidney, etc.).

The foundational nanotechnology research portfolio at NIST includes research to measure and advance the understanding of functional nanostructured materials, nanoscale imaging, and nanomechanical properties of materials. For example, NIST is collaborating with industry to explore the use of atom probe tomography for sub-nanometer-resolved three-dimensional (3D) chemical mapping.

Nanotechnology research investments at the Forest Service include focus on the understanding of wood properties at the nanoscale. This effort will lead to improved wood adhesives and development of high-performance wood-based composite materials.

NIFA continues to advance the frontier of interdisciplinary nanoscale science, engineering, and technology research, supporting discovery and characterization of nanoscale phenomena, processes, and structures important to agriculture and food, as well as the development of new nanotechnology platforms. NIFA also supports research projects to assess social, ethical, legal, and other potential impacts that nanotechnology may pose for society and agriculture.

DOD recognizes the need for strong efforts in foundational nanoscience research as part of its overall nanotechnology investment portfolio, in order 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.

NASA is supporting the development of novel nanomaterials and nanotechnologies for aerospace applications. Foundational nanotechnology research investments include development of advanced lightweight and multifunctional materials with potential structural, electronic, and power generation/storage applications; advanced catalysts and membranes for air and water purification; new materials synthesis and manufacturing methods; and modeling and simulation.

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 sensors, medical devices, and novel computing paradigms. Nanotechnology-enabled applications, devices, and systems make up the largest component of the NIH nanotechnology investment portfolio. Programs and projects include medical devices, nanotherapeutics, drug delivery systems, and novel radiotherapeutics, supported through several funding opportunity announcements renewed in 2016–2018. The 2019 NSF request includes a variety of research activities on nanotechnology-enabled devices and systems. For example, core programs in several NSF directorates will address the development of new principles, design methods, and constructive solutions for nanodevices, with a special focus on smart, autonomous devices and systems. NIFA will support innovation and applied research in many areas, including for early detection and effective intervention technologies for ensuring food safety and biosecurity; more effective therapies to improve animal health and wellness; development of biology-based novel products; and protection of natural resources, the environment, and agricultural ecosystems. Systems approaches are emphasized, addressing the convergence of agricultural sciences with engineering, nutritional and food sciences, social sciences, and other disciplines (including nanotechnology) to generate new scientific discoveries, products, markets, and consequently new high-skilled jobs.

NIST measurement science programs relevant to nanotechnology-enabled applications, devices, and systems include efforts for photonic circuits, polymer membranes, and energy-efficient electronics. NIST will continue to develop new methods to measure functional nanostructured materials, advance the development of single-photon detectors, and harness the unique properties of graphene to develop improved quantum resistance reference standards. NIST is also advancing the use of scanning probe microscopies to evaluate nanoscale properties of materials. The DOE Office of Energy Efficiency and Renewable Energy supports nanotechnology R&D in its vehicle and fuel cell technologies and its advanced manufacturing research programs. Examples include development of nanoscale materials and designs to enhance high-energy and high-power lithium-ion batteries and incorporation of nanomaterials into manufacturing processes. DOE's Office of Nuclear Energy will maintain its nanotechnology research investments at national laboratories and universities, with a focus on confirming the benefits of nanostructuring via innovative manufacturing, and on advancing understanding of nanoscale structural changes in materials for advanced reactors and fuels. Building on prior work on cementitious materials, multifunctionality for structural health monitoring, and advanced coatings, new FHWA investments in 2018 and 2019 will seek to improve the performance, durability, and resiliency of these nanotechnology-enabled innovations, which have the potential to open new markets for transportation infrastructure materials.

Ongoing and planned DOD activities will support research and development across a broad range of nanotechnology-enabled applications, devices, and systems. The Army will continue to collaborate with a small business and academia to grow large single-crystal domains of MoS_2 two-dimensional (2D) nanomaterials for novel high-performance radio frequency (RF) field-effect transistors. Future plans include exploring additional extraordinary functional properties (such as color centers) in other novel 2D nanomaterials and their heterostructures. Several examples of ongoing and planned research funded by the Defense Threat Reduction Agency include the application of nanoscience to combat organophosphate nerve agents and quantum-enhanced motion sensing using entangled spins in quantum dots, which has possible future applications in nuclear detection. Air Force researchers, in collaboration with industry, are developing dielectric metamaterials for optical components, including single-layer metamaterials to augment current multiline filter designs and create mirrors with no chromatic aberrations, with potential applications in intelligence, surveillance, and reconnaissance and directed energy devices. The Air Force will continue research on single-photon quantum emitters for use in optical integrated circuits. Air Force-supported academic research on novel photonic plasmonic interconnects will set the foundation for nanophotonic-enabled computing, including a proposed analog reconfigurable optical computer and a nanophotonic neuromorphic computer.

Examples of ongoing and planned NASA investments for 2018–2019 include low-mass, high-performance polymer aerogel-based conformal antennas for use in beyond line-of-sight communication for unmanned aerial vehicles (UAVs). In 2019, a reconfigurable antenna array fabricated on a flexible polyimide aerogel substrate will be flight tested on the NASA Ikhana UAV. To reduce the mass and improve heat dissipation in electric motors for use in propulsion systems, NASA continues an investigation of the use of carbon nanoconductor-based wiring and thermally conductive boron nitride nanocomposite electrical insulation. Nanocomposite-based multifunctional multilayer insulation is also under development. Nanosensors for use in astronaut health management, detection of chemical and biological species on other planets, and aerospace vehicle health monitoring are another area of interest. Carbon nanotube and graphene-based nanosensors that are 3D printed as embedded strain sensors are expected to be flight tested in 2018.

ARS will support, among other topics, ongoing and planned research on antimicrobial and odor reduction in livestock production, as well as extraction and characterization of nanoparticles from agricultural residues for air pollution mitigation. Additional ARS-funded work will include the use of conventional and novel processing technologies to produce and characterize nanofibers from biopolymers and investigate potential applications. New commercial processes will be explored for the production of cotton-based products with enhanced flame retardant and moisture control properties; for manufacturing cotton-based body-contact materials for use in biomedical, biosensor, and hygienic applications; and involving supercritical fluids, microwaves, ultrasound, or ionic liquids for the production of cotton-based products.

Novel *in vitro* and *ex-vivo* approaches will be investigated for cellular and tissue biophotonic imaging using nanoparticles. These nanoparticles will allow for the tracking of pathogens to address bacterial abundance and persistence related to livestock well-being and production performance. New commercial value-added bio-based materials and novel processing technologies will be advanced for the production and characterization of nanofibers from biopolymers. ARS will also support research and development on nanobiosensors for pathogen detection in food animals and plants.

PCA 4. Research Infrastructure and Instrumentation

The 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 2019 NSF request includes continued support for the National Nanotechnology Coordinated Infrastructure (NNCI). NSF will also increase coordinated research on its Mid-scale Research Infrastructure priority area. DOE BES will continue to operate the five Nanoscale Science Research Centers (NSRCs), national user facilities for interdisciplinary nanoscale R&D that serve as the basis for a national program that encompasses new science, new tools, and new computing capabilities. NSRC laboratories 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. Facilities are made available to academic, government, and industry researchers with access determined through external peer review of user proposals. The NSRCs also provide training for graduate students and postdoctoral researchers.

Consistent with the administration's priorities to redirect domestic discretionary resources, NIST is requesting reduced funding for its user facilities, which provide U.S. scientists with access to world-class neutron measurement capabilities and state-of-the-art nanofabrication facilities. NIST will prudently reduce user support and defer upgrades for these facilities, while continuing to provide access to instruments that are of the greatest benefit to the user community. The Department of Defense will continue to invest in maintenance and upgrading of nanotechnology research facilities and instrumentation at DOD laboratories.

Several agencies also fund ongoing centers that serve as resources for the community. NIH provides funds for resource centers in cardiac, cancer, dental, and other clinical research areas. For example, the National Cancer Institute (NCI) supports the Centers of Cancer Nanotechnology Excellence and the Cancer Nanotechnology Training Centers. Some NSF-supported Science and Technology Centers, ERCs, and Materials Research Science and Engineering Centers have a focus that supports the NNI, e.g., the Center for Cellular Construction and two new Nanotechnology ERCs, one each on nanobiotechnology and on cell technology.

Workforce development remains an area of interest for agencies participating in the NNI. NSF will continue to sponsor nanotechnology education and related activities, such as disseminating the video series with NBC Learn, *Nanotechnology: Super Small Science*. Other examples are the high-school student competitions, *Video Nanotechnology Student Competition* and *Generation Nano*. NIFA programs support universities to develop new curricula and to develop the future workforce. NIFA's higher education programs support competitive grants to universities for developing nanotechnology curricula for undergraduate and graduate students in agriculture and food science and technology. NIFA's education and literacy programs will focus on building institutional capacity and on enhancing the pipeline for producing more STEM graduates to meet the projected shortfall in agriculture-related fields. NIFA is also planning new programs focused on maximizing the value of data-driven research in specific foundational domains of agricultural science. DOD funding of university research will continue to support research infrastructure and the education of students working on DOD-funded projects.

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 environmental, health, and safety 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.

Several agencies will fund or conduct fundamental research to expand the nanotechnology-related environmental, health, and safety (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 sponsors two ongoing university-based Centers for Environmental Implications of Nanotechnology. NIOSH will continue to conduct toxicology studies to evaluate biomarkers of exposure; cardiovascular, pulmonary, and dermal effects of exposure; and immune response to a wide variety of nanomaterials and nanotechnology-enabled products. DOD will continue to work with industry to develop "organ-on-a-chip" technology for next-generation toxicity testing of advanced nanomaterials used in aerospace applications, for portable, low-cost toxicology testing methods to influence material formulation, material down-select, and risk mitigation.

NanoEHS research at NIH is led by the National Institute of Environmental Health Sciences (NIEHS). These research efforts are designed to gain a fundamental understanding of the molecular and pathological pathways involved in mediating responses to engineered nanomaterials (ENMs). To continue the success achieved with a small library of ENMs, ongoing centers for nanotechnology health implications research are funded through two NIEHS funding opportunity announcements through 2021. The NIEHS National Toxicology Program will also continue to conduct research in collaboration with FDA to understand the potential health hazards of nanomaterials and to develop novel methods and approaches for detection of nanomaterials in FDA-regulated products. In addition, the Nanotechnology Health Implications Research (NHIR) Consortium research efforts will be expanded to include an additional 20 ENMs, including graphene, graphene oxide, nanocellulose, and other anisotropic ENMs. Work on these ongoing projects will continue into 2019.

NNI agencies develop and share a diverse collection of resources for stakeholders—from academic researchers to product developers. NIOSH plans to develop, test, and evaluate direct-reading instruments capable of detecting and measuring airborne nanoparticles. Additional plans include continuing field tests of the portable aerosol multielement spectrometer developed by NIOSH at nanomaterial producer and user facilities, as well as efforts in detection of airborne nanoparticles, including in biological systems, to evaluate and predict biological behavior and translocation between organ systems. NIOSH will also explore the feasibility of applying advanced sensing technology to biomarkers as a means of evaluating nanomaterial exposure and possible early response. CPSC and NIST will collaboratively work on the development of a bioassay validation program, including a protocol and validation procedures for analysis of nanomaterials in various matrices, evaluating the sensitivity of *in vitro* assays such as the NIOSH electrophilic allergen screening assay. CPSC and NIST will also assess the presence of nanomaterials in house dust, including the development of a protocol for analyzing dust samples collected from the Department of Housing and Urban Development Healthy Homes Survey.

The continued creation and deployment of computational tools to inform nanosafety researchers and guide responsible development remains an active area for several NNI agencies. For instance, DOD will integrate the Army Engineer Research and Development Center-developed Nano Guidance for Risk Informed

Deployment (NanoGRID) framework[19] for collection and assessment of chemical, physical, and toxicology data to support systems acquisition decision-making. Based on a previously funded state-of-the-science literature review on the toxicity of commercially relevant forms of nanoscale silver, carbon nanotubes, and titanium dioxide, CPSC will assemble a database that identifies and evaluates the strengths and weaknesses of analytical methods that detect the presence and measure release of nanomaterials. An additional database will include a summary of hazard and characteristics/properties data on 10 nanomaterials.

NNI agency activities will continue to contribute to the suite of adaptable, transparent, and robust tools and frameworks that support the safety assessment of nanotechnology. DOD will support work towards demonstrating the utility of multi-criteria decision analysis approaches to risk assessment, and transitioning from traditional risk assessment towards risk-based decision-making and alternatives-based governance for nanotechnology and other emerging technologies. Ongoing DOD work with industry and academia will support the life-cycle assessment of nanotechnology-enabled products, and will disseminate standard operating procedures for assessment of characterization, release fate, and hazard. DOD will also work with NIOSH to finalize a framework for conceptualizing the sustainability of advanced materials (including nanomaterials), including a new point source nanomaterial fate and transport model (NanoTRAK).

The development and adoption of standards for consistent and globally recognized terminology, nomenclature, specifications, and tests are indispensable to evaluating nanoEHS research. Representatives from NNI agencies, including the NNI Coordinator for Standards Development, continue to be actively engaged with standards developing organizations. For example, NIST—in collaboration with other agencies, academic institutions, and the private sector—is leading efforts in the International Organization for Standardization's Technical Committee 229: Nanotechnologies (ISO TC 229) to develop methods for assessing the release of manufactured nanomaterials from commercial, manufactured nanomaterial-containing polymer composites. This work will help improve understanding of how ENMs may be released from commercial products.

NNI agencies will continue to share information and best practices with the research and development community through a variety of mechanisms, including guidance documents and other publications. FDA's Center for Biologics Evaluation and Research and Center for Drug Evaluation and Research will assess public comments received on their December 2017 joint draft guidance document, *Drug Products, Including Biological Products, that Contain Nanomaterials, Guidance for Industry*.[20] DOD will work with EPA, NIST, and industry to develop internationally recognized guidance documents and methods to assess potential EHS impacts of nanomaterials and nanotechnology-enabled products. NIOSH plans to finalize the Current Intelligence Bulletin (CIB) on *Occupational Exposure to Silver Nanomaterials* and release a draft CIB, *Approaches to Developing Occupational Exposure Limits or Bands for Engineered Nanomaterials*. NIOSH recently published four new documents, including three workplace design solutions and one poster, to provide options to companies for controlling possible exposure of their workers to nanomaterials on the job.[21] NIOSH will continue to develop occupational safety and health guidance that can be incorporated into business plans to both protect worker safety and promote application development and commercialization.

As nanotechnology-enabled innovations and products increasingly make their way into the marketplace, NNI agencies are targeting their activities to address nanoEHS considerations that are specific to the use of nanomaterials in manufacturing and consumer products, as well as in food and agriculture. DOD will continue to work with academia and industry to organize a series of workshops on the EHS decision process for implementing nanomaterials, other advanced materials, and additive manufacturing. NIOSH and CPSC will collaborate to study the release of engineered nanomaterials from laser printer toner and from 3D

[19] https://www.youtube.com/watch?v=SM92WzHA87w
[20] https://www.fda.gov/downloads/Drugs/GuidanceComplianceRegulatoryInformation/Guidances/UCM588857.pdf
[21] https://www.cdc.gov/niosh/topics/nanotech/pubs.html

printers. NIOSH will also work with universities and industry to promote safe practices in nanotechnology and advanced manufacturing, including organizing a technical conference session on this topic. NIOSH plans to work with industry to develop practical, “real world” evaluation of hazard and risk represented by nanomaterials through their life cycles, focus the NIOSH field research effort on outputs that support the Sustainable Nanomanufacturing NSI, and collaborate with industry to assess the toxicology of carbon-based, metal-based, and nanoclay-enabled materials.

Work on evaluating the use of nanomaterials in consumer products spans several agencies. CPSC and NIST will participate in an ISO project, “Nano-screening Program on Nanomaterial Release from Consumer Products,” to review and evaluate the utility of available methods to assess material released from commercial polymer composites containing added nanomaterials, in support of product use and safety decisions. CPSC and DOD will develop models for the risk of exposure to nanomaterials released from consumer products. NIST’s 2019 request includes research to understand and measure the reduced flammability of upholstered materials incorporating nanomaterials, and the analysis of nanomaterials in complex matrices. NIOSH plans to continue collaborations to evaluate zinc and titanium-enabled sprays and treated surfaces.

NIFA’s nanotechnology programs will continue to support EHS research relevant to agricultural production and food applications, including characterization of hazards, exposure levels, and transport and fate of engineered nanoparticles or nanomaterials in crops, soils (and soil biota), livestock, and production environments. These assessments may also include animal feed formulations and processes that utilize novel nanomaterials or the development of new nanostructured materials or nanoparticles that are bio-persistent in digestive pathways.

Utilization 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, NIOSH, 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 2013 through 2016 (the latest year for which data are available).

Some NNI agencies (e.g., NSF and NIH) 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, nanoelectronics and active nanostructures, nanotechnology for biological and medical applications, and instrumentation for nanotechnology. Some agencies have had topical or applications-oriented solicitations for which many awardees have proposed nanotechnology-based innovations. SBIR/STTR data for 2004 through 2016 indicate that the NNI agencies have cumulatively funded nearly $1.3 billion of nanotechnology-related SBIR and STTR awards during this period, in addition to the funding reported under the NNI PCAs. A complete listing by year (including data from 2004 through 2012) can be found at a download link in the Overview section of nanodashboard.nano.gov.

Table 6: 2013–2016 Agency SBIR and STTR Awards
(dollars in millions)

	2013			2014			2015			2016		
Agency	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**
DHS	0.3	0.0	0.3	0.3	0.0	0.3	4.0	0.0	4.0	0.0	0.0	0.0
DOC/NIST	0.6	0.0	0.6	0.7	0.0	0.7	0.2	0.0	0.2	0.3	0.0	0.3
DOD	22.6	5.5	28.1	11.1	6.5	17.6	24.6	2.8	27.4	41.9	7.3	49.2
DOE	3.9	2.3	6.2	15.1	2.5	17.5	20.5	4.0	24.5	26.2	4.7	30.9
EPA	0.5	0.0	0.5	0.9	0.0	0.9	0.9	0.0	0.9	1.7	0.0	1.7
HHS/NIH	22.9	1.9	24.8	26.9	3.2	30.1	21.8	3.2	24.9	18.2	5.7	24.0
HHS/NIOSH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NASA	5.7	1.3	7.1	2.1	1.9	4.0	3.3	0.9	4.2	3.5	1.1	4.6
NSF	17.9	0.9	18.9	22.1	3.6	25.8	19.6	3.8	23.4	22.9	3.5	26.5
USDA	0.1	0.0	0.1	0.1	0.0	0.1	1.5	0.0	1.5	0.0	0.0	0.0
TOTAL	**74.5**	**11.9**	**86.4**	**79.3**	**17.7**	**97.0**	**96.4**	**14.7**	**111.0**	**114.8**	**22.4**	**137.2**

Table 6 illustrates the steady increase in recent years in the level of nanotechnology-related SBIR and STTR funding, with 2016 at a record high of $137 million. Even though few agencies specifically call out nanotechnology in their SBIR/STTR solicitations, it is enabling innovations in many R&D application areas with potentially important commercial and public benefits. Topical areas supported by agency SBIR and STTR awards (and enabled by nanotechnologies) include the following:

- Nanophotonic sensors, enabling hand-held gas sensors, portable bioassays, and photonic sensing of electromagnetic fields (DOD).
- Ultrafast lasers, enabling tabletop x-ray sources to provide nanometer-resolution 3D tomography (DOE).
- Nanoparticle inks to optimize inkjet printing of contacts for low-cost photovoltaic cells (DOE).
- Nanocomposite materials for fast-charging and high-energy-density lithium ion batteries (DOE).
- Use of carbon nanotube yarns in stitched hybrid composites for enhanced damage tolerance (NASA).
- Nanoparticles for targeted and controlled delivery of immunogens and adjuvents for HIV vaccines (NIH).
- Nanocrystalline ceramic coatings and nanocomposites for orthodontic and dental applications (NIH).
- Zero valent iron composites for *in situ* remediation of chemically contaminated waste sites (NIST).
- Non-contact microwave measurement technologies for real-time inline inspection of nanocarbon composite materials (NIST).
- Nanoelectromechanical scanning probes for failure analysis of nanoscale integrated circuits (NSF).
- Novel nanocrystal-based phosphors for high-efficiency white LEDs (NSF).
- Plasmonic photocatalysis for conversion of carbon dioxide to liquid fuels using solar energy (NSF).
- Magnetic nanoparticles for high-throughput benchtop *Salmonella* detection (USDA).
- The use of nanophase silica derived from agricultural waste as a key ingredient in ultra-high-performance concrete (USDA).

Other notable programs and activities contributing to commercialization of nanotechnology innovations include the NSF Industry/University Cooperative Research Centers (I/UCRC) program,[22] the NIH Nano Startup Challenge in Cancer,[23] and several public/private partnerships aimed at accelerating progress in the semiconductor industry[24] and in the commercialization of cellulose nanomaterials from forests in the packaging, food, oil drilling, and health care industries.[25] Of particular note is the Innovation Corps (I-Corps™) Program, which was initiated by NSF and is being implemented in several other agencies. Examples of nanotechnology-related topics supported under I-Corps funding include high-power laser processing to create nanostructured superhydrophobic surfaces for anti-icing and anti-reflection applications, and the development of nanophotonic transceivers for low-cost, high-efficiency fiber optic networking. Additional programs aimed at unleashing American innovation, including NSF's Convergence Accelerators[26] and focused Lab-to-Market efforts, will further support the acceleration of nanotechnology research advancements into commercial products.

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[22] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5501

[23] https://www.nscsquared.org/

[24] For example, the DARPA JUMP program and the NSF E2CDA program (described elsewhere in this report) and the NIST NEW LIMITS program (see https://www.src.org/program/ncore/newlimits/).

[25] P³Nano, a partnership between the USDA Forest Service and the U.S. Endowment for Forestry and Communities, Inc., http://www.usendowment.org/p3nano.html.

[26] https://www.nsf.gov/news/news_summ.jsp?cntn_id=244676

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

The frontiers of science are ever expanding, and NNI agencies are committed to supporting basic and early-stage applied research at the leading edge, enabling the development of next-generation nanotechnology-enabled innovations. Meanwhile, research results from past NNI investments are being broadly applied by the private sector in new commercial products. Continued Federal investments will enable future discoveries that build upon and expand the body of knowledge already developed under the auspices of the NNI, and will ensure that the United States remains at the forefront of nanotechnology and realizes the benefits to our national and economic security.

Research and development activities in the areas of nanoelectronics, nanomanufacturing, informatics, sensors, and water are more closely coordinated through the Nanotechnology Signature Initiative[27] mechanism to enhance interagency collaboration and better leverage knowledge and resources.

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

Understanding the electrical, optical, and magnetic properties of nanomaterials. Scientists funded by DOE have experimentally validated the theoretical prediction that magnetic skyrmions will move intact in a direction perpendicular to the electric current. This phenomenon is called the skyrmion Hall effect, an analogy to electrons with similar behavior. The high stability and easy manipulation of skyrmions could revolutionize energy-efficient information technologies including memory and logic devices.[28] Other breakthroughs may also impact information technologies. For example, an international team led by DOD-funded scientists and engineers has developed the first computer chip with nanoscale optical quantum memory. Quantum memory stores information with individual quantum particles—in this case, photons of light—taking advantage of quantum effects such as superposition to store data more efficiently and securely. This development is an essential step for the future development of optical quantum networks.[29] In collaboration with academic researchers, NIST scientists have identified a toolset to study memristors, semiconductor elements that can act like the short-term memory of nerve cells and may serve as a key element in future electronics, and used it to more deeply probe how memristors operate.[30] NSF researchers have demonstrated cavity-enhanced electroluminescence from atomically thin monolayer materials, an important first step in the development of electrically pumped nanolasers needed for integrated photonic-based, short-distance optical interconnects, which could lead to improvement in the performance of data centers.[31] Researchers supported by DOD have used computer chip patterning techniques to create the first metamaterial lens, or metalens, that can focus the full spectrum of visible light. Metalenses are cheap to

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[27] http://nano.gov/signatureinitiatives

[28] https://science.energy.gov/bes/highlights/2017/bes-2017-06-n/

[29] http://www.caltech.edu/news/first-chip-nanoscale-optical-quantum-memory-developed-79591

[30] https://www.nist.gov/news-events/news/2018/01/thanks-memory-nist-takes-deep-look-memristors

[31] http://www.ee.washington.edu/spotlight/professors-majumdar-and-xu-discover-an-important-first-step-towards-building-electrically-pumped-nano-lasers/

produce, thinner than a sheet of paper, and far lighter than glass. Future applications include camera modules for cell phones and laptops, wearable optics for virtual and augmented reality, and telescopes in space.[32] This result was recognized as Runner-up for *Science* magazine's Breakthrough of the Year.[33]

Expanding the boundaries of materials science. Researchers continue to expand the boundaries of materials science with the discovery of new nanomaterials, development of complex composites, and investigations into properties targeting a wide range of applications. For example, advanced multifunctional magnetically-responsive materials have been developed by DOD researchers for integration into polymeric nanocomposites and fabrics, where strength and stiffness can be controlled with an externally applied magnetic field. Engineers, designers, and mathematicians funded by NSF have collaborated to develop a general framework to design reconfigurable metamaterials.[34] This framework may be used to develop reconfigurable nanoscale systems such as photonic crystals, waveguides, and metamaterials to guide heat. NIH researchers have developed tunable nanoscale metal organic frameworks for enhanced x-ray-inducible deep tissue photodynamic therapy and radioimmunotherapy.[35] Novel nanocomposite materials, with significant improvements in strength and orders-of-magnitude improvements in toughness and ductility, have been developed by DOD researchers using carbon nanofibers as additives.

Many Federal agencies (including DOD, NIST, NASA, DOE, and NSF) are investing in a materials-by-design approach, which represents a new paradigm in materials discovery to accelerate the development of new materials. For example, computational chemistry and micromechanical analysis (including nanoscale indentation and shear experiments) are being used to design two-dimensional polymer ensembles with specific properties for high-performance structural applications for DOD. The most promising computationally designed materials are then synthesized for further testing through collaboration with academia. NASA is also advancing this paradigm and has established a multi-university Space Technology Research Institute focused on the development of computational tools, carbon nanotube material synthesis techniques, and composite processing and testing methods to produce carbon nanotube composites with mechanical properties that exceed those of today's carbon fiber reinforced composites.[36] Complementary in-house NASA efforts are focused on approaches to enhance load transfer between carbon nanotube bundles.

Advancements in materials properties such as creep resistance, strength, conductivity, dielectric behavior, and improved cycle lifetime have also been achieved. DOD scientists have developed a divergent, bulk nanocrystalline copper-tantalum alloy that is able to achieve and retain high strength and creep resistance at elevated temperatures.[37] This methodology for designing thermodynamically stable, nanoscale microstructures across a broad range of alloy types has potential applications in turbine engines and hypersonics. Improved stability could lead to increases in engine operating temperatures, with the potential to revolutionize engine and flight technologies. Researchers funded by DOE have verified that the electrical conductivity of copper can be increased by 30% using nanocarbon. Investigators funded by NIH have demonstrated improvement in mechanical performance of novel dental materials that combine nanoparticle-based biomaterials with a variety of polymer resins.[38] NASA researchers have developed a class of thermally reversible polymer gels and utilized them in a continuous process to coat carbon nanotube

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32 http://science.sciencemag.org/content/352/6290/1190

33 http://www.sciencemag.org/news/2016/12/ai-protein-folding-our-breakthrough-runners

34 https://www.seas.harvard.edu/news/2017/01/toolkit-for-transformable-materials

35 http://linlab.uchicago.edu/current_research.html#nanomedNMOF

36 https://www.nasa.gov/directorates/spacetech/strg/stri/us_comp

37 https://phys.org/news/2016-09-nanocrystalline-alloy-combines-mechanical-strength.html

38 See https://grants.nih.gov/grants/guide/rfa-files/RFA-DE-13-001.html and https://www.sciencedirect.com/science/article/pii/B9780128122914000029

wires. These materials may be used to replace conventional fluoropolymer dielectrics in data cables to reduce cable mass. The 2017 Forest Products Society Wood Engineering Achievement Award for Engineering Innovation was awarded to a USDA Forest Service scientist for research at the nanoscale leading to improvements in wood adhesives and the development of new high-performance wood composite materials.[39] A nanoscale coating developed by DOE-funded researchers was used in high-energy Li-Ion battery cells with a cycle life more than two times better than that achieved by battery cells without the coating.

Materials discoveries are also impacting future prosthetics and textiles. Artificial cartilage has been developed by researchers funded by NSF and DOD (see sidebar, below).[40] Unlike textiles that are simply coated with nanoparticles, a silver nanoparticle-cotton system[41] developed by USDA's Agricultural Research Service has resulted in a uniform dispersion of silver nanoparticles inside the fiber. This dispersion remained uniform even after 50 cycles of laundering, and 92% of the silver was retained, as was the antimicrobial activity against *E. coli* and *Staphylococcus aureus*. This nanocomposite fiber, which can continuously deliver antibacterial activity wash after wash, has potential for use in antimicrobial washable wipes.[42] ARS researchers are also addressing flammability. Using a layer-by-layer self-assembly process, ARS researchers have developed clay treatments to cotton for moisture management, strength, and absorptivity. By treating fabric with intumescent nanoscale coatings composed of phosphorous-nitrogen-rich polymers, cotton could also be rendered anti-flammable.[43]

Kevlartilage: Kevlar nanofibers help artificial cartilage perform like real tissue

Artificial cartilage that more closely mimics real tissue has been developed by researchers funded by NSF and DOD. Existing varieties of synthetic cartilage have had to choose between strength and water content. The new material, Kevlartilage, however, combines a network of durable Kevlar nanofibers with a polyvinyl alcohol hydrogel that effectively transports vital nutrients to cells. The artificial cartilage is comparable to real tissue in its flexibility and capacity to withstand stress. Future applications of this system may extend to replacing other soft tissue types.

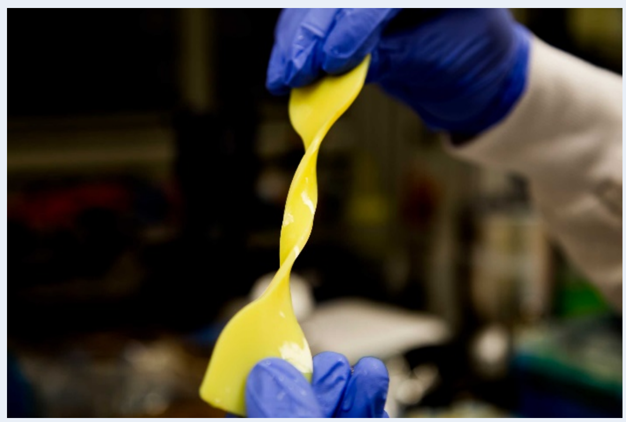

Image credit: Joseph Xu, University of Michigan

Advancing sensing and metrology. Scientific breakthroughs in nanotechnology are advancing sensing capabilities in a wide range of applications. For example, researchers funded by NIFA have developed wearable sensors for plants, enabling measurement of the time it takes for two kinds of corn plants to move water from their roots to their lower leaves, and then to their upper leaves. This new, low-cost, easily produced, graphene-based, sensors-on-tape technology can be attached to plants and provide new kinds of data to researchers and farmers.[44]

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[39] http://www.multibriefs.com/briefs/fps/fpsexcellence.pdf
[40] http://ns.umich.edu/new/releases/25262-kevlar-based-artificial-cartilage-mimics-the-magic-of-the-real-thing
[41] https://www.ars.usda.gov/research/programs-projects/project/?accnNo=428080&fy=2017
[42] https://www.ars.usda.gov/news-events/news/research-news/2017/wiping-out-bacteria-with-nanoparticle-cotton-fibers/
[43] https://www.ars.usda.gov/research/project/?accnNo=428425&fy=2017
[44] https://scienmag.com/engineers-make-wearable-sensors-for-plants-enabling-measurements-of-water-use-in-crops/

DOD has funded sensors research in a number of areas ranging from brain imaging, to detection of nerve agents, to minimizing the need for cold-chain logistics. Scientists supported by DOD have developed and reduced to practice the use of new super-bright, photo-stable, nanometer-scale voltage sensors for imaging brain activity[45] with 20- to 40-fold greater sensitivity than currently possible. This advancement has paved the way for the design of new voltage-sensitive probes for deeper tissue imaging of brain activity for the diagnosis of brain disease and injury. By analyzing data from light reflected from natural photonic crystals (butterfly wings), DOD researchers have been able to detect simulated nerve agents.[46] These results demonstrate that vapor sensors based on photonic crystals may enable long-term, passive, cheap sensors for nerve agents. Another group of researchers supported by DOD has created protein ionic liquids that represent new nanoscale multifunctional systems that are ultra-stable, resistant to extreme temperatures, biologically active, exhibit a long shelf life, and do not require "cold chain" logistics. This development will enable use of biological materials in biosensors, diagnostics, biomedical devices, and composite-based materials and structures in resource-limited settings such as military medevac operations, where equipment weight and accessibility are major tactical concerns.

Nanosensors for medicine have been advanced by several agencies. FDA researchers have utilized nanosensors to develop novel and sensitive diagnostic assays for human immunodeficiency virus (HIV), influenza, West Nile virus, dengue virus, and Zika virus.[47] NSF-funded researchers have developed a test that can detect the presence of the Zika virus in blood in minutes.[48] This proof-of-concept technology would eliminate the delay in diagnosis and possible treatment currently resulting from the need to refrigerate the blood and ship it to a medical center or laboratory for testing. To accelerate next-generation prophylactic and therapeutic vaccine development against prevalent and emergent infectious diseases, NIH convened a multidisciplinary meeting to promote the exchange of ideas in diverse areas of vaccination, innovative therapies, and delivery systems to provide impetus for innovative and enabling nanotechnologies and drug delivery systems that can serve as platforms for vaccine/immunogen delivery.[49]

Developing new tools and devices. Research breakthroughs have been made in the development of tools and devices. For example, engineers supported by NSF have developed a miniature device that is sensitive enough to feel the forces generated by swimming bacteria and hear the beating of heart muscle cells. The device is a nanoscale optical fiber that detects forces as small as 160 femtonewtons and sound levels down to -30 decibels. Applications include measuring bioactivity at the single-cell level, or ultrasensitive mini stethoscopes to monitor cellular acoustics *in vivo*.[50] NIST scientists have developed a microflow measurement system, about the size of a nickel, that can track the movement of extremely tiny amounts of liquids, as small as nanoliters per minute. A provisional patent application has been filed for this invention designed to fill an urgent need in the rapidly expanding field of microfluidics.[51] To enable measurement of nanodevices, NIST researchers have pioneered new methods to locate nanometer-scale patterned devices and to connect e-beam patterned contacts. This work results from a research effort in atomically precise fabrication, atomic-scale device metrology, and fundamental measurement science at the atomic limit. Portions of this research were done in collaboration with DOE, academia, and industry. Researchers funded

[45] http://www.navy.mil/submit/display.asp?story_id=92050

[46] https://pubs.acs.org/doi/full/10.1021/acsomega.7b01680

[47] https://www.ncbi.nlm.nih.gov/pubmed/29528198

[48] https://medicine.wustl.edu/news/test-uses-nanotechnology-quickly-diagnose-zika-virus/

[49] https://ncl.cancer.gov/meetings/2nd-nanotechnology-workshop-hiv-rna-infectious-diseases-and-vaccine-delivery-september-25

[50] http://ucsdnews.ucsd.edu/pressrelease/nano_fiber_feels_forces_and_hears_sounds_made_by_cells

[51] https://www.nist.gov/news-events/news/2018/01/stopwatch-nanofluids-nist-files-provisional-patent-measuring-nanoliter-flow

by NSF have developed an actuator that can convert electrical energy to mechanical energy. With the application of a small voltage, the device can lift something more than 150 times heavier than itself.[52]

Other advances. Scientists supported by DOE have demonstrated for the first time that two electron-hole pairs, and two electron-hole pairs' worth of chemical work, can be produced from a single photon. This research could make the conversion of sunlight into chemical fuels more efficient by harvesting more energy from highly energetic photons, whose energy is discarded as heat in conventional systems.[53] DOE also funded research that has resulted in a new world record for the highest efficiency in solar hydrogen production via photoelectrochemical (PEC) water-splitting using a nanostructured inverted metamorphic multijunction (IMM) semiconductor device. The new record of 16.2% tops the efficiency of 14% reported in 2015 and the researchers' own previous record of 12% set in 1998.[54]

Nanotechnology research has led to methods to keep us safe from carbon monoxide and food contaminants. Currently, carbon monoxide detectors are relied on for safety. Research funded by DOE points the way to a new approach: direct elimination of the gas. Collaborative research teams recently succeeded in creating tiny, uniquely structured wires that remove carbon monoxide from an enclosed area with 100 percent efficiency at room temperature. This work could lead to a highly efficient and cost-effective method to remove carbon monoxide and provide insight toward the development of other advanced catalysts.[55] The contamination of ready-to-eat meat products by foodborne pathogens is a concern for the meat industry. One potential solution is to wrap meats in films composed of natural biopolymers combined with nanotechnology. ARS researchers have developed edible antimicrobial composite films from microemulsions containing all-natural compounds using high-pressure homogenization technology. Studies mimicking industry food processing conditions revealed a 99.99 percent inactivation of pathogens after 35 days at 10 degrees Celsius. New disinfection methods using polymer membranes to reduce cross-contamination during food processing and remove or inactivate bacteria in protected structures called "biofilms" have been developed with support from NIFA. These membranes can inactivate pathogens like *Listeria momocytogenes* and pathogenic *E. coli* on contact and prevent outbreaks in the food processing industry.[56] Nanotechnology is also being used to stimulate the immune systems in plants to protect against fungal infections (see sidebar, next page).

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

The science and technology advances supported under Goal 1 form the basis for new materials, devices, and systems. Early applications of nanotechnology can already be found in products throughout the marketplace, but there is significant potential for the novel properties that exist at the nanoscale to be used in entirely new devices and systems in a broad array of applications, 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. Goal 2 encompasses how the NNI aims to complement private sector investments and activities by sharing information, promoting access to user facilities, leveraging resources through public-private partnerships, and participating in international standards activities that are critical to commercialization.

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[52] https://news.rutgers.edu/news/acting-muscle-nano-sized-device-lifts-165-times-its-own-weight/20170829#.WqGJ2OjwY2x

[53] https://science.energy.gov/bes/highlights/2017/bes-2017-08-g/

[54] https://www.nrel.gov/news/press/2017/1117-nrel-establishes-world-record-for-solar-hydrogen-production.html

[55] https://science.energy.gov/bes/highlights/2016/bes-2016-11-i/

[56] http://aem.asm.org/content/early/2017/07/24/AEM.00975-17.long?utm_content=&utm_medium=email&utm_name=&utm_source=govdelivery&utm_term=

Revolutionizing the fight against plant pathogens: Nanoscale micronutrients boost plants' disease fighting ability

Nearly 42% of global production of six major food crops is lost to pathogens. NIFA is supporting experiments to stimulate a plant's own immune system to fight fungal infections by supplying nanoscale particles of essential micronutrients such as copper, zinc, and manganese. By making nutrients more available, crops such as eggplant and watermelon treated with the nanoparticle nutrient have shown several positive effects over those plants treated with bulk versions of the same nutrient, potentially increasing production without adding pesticides. In one field trial, the treatment cost an estimated at $44 per acre, and raised the per-acre value of the yield from $17,000 to $28,000.[57] This work is continuing with additional support from the NSF-funded Center for Sustainable Nanotechnology (CSN).

Dr. Nubia Zuverza-Mena with eggplant harvested from field trials conducted with CSN. Image credit: Jason White, Connecticut Agricultural Research Station

The following highlights illustrate the transfer of new technologies into application for public benefit.

Fostering entrepreneurship. The agencies participating in the NNI use a variety of programs and mechanisms to foster the transfer of promising nanotechnologies to the commercial sector. For example, the NSF I-Corps™ program prepares scientists and engineers to extend their focus beyond the university laboratory, and accelerates the economic and societal benefits of basic-research projects that are ready to move toward commercialization. NSF I-Corps nodes are designed to support regional needs for innovation education, infrastructure, and research. The nodes work cooperatively to build, utilize, and sustain a national innovation ecosystem that further enhances the development of technologies, products, and processes that benefit society. Many of the technologies supported by NSF I-Corps involve nanotechnology, including nanotextured anti-reflection surfaces[58] and use of nanomaterials in environmental remediation.[59] The I-Corps program has expanded to several other agencies.

Transitioning information and communication technologies. Advances in computing and communication devices supported by DOD are advancing toward commercialization. Flexible gallium nitride RF devices that can be easily integrated into more effective wireless communication, the Internet of Things, autonomous vehicles, and radar applications have been pioneered and patented. These devices are being developed for military applications including wearable human performance monitoring systems and future conformal radar concepts.[60] DOD is also collaborating with academia and industry to develop hybrid complementary metal-oxide semiconductor (CMOS)/memristor circuits and integrated CMOS with on-chip nanophotonics, leveraging existing multi-billion dollar manufacturing facilities.[61] These circuits will support dynamic learning by neuromorphic computers, a key step required for advancements in autonomous systems. DOD scientists have demonstrated that the spin polarization generated by spin-momentum

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[57] https://undark.org/article/nanoscale-connecticut-agricultural-station/

[58] https://nsf.gov/awardsearch/showAward?AWD_ID=1522607

[59] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1156513

[60] http://www.wpafb.af.mil/News/Article-Display/Article/1387199/afrl-research-to-enable-next-gen-flexible-wireless-communications/

[61] http://www.dtic.mil/docs/citations/AD1009567

locking in the topologically protected surface states of Bi_2Se_3 can be used to modulate the magnetization of an adjacent ferromagnetic film by spin transfer torque arising from the flow of pure spin current from the Bi_2Se_3 into the ferromagnetic film.[62] This approach provides a path towards non-volatile random access memory with high density and low power consumption.

Bringing nanotechnology to aerospace and automotive markets. Technologies with applications in the aerospace and automotive industries are being patented and licensed. NASA researchers have developed a family of polymer aerogels that are mechanically robust, have electrical and thermal insulation capabilities equivalent to those of conventional aerogels, and are flame-resistant.[63] Thin films processed from these aerogels can be folded and creased and do not tear or crack. A small business licensed this technology, has developed a cost-effective method to produce these aerogels at scale, and is working with end users for commercial application in aircraft interiors and automotive components. DOD researchers invented, patented, and demonstrated a bio-inspired artificial hair flow sensor that predictably measures the air flow in and above the boundary layer using the piezoresistive properties of carbon nanotube (CNT) arrays grown between a single glass fiber and an electroded glass capillary.[64] The cantilevered hairs can sense the onset of turbulence. Integrated into arrays on the surface of an airfoil, these sensors have successfully detected airfoil angle of attack, speed, coefficient of lift, moment, and flow separation. As small, agile fliers continue to join the fleet, lightweight, distributed sensors will increasingly be needed for "fly-by-feel" systems.

Translating nanotechnology from bench to bedside. NIH awardees, FDA representatives, and industry experts have worked together to develop a strategic framework to accelerate development and clinical translation of novel dental materials that combine nanoparticle-based biomaterials with a variety of polymer resins. NIH is also supporting two resource centers to deliver technical support, research capacity, administrative infrastructure, and regulatory expertise for the Dental, Oral, and Craniofacial Tissue Regeneration Consortium.[65] The resource centers will facilitate development of promising strategies, including nanotechnology-based strategies, for regenerative dental, oral, and craniofacial tissues to advance to clinical trials.

NCI continues to support the Alliance for Nanotechnology in Cancer program, which uses nanotechnology as a tool for cancer biology and oncology research. The program has matured and evolved into defining relevant biological and clinical problems that apply nanotechnologies developed under the Alliance and are entering clinical trials. NIH also continues to support its open innovation startup collaboration with the Center for Advancing Innovation to commercialize cancer nanotechnology inventions originally conceived at NIH.[66] In the final phase of the challenge, NIH's Office of Technology Transfer will evaluate licensing applications to determine the viability of commercialization and development plans.

Working with standards developing organizations. A critical aspect to commercialization of nanotechnologies is the development of voluntary consensus standards developed by organizations such as ASTM International, the International Electrotechnical Commission (IEC) and the International Organization for Standardization. Federal agencies actively participate in these standards efforts. For example, NIST chairs the U.S. Technical Advisory Group to ISO TC 229 on Nanotechnologies, which includes representatives from NIST, other Federal agencies (including CPSC, DOE, EPA, FDA, NIOSH, USDA, and the Army Corps of Engineers), and private sector organizations. Work projects led by Federal agency staff are

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[62] https://www.nrl.navy.mil/media/news-releases/2017/NRL-Detects-Opposite-Spin-in-Topological-Insulator-Surface-States
[63] https://technology.nasa.gov/patent/TOP3-411
[64] http://www.wpafb.af.mil/News/Article-Display/Article/1175838/bio-inspired-crickets-bats-inspire-afrl-researchers-to-develop-smart-hair-senso/
[65] https://www.nidcr.nih.gov/grants-funding/funding-priorities/dental-oral-and-craniofacial-tissue-regeneration-consortium
[66] https://www.nscsquared.org/

resulting in standards that are critical for generating greater confidence in the safety of nanomaterials and nanotechnology, and are contributing to the growth and commercialization of nanotechnology by supporting trade and commerce. Examples of such standards include terminology for nanomanufacturing process vocabulary, techniques for measuring or characterizing particle size populations, and approaches to evaluating methods that assess the release of manufactured nanomaterials from commercial nanomaterial-containing polymer composites. Federal agency laboratories perform research that informs these standards and results in outputs such as NIST reference materials and instruments, which ensure reliable nanoscale measurements to ensure data consistency and to verify the performance of analytical instruments. For example, the use of NIST SRM 1980, a Standard Reference Material issued by NIST for positive electrophoretic mobility, is required to implement ASTM E2865, *The Standard Guide for Measurement of Electrophoretic Mobility and Zeta Potential of Nanosized Biological Materials*. NIH and NIST, though an interagency agreement, have collaborated on the development of the NIST Standard Reference Instrument 6005 Polymerization Stress Tensometer for inter-comparability testing of dental composites and nanocomposites, and on the development of standards for determining key polymerization properties for photopolymerized dental materials.[67] The NNI Standards Coordinator from NIST facilitates sharing of information among the agencies. NNCO has broadened its efforts to support this activity and has expanded resources available on Nano.gov.

Reusable sponge boosts oil spill cleanup technology

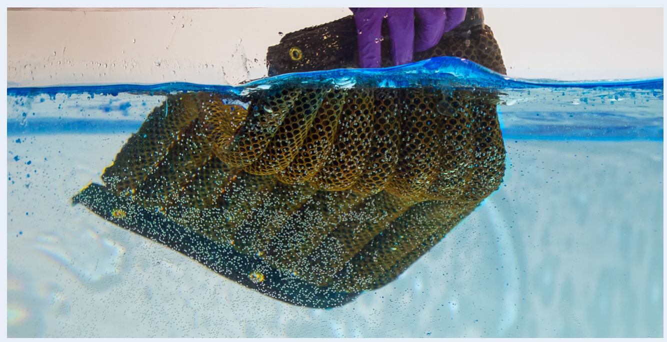


Image credit: Mark Lopez, Argonne National Laboratory

Mitigating uncontrolled release of petroleum in our oceans and other bodies of water received a boost with the development of the Oleo Sponge, a new foam that readily adsorbs dispersed oil in water. Researchers at DOE's Argonne National Laboratory created a thin layer of metal oxide "primer" within the interior surfaces of polyurethane foam. The metal oxide nanostructures attached within the surface-modified foam enable the tight chemical binding sites of the oil-loving molecules, which grab oil from the spill. The Oleo Sponge performs better than current oil spill remediation techniques, and allows for recovery of the collected oil. During tests at a national test facility, the sponge successfully collected diesel fuel and crude oil from both below and on the water surface. The foam did not break down even after hundreds of wring and reuse cycles. These innovations make the Oleo Sponge a radical improvement on current technology.[68] This work was supported by DOE and the U.S. Coast Guard.

Advancing technologies for energy and infrastructure. Many other technological breakthroughs, with applications ranging from infrastructure to batteries, are working their way through the development and demonstration pipeline. Technologies at the earlier stages of development include a new foam called the Oleo Sponge, invented by DOE-supported researchers (see sidebar, above). Nanoscale coatings have been used by DOD scientists to entirely eliminate dangerous dendrite formation while simultaneously increasing capacity retention in nanoscale Li-ion battery electrode materials. By stabilizing the electrolyte/electrode interface and eliminating dendrite formation, batteries can be charged and discharged repeatedly without

[67] https://www.nist.gov/fusion-search?s=SRI+6005

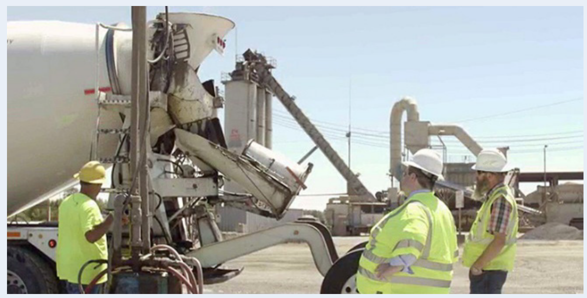
[68] https://science.energy.gov/bes/highlights/2017/bes-2017-05-f/

loss of capacity, and more importantly, without regard for accidental overcharge and the consequent thermal runaway.

At the more mature end of the spectrum, Forest Service researchers are collaborating with a public-private partnership to accelerate technology transfer of cellulose nanomaterials. Projects include industry representatives and academic researchers.[69] A demonstration project in Yreka, California, is underway that will use cellulose nanomaterials as a strength enhancer in a concrete bridge (see sidebar, below).[70] Industry, in collaboration with DOD, has developed a class of lightweight CNT sheet, tape, film, and array products that original equipment manufacturer (OEM) and Tier 1 suppliers can seamlessly integrate into existing composite manufacturing processes for improved mechanical and electrical properties. Continuous manufacturing capabilities will enable potential applications such as deicing, electromagnetic interference (EMI) shielding, lightning strike protection, and directed energy protection.[71]

Concrete evidence that cellulose nanotechnology works: USDA-supported partnership test pours new bridge material

A demonstration project in Yreka, California, will use cellulose nanomaterials (CNMs) as a strength enhancer in a concrete bridge deck. CNMs have unique properties and are generating new uses for renewable forest-sourced materials, turning low-value woody biomass into high-value materials. For example, cellulose nanocrystals, the short-aspect-ratio rod-like CNMs, have unique interactions with water and cement, making them suitable for infrastructure projects. The Yreka Project is the first practical test of cellulosic nanocrystals in concrete. Researchers conducted a test pour from a truck in July 2017. The project is supported by the USDA Forest Service and several public and private partners.



Jason Weiss, professor of infrastructure materials at Oregon State University's College of Engineering (center), and researchers test cellulose nanocrystals in concrete in the first commercial-scale trial. Image credit: Darryl Lai, Oregon State University

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 NNI-funded academic research—including students actively engaged in the research at the community college, undergraduate, graduate, or post-doctoral levels—as well as the development of resources for and outreach to K-12 teachers and students.

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[69] http://www.usendowment.org/p3nano.html

[70] https://www.fs.usda.gov/detailfull/r5/home/?cid=FSEPRD558114&width=full

[71] See http://www.uc.edu/news/NR.aspx?id=23339 and https://www.compositesworld.com/articles/nanocomp-technologies-inc-merrimack-nh-us-

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

Developing tools and instrumentation for nanotechnology. The suite of tools to fabricate, manipulate, image, characterize, and model materials at the nanoscale continues to expand. For example, researchers from DOD, NIST, and DOE are collaborating to develop the world's first polarized resonant soft x-ray scattering facility that can readily probe nanomaterial and biomolecular interactions at the atomic level in aqueous environments.[72] Using a focused ion-beam machining technique, NIST scientists have fabricated devices that allow precise measurement of the size of nanoparticles in a liquid. This technique could become a new laboratory standard for determining nanoparticle size and could expedite quality control in industrial applications.[73]

Providing research infrastructure, including centers, user facilities, and educational resources. A cornerstone of the physical research infrastructure for the NNI is the user facilities available to researchers across the country. The NSF-funded NNCI is a network of university-based user facilities.[74] 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 within all disciplines of nanoscale science, engineering, and technology. In its second year of operation (April 2017 through March 2018), NNCI provided access to over 2,000 tools at 66 facilities. These tools were accessed by more than 12,000 users representing over 200 academic institutions, 900 companies, and 40 government and non-profit institutions. During the second year, the network has trained more than 4,500 new users. The five NSRCs are DOE's premier user centers for interdisciplinary research at the nanoscale.[75] Each center has particular 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. NIST has released the NanoFab Equipment and Operations (NEMO) web application as open source and free software.[76] Nanotechnology fabrication facilities and laboratories across the Nation can customize the software to enable users to view the operating status of instruments or seek assistance from laboratory staff.

NIH addresses infrastructure needs, including information technology R&D and educational resources, through existing funding mechanisms. Many NIH institutes support training through networks and centers. For example, the NCI Cancer Nanotechnology Training Centers provide graduate and post-graduate training to researchers from diverse disciplinary backgrounds in the use of nanotechnology as an enabling tool for cancer biology and oncology research.[77] Other NNI agencies take a similar approach in their mission-specific areas and support specialized research facilities and laboratories to advance intramural nanotechnology research and development.

The NSF-funded NCN supports the NNI by designing, constructing, deploying, and operating a national cyber resource for nanotechnology theory, modeling, and simulation.[78] The NCN cyber platform uses the nanoHUB online science and engineering gateway.[79] Over 1.4 million visitors participate in nanoHUB for simulation, research collaboration, teaching, learning, and publishing every year. NanoHUB provides a library of over 450 simulation tools used by over 12,000 people annually, and 4,500 resources for research and education, including a searchable database of resources for K-12 teachers.

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[72] http://usersmeeting.ps.bnl.gov/workshops/workshop.aspx?year=2017&id=139
[73] https://www.nist.gov/news-events/news/2017/12/atomic-blasting-creates-new-devices-measure-nanoparticles
[74] http://www.nnci.net/
[75] https://nsrcportal.sandia.gov/
[76] https://github.com/usnistgov/NEMO
[77] https://www.cancer.gov/sites/nano/research/alliance/cntc
[78] https://nanohub.org/groups/ncn
[79] https://nanohub.org/

NNCO supports and amplifies the NNI agencies' education and outreach efforts. Example activities are illustrated on the inside back cover of this report, and in the sidebar below.

Fostering the young scientist-to-entrepreneur pipeline

The U.S. Nano and Emerging Technologies Student Network connects undergraduate student scientists, engineers, and entrepreneurs in student-run technology clubs from across the country. Students from the network help to organize the Nano and Emerging Technologies Student Leaders Conference, co-located with the National SBIR/STTR Conference. This student conference provides undergraduates with an opportunity to hear from entrepreneurs, industry leaders, venture capitalists, and representatives of Federal agencies funding research in emerging technologies. The conference sessions include a panel featuring people who have successfully commercialized their student research projects. Additionally, the network will host a webinar on entrepreneurship in 2018. Participants will discuss the challenges nanotechnology spin-off companies face and how university innovation ecosystems can help.

Image credit: Quinn Spadola, NNCO

Goal 4. Support Responsible Development of Nanotechnology

The responsible development of nanotechnology has been a primary goal of the NNI since its inception. An understanding of the behavior of nanomaterials with respect to nanoEHS considerations—in addition to potential ethical, legal, and societal implications (ELSI)—is essential 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 2011 NNI Environmental, Health, and Safety Research Strategy continues to guide the extramural programs and intramural activities within the agencies focused on nanoEHS.[80] The NSET Subcommittee's Nanotechnology Environmental and Health Implications (NEHI) Working Group and the NNI Coordinator for Environmental, Health, and Safety Research provide extensive coordination for these efforts across the Federal Government.

The following highlights showcase NNI agency activities that support the responsible development of nanotechnology.

Detecting and understanding the effects of nanomaterials in the environment and the human body. The ability to detect nanomaterials in products and understand their interactions within the human body is

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

central to understanding the potential EHS impacts of nanomaterials. FDA and NIEHS have collaborated to develop novel methods and approaches for detection of nanomaterials in FDA-regulated products, including physicochemical characterization and standards development. FDA researchers aim to better understand the complex interactions that occur between the body's physiological processes and various types of nanoengineered surfaces. Knowledge gained from this research has enabled FDA to better assess the safety and efficacy of medical products with this novel technology, for premarket review, postmarket assessment, and guidance development.[81]

Examples of programs supporting research on material-specific effects include the NHIR Consortium, funded by NIH.[82] NHIR has developed a system to prioritize the selection criteria for sets of engineered nanomaterials to be investigated using a wide range of test systems to reflect diverse routes of exposure (inhalation, ingestion, and ocular). Efforts are focused on developing biological response profiles for 15 engineered nanomaterials. The NIEHS National Toxicology Program has completed an evaluation of the immune system impact of inhalation of multiwalled CNTs in rodent models to better understand the potential health effects from low-dose exposure in workers.[83] This work complements the exposure assessment of nanomaterial manufacturing facilities conducted in collaboration with NIOSH.[84]

Understanding and mitigating potential impacts in the workplace. As nanomaterials and nanotechnology-enabled products make their way into commerce, NIOSH works to fully 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, including carbon nanotubes; metal oxides; silver; the nanowire forms of silver, silica, and titania; graphene and graphene oxide; and cellulose nanocrystals and nanofibers. "Real-world" evaluations of hazard and risk represented by various nanomaterials through their life cycles have been performed by NIOSH, including the characterization of 22 commercially available spray products that advertised the use of nanoscale silver or colloidal silver as the active ingredient. NIOSH also has collaborated with over 20 national and international universities in the characterization of toxicological effects of pulmonary and dermal exposure to a wide range of industrially relevant nanoparticles and nanotechnology-enabled materials.[85]

Agencies participating in the NNI are also actively engaging with industry to share nanoEHS knowledge and best practices. NIOSH field research teams visit nanomaterials producers and users and conduct industrial hygiene evaluations (see sidebar, next page).[86] DOD researchers have developed and released the NanoGRID v1.0 tool.[87] NanoGRID is a software program that implements a tiered-based approach for EHS testing and assessment. DOD also has published a methodology and website supporting the life-cycle assessment of nanotechnology-enabled products developed by small businesses in collaboration with industry and academia.[88] The effort is streamlining sustainability, safety, and insurance liability decisions.

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[81] https://www.fda.gov/ScienceResearch/SpecialTopics/Nanotechnology/default.htm
[82] https://www.niehs.nih.gov/research/supported/exposure/nanohealth/index.cfm
[83] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5215911/
[84] https://ntp.niehs.nih.gov/annualreport/2015/partners/niosh/index.html
[85] https://www.cdc.gov/niosh/topics/nanotech/default.html
[86] https://www.cdc.gov/niosh/topics/nanotech/field.html
[87] https://nano.el.erdc.dren.mil/tools.html
[88] https://nano.el.erdc.dren.mil/index.html

NIOSH collaborates with industry to conduct voluntary* in situ *assessments of workplace exposures

NSF has estimated that approximately six million workers will be employed in nanotechnology industries worldwide by 2020. As part of its nanotechnology research program, NIOSH has established collaborations that evaluate in situ *workplace processes, and develops methods to identify and quantify worker nanomaterial exposure. Collaborating organizations gain access to NIOSH's expertise in nanomaterial characterization and exposure control technology. NIOSH field research teams visit nanomaterials producers and users, including additive manufacturing and 3D printing facilities. During 2017, NIOSH collaborated with 8 companies and completed 12 field assessments. NIOSH has used its research findings to develop guidance documents to protect workers from occupational injury and illness.*

Image credits: Provided by NIOSH and used with permission

Developing and disseminating information. An important activity in support of this goal is the development and dissemination of information to support the responsible development of nanotechnologies. NNI agencies develop publications such as guidance documents, safe handling procedures, and current intelligence bulletins to inform researchers, manufacturers, and the broader public. For example, in response to a critical need expressed by the nanomanufacturing community, NIOSH has published a new chapter in the *NIOSH Manual of Analytical Methods*: Analysis of Carbon Nanotubes and Nanofibers on Mixed Cellulose Ester Filters by Transmission Electron Microscopy.[89] FDA has released draft guidance on *Drug Products, Including Biological Products, that Contain Nanomaterials* for public comment.[90] The draft guidance provides recommendations to industry engaged in developing human drug products in which nanomaterials are present in the finished dosage form, including recommendations regarding investigational, premarket, and postmarket submissions for these products.

In addition to actively raising awareness of guidance documents developed by NNI agencies, NNCO hosts a webinar series to inform the public of nanoEHS research advancements and available resources. These webinars are archived on Nano.gov.

[89] https://www.cdc.gov/niosh/nmam/pdf/chapter-cn.pdf

[90] https://www.fda.gov/downloads/Drugs/GuidanceComplianceRegulatoryInformation/Guidances/UCM588857.pdf

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)

CPSC 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 entail significant use 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, CPSC is supporting research intramurally and with 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, and to develop and validate *in vitro* methods to test existing and emerging nanomaterials that are used in consumer products. CPSC staff members also participate in voluntary standards development activities to create validated methods for quantifying and characterizing exposures from 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 NanoFab. 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 NanoFab provides rapid access to state-of-the-art tools needed to make and measure nanostructures. NIST staff members participate widely and lead in nanotechnology-related standards development and international cooperation activities such as the Organisation for Economic Co-operation and Development's Working Party on Manufactured Nanomaterials, ISO TC 229, IEC Technical Committee 113, and ASTM International Committee E56. Interagency coordination and information sharing related to these activities is facilitated through the NSET Subcommittee.

Department of Defense (DOD)

DOD aggressively pursues nanotechnology and nanomaterials to meet the needs of our warfighters on the battlefield, both for current conflicts and for the challenging missions our military will face in the future. In that vein, the department recognizes the need for strong efforts in foundational nanoscience research, the need to maintain a solid nanoscience infrastructure within the DOD service laboratories, and the importance of collaboration with other Federal agencies. DOD's efforts to transition state-of-the-art nanotechnologies for the benefit of our warfighters and continue to drive nanotechnologies into the DOD industrial base include the use of DOD ManTech (Manufacturing Technology), Defense Production Act Title III, Defense Innovation Unit Experimental, and SBIR programs. Examples of these programs include Advanced

Functional Fabrics of America, a DOD-sponsored institute under Manufacturing USA, as well as several Title III programs to include production of carbon nanotubes and other advanced nanomaterials.

Department of Energy (DOE)

DOE supports a broad range of pioneering research and development in nanoscale science and engineering to promote scientific and technological innovation and benefit the agency's mission of advancing the energy, economic, and national security of the United States. DOE's Office of Science manages the majority of DOE NNI funding, with additional support 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 university, industry, and DOE national laboratories. In addition, the Office of Science supports Nanoscale Science Research Centers, user facilities that provide access to leading-edge synthesis, characterization, and computational tools and scientific expertise for interdisciplinary research at the nanoscale. Nanotechnology has a vitally important role to play 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 continues to invest 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 help support the responsible development of nanotechnology, in cooperation with other national and international stakeholders. The FDA Nanotechnology Task Force provides the overall coordination of FDA's nanotechnology research efforts in the following programmatic investment areas: (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 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 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 and cooperative agreements.

Current research efforts focus (and will continue to focus) on advancing new medical diagnostics and therapeutics; supporting nanotechnology-related EHS 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 that are supported by a large number of NIH institutes. Notable research areas of interest include vaccine development at the National Institute of Allergy and Infectious Diseases, tissue regeneration/repair and biosensor research at NIDCR, continuation of the Alliance for Nanotechnology in Cancer program at NCI, and NIEHS support for research to understand the interactions between ENMs and biological systems.

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.

National Aeronautics and Space Administration (NASA)

NASA 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 institutions. The team and center projects are particularly fruitful because nanoscale research and education are inherently interdisciplinary pursuits, often combining elements of materials science, engineering, chemistry, physics, and biology. Several new directions planned for 2019 are nanotechnology for brain-like computing, including highly energy-efficient systems and intelligent cognitive assistants; nanobiomanufacturing and nanobiomedicine, including cell technology; food-energy-water processes such as point-of-use nanofiltration; nanomodular materials and systems by design, including 3D nanoscale materials; and emerging aspects of nanoelectronics, photonics, use of artificial intelligence for smart materials and systems, papertronics (paper-based electronics), and neuroscience. NSF also will increase its focus on convergence research and education activities in confluence with other interagency initiatives and NSF priority areas (e.g., NSF's 10 Big Ideas). NSF will continue its contributions to nanotechnology innovation and translation through programs such as Grant Opportunities for Academic Liaison with Industry (GOALI); I/UCRC; I-Corps™; Partnerships for Innovation, and SBIR. NSF has mainstreamed nanotechnology-related research, education, and infrastructure in core programs in several directorates.

U.S. Department of Agriculture (USDA)

Agriculture Research Service (ARS). ARS nanotechnology-related investments include research on novel nanostructured materials and nanotechnology-enabled products derived from agricultural sources (e.g., cotton or crop waste); the development of advanced imaging technologies using nanoparticles to improve understanding of health and fertility in food animal reproduction systems, and to track and mitigate bacterial pathogens in livestock hosts and foods; and the development of novel food processing and packaging technologies to improve appearance, nutritional value, or product quality.

Forest Service (FS). The primary focus of nanotechnology research at the Forest Service 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 such as lightweight paper, reinforcements for high-performance concrete, rheology modifiers, improved packaging, and polymeric composites. Other nanotechnology research in the Forest Service includes improving understanding of the nanostructure of wood and wood properties and wood-water interactions using nanotechnology techniques.

National Institute of Food and Agriculture (NIFA). NIFA is the primary extramural science agency of USDA, and nanoscale science, engineering, and technology has been recognized in the agency and by its broad stakeholders as an integral part of NIFA's comprehensive science and technology portfolio. NIFA will continue to advance the frontiers of interdisciplinary nanoscience and nanotechnology for addressing significant issues facing agriculture and food systems, including sustainable agricultural production systems, food and nutrition security, food safety and biosecurity, the bio-based economy, environmental systems, natural resources, water quality, and climate variability. The program also encourages studies of risk assessment and management, public deliberation, social acceptance, and communication about nanotechnology and nanotechnology-enabled products by agricultural stakeholders (including consumers).

Appendix B. Abbreviations and Acronyms

2D	two-dimensional
3D	three-dimensional
ARS	Agricultural Research Service (USDA)
BES	[Office of] Basic Energy Sciences (DOE)
BIS	Bureau of Industry and Security (DOC)
CNT	carbon nanotube
CPSC	Consumer Product Safety Commission
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOEd	Department of Education
DOJ	Department of Justice
DOL	Department of Labor
DOS	Department of State
DOT	Department of Transportation
DOTreas	Department of the Treasury
EHS	environment(al), health, and safety
ENM	engineered nanomaterial
EPA	Environmental Protection Agency
ERC	Engineering Research Centers (NSF)
EU	European Union
FDA	Food and Drug Administration (HHS)
FHWA	Federal Highway Administration (DOT)
FS	Forest Service (USDA)
GC	grand challenge
HHS	Department of Health and Human Services
IC	Intelligence Community
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
nanoEHS	nanotechnology environment, health, and safety (research, etc.)
NanoGRID	Nano Guidance for Risk Informed Deployment (DOD nanoEHS tool)
NASA	National Aeronautics and Space Administration
NCI	National Cancer Institute (HHS/NIH)
NCN	Network for Computational Nanotechnology
NEHI	Nanotechnology Environmental and Health Implications Working Group of the NSET Subcommittee
NEP	nanotechnology-enabled product
NHIR	Nanotechnology Health Implications Research consortium (NIH/NIEHS)
NIDCR	National Institute of Dental and Craniofacial Research (HHS/NIH)
NIEHS	National Institute of Environmental Health Sciences (HHS/NIH)
NIFA	National Institute of Food and Agriculture (USDA)
NIH	National Institutes of Health (HHS)
NIOSH	National Institute for Occupational Safety and Health (HHS/CDC)
NIST	National Institute of Standards and Technology (DOC)
NKI	Nanotechnology Knowledge Infrastructure (Nanotechnology Signature Initiative)
NNCI	National Nanotechnology Coordinated Infrastructure (NSF)
NNCO	National Nanotechnology Coordination Office
NNI	National Nanotechnology Initiative
NRC	Nuclear Regulatory Commission
NSET	Nanoscale Science, Engineering, and Technology Subcommittee of the NSTC
NSF	National Science Foundation
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)
OSHA	Occupational Safety and Health Administration (DOL)
OSTP	Office of Science and Technology Policy (Executive Office of the President)
PCA	Program Component Area of the National Nanotechnology Initiative
RF	radio frequency
SBIR	Small Business Innovation Research Program
STEM	science, technology, engineering, and mathematics
STTR	Small Business Technology Transfer Research Program
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USITC	U.S. International Trade Commission
USPTO	U.S. Patent and Trademark Office (DOC)

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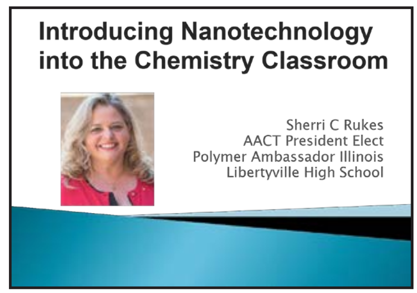

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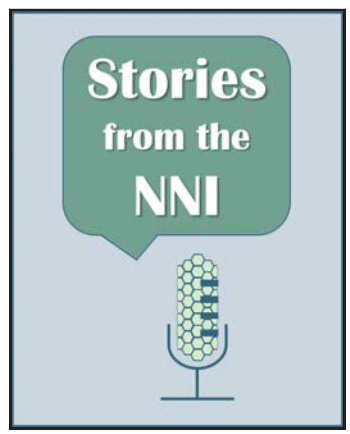

How Do You See The NANOSCALE?

- Conferences, including the USA Science and Engineering Festival, National Science Teachers Association, Student Leaders Conference, and professional society meetings.
- Contests for middle school, high school, undergraduate, and graduate students, and the general public (www.nsf.gov/news/special_reports/gennano/, www.nano.gov/EnvisioNano, www.nano.gov/VideoContest).
- National Nanotechnology Day, October 9th, in honor of 10^{-9} (www.nano.gov/NationalNanotechnologyDay).
- Networks for undergraduate students and K-12 teachers (www.nano.gov/StudentNetwork, www.nano.gov/Teacher-Network).
- Podcast and videos featuring stories from the NNI community (www.nano.gov/NanoTV) and student-produced animations answering questions about nanotechnology (www.nano.gov/TargetCancerCells).