Progress and Plans of National Nanotechnology Initiative (NNI) Agencies

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National Science Foundation (NSF)

Summary

The National Science Foundation 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 efforts in team and center projects have been particularly fruitful because nanoscale research and education are inherently interdisciplinary pursuits, often combining elements of materials science, engineering, chemistry, physics, and biology.

The NSF nanotechnology investment in 2017 supported about 5,500 active projects, over 30 research centers, and several infrastructure networks for device development, computation, and education. It impacted over 10,000 students and teachers. Approximately 150 small businesses were funded to perform research and product development in nanotechnology through the Small Business Innovation Research (SBIR) and Small Business Technology Transfer Research (STTR) programs. NSF sponsors an annual nanoscale science and engineering (NSE) grantee conference to assess progress in nanotechnology and facilitate identification of new research directions.

Several new directions planned for fiscal year (FY) 2019 are nanotechnology for brain-like computing and the human-technology frontier, including highly energy-efficient systems and intelligent cognitive assistants; nanobiomanufacturing and nanobiomedicine (including cell technology); chromatin and epigenetic engineering and its nanoscale environment; semiconductor synthetic biology for information processing and storage technologies; food-energy-water processes such as nanostructured membranes and point-of-use nanofiltration; nanomodular materials and systems by design, including hierarchical three-dimensional nanoscale materials; advancing communication quantum information research in engineering; and emerging aspects of nanoelectronics, photonics, use of artificial intelligence for smart materials and systems, papertronics (paper-based electronics), and neuroscience.

In FY 2019, NSF support will increase focus on convergence research and education activities in confluence with other priority areas such as: the Networking and Information Technology Research and Development (NITRD) Program and the National Strategic Computing Initiative (NSCI); Science, Engineering, and Education for Sustainable Chemistry, Engineering, and Materials (SusChEM); Designing Materials to Revolutionize and Engineer our Future (DMREF); Materials Genome Initiative; smart systems; quantum information science and engineering; and synthetic biology. Partnerships of new Nanoscale Engineering Research Centers (NERCs) with small businesses in the areas of nanomanufacturing and commercialization will be strengthened while maintaining about the same level of NSF investment. A new industrial internship in emerging nanotechnology areas is planned with IBM. NSF continues its contributions to translational innovation programs, including Grant Opportunities for Academic Liaison with Industry (GOALI); Industry/University Cooperative Research Centers (I/UCRC); the NSF Innovation Corps (I-Corps™) program;

and the two subcomponents of Partnerships for Innovation (PFI): the *Technology Translation* (PFI-TT) track and the *Research Partnerships* (PFI-RP) track. The NSF SBIR program has an ongoing nanotechnology topic. Nanotechnology research will contribute to and synergize in the future with eight of NSF's 10 Big Ideas,[1] and particularly with: Quantum Leap, Understanding the Rules of Life, Future of Work at the Human-Technology Frontier, Harnessing the Data Revolution, and Growing Convergence Research.

The FY 2019 budget reflects that NSF has mainstreamed nanotechnology-related research, education, and infrastructure in core programs in several directorates.

Key Technical Accomplishments by NNI Goal

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

The main contribution of NSF research is to create the foundational science and tools for nanoscience and nanotechnology, with contributions to all disciplines and areas of activity. The main progress is in modeling and simulation using specialized algorithms, artificial intelligence and manipulation of large sets of data; better understanding of small living systems; creating new structures with motion (nanomachines, nanomotors) and dynamics at the nanoscale, assembling larger nanostructures, two-dimensional materials, nanoscale neurotechnology, nanophotonics, and brain-like cognitive systems. Representative research results achieved in a fiscal year are presented at the annual NSF Nanoscale Science and Engineering Grantees Conference in December.[2]

Several specific examples are as follows:

- New Brunswick engineers have discovered a simple, economical way to make a nanoscale device acting like a muscle that lifts 165 times of its own weight.[3] The new devices may have applications in robotics, aircraft wings, steerable catheters in medicine, wind turbines with reduced drag resistance, and other fields.
- Engineers at the University of California, San Diego, have developed a miniature device that's 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 down to 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*.[4]
- Researchers at the University of Minnesota College of Science and Engineering have found yet another remarkable use for graphene—tiny electronic “tweezers” that can grab biomolecules floating in water with incredible efficiency. This capability could lead to a revolutionary handheld disease diagnostic system that could be run on a smartphone.[5]

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[1] https://www.nsf.gov/about/congress/reports/nsf_big_ideas.pdf

[2] www.nseresearch.org/2017 for FY 2017

[3] https://news.rutgers.edu/acting-muscle-nano-sized-device-lifts-165-times-its-own-weight/20170829#.WlkdmK6nHX4

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

[5] https://cse.umn.edu/news-release/researchers-develop-graphene-nano-tweezers-can-grab-individual-biomolecules/

- Harvard University researchers have developed a general framework to design reconfigurable metamaterials. The design strategy is scale-independent, meaning it can be applied to everything from meter-scale architectures to reconfigurable nanoscale systems such as photonic crystals, waveguides and metamaterials to guide heat.[6]
- Currently, testing for the Zika virus requires that a blood sample be refrigerated and shipped to a medical center or laboratory, delaying diagnosis and possible treatment. Now, Washington University in St. Louis researchers have developed a test that can quickly detect the presence of the Zika virus in blood. Although the new proof-of-concept technology has yet to be produced for use in medical situations, test results can be determined in minutes.[7]
- University of Washington engineers have discovered cavity-enhanced electroluminescence from atomically thin monolayer materials, which will allow realization of highly energy-efficient data centers. The so-called “electrically pumped nanolasers” are planned to be used for the development of integrated photonic-based, short-distance optical interconnects and sensors.[8]

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

The transfer of technology is carried out through publication of papers and patents, center activities and outreach, and dedicated programs in the NSF Division of Industrial Innovation and Partnerships, including SBIR and STTR programs. In 2019, the agency will continue its contributions to translational innovation programs, including GOALI, I/UCRC, I-Corps™, PFI, and its *Technology Translation* (PFI-TT) and *Research Partnerships* (PFI-RP) tracks. 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. Currently, almost 60% of the Materials Research Science and Engineering Centers (MRSECs) pursue NSE-related research. Strong support will continue for the Nanoelectronics for 2020 and Beyond Nanotechnology Signature Initiative (NSI) through core programs and for the Nanomanufacturing NSI through the Advanced Manufacturing (including Scalable Nanomanufacturing) solicitation.[9] Other NNI-affiliated awards include Nanoscale Science and Engineering Centers (NSECs), the National Nanotechnology Coordinated Infrastructure (NNCI), the NERCs (in the Directorate for Engineering, ENG), and Mathematical and Physical Sciences (MPS) Directorate centers investments (MRSECs and the Centers for Chemical Innovation).

Examples of I-Corps awards include the following:

- **Replication of Laser-Generated Surface Textures for Anti-Icing and Sun-Light-Trapping Applications:** Using high-power laser processing to create superhydrophobic micro/nanotextured surfaces on metal, semiconductor, and polymer surfaces for anti-icing and also for anti-reflection coatings.[10]

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

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

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

[9] https://www.nsf.gov/pubs/2016/nsf16604/nsf16604.htm

[10] www.nsf.gov/awardsearch/showAward.do?AwardNumber=1157881

- **Multiwavelength Integrated Nanophotonic Transceivers:** Incorporating materials research and nanofabrication technology with new system approaches to enhance current fiber optic networking capabilities; miniaturizing optical components to the nanoscale.[11]

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

The academic infrastructure supported by NSF is in more than 500 universities. In addition, there are centers for research, education, and technology transfer.

Two representative examples are NNCI and the Network for Computational Nanotechnology (NCN):

- **NNCI:** To advance research in nanoscale science, engineering, and technology, NSF will provide a total of $81 million over five years to support 16 sites and a coordinating office as part of the 2015-2020 National Nanotechnology Coordinated Infrastructure.[12] The NNCI sites will provide researchers from academia, small and large companies, and government with access to university user facilities with leading-edge fabrication and characterization tools, instrumentation, and expertise within all disciplines of nanoscale science, engineering, and technology.
- **nanoHUB (NCN):** NCN's mission is to advance nanoscience and nanotechnology modeling, simulation and networking through nanoHUB.org, which has become a successful scientific end-to-end cloud computing environment, hosting over 3,000 resources for research, collaboration, teaching, learning, and publishing. NCN served 1,400, 000 users in 2017, in multiple domain networks.[13]

Goal 4. Support Responsible Development of Nanotechnology

Research in support of nanomaterials characterization and exposure is performed in NSF's core programs.

One example of public outreach in support of Goal 4 is the Generation Nano comic competition, which is designed to inspire high school and middle school students to learn more about the science behind nanotechnology. The competition, which is a partnership between NSF and the NNI, challenges students to imagine novel superheroes who use the power of nanotechnology to solve crimes or tackle a societal challenge. In 2017 and 2018, NSF named the first- and second-place winners, as well as the People's Choice winner, for the second annual Generation Nano competition.[14]

Plans and Priorities by Program Component Area (PCA)

PCA 1. Nanotechnology Signature Initiatives and Grand Challenges

The first PCA encompasses the five Nanotechnology Signature Initiatives and the new Grand Challenge. The Water Sustainability through Nanotechnology NSI began in FY 2016 and will continue in FY 2019. The Nanotechnology-Inspired Grand Challenge for Future Computing began in FY 2017.

Special emphasis will be on the following:

- *Sustainable Nanomanufacturing:* Establishing manufacturing technologies for economical and sustainable integration of nanoscale building blocks into complex, large-scale systems by supporting

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[11] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1342641

[12] https://www.nnci.net/

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

[14] https://www.nsf.gov/news/news_summ.jsp?cntn_id=241819&org=NSF

product, tool, and process design informed by and adhering to the overall constraints of safety, sustainability, and scalability. This signature initiative specifically focuses on high-performance structural carbon-based nanomaterials, optical metamaterials, cellulosic nanomaterials, nanobiomanufacturing, and nanomodular systems. A Dear Colleague Letter, *Advanced Manufacturing Research to Address Basic Research Enabling Innovation at Manufacturing USA Institutes,* has been issued for 2019. Engineering biology at the nanoscale for advanced manufacturing activities in the Biological Sciences (BIO), ENG, and MPS directorates are being organized for 2019. Methods for nanomanufacturing design are in synergy with the Materials Genome Initiative. A new direction is manufacturing of nanomachines and nanobiostructures.

- *Nanoelectronics for 2020 and Beyond.* This initiative 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 plans ongoing collaboration with the semiconductor industry and other agencies in activities such as the Energy-Efficient Computing: from Devices to Architectures (E2CDA) program, which is continuing in 2019, and the Semiconductor Synthetic Biology for Information Processing and Storage Technologies program, with a new solicitation for 2019, 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.
- *Nanotechnology Knowledge Infrastructure.* This initiative is aimed at activities surrounding the fundamental, interconnected elements of collaborative modeling and computer simulation, an interacting cyber-toolbox, and data infrastructure for nanotechnology, and aims to provide a community-based, solution-oriented knowledge infrastructure for discovery, innovation, and nanoinformatics of research, education, and regulatory interest to NNI agencies. The Network for Computational Nanotechnology (NCN) conducts key activities in support to this NSI with about 1.4 million users per year, and has been awarded an extension for 2017-2022. The program solicitation on "Cyberinfrastructure for Sustained Innovation"[15] will contribute to data infrastructure, software advances, and high-throughput computation. NSF will increase coordinated research on Harnessing the Data Revolution.
- *Nanotechnology for Sensors and Sensors for Nanotechnology*. This NSI involves use of nanotechnology and nanoscale 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. This initiative supports materials and technologies that enable novel sensing mechanisms for biological, chemical, and nanoscale materials, including sensors for nanotechnology-related environment, health, and safety research. A dedicated program on nanobiosensing and biophotonics in ENG's Division of Chemical, Bioengineering, Environmental, and Transport Systems (CBET) will support this effort.
- *Water Sustainability through Nanotechnology*. The Water NSI takes 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. The NSF Innovations at the Nexus of Food, Energy and Water Systems initiative supports projects in nanotechnology. 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 2020, aims at developing high-performance water treatment systems that will broaden access to clean

[15] https://www.nsf.gov/pubs/2018/nsf18531/nsf18531.htm

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.

- *Nanotechnology-Inspired Grand Challenge for Future Computing*. Planned research in support of this NNI Grand Challenge includes "Brain-like Computing" and "Intelligent Cognitive Assistants" (ICAs).[16] Two examples of active centers are the Science and Technology Center (STC) on Quantum Materials and Devices at Harvard University and the MRSEC on Quantum and Spin Phenomena in Nanomagnetic Structures at the University of Nebraska, Lincoln. NSF will complete in 2018 a report with the Semiconductor Research Corporation (SRC) on ICA research needs and new opportunities, and plans to sponsor research on ICAs in FY 2018 and 2019 on "Developing Intelligent Cognitive Assistance Devices and Platforms" and "Foundations for Augmenting Human Capabilities," as part of program announcements for two NSF Big Ideas: The Future of Work at the Human-Technology Frontier and Growing Convergence Research. Further collaboration is planned with industry groups developing hardware (with a focus on a "beyond Moore" system architecture and corresponding devices), software (with a focus on artificial intelligence), and implementation in various applications. The research will be conducted in collaboration with other agencies (e.g., National Institutes of Health, Defense Advanced Research Projects Agency).

PCA 2. Foundational Research

The NSF FY 2019 Budget 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 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; and research directed at identifying and quantifying the broad implications of nanotechnology for society, including social, economic, ethical, and legal implications. About 60 percent of the MRSECs pursue NSE-related fundamental research.

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

The FY 2019 Request is for research that applies the principles of nanoscale science and engineering to create novel devices and systems, or to improve existing ones. 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 Computer and Information Science and Engineering (CISE) directorates support development of new principles, design methods, and constructive solutions for nanodevices. A special focus is on smart, autonomous nanoscale-based devices and systems.

PCA 4. Research Infrastructure and Instrumentation

The FY 2019 Request is 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 human 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

[16] https://www.nsf.gov/crssprgm/nano/reports/ICA2_Workshop_Report_2018.pdf

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 2015–2020, whose national coordination office was added in FY 2016. Other STCs, ERCs, 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) and two NERCs, one each on nanobiotechnology and cell technology. NSF continues to sponsor nanotechnology education and related activities, such as disseminating the video series developed with NBC Learn, *Nanotechnology: Super Small Science*.[17] Other examples are student competitions, "Video nanotechnology student competition" and "Generation Nano," sponsored by NSF and the NNI through the NSF ENG and MPS directorates, NSF's Office of Legislative and Public Affairs, and the National Nanotechnology Coordination Office.[18] NSF will increase coordinated research on its Mid-scale Research Infrastructure priority area.

PCA 5. Environment, Health, and Safety

In FY 2019, NSF will continue its funding for the Environment, Health, and Safety (EHS) PCA. Requests for research are primarily directed at understanding nano-bio phenomena and processes, as well as environmental, health, and safety implications and methods for reducing the risks of nanotechnology development. NSF continues to sponsor two Centers for Environmental Implications of Nanotechnology at the University of California, Los Angeles (UCLA) and Duke University. ENG's Nano EHS Program has changed the name to Biological and Environmental Interactions of Nanoscale Materials.[19]

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[17] http://www.nbclearn.com/nanotechnology

[18] www.nsf.gov/news/special_reports/gennano/index.jsp

[19] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505553