NATIONAL NANOTECHNOLOGY INITIATIVE (NNI)

Total Funding for NNI[1]
(Dollars in Millions)

	FY 2020 Actual	FY 2021 Estimate	FY 2022 Request
BIO	$42.50	$39.95	$39.95
CISE	14.36	14.05	14.05
EHR	13.74	2.50	2.50
ENG	221.52	190.95	219.99
MPS	330.70	183.50	183.50
SBE	0.40	0.40	0.40
TIP[2]	11.67	10.05	10.05
OISE	0.10	0.10	0.10
Total	**$634.99**	**$441.50**	**$470.54**

[1] Funding displayed may have overlap with other topics and programs.

[2] FY 2020 and FY 2021 funding for TIP is shown for comparability across fiscal years.

Overview

NSF's contribution to the multiagency NNI encompasses the systematic understanding, organization, manipulation, and control of matter at the atomic, molecular, and supramolecular levels in the size range of about 1 nanometer to 100 nanometers. Novel materials, devices, and systems—with their building blocks designed on the scale of nanometers—open new directions in science, engineering, and technology with potentially profound implications for society. With the capacity to interact with and control matter at this scale, science, engineering, and technology researchers are realizing revolutionary advances in areas such as order-of-magnitude faster computers with less energy consumption; catalysts for industry; molecular medicine; imaging and understanding of the brain; quantum qubits and systems; nanosensors to monitor health, the environment, and human-machine interactions; hardware designed by and for artificial intelligent (AI) systems; efficient and large-scale nanomanufacturing; more resilient materials and system architectures; and sustainable development for water, energy, and food resource utilization. An increased focus will be on using nanotechnology for reducing and mitigating climate change including research on capture, sequestration, and reuse of CO_2. A new research thrust has emerged in 2021 and will expand in 2022 that is focused on understanding the structure and nanoscale behavior of the novel SARs-COV2 virus and supporting foundational concepts for vaccine developments. NSF contributes to the NNI goals and five Program Component Areas (PCAs) outlined in the current draft of 2021 NNI Strategic Plan.[1] Funding by PCA is shown at the end of this discussion.

FY 2022 NNI Funding

NSF supports nanoscale science and engineering throughout all the research and education directorates as a means to advance discovery, invention, and innovation and to integrate various fields of research. NNI enables increased interdisciplinarity in areas of atomic and molecular research in about 6,000 active awards with full or partial contents on nanoscale science and engineering (NSE). Approximately 10,000 students and teachers will be educated and trained in NSE in FY 2022.

Overall, NSF's total NNI funding in the FY 2022 Request is $470.54 million. Several new directions planned for FY 2022 include research connected to COVID-19, mitigation of global change, advanced

[1] www.nano.gov

manufacturing, AI systems including using artificial intelligence for creating smart materials and systems, the bioeconomy, sustainability, and quantum information science and engineering including quantum biology. Nanotechnology research will contribute and synergize with NSF's Big Ideas, particularly with URoL, FW-HTF, HDR, and GCR, as well as with research supporting emerging industries such as semiconductors for AI and advanced wireless. NSF sponsors an annual NSE grantee conference to assess the progress in nanotechnology and facilitate identification of new research directions.[2]

In FY 2022, NSF support will increasingly focus on convergence research and education activities in confluence with other priority areas. NSF will strengthen partnerships of the Nanoscale Engineering Research Centers (NERCs) with small businesses in the areas of nanomanufacturing and commercialization and will support an industrial internship program (INTERN) in emerging areas. NSF will continue its contributions to translational innovation programs, including Grant Opportunities for Academic Liaison with Industry (GOALI); Industry-University Cooperative Research Centers (IUCRC); the NSF Innovation Corps (I-Corps™) program; and the Partnerships for Innovation (PFI). The NSF Small Business Innovation Research (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.

Various assessments and reports have assisted with informing plans for NNI going into the future. NSF sponsored an international study on long-term research entitled *Nanotechnology Research Directions for Societal Needs in 2020,*[3] which provides a vision of the field to 2020 and beyond. With the National Institutes of Health (NIH), National Aeronautics and Space Administration (NASA), Environmental Protection Agency (EPA), Office of Naval Research (ONR), and the U.S. Department of Agriculture (USDA), NSF co-sponsored the study entitled *Converging Knowledge, Technology, and Society*[4] evaluating the convergence of nanotechnology with other emerging areas by 2030. Other reports address aspects of fundamental research for energy-efficient sensing and computing, data storage, real-time communication ecosystem, multi-level and scalable security, a new fabrication paradigm, and insight computing.[5,6,7]

National Academies (NASEM) report to Congress in 2020 provides guidance on research priorities, partnerships, and future growth, including: "Finding 1.2 - The National Quantum Initiative (NQI) is, in large part, an important outgrowth of the National Nanotechnology Initiative (NNI)," "Impacts of NNI to date: Impressive, tangible outcomes that have emerged from these coordination efforts, including the recent formation of the NQI."[8,9]

PCAs are the major subject areas of relevance to the NNI agencies, where progress is critical to achieving NNI's goals and to realizing its vision.[10] NSF supports funding in all five PCAs.

PCA 1: Foundational Research ($306.30 million)

The first PCA will be funded at a total of $306.30 million. It includes funding for the discovery and development of fundamental knowledge pertaining to new phenomena in the physical, biological, and engineering sciences that occur at the nanoscale. Also included is funding for research aiming to understand

[2] 2020 Nanoscale Science and Engineering Grantees Conference: www.nsf.gov/nano and www.nseresearch.org/2020/
[3] NSF/WTEC 2010, Springer, available on www.nsf.gov/nano and www.wtec.org/nano2/
[4] NSF/WTEC 2013, Springer, available on www.nsf.gov/nano and www.wtec.org/NBIC2-Report/
[5] www.nsf.gov/nano
[6] 1.usa.gov/1Fg90Dw; www.src.org/nri/energy-efficient-computing-workshop.pdf
[7] www.semiconductors.org/issues/research/research/
[8] www.nationalacademies.org/our-work/quadrennial-review-of-the-national-nanotechnology-initiative
[9] www.nap.edu/resource/25729/A%20Quadrennial%20Review%20NNI%20Presentation%20slides%20v15.pdf
[10] www.nano.gov/about-nni/what/vision-goals

scientific and engineering principles related to nanoscale systems, structures, processes, and mechanisms; research on the discovery and synthesis of novel nanoscale and nanostructured materials including biomaterials and modular structures; quantum biology for understanding natural phenomena and interfaces; and research directed at identifying and quantifying the broad implications of nanotechnology for society, including social, economic, ethical, and legal implications. It includes foundational research on COVID-19 and global change understanding and mitigation, and nano-Ethical, Legal and Societal Implications (ELSI). Most of the research is sponsored in individual and small group research across NSF directorates. A subset of ERCs, Science and Technology Centers (STCs), Centers for Chemical Innovation (CCIs) and other center program support various aspects of nanoscale science and engineering. About 60 percent of the Materials Research Science and Engineering Centers (MRSECs) pursue NSE-related fundamental research.

NSF has invested in understanding the nanoscale machines that make up the nucleus of a cell and control cell function through its programs in Understanding the Rules of Life: Epigenetics, the Physics Frontiers Center program, and core programs in Molecular and Cellular Biosciences (Genetic Mechanisms) as well and Chemistry (Chemistry of Living Processes). NSF will expand its efforts in 2022 in nanobiotechnology associated with synthetic biology and synthetic cells through a new solicitation, Designing Synthetic Cells Beyond the Bounds of Evolution, a new Dear Colleague Letter, Sentinel Cells for Surveillance and Response to Emergent Infectious Diseases, and through core programs in BIO/MCB and ENG/CBET.

This PCA includes foundational research supporting the NSI (Nanotechnology Signature Initiative) on: Sustainable Nanomanufacturing, Nanoelectronics including semiconductors, Nanotechnology for Sensors and Sensors for Nanotechnology, the Water Sustainability through Nanotechnology NSI (to continue until end of FY 2021), and the Nanotechnology-Inspired Grand Challenge for Future Computing.

- *Sustainable Nanomanufacturing:* Support foundational concepts for new nanomanufacturing methods at confluence with digitization, biotechnology, AI, and cognitive sciences. A new activity in Designing Synthetic Cells beyond the bounds of Evolution, that will have enabled novel nanomanufacturing applications and Reproducible Cells and Organoids via Directed-Differentiation Encoding (RECODE) that will lead to scalable and reproducible cell and organ production for biomanufacturing and biomedicine applications. Another new direction is manufacturing of quantum systems, nanomachines and nano biostructures. Methods for nanomanufacturing design are in synergy with the Materials Genome Initiative.
- *Nanoelectronics and semiconductors:* Research is aimed at discovering and using novel nanoscale fabrication processes and innovative concepts to produce revolutionary materials, devices, systems, and architectures to advance the field of electronics beyond Moore's Law. NSF will increase coordinated research on quantum-related research and the FW-HTF.
- *Nanotechnology for Sensors and Sensors for Nanotechnology*: Research is aimed at use of nanoscale principles and materials to build more sensitive, specific, and adaptable sensors and the development of new sensors to detect engineered nanomaterials across their life cycles to assess their potential impacts. It supports materials and technologies that enable new sensing of biological, chemical, and nanoscale materials. Programs on biosensing and biophotonics in ENG's Division of Chemical, Bioengineering, Environmental, and Transport Systems (CBET) will support this effort.
- *Nanotechnology-Inspired Grand Challenge for Future Computing*: Research is planned on the NNI Grand Challenge related research on "Brain-like Computing" and "Intelligent Cognitive Assistants" (ICA). Two examples of active centers are the STC on Integrated Quantum Materials at Harvard University and the MRSEC on Quantum and Spin Phenomena in Nanomagnetic Structures at the University of Nebraska, Lincoln.

Even though the Water NSI has graduated in 2020, research continues to take advantage of the unique properties of engineered nanomaterials and systems to increase water availability; improve the efficiency of water delivery; and enable next-generation water monitoring systems.

PCA 2: Nanotechnology-Enabled Applications, Devices, and Systems ($96.97 million)
The FY 2022 Request includes $96.97 million for research that applies the principles of nanoscale science and engineering to create novel devices and systems. This includes the incorporation of nanoscale or nanostructured materials and the processes required to achieve improved performance or new functionality, including metrology, scale up, manufacturing technology, and nanoscale reference materials and standards. Core programs in the ENG, MPS, and CISE directorates support development of new principles, design methods, and constructive solutions for nanomaterials and nanodevices. A special focus is on smart, autonomous nanoscale-based devices and systems. The PCA 2 includes applications-, device-, or systems-focused research related Sustainable Nanomanufacturing, Nanoelectronics (semiconductors), Nanotechnology for Sensors and Sensors for Nanotechnology, and the Nanotechnology-Inspired Grand Challenge for Future Computing. A new Future Manufacturing Solicitation was announced in 2020 and is continuing into 2021 and 2022.[11] The goal of Future Manufacturing is to support fundamental research and education of a future workforce to overcome scientific, technological, educational, economic, and social barriers to enable new manufacturing capabilities that do not exist today. The Real Time Machine Learning (RTML) 3-year NSF/CISE-ENG program[12] started in FY 2019 in collaboration with the Defense Advanced Research Projects Agency (DARPA) ($10.0 million from NSF and $10.0 million from DARPA) and will continue through 2022.

Besides core nanoscience-related programs on water filtration and applications, the NERC for Nanotechnology Enabled Water Treatment Systems (NEWT), led by Rice University and funded between 2015 and 2024, aims at developing high-performance water treatment systems that will broaden access to clean drinking water from a variety of unconventional sources (briny well water, seawater, wastewater), and enable industrial wastewater reuse at remote locations such as oil and gas fields.

PCA 3: Research Infrastructure and Instrumentation ($25.68 million)
The FY 2022 Request includes $25.68 million for the establishment and operation of user facilities and networks, acquisition of major instrumentation, workforce development, and other activities that develop, support, or enhance the Nation's physical or workforce infrastructure for nanoscale science, engineering, and technology. This PCA includes research pertaining to the tools needed to advance nanotechnology research and commercialization, including next-generation instrumentation for characterization, measurement, synthesis, and design of materials, structures, devices, and systems.

While student support to perform research is captured in other categories, dedicated educational and workforce efforts, ranging from curriculum development to advanced training, are included here as resources supporting the human infrastructure of the NNI. NSF has funded an award of about $16 million per year for the NNCI sites for FY 2015–2024, with a national coordination office added in FY 2016. Five-year renewal of NNCI has been completed in FY 2020. Other STCs, ERCs, CCIs, and MRSECs have a focus on supporting the NNI, including the Center for Cellular Construction at the University of California-San Francisco (annual award since 2016 of approximately $5 million), two NERCs, one each on nanobiotechnology and cell technology, and a CCI at University of Wisconsin (annual award of $4 million per year) which investigates the fundamental molecular mechanisms by which nanoparticles interact with biological systems. NSF will increase coordinated research on its Mid-scale Research Infrastructure priority area. The Major Research Instrumentation (MRI) Program[13] serves to increase access to multi-user scientific and engineering instrumentation, including instrumentation needed for NSE activities, for research and research training in the Nation's institutions of higher education and not-for-profit scientific/engineering research organizations.

[11] www.nsf.gov/funding/pgm_summ.jsp?pims_id=505737
[12] www.nsf.gov/pubs/2019/nsf19566/nsf19566.htm
[13] www.nsf.gov/funding/pgm_summ.jsp?pims_id=5260

PCA 4: Education and Workforce Development ($20.50 million)
In FY 2022, NSF will fund education and workforce development activities in all areas of nanoscale science and engineering at $20.50 million. Typical activities supported by the Directorate for Education and Human Resources, the Directorate for Engineering's Division of Engineering Education and Centers, and other divisions are fellowships, single investigator awards and centers. Illustrations of projects at the undergraduate and graduate levels are "Supporting micro and nano technicians through hybrid teaching methods" and "Nano-makerspace to make and explore in the world of the small". Super Small Science or hosting a nationwide communication competition with the Boston Museum of Science for undergraduate and graduate students.[14]

PCA 5: Environment, Health, and Safety ($21.09 million)
In FY 2022, NSF will continue its funding for the Environment, Health, and Safety (EHS), ELSI, and diversity/equity/inclusion/access, as well as nanotechnology research integrity, safety, and reproducibility at $21.09 million, representing roughly 4.5 percent of its overall NNI budget. Requests for research are primarily directed at understanding nano-bio phenomena and processes, as well as environment, health, and safety implications and methods for reducing the respective risks of nanotechnology development. ENG's nano EHS program has changed to *Nanoscale Interactions*. MPS supports the CCI: Center for Sustainable Nanotechnology. NSF continues to sponsor the Center for Sustainable Nanotechnology at University of Wisconsin.[15] Support of diversity and equity by inclusion and access will be advanced for minorities, women, and persons with handicaps interested in nanoscale science and engineering, for various knowledge and technology fields to be explored in conjunction with nanotechnology, and for broad geographical representation in all 50 states.

Coordination with Other Agencies

NSF's NNI program is coordinated with 32 other departments and agencies through the National Science and Technology Council subcommittee on Nanoscale Science, Engineering, and Technology (NSET). These agencies also partner with NSF to sponsor joint funding activities and workshops on nanotechnology research directions and send representatives to participate in grantees conferences. Some specific coordination efforts are:

- Sustainable Nanomanufacturing—NSF, NIST, Department of Energy (DOE), EPA, NIH, National Institute for Occupational Safety and Health (NIOSH), Occupational Safety and Health Administration (OSHA), USDA/Food Safety (FS).
- Collaboration with NIST, Air Force Office of Scientific Research (AFOSR), and DARPA will continue in 2020 with a focus on "Brain-like Computing".
- Nanoelectronics and semiconductors—NSF, NIST, Department of Defense (DOD), DOE, Intelligence Community (IC)/Director of National Intelligence (DNI), and NASA.
- NSF collaborates with other 14 other agencies in the NNI task force on "Nanoplastics".
- NNCI and NCN centers and networks—NSF, DOD, NASA, DOE, and NIH.
- Nanosensors—NSF, NIOSH, NIH, FDA, NIST, DOD, NASA, and EPA.
- NSF collaboration with NIOSH, NIH's National Cancer Institute (NCI), NIST, Pacific Northwest National Laboratory, and DOD, and many public- and private-sector partners with the Nanoinformatics Consortium: UCLA, the National Nanomanufacturing Network, nanoHUB, RTI International, MIT, and the NanoBusiness Commercialization Association.
- OECD (Working Group on Bio, Nano, and other Converging Technologies) and other international forum activities—participation by NSF in collaboration with State Department and other NNI agencies.

[14] www.mos.org/quantum-matters-competition
[15] www.susnano.wisc.edu/

NNI Funding by Program Component Area

(Dollars in Millions)

	FY 2020 Actual	FY 2021 Estimate	FY 2022 Request
Foundational Research	$396.89	$293.30	$306.30
Nanotechnology-Enabled Applications, Devices, and Systems	115.13	83.97	96.97
Research Infrastructure and Instrumentation	43.02	25.68	25.68
Education and Workforce Development	31.74	19.00	20.50
Responsible Development	48.21	19.55	21.09
Total	**$634.99**	**$441.50**	**$470.54**