PROGRESS AND PLANS OF NATIONAL NANOTECHNOLOGY INITIATIVE (NNI) AGENCIES

February 2019

National Science Foundation (NSF)[1]

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 and small business institutions. The efforts in team and center projects have been particularly fruitful because nanoscale research and education are inherently interdisciplinary, and some have translational pursuits, often combining elements of materials science, engineering, chemistry, physics, biology, and neuroscience.

The NSF nanotechnology investment in 2018 supported about 5,500 active projects, over 30 research centers, and several infrastructure networks for device development, computation, and education. This investment 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 nanoscience and nanotechnology and facilitate identification of new research directions.

Several new directions planned for fiscal year (FY) 2019 are nanotechnology for quantum systems and the human-technology frontier, including highly energy-efficient systems and intelligent cognitive assistants; nanobiomanufacturing and nanobiomedicine, including cell technology; chromatin and epigenetic engineering and its nanoscale environment; semiconductor synthetic biology for information processing and storage technologies; food-energy-water processes such as nanostructured membranes and point-of-use nanofiltration; nanomodular materials and systems by design, including hierarchical three-dimensional nanoscale materials; advanced 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), nanoplastics in the environment, and neuroscience. NSF sponsors the "Generation Nano - Communication Competition" for high-school students, and "Quantum Matters - Communication Competition" for undergraduate and graduate students, both nationwide, with the participation of the Boston Museum of Science.[2]

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[2] https://www.mos.org/quantum-matters-competition

In FY 2020, 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; the National Quantum Initiative (NQI); the Artificial Intelligence (AI) focus area, 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 the 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. An industrial internship program ("INTERN") in emerging technologies, including nanotechnology, has been expanded. NSF continues its contributions to translational innovation programs, including Grant Opportunities for Academic Liaison with Industry (GOALI); Industry/University Cooperative Research Centers (I/UCRCs); the NSF Innovation Corps (I-Corps™) program; and the 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,[3] 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. NSF will also renew support for the National Nanotechnology Coordinated Infrastructure (NNCI) of user facility sites in nanotechnology. The Biological and Environmental Interactions of Nanoscale Materials program within the Engineering Directorate provides support for biological and environmental research.

The FY 2020 budget reflects that NSF has mainstreamed nanotechnology-related research, education, and infrastructure in core programs in several directorates.

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 (NSIs) and a Grand Challenge. The Nanotechnology Knowledge Infrastructure (NKI) NSI will be completed in FY 2019. The Water Sustainability through Nanotechnology NSI began in FY 2016 and will continue in FY 2020. 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 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, Supporting Fundamental Research to Enable Innovation in Advanced Manufacturing at Manufacturing USA Institutes,[4] was issued in 2017 and continues in 2020. It solicits proposals addressing critical fundamental research needs in advanced manufacturing, including nanomanufacturing and manufacturing across length scales, particularly projects that may enable innovations in the technical focus areas of one or more of

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

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

the Manufacturing USA institutes. Such proposals leverage the facilities, infrastructure, and expertise of one or more institutes and member companies. Engineering biology at the nanoscale for advanced manufacturing activities in the NSF directorates for Biological Sciences (BIO), Engineering (ENG), and Mathematical and Physical Sciences (MPS) are being organized for 2020. Methods for nanomanufacturing design are in synergy with the Materials Genome Initiative. The Nanomanufacturing Node of the nanoHUB was launched in 2017 with a lifetime of five years, with a focus on modeling and simulation of manufacturing processes. Exploratory research directions are manufacturing of nanomachines and nanobiostructures, cellular nanobiomanufacturing, atomically precise manufacturing, and nanomanufacturing for quantum devices and sensors.

- *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 other agencies in activities such as the Energy-Efficient Computing: from Devices to Architectures (E2CDA) program, which is continuing in 2020, and the Semiconductor Synthetic Biology for Information Processing and Storage Technologies (SemiSynBio) program, with awards continuing in 2020, with a focus on the E2CDA program. NSF will increase coordinated research on its Quantum Leap and Future of Work at the Human-Technology Frontier "Big Ideas" priority areas.
- *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 environmental, 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 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). Two examples of active centers are the Science and Technology Center (STC) on Quantum Materials and Devices at Harvard University and the Materials Research Science and Engineering Center (MRSEC) on Quantum and Spin Phenomena in Nanomagnetic Structures at the University of Nebraska, Lincoln. In 2018 NSF completed a report with the Semiconductor Research Corporation (SRC) on ICA research needs.[5] NSF plans to continue supporting ICA research in FY 2019 and 2020 as part of program announcements for two NSF Big Ideas: The Future of Work at the Human-Technology Frontier and Growing Convergence Research. Further collaboration is planned with industry groups developing

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

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 (including ELSI)

The NSF FY 2020 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 2020 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 2020 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 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 2015–2019, whose national coordination office was added in FY 2016. A five-year renewal of NNCI is planned for FY 2020. Other STCs, ERCs, Centers for Chemical Innovation (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 the University of Wisconsin (annual award of $4 million per year), which investigates the fundamental molecular mechanisms by which nanoparticles interact with biological systems. NSF continues to sponsor nanotechnology education and related activities, such as disseminating the video series developed with NBC Learn, *Nanotechnology: Super Small Science*.[6] NSF also plans to continue sponsoring student competitions, in cooperation with the National Nanotechnology

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

Coordination Office (NNCO), through the ENG and MPS directorates and NSF's Office of Legislative and Public Affairs. NSF will increase coordinated research on its Mid-scale Research Infrastructure priority area.

PCA 5. Environment, Health, and Safety

In FY 2020, 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 a Center for Environmental Implications of Nanotechnology at the University of California, Los Angeles (UCLA). ENG's Nano EHS Program has been renamed "Biological and Environmental Interactions of Nanoscale Materials.[7]

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, nanophononics, and brain-like cognitive systems. Representative research results achieved in each fiscal year are presented at the annual NSF Nanoscale Science and Engineering Grantees Conference.[8] A special area of focus has been on nanostructure assembly in synthetic cells that is a part of the NSF Big Idea, "Understanding the Rules of Life," by predicting phenotype and tissue engineering.

Several specific examples are as follows:

- *Spintronics: Magic-angle graphene bilayer superlattice that behaves like a high-temperature superconductor.* This work by Pablo Jarillo-Herrero of the Massachusetts Institute of Technology (MIT), et al., published in *Nature* in April 2018,[9] was named the Physics World 2018 Breakthrough of the Year. It was supported by the NSF-funded Center for Integrated Quantum Materials at Harvard University (NSF award DMR-1231319), the Army Research Office, and others. (See Figure 1 below and footnote 10 for more information.) Subsequent work at Columbia University, published in January 2019, demonstrated that applying pressure to twisted bilayer graphene transforms the material from a metal to a superconductor. The study, "Tuning superconductivity in twisted bilayer graphene,"[10] was supported by the Army Research Office, the Department of Energy, the David and Lucile Packard Foundation, and NSF.

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

[8] http://www.nseresearch.org/2017 for FY 2017

[9] https://www.nature.com/articles/nature26154

[10] https://science.sciencemag.org/content/363/6431/1059

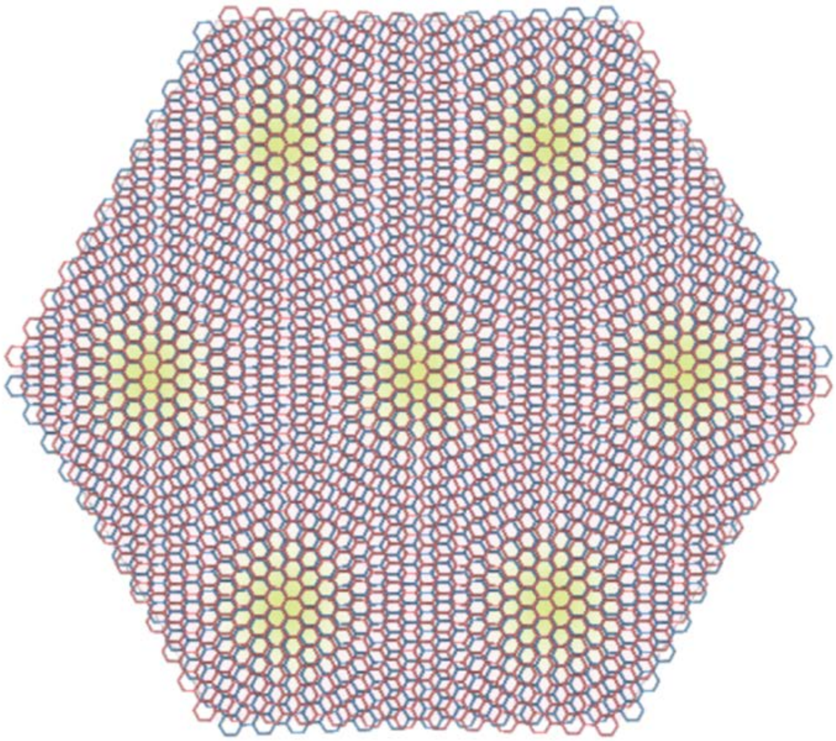

Figure 1. Moiré pattern formed by twisting two layers of graphene by a small angle. Image credit: Pablo Jarillo-Herrero group, MIT.

- *Imaging live cells with carbon dots*. Visualizing living systems at the cellular level is an important tool for biomedical research, but the diffraction limits of light restrict the resolution of conventional microscopy techniques to scales of ~250 nm. Super-resolution fluorescence microscopy techniques give researchers the ability to visualize feature sizes far smaller. This process starts by attaching fluorescent materials to an object of interest, stimulating those attached materials, and statistically mapping their location to generate an image with a 20-fold increase in resolution over conventional microscopy (see Figure 2, below). Creating high-emission, stable, and biocompatible fluorescent materials, however, is a challenge. Researchers at the Center for Sustainable Nanotechnology developed a high-throughput technique to create carbon dots with tunable sizes and emission wavelengths, or colors. This method, called C_{18} – reversed phase silica gel column chromatography, allowed researchers to study how size distributions influence optical properties like bandgap energies and photoluminescence behaviors. These dots are also highly biocompatible, making them a good candidate for the super-resolution imaging of living cells. This work is funded in part by NSF award CHE-1503408, and was published in *ACS Nano*.[11]

[11] DOI: 10.1021/acsnano.8b01619: https://pubs.acs.org/doi/10.1021/acsnano.8b01619

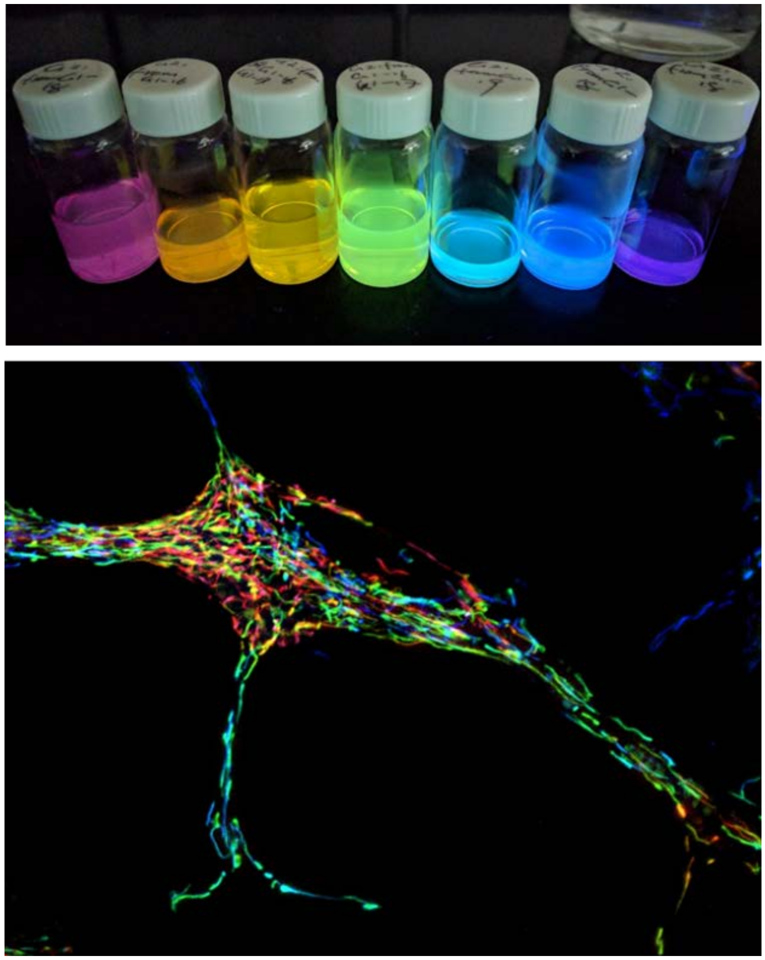

Figure 2. A Center for Sustainable Nanotechnology study, published in *ACS Nano,* describes the synthesis of carbon dots with fluorescence properties (top) that enable super-resolution imaging in live cells (bottom).

- *Fine tuning semiconductor nanocrystals.* Changing the size and shape of semiconducting nanocrystals can alter their properties, but many of the processes for nanocrystal fine-tuning were developed for heavy-metal-containing semiconductors. Looking to fine-tune heavy-metal-free nanocrystals, Anatoly Frenkel's group at Stony Brook University co-developed (with colleagues at Hebrew University of Jerusalem) a new method to control the shape and length of ZnSe nanocrystals. This method starts by forming magic size clusters (MSCs) of ZnSe. On their own, these MSCs of ZnSe can form nanowires hundreds of nanometers long. However, the addition of $[Zn_4(SPh)_{10}](Me_4N)_2$ to the reaction, otherwise referred to as Zn_4, truncates this nanowire growth. As the concentration of Zn_4 in the reaction increases, the length of the nanowires decreases, forming nanorods or even nanocrystals. By raising the reaction temperature, the diameter of the nanorods and nanocrystals increases as well, leading to a change in their absorption and emission properties. Finally, adding an analogous Cu_4 compound to the reaction leads to the formation of Cu-doped ZnSe nanorods. This method ultimately yields control over the length, diameter, and Cu doping of ZnSe nanorods, allowing researchers to explore new electronic properties. This work is funded in part by NSF award CHE-1719534 and was published in the *Journal of the American Chemical Society*.[12]

[12] DOI: 10.1021/jacs.8b05941: https://pubs.acs.org/doi/pdf/10.1021/jacs.8b05941

- *Processing inert boron nitride nanotubes.* Boron nitride nanotubes (BN NTs) are nanomaterials with an impressive set of properties: they are stronger and lighter than steel, conduct heat like copper, are electrically insulating, and resist thermal decomposition at temperatures higher than 700 °C. Unfortunately, what makes BN NTs attractive materials, inertness, also makes them difficult to process. Looking to disperse individual BN NTs into solution for easy processing and deposition, Angel Marti's team at Rice University discovered a route to chemically modify their stubbornly inert surfaces. Adapting the Billups-Birch reaction, often used for functionalizing carbon nanotubes, the BN NTs are submersed in liquid ammonia with lithium metal. This readies sites on the surfaces of the BN NTs so that as they are exposed to 1-bromododecane, dodecyl chains graft onto the surfaces. With the alkyl chains attached to their surfaces, BN NTs are dispersible in various organic solvents, potentially making them amenable to manufacturing processes. Because BN NTs are resistant to oxidation, removing the alkyl chains is as simple as heating BN NTs to temperatures over 500 °C. This work is supported in part by NSF award CHE-1610175 and was published in *ACS Applied Nano Materials*.[13]

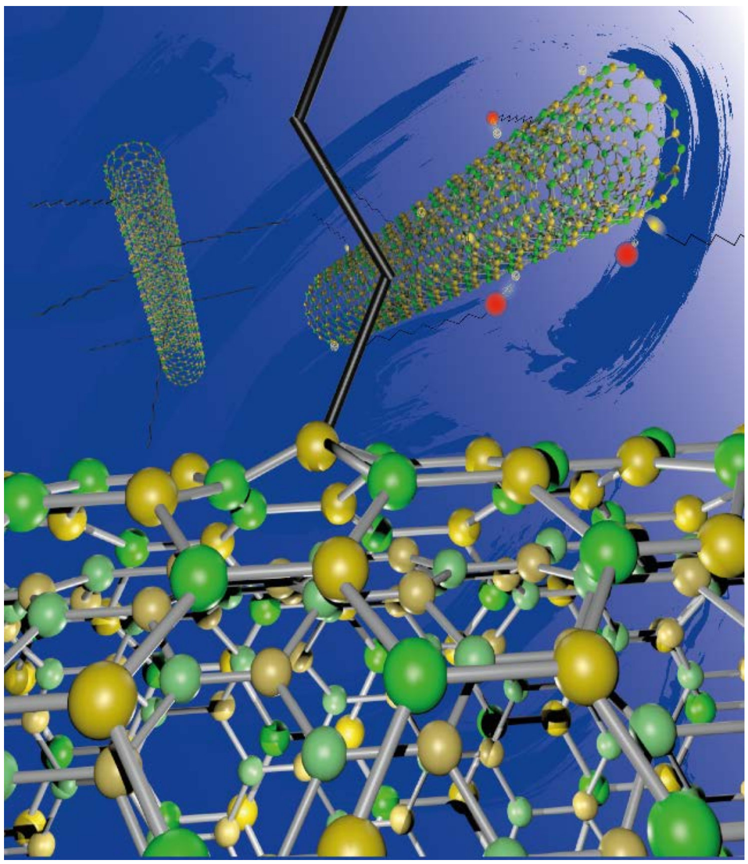

Figure 3. Processing inert boron nitride nanotubes.

- *Next-generation artificial nanopores can improve water desalination, biosensing, and energy conversion.* Northwestern University researchers used a sequence-designed polymer as molecular code to build function-programmable nanopores. Controlling the structure of soft materials at the nanoscale is prohibitively difficult through traditional engineering approaches because every component must be placed with molecular accuracy. These researchers explored a strategy to overcome this challenge by inducing molecules to self-assemble into functional structures, just as biomolecules do inside cells to

[13] DOI: 10.1021/acsanm.8b00633: https://pubs.acs.org/doi/10.1021/acsanm.8b00633

form the molecular machines that make life processes possible. Through molecular design of polymers, and using the hydrophobic force that separates oil from water, the team has for the first time theoretically demonstrated the potential of polymer-functionalized artificial nanopores to switch between open and closed states in a controllable way. This theory provides guidelines for the rational design of multifunctional nanopores that can direct the transport of molecules at the nanoscale, and could lead to applications ranging from water desalination to biosensing and energy conversion. The work has been published in the *Journal of the American Chemical Society*.[14]

- *Novel electron liquid obtained by bombarding an ultrathin (nanolayered) semiconductor sandwich with powerful laser pulses*. University of California, Riverside, researchers have created the first "electron liquid" at room temperature. The achievement opens a pathway for development of the first practical and efficient devices to generate and detect light at terahertz wavelengths—between infrared light and microwaves. Such devices could be used in applications as diverse as communications in outer space, cancer detection, and scanning for concealed weapons. The research could also enable exploration of the basic physics of matter at infinitesimally small scales and help usher in an era of quantum metamaterials, whose structures are engineered at atomic dimensions. The work was supported by NSF, the Air Force, the Department of Energy, the National Aeronautics and Space Administration, and the Canadian Institute for Advanced Research, and was published in *Nature Photonics*.[15]
- NSF-funded research in support of the NKI NSI has been aimed at activities surrounding the fundamental, interconnected elements of collaborative modeling and computer simulation, an interacting cyber-toolbox, and data infrastructure for nanotechnology, and provides a community-based, solution-oriented knowledge infrastructure for discovery, innovation, and nanoinformatics of research, education, and regulatory interest to NNI agencies. The program solicitation, "Cyberinfrastructure for Sustained Innovation,"[16] has contributed to data infrastructure, software advances, and high-throughput computation, in support of NSF's coordinated research on Harnessing the Data Revolution. The NKI NSI has achieved its primary objectives and is being retired at the end of FY 2019.

Examples NSF awards in the areas of nanomanufacturing

- Researchers at the University of Michigan at Ann Arbor have developed a battery with the potential for being a load-bearing element in drones. They further engineered the actual drones that integrated the battery as a part of the structure. The research involved engineering a solid Zn^{2+} battery electrolyte as a composite of branched aramid nanofibers and polyethylene oxide by using the nanoscale organization of articular cartilage as a blueprint for its design.[17] The work was supported by NSF awards CMMI-1538180 and -1463474.
- Researchers at Virginia Tech and Penn State have developed an additive manufacturing process for perovskite-based piezoelectric nanocomposites with designed anisotropy. The team believes it is the first study to truly print three-dimensional electrochemical metamaterials, which can have applications in smart materials, resilient infrastructures, vector sensing, and more. The work was supported by NSF award CMMI-1727492 and was published in *Nature Materials*.[18]

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[14] https://pubs.acs.org/doi/abs/10.1021/jacs.7b02057

[15] https://www.nature.com/articles/s41566-019-0349-y

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

[17] https://pubs.acs.org/doi/10.1021/acsnano.8b05068

[18] https://www.nature.com/articles/s41563-018-0268-1

- Researchers at New York University have developed graphene sensors for *in vitro* detection of dopamine and serotonin molecules. The research demonstrated that sensitivity of graphene electrodes to neurochemicals is strongly linked to point defects in graphene. The approach achieved reproducible fabrication of miniaturized sensors with extraordinarily higher sensitivity than conventional materials and laid the foundation for new integrated electrochemical sensor arrays based on nanoengineered graphene. The work was supported by NSF award CMMI-1728051 and was published in *Advanced Materials*.[19]
- Researchers at Drexel University investigated the nanomanufacturing of water desalination electrodes containing intercalation compounds for hybrid capacitive deionization systems. They investigated the role of carbon nanoparticles as conductive additives in the electrodes. The goal is to fabricate porous electrodes with the right carbon nanostructures for flow-through desalination cells. The work was supported by NSF award CMMI-1635233 and published in *Desalination*.[20]
- Researchers at the University of Buffalo have developed a new nanogap chip for on-site drug sensing. The chip could be integrated into a handheld, portable device for detecting drugs in biological samples such as blood, breath, urine, or spit. The chip works by trapping light at the edges of gold and silver nanoparticles. When biological or chemical molecules land on the chip's surface, some of the captured light interacts with the molecules and is "scattered" into light of new energies. The work was supported by NSF award CMMI-1562057 and published in *Small Methods*.[21]
- Researchers at Purdue University and the University of Notre Dame have developed block copolymer membranes in hollow fiber configuration as adsorbers for metal ion capture. The researchers studied the role of triblock terpolymer chemistry and solvent evaporation over the mechanical strength development of polymer solutions used to fabricate self-assembly and nonsolvent induced phase separation membranes. The work was supported by NSF award CMMI-1436255 and published in the *Journal of Applied Polymer Science*.[22]
- A research team headed by West Virginia University synthesized free-standing, high-aspect-ratio sulfur-doped carbon nanodot-based hybrid nanowires with a microtubular aspect using self-recognition and self-assembly processes of tubulin, a biological molecule precursor of the cytoskeletal cellular and structural microtubule filaments. This allowed printing of nanostructures with ultra-high resolution below 10 nm. The work was supported by NSF award CMMI-1300757 and published in *ACS Applied Materials Interfaces*.[23]
- Researchers at Northwestern University have developed a rapid fabrication method to 3D print customized optical components with high accuracy. The team has demonstrated sub-5 μm-scale precision, sub-7 nm surface roughness by employing projection micro-stereolithography, gray-scale photopolymerization, and meniscus equilibrium post-curing. By this method, customized aspheric lenses with high resolution and low distortion were fabricated for cell phone applications. The work was supported by NSF award CMMI-1530734 and published in *Advanced Materials*.[24]

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[19] https://onlinelibrary.wiley.com/doi/10.1002/adma.201805752
[20] https://doi.org/10.1016/j.desal.2018.10.025
[21] https://onlinelibrary.wiley.com/doi/full/10.1002/smtd.201800045
[22] https://onlinelibrary.wiley.com/doi/full/10.1002/app.47038
[23] https://pubs.acs.org/doi/10.1021/acsami.8b09421
[24] https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201705683

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 is continuing 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, nanotechnology solutions for grand challenges, nanoelectronics and active nanostructures, nanotechnology for biological and medical applications, and instrumentation for nanotechnology. Strong support is continuing for the Nanoelectronics for 2020 and Beyond NSI through core programs and for the Nanomanufacturing NSI through the Advanced Manufacturing (including Scalable Nanomanufacturing) solicitation.[25] Other NNI-affiliated awards include Nanoscale Science and Engineering Centers (NSECs), the National Nanotechnology Coordinated Infrastructure, the nanotechnology-inspired Engineering Research Centers (in the ENG Directorate), awards mapped into the Advanced Manufacturing Program (in the ENG Directorate, Division of Civil, Mechanical and Manufacturing Innovation, CMMI) and MPS Directorate centers investments (MRSECs and CCIs).

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 has provided a total of $81 million over five years to support 16 sites and a coordinating office as part of the 2015–2019 National Nanotechnology Coordinated Infrastructure.[26] The NNCI sites 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.[27]
- One example of public outreach in support of Goal 3 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.[28]

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

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

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

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

Goal 4. Support Responsible Development of Nanotechnology

Research in support of nanomaterials characterization and exposure is performed in NSF's core programs. Some examples of accomplishments in these efforts include the following:

- An undergraduate working on an NSF-funded project, "Forecasting the Environmental Fate and Ecotoxicity of Nanomaterials in Aquatic Systems,"[29] received the 2018 College of Agricultural Sciences Outstanding Senior Award from Oregon State University (OSU).
- A researcher at the University of Hawaii-Manoa has developed a novel *in vitro* method for characterizing inhaled nanoparticles called constrained drop surfactometry (CDS), which mimics the intra-alveolar environment and nano-bio interactions in the lungs. This will enable prediction of the extent of lung injury and toxicity of various inhaled nanoparticles.

[29] https://nsf.gov/awardsearch/showAward?AWD_ID=1438165&HistoricalAwards=false