NATIONAL NANOTECHNOLOGY INITIATIVE STRATEGIC PLAN

A Report by the

SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

COMMITTEE ON TECHNOLOGY

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

October 2021

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 that science and technology policy decisions and programs 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. More information is available at http://www.whitehouse.gov/ostp/nstc.

About the Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976 to provide the President and others within the Executive Office of the President with advice on the scientific, engineering, and technological aspects of the economy, national security, homeland security, health, foreign relations, the environment, and the technological recovery and use of resources, among other topics. OSTP leads interagency science and technology policy coordination efforts, assists the Office of Management and Budget with an annual review and analysis of Federal research and development in budgets, and serves as a source of scientific and technological analysis and judgment for the President with respect to major policies, plans, and programs of the Federal Government. More information is available at http://www.whitehouse.gov/ostp.

About the Subcommittee on Nanoscale Science, Engineering, and Technology

The Subcommittee on Nanoscale Science, Engineering, and Technology (NSET) contributes to the activities of NSTC's Committee on Technology. NSET's purpose is to advise and assist the NSTC and OSTP on policies, procedures, and plans related to the goals of the National Nanotechnology Initiative (NNI). As such, and to the extent permitted by law, NSET Subcommittee defines and coordinates Federal efforts in support of the goals of the NNI and identifies policies that will accelerate deployment of nanotechnology. NSET also tracks national priority needs that would benefit from the NNI, identifies extramural activities that connect to NNI goals, and explores ways the Federal Government can advance the development of nanotechnology. More information is available at https://www.nano.gov/.

About this Document

This document is the strategic plan for the NNI, as called for in the 21st Century Nanotechnology Research and Development Act (15 USC §7501). It describes the NNI vision and goals and the strategies by which these goals are to be achieved, and it also identifies specific objectives toward collectively achieving the NNI vision. This plan updates and replaces the NNI Strategic Plan of October 2016.

Disclaimer

Reference in this document to any specific commercial product, process, service, manufacturer, company, or trademark is to provide clarity and does not constitute its endorsement or recommendation by the U.S. Government.

Copyright Information

EXECUTIVE OFFICE OF THE PRESIDENT
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
WASHINGTON, D.C. 20502

October 7, 2021

Dear Members of Congress:

I am pleased to share with you the 2021 National Nanotechnology Initiative (NNI) Strategic Plan. This plan builds on the scientific advances, research infrastructure, and vibrant interdisciplinary nanotechnology community developed under the auspices of the NNI. It also sets a course to refresh and reinvigorate the initiative to best serve the American people.

Since the launch of the NNI in 2000, nanoscience has transformed from an emerging area of research to a technology that is fueling real-world applications. For example, the COVID-19 vaccines developed in record time require nanomaterials for delivery. Powerful consumer electronics—from phones to batteries to vivid displays—are made possible by nanotechnology. Nanomaterials are also critical for smart windows, solar cells, and low-carbon concrete to combat climate change.

While the U.S. has long been a leader in nanotechnology research and development, global competition is intensifying. It is critical that we double-down on our innovation infrastructure by investing in research and accelerating our ability to move nanotechnology innovations from the lab to the marketplace. To be successful, the NNI must draw on all of America's assets—chief among them, our unrivaled diversity. The NNI must also strengthen the nanotechnology R&D ecosystem—including the connections among researchers, innovators, teachers, and students—and its relationships with allies and partners who share our values.

In this document, the NNI lays out a plan to do just that. Specifically, the plan introduces new mechanisms to deliberately connect and support the entire nanotechnology enterprise. The strategic plan also recognizes the importance of the NNI research infrastructure—for nanoscientists and the researchers advancing areas such as quantum science, artificial intelligence, and microelectronics—and its role in training the future workforce. NNI efforts will enhance attention on diversity, inclusion, equity, and access, and promote opportunities for all of America. And this plan unveils the National Nanotechnology Challenges to mobilize the nanotechnology community to help solve critical world issues such as pandemic preparedness, climate change, access to clean water, and food insecurity.

This strategic plan provides the framework for the NNI to help build a healthier, safer, more prosperous, and sustainable future.

Sincerely,

Eric S. Lander
Director, Office of Science and Technology Policy

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

Chair

Eric Lander, Director, Office of Science and Technology Policy

Executive Director

Kei Koizumi, Acting Executive Director, National Science and Technology Council

SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

Co-Chairs

Lisa Friedersdorf, OSTP
Antti J. Makinen, DOD
Andrew R. Schwartz, DOE

Executive Secretary

Geoffrey Holdridge, NNCO

Participants

Kumar Babu, DHS
Janet Carter, DOL/OSHA
Hongda Chen, USDA/NIFA
Khershed Cooper, NSF
Jeffrey DePriest, DOD
Angela Ervin, DHS
Heather Evans, DOC/NIST
Rodney P. Feazell, Treasury/BEP
Meg Flanagan, State
Michael Focazio, DOI/USGS
Eric W. Forsythe, DOD
Lisa E. Friedersdorf, OSTP/NNCO
Kelly Gardner, DOC/BIS
Tracy Gerstle, DOC/ITA
Lawrence S. Goldberg, NSF
Mark Greene, DOJ/NIJ
Mark H. Griep, DOD
Piotr Grodzinski, HHS/NIH
Annette Guiseppi-Eli, EPA
Tariq Hafiz, DOC/USPTO
Lori A. Henderson, HHS/NIH
Laura Hodson, HHS/NIOSH
Michael Holthe, DOD
Stephanie Hooker, DOC/NIST
Linda Horton, DOE
Candi Hudson, DOI/BSEE
Candis M. Hunter, HHS/NCEH
Danielle Jones, OMB
Tina M. Kaarsberg, DOE
Akbar Khan, DOD
Fred Kronz, NSF
David Kuehn, DOT/FHWA
Harriet Kung, DOE
JihFen Lei, DOD
Gene E. Lester, USDA/ARS
Thomas Libert, OMB
J. Alexander Liddle, DOC/NIST
James Lindsay, USDA/ARS
Louise Lund, NRC†
Lynnette Madsen, NSF
Antti J. Makinen, DOD
Jalal Mapar, DHS
George Maracas, DOE
Joanna Matheson, CPSC†
William McNavage, OMB
Heather Meeks, DOD
Custodio V. Muianga, HHS/ATSDR
Vladimir V. Murashov, HHS/NIOSH
Elizabeth R. Nesbitt, USITC†
World L.-S. Nieh, USDA/FS
Brian D. Pate, DOD
Anil Patri, HHS/FDA
Andreea Paulopol, State
Gernot S. Pomrenke, DOD
Yuliana Porras Mendoza, DOI/USBR
Victor Pugliano, DOD
David Rampulla, HHS/NIH
Mihail C. Roco, NSF
Nora Savage, NSF
Andrew R. Schwartz, DOE
Birgit Schwenzer, NSF
Seila Selimovic, HHS/BARDA
Stacey Standridge, NNCO
Jeffery Steevens, DOI/USGS
David M. Stepp, DOD
Matt Such, DOC/USPTO
Maher Tadros, State
Treye A. Thomas, CPSC†
Jay Vietas, HHS/NIOSH
Tiffany S. Williams, NASA
Max Zarate-Bermudez, HHS/NCEH

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

Table of Contents

Abbreviations and Acronyms

2D two-dimensional

AFOSR Air Force Office of Scientific Research

AI artificial intelligence

ARS Agricultural Research Service

ATSDR Agency for Toxic Substances and Disease Registry

BARDA Biomedical Advanced Research and Development Authority

BEP Bureau of Engraving and Printing

BIS Bureau of Industry and Security

BSEE Bureau of Safety and Environmental Enforcement

COR Community(ies) of Research

CPSC Consumer Product Safety Commission

DHS Department of Homeland Security

DOC Department of Commerce

DOD Department of Defense

DOE Department of Energy

DOI Department of the Interior

DOJ Department of Justice

DOL Department of Labor

DOT Department of Transportation

EHS environment(al), health, and safety

ELSI ethical, legal, and societal implications

EPA Environmental Protection Agency

FDA Food and Drug Administration

FHWA Federal Highway Administration

FS Forest Service

HBCUs historically black colleges and universities

HHS Department of Health and Human Services

IDEA inclusion, diversity, equity, and access

ITA International Trade Administration

MSI minority-serving institution

nanoEHS nanotechnology environmental, health, and safety

NASA National Aeronautics and Space Administration

NASEM National Academies of Sciences, Engineering, and Medicine

NCEH National Center for Environmental Health

NCL Nanotechnology Characterization Laboratory

NEHI Nanotechnology Environmental and Health Implications (Working Group, NSET)

NIFA National Institute of Food and Agriculture

NIH National Institutes of Health

NIJ National Institute of Justice

NIOSH National Institute for Occupational Safety and Health

NIST National Institute of Standards and Technology

NNC National Nanotechnology Challenge

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, NSTC)
NSI	Nanotechnology Signature Initiative
NSF	National Science Foundation
NSRC	Nanoscale Science Research Center (DOE)
NSTC	National Science and Technology Council
OECD	Organisation for Economic Co-operation and Development
OMB	Office of Management and Budget
OSHA	Occupational Safety and Health Administration
OSTP	Office of Science and Technology Policy
PPP	public-private partnership
R&D	research and development
State	Department of State
STEM	science, technology, engineering, and mathematics
Treasury	Department of the Treasury
U.S.	United States
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USITC	U.S. International Trade Commission
USPTO	U.S. Patent and Trademark Office

Introduction

Nanotechnology[1] has become ubiquitous throughout modern society, from supercomputers that can be carried in a pocket to lifesaving shots in arms to combat the global pandemic. Nanoscience, too, is prevalent across the full research and development landscape, promising lighter, stronger, and more functional materials, new ways to store and manipulate information, and early detection of diseases. Opportunities at the nanoscale promise to produce clean water, provide abundant food, deliver green energy technologies, combat climate change, and develop new therapies for diseases that currently have no treatment options.

So, has the National Nanotechnology Initiative (NNI) done its job? Should the spotlight instead focus on another emerging technology? Those are exactly the questions the Federal Government considered and even tasked the National Academies of Sciences, Engineering, and Medicine (NASEM) to address in its Congressionally mandated[2] quadrennial review of the NNI. After careful review of the global landscape and considerable stakeholder engagement, the committee concluded that it is important for the NNI to continue. The committee's report[3] noted that "*The NNI is widely viewed nationally and globally as a highly successful cross-disciplinary and interagency coordination effort—arguably the best modern example of such an effort in the United States. The committee is deeply impressed with tangible outcomes that have emerged from these coordination efforts.*" The report emphasized the continued importance of nanotechnology, noting that "*Global advances in medicine, food, water, energy, microelectronics, communications, defense and other important sectors in the economy are increasingly driven by discoveries in nanoscience and the development of nanotechnologies and justify a continued focus by the United States on, and investment in, these fields*," but also that an "urgent redesign" of the initiative should be considered. The committee highlighted an increased impact of nanotechnology on the economy and intensifying global competition. To rapidly harvest the economic benefits and meet the challenge of global competition, the committee recommended reorganizing and relaunching the NNI and provided key recommendations. While "*the committee was unified in a positive assessment of the value of the NNI to the U.S. economy*," comparison with international efforts, specifically related to commercialization approaches, led to the suggestion for increased focus and reorganization to better support NNI efforts in this area.

Over the past year and a half, the Office of Science and Technology Policy (OSTP) and the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council (NSTC) have assessed the NASEM recommendations, along with those from earlier evaluations by the President's Council of Advisors for Science and Technology. The strategic planning process actively sought input from every corner of the nanotechnology community through engagement at a wide variety of conferences, workshops, and other meetings; an OSTP Request for Information;[4] and a dedicated public workshop[5] to identify how to best support the nanotechnology research and development (R&D) community now and into the future.

---

1 https://www.nano.gov/nanotech-101/what/definition

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

3 National Academies of Sciences, Engineering, and Medicine, 2020. *A Quadrennial Review of the National Nanotechnology Initiative: Nanoscience, Applications, and Commercialization.* Washington, DC, The National Academies Press: https://doi.org/10.17226/25729.

4 https://www.federalregister.gov/documents/2020/10/13/2020-22556/request-for-information-national-nanotechnology-initiative-strategic-planning

5 https://www.nano.gov/2021stakeholderworkshop

Since the NNI was launched, there has been much progress. Understanding of the nanoscale has grown enormously, thanks to a constant flood of new discoveries. Early domains of nanoscience, such as nanophotonics, have grown and spun off into their own fields. New tools and capabilities to model, make, characterize, and integrate nanomaterials into devices and systems have been developed. Nanotechnology lessons, courses, departments, and even colleges and schools have been created. The environmental, health, and safety (EHS) implications of nanomaterials are better understood, and a vast array of nanosafety resources are available. International standards have been established to help speed commercialization; and, perhaps most importantly, nanotechnology-enabled products are prevalent in the marketplace.

However, the interagency community found that many of the driving forces that led to the establishment of the NNI twenty years ago still hold true. Nanoscience spans the boundaries of traditional disciplines, and facilitating collaboration across these boundaries is essential. Understanding, imaging, and manipulating matter at the nanoscale requires specialized instrumentation that can be cost-prohibitive for individual research groups or institutions, and especially small businesses, to afford on their own. The novel properties exhibited at the nanoscale can be applied to a wide variety of areas, and disparate communities that would not otherwise interact can learn from each other if brought together (e.g., see call-out box on nanomedicine and agriculture, page 12).

With this background in mind, the NNI agencies have carefully considered recommendations from the advisory bodies, stakeholder responses to the OSTP Request for Information, and input from the public. The NNI agencies determined that the overarching NNI goals to support nanotechnology R&D, commercialization, infrastructure, and responsible development should remain consistent, with the addition of a new goal to more clearly focus efforts on education and workforce. The operational structure and engagement mechanisms of the NNI, however, have been redesigned to include new elements to respond to changes in the NNI ecosystem and to better support the current and future needs of the nanotechnology community. This document presents goals and objectives to guide agencies and the community over the next five years. While individual agency efforts will be informed by respective missions, priorities, and authorities, collectively, the NNI agencies and National Nanotechnology Coordination Office (NNCO) will advance the full suite of goals and objectives outlined in this document. Examples of specific actions to support the goals and objectives are also identified.

NNI Goals

Goal 1. Ensure that the United States remains a world leader in nanotechnology research and development.

At the heart of the NNI is support for nanotechnology R&D across the entire continuum, from basic research that fuels new discoveries through application-driven advanced research and development that leads to new products in the market. Proposed solutions leveraging the unique properties at the nanoscale successfully compete for funding in general research solicitations, and agencies now rarely specify nanotechnology in requests for proposals, in contrast to the early days of the NNI. While this reflects the successful embedding of nanotechnology throughout the R&D enterprise, it makes coordination more difficult, and perhaps more important than ever to ensure that resources, knowledge, and synergies are fully leveraged. The NNI agencies will continue to use their full suite of authorities and mechanisms to fund nanotechnology R&D, and more deliberate mechanisms will be used to connect and build communities, both within the NNI and with other initiatives and priorities. National Nanotechnology Challenges are being introduced in this plan to mobilize the nanotechnology community to help address global issues.

Goal 2. Promote commercialization of nanotechnology R&D.

The NNI will enhance efforts to accelerate the scale-up, translation, and commercial application of nanotechnology R&D into the marketplace to ensure that economic, environmental, and societal benefits are realized and to help the Nation build back better with high-paying jobs. Additional efforts supporting this goal are perhaps the most significant updates to the strategic plan and address the critical needs identified by the NASEM committee. More explicit connections will be made to broad agency efforts that support transition of nanotechnologies to the regional ecosystems that exist across all of America. Efforts will include expanding the Nanotechnology Entrepreneurship Network[6] as a forum to connect innovators and share best practices.

Goal 3. Provide the infrastructure to sustainably support nanotechnology research, development, and deployment.

The need for expensive, specialized tools remains a key requirement for much of nanotechnology R&D. A hallmark of the NNI has been the support of physical and cyber user facilities, which not only democratize nanoscience across the ecosystem but also serve as a platform to educate and train students who will become the next generation of instrument users, designers, and builders. NNI agencies recognize the importance of providing access to cutting-edge tools by upgrading and refreshing toolsets, as well as supporting the acquisition and maintenance of "workhorse" instruments. The NNI will support the increasing role of the cyber infrastructure (e.g., models, simulations, and data) that is critical for nanotechnology innovation enhanced by artificial intelligence, machine learning, and advanced design tools. Facilities that support prototyping and early stages of the manufacturing process are also important for the development community and will be explored in collaboration with the private sector.

Goal 4. Engage the public and expand the nanotechnology workforce.

The future of the NNI depends on a highly skilled workforce across the entire technology development pathway. In addition to targeted nanotechnology education, the novel properties at the nanoscale can provide a spark to excite students to pursue science, technology, engineering, and mathematics (STEM) careers and help build a robust domestic workforce. NNCO and the NNI agencies use a variety of mechanisms to support public outreach and education from "K to grey" and will emphasize opportunities and access to resources, especially for people in traditionally underserved communities. In recognition of the importance of education, workforce development, and public engagement to the entire nanotechnology enterprise, these areas are now a stand-alone goal of the NNI.

Goal 5. Ensure the responsible development of nanotechnology.

The responsible development of nanotechnology has been an integral part of the NNI since its inception, and the initiative has proactively considered potential implications and technology applications at the same time. Just as scientific understanding of nanomaterials has deepened and matured, the understanding of responsible development also has evolved. The responsible

[6] https://www.nano.gov/nanoentrepreneurshipnetwork

development framework articulated in this plan embraces new ideas that have emerged and builds upon concepts originally included in the NNI's responsible development efforts. A key tenet of responsible development remains the protection of human health and the environment through an understanding of not only the applications of nanomaterials, but also the potential implications. Responsible development further includes consideration of ethical, legal, and societal implications (ELSI) as well as a new emphasis on inclusion, diversity, equity, and access (IDEA) and the responsible conduct of research.

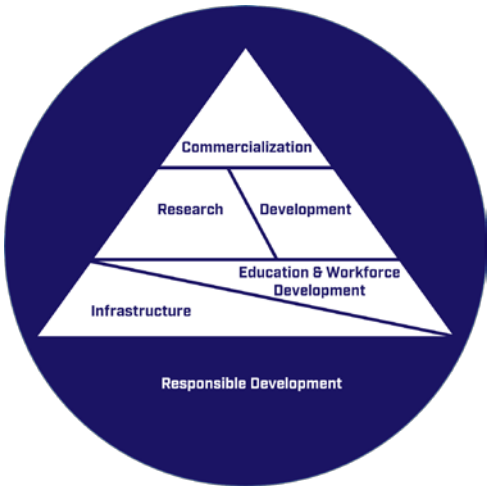


Figure 1. Diagram depicting the NNI goals. Credit: NNCO.

These five goals are highly interrelated and interdependent. World-class research requires top STEM talent, but also serves as a training ground for future researchers. Cutting-edge equipment is required to conduct research and to attract top talent, but also supports the transformation of ideas into products, and enables education and workforce training efforts. The overarching principles of responsible development apply to all aspects of the NNI.

NNI Operational Structure Supports the Entire Nanotechnology Community

Building on the past twenty years of experience, the new NNI operational structure provides a variety of mechanisms to support the entire nanotechnology community and to advance all five of the initiative's goals. These mechanisms are introduced here in general terms. Details regarding how these mechanisms are being used to advance each goal are described below. The NNI is not a discrete funding program but is the sum of all the related agency activities and the community that works together to advance nanotechnology. The goals, objectives, and actions in this plan aim to support, expand, and diversify the nanotechnology community to realize the NNI vision *of a future in which the ability to understand and control matter at the nanoscale leads to ongoing revolutions in technology and industry that benefit society*.

The strength of the NNI stems from the broad and diverse nanotechnology community. A theme emphasized throughout the strategic planning process was how the NNI is the embodiment of convergence.[7] The concepts of interdisciplinarity and convergence were novel in the early days of the NNI. The natural focus of nanoscience across the boundaries of disciplines necessitated different fields working together, leading to the vibrant interdisciplinary nanotechnology community that exists today, sometimes referred to as the NNI's "superpower."[8] Although some claim that the NNI played a role in fundamentally changing the approach to science, with collaborative teams now routinely involving

[7] *Deep integration across disciplines. As experts from different disciplines pursue common research challenges, their knowledge, theories, methods, data, research communities, and languages become increasingly intermingled or integrated. New frameworks, paradigms or even disciplines can form sustained interactions across multiple communities. … the convergence paradigm intentionally brings together intellectually diverse researchers to develop effective ways of communicating across disciplines by adopting common frameworks and a new scientific language, which may, in turn, afford solving the problem that engendered the collaboration, developing novel ways of framing research questions, and opening new research vistas:* https://www.nsf.gov/od/oia/convergence/index.jsp.

[8] Per presentation at the January 2021 NNI Stakeholder Workshop by Paul S. Weiss, UCLA and *ACS Nano*: https://www.youtube.com/watch?v=sSpIKxWMoNg.

Inclusion, diversity, equity, and access in the NNI

The science, technology, engineering, and mathematics innovations that impact our daily lives are developed through the creativity and hard work of individuals working together to solve problems. While STEM disciplines contribute to the fastest growing job sectors in the United States, this workforce does not reflect the diversity of the country, and the STEM workforce is 89% white and 72% male.[9] *Historic and entrenched systemic inequities deny some groups meaningful participation in, and access to, STEM fields. The underrepresentation of many groups in STEM fields has real financial and economic implications for these communities. The typical STEM worker, on average, earns roughly two-thirds more than a non-STEM worker.*[10] *It is important to help lift up communities that have traditionally been left behind so that all Americans have the opportunity to fulfill their potential. In addition, studies have shown that diverse teams are more innovative and outperform homogenous teams considered to have "greater ability."*[11] *Diversity can stem from differences in race, ethnicity, geographic location, gender, culture, sexual orientation, disability status, socioeconomic status, religion, and other factors. People with different backgrounds have a variety of perspectives and experiences that result in multiple approaches to solving problems, asking different questions, and developing more innovative solutions. Only when the STEM workforce reflects the diversity of the country will the United States benefit from the full breadth of ideas across America.*

The 2019 cohort of National Nanotechnology Coordinated Infrastructure Research Experiences for Undergraduates students. Credit: Cornell University.

In support of the Administration's commitment in this area, the NNI will strive to enhance inclusion, diversity, equity, and access across the entire nanotechnology R&D ecosystem. Building on the work done by IDEA experts, best practices will be implemented across all five goals of the NNI to create broad, cross-cutting, and meaningful change. The NNI will identify an IDEA Liaison to engage and collaborate with experts within the Federal Government and relevant external organizations to ensure that IDEA efforts are effective and pertinent. NNI participating agencies will continue and enhance programming and activities that promote IDEA, such as NSF INCLUDES[12] *and ADVANCE,*[13] *NIH's UNITE effort,*[14] *NASA's Minority University Research and Education Project*[15]*and Mission Equity effort,*[16] *and DOD's Research and Education Program for Historically Black Colleges and Universities (HBCUs) and Minority-Serving Institutions (MSIs).*[17] *Educational and outreach efforts will be employed to engage with a wide range of underserved communities through targeted activities and collaborative programming with external organizations, such as 4-H and Girl Scouts. The NNI will also collaborate with existing scientific societies supporting underrepresented groups in STEM to advance IDEA across the nanotechnology R&D community. Through these activities, the NNI will seek to build a more diverse and inclusive nanotechnology community that is better able to advance nanotechnology R&D, bring products to market, and provide solutions to global challenges.*

[9] https://www.nsf.gov/statistics/2018/nsb20181/report/sections/science-and-engineering-labor-force/women-and-minorities-in-the-s-e-workforce#minorities-in-the-s-e-workforce

[10] https://www.pewresearch.org/social-trends/2018/01/09/diversity-in-the-stem-workforce-varies-widely-across-jobs/

[11] L. Hong and S.E. Page, 2004. Groups of diverse problem solvers can outperform groups of high-ability problem solvers. *PNAS USA* **46**, 16385-16389: https://doi.org/10.1073/pnas.0403723101.

[12] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505289

[13] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5383

[14] https://www.nih.gov/ending-structural-racism/unite

[15] https://www.nasa.gov/stem/murep/home/index.html

[16] https://www.nasa.gov/mission-equity

[17] https://basicresearch.defense.gov/News/Articles/News-Display/Article/2374561/dod-invests-50-million-in-minority-serving-institutions-to-conduct-boundary-pus/

many disciplines, there is also strong caution that interdisciplinarity takes time, sustained effort, and continued focus on bringing people together. These elements are essential for advancing nanotechnology and remain an important role for the NNI.

The positive synergistic effects of bridging boundaries are also seen across the nanotechnology development pathway, where researchers and developers working together can more quickly advance the transition of discoveries to products. Public-private partnerships (PPPs) can bring together representatives from academia, industry, and government to address a specific topic. The NNI user facilities have fostered another approach to bridging these communities by anchoring their local ecosystems and serving as collaborative innovation platforms. A recent Organisation for Economic Co-operation and Development (OECD) study[18] explored how collaborative platforms such as the National Nanotechnology Coordinated Infrastructure (NNCI) sites stimulate the convergence of technical disciplines, development stages, and diverse communities.

To ensure that the United States remains a world leader in nanotechnology, the NNI must support and nurture all aspects of the nanotechnology R&D ecosystem and build connections with synergistic efforts. The NNI will also enhance IDEA throughout the community to ensure that all Americans have opportunities to participate and to enrich nanotechnology innovation.

Coordination and collaboration across the Government

The Federal nanotechnology community is extremely diverse, with each agency having its own role and responsibilities. Over the course of the NNI, the number of agencies with interests in nanotechnology has grown dramatically; now over 30 Federal entities are engaged. Furthermore, nanotechnology underpins and supports many other national priorities, including quantum information science, microelectronics, pandemic preparedness, climate change, carbon-free energy options, clean water, and abundant and safe food. While there has been collaboration between the NNI and other priority efforts in the past, this plan presents new mechanisms that are more intentional and deliberate, while also providing the agility to adjust to changing priorities.

The formal organizational structure for the NNI includes the NSET Subcommittee, the Nanotechnology Environmental and Health Implications (NEHI) Working Group, and the NNCO. Representatives from NNI agencies serve together on the NSET Subcommittee under the National Science and Technology Council structure. NSET representatives work together to develop shared goals and priorities for the NNI and to develop a comprehensive nanotechnology R&D program that leverages individual agency resources and investments. NEHI has long been an exemplar for interagency collaboration, and participating agencies actively collaborate and leverage their respective authorities to advance the NNI Environmental, Health, and Safety Research Strategy.[19] NNCO provides technical and administrative support to NSET and the interagency nanotechnology community.

A lesson learned over the ten years of the Nanotechnology Signature Initiatives (NSIs) was that the greatest added value of the effort was the convening and building of a cohesive interagency community. Based on this experience, the NNI will expand the community of interest model to support and build interagency engagements in priority areas. As the needs of the community evolve, the community of interest model provides a flexible mechanism for the interagency community to rapidly

[18] OECD, 2020. Collaborative platforms for innovation in advanced materials. *OECD Science, Technology and Industry Policy Papers*, No. 95: https://doi.org/10.1787/bb5225f1-en.

[19] National Science and Technology Council, 2011. *National Nanotechnology Initiative: Environmental, health, and safety research strategy.* Washington, D.C.

establish and/or retire efforts. The communities of interest will be reviewed annually by the NSET Subcommittee. A nanoplastics community of interest has been established to address this critical area of emerging concern. This community is building on more than twenty years of EHS research on engineered nanomaterials, including detection and characterization methods, to develop techniques to understand and mitigate the impacts of incidental nanomaterials. Facilitated by NNCO, this informal group now involves more than 18 agencies and over 100 participants. Additional NNI communities of interest will be established around shared priorities. The interagency groups established as sensors and water NSIs will continue as communities of interest.

As noted above, key advances in many other national efforts and Administration priorities are enabled by progress in nanotechnology. Furthermore, the various R&D-related initiatives may have common technical and policy needs, such as promoting STEM education. The NASEM committee recommended that the NNI clearly connect with these priority areas. While the NNI and other initiatives have often collaborated in the past, Strategic Liaisons will be identified to connect synergistic efforts more explicitly. The Strategic Liaisons will serve as the conduit for information sharing across activities and will report to NSET. For example, a Strategic Liaison to the NSTC Lab2Market Subcommittee will support NNI efforts in Goal 2, and the NSET Subcommittee has become an affiliated partner of the Lab2Market Subcommittee. The liaisons will be identified in the NNI Supplement to the President's Budget, which serves as the NNI's annual report to Congress.

As a complement to the Strategic Liaison mechanism, the NNI will continue to employ Coordinators in key areas to serve as points of contact both inside and outside of the Government, and to actively coordinate interagency efforts. NNI Coordinators in the areas of Global Issues and Standards will continue. With this plan, additional Coordinators for Infrastructure and for Education and Workforce will be identified. Furthermore, the NNCO has a devoted Industry and Regional Liaison to engage the business community and regional innovation ecosystems.

Together these formal and informal mechanisms will provide the framework to coordinate and leverage the activities of the growing list of agencies engaged in nanotechnology and to collaborate with related Federal activities in an intentional manner.

Engaging stakeholders to inform, build, and connect communities

The broad nanotechnology community consists of many stakeholders, including researchers; small and large businesses; teachers and students; Federal, state, and local government officials; nonprofits; and the general public, both in the United States and around the world. The NNI has targeted activities to engage all its stakeholders and will expand and strengthen these efforts over the next five years. In its role as the point of contact for the NNI, and its responsibilities for promoting commercialization and public engagement as identified in the 21st Century Nanotechnology R&D Act (15 U.S.C. §7501), NNCO has a broad suite of mechanisms to engage the community. In addition to the NNI website, Nano.gov, and social media channels, NNCO delivers targeted content via brochures, webinars, workshops, and podcasts, and facilitates networks to foster and nurture key communities. NNCO also meets members of the community where they gather, embedding technical sessions, panels, and town hall discussions in conferences, trade shows, and other events. An emphasis over the next five years will be to better reach underserved communities and collaborate with organizations to reach all of America.

The NNI will expand and intensify its efforts to ensure that nanotechnology discoveries are transitioned into products that benefit all Americans. In addition to continuing to build the Nanotechnology Entrepreneurship Network, the NNI will help connect inventors and developers and leverage regional

innovation ecosystems. The NNCO Industry and Regional Liaison serves as a point of contact and actively monitors and supports the nanotechnology business community. While all small businesses face challenges, working at the nanoscale can bring additional burdens, for example in safe handling of materials and accessing specialized equipment. The NNI will develop and share nanotechnology resources to assist with these unique issues, including with the Manufacturing Extension Partnership sites found in every U.S. state and territory. The NNI will also leverage and work with the private sector to accelerate progress in targeted areas with public-private partnerships.

The Community of Research (COR) model, which brings together researchers from all over the world to work together on specific topics, has been used effectively over the past decade to foster active and productive collaborations. The researcher-led nanotechnology environmental, health, and safety (nanoEHS) CORs, facilitated by NNCO in collaboration with the European Commission, are vibrant efforts that are having tangible impacts on both participants and the broader field. The strong relationships that have developed within the nanoEHS CORs help to accelerate progress in critical areas such as data sharing and protocol development, and in research reproducibility and reliability to fully leverage the breadth of nanoEHS knowledge. The NNI will expand this powerful model to bring together the international community in specific areas of worldwide interest.

The use of nanotechnology-enabled vaccines and diagnostics to help address the current global pandemic clearly illustrates the power of small science. Nanotechnology can play a role in fighting disease, combatting climate change, cleaning water, increasing food production, and tackling many other global concerns. The NNI will establish a new mechanism, National Nanotechnology Challenges, to mobilize and connect the nanotechnology community to help address critical issues. Nanotechnology researchers working in these areas will be connected with broader efforts focused on these issues to accelerate solutions that benefit society.

Building on the experience of the past twenty years of the NNI and reflecting on the current needs of the nanotechnology research and development community, this strategic plan leverages lessons learned and introduces new mechanisms to increase impact in key areas. Utilizing both formal (NSET) and informal (communities of interest) structures, this framework more deliberately builds connections to advance nanotechnology into the future. Furthermore, the mechanisms introduced here provide the agility for the NNI to address new priorities in a rapidly changing world.

Goals & Objectives

Goal 1. Ensure that the United States remains a world leader in nanotechnology research and development.

Objectives:

Enable and advance world-class nanotechnology R&D.

Advance areas of common interest through targeted collaboration among NNI agencies.

Strengthen NNI connections to both existing and newly identified Federal priorities and initiatives.

Focus efforts where nanotechnology can address global challenges.

Promote international collaboration and communication in areas of mutual interest.

At the heart of the NNI is agency support for nanoscale research and development across the entire continuum, from the early stage-research that fuels new discoveries and expands the boundaries of understanding, through applied and use-inspired research, to scale-up and manufacturing. While individual agencies direct and support specific funding programs in pursuit of their respective missions, the strength of the NNI stems from the connections and collaborations that bring these efforts together and build out the entire ecosystem. This strategic plan explicitly strengthens these connections, expands and seeds new focus areas and collaborations, and provides the agility to both nurture and easily adapt support of the nanotechnology ecosystem to succeed in a rapidly changing world.

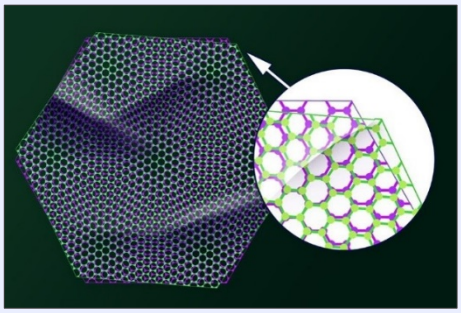
R&D advancements under the NNI have dramatically increased understanding of the nanoscale world, and have resulted in the creation of completely new scientific disciplines like nanophotonics and twistronics (see call out box below). Advances in nanomedicine and nanoelectronics contribute to Americans' daily lives, health, and national and economic security, and are just two powerful examples of how nanotechnology research has driven progress in areas vital to the Nation. At the launch of the NNI, targeted drug delivery for cancer treatment was one of the major medical applications envisioned. Now, cancer nanomedicine is a dynamic and robust research area, and nanomedicine has expanded broadly to include efforts in tissue engineering, regenerative medicine, infectious disease, genome sequencing, dental and craniofacial treatments, cardiovascular diseases, sensors for health monitoring, and many other areas. Nanomedicine has also matured to the point of bringing treatments to patients, with 70 nanotechnology-enabled drug products approved by FDA.[20] Nanoelectronics was another area that was expected to have a high impact at the inception of the NNI. Strategic investments and partnerships from the NNI agencies have pushed the research far beyond the march of Moore's Law to exploring new state variables, leading to areas such as spintronics, and developing innovative devices and architectures that can only be achieved with nanomaterials.[21] Further, advances in nanoelectronics and nanomaterials have enabled the current era of wearable and flexible electronics that contribute to the Internet of Things and to new, high-performance three-dimensional printable aerospace alloys that enable the fabrication of topologically optimized components. While these advances have been transformative to their respective fields, the promise of nanotechnology is just

[20] U.S. Food and Drug Administration, 2020. *Nanotechnology—Over a Decade of Progress and Innovation:* https://www.fda.gov/media/140395/download.

[21] https://spectrum.ieee.org/nanoclast/semiconductors/devices/first-3d-nanotube-and-rram-ics-come-out-of-foundry

beginning to be realized. The NNI will continue to support the innovative research that will drive the next generation of scientific breakthroughs and technological advances for the benefit of all people.

Physics "Breakthrough of the Year" leads to the development of the new field of twistronics



Two sheets of graphene are stacked together at a slightly offset "magic" angle, which can impart either insulating or superconducting properties. Credit: José-Luis Olivares, MIT.

Advances in the ability to manipulate matter on the nanoscale are generating new and exciting breakthroughs and have even led to the evolution of an entirely new field, "twistronics." Twistronics is the study and application of novel properties of magic-angle twisted bilayer graphene (MATBG) and other bilayer and multilayered two-dimensional (2D) materials systems. In 2018, researchers were awarded the Physics World Breakthrough of the Year award[22] and in 2020 the American Physical Society Oliver E. Buckley Condensed Matter Physics Prize[23] for demonstrating high-temperature superconductivity in two layers of graphene laid on top of each other at an angle of precisely 1.1 degrees (the magic angle). Since this discovery, researchers have continued to explore the unique properties of twisted bilayer graphene and other 2D materials. To date research groups supported by NSF, the Air Force Office of Scientific Research (AFOSR), the Army Research Office, the Office of Naval Research, and DOE have: developed a new method to finely tune MATBG to induce superconductivity by applying pressure, demonstrating that squeezing the layers has a similar effect as twisting them;[24] observed unexpected insulating phases in MATBG;[25] and demonstrated that dispersion- and diffraction-free propagation is possible, with a resolution that beats the diffraction limit by more than an order of magnitude, in twisted layers of 2D molybdenum trioxide.[26] These discoveries have a broad spectrum of potential applications including quantum computing and other information technologies, and ultrasensitive photodetectors. Twistronics research is advancing fundamental understanding of materials and will likely lead to the discovery of additional exotic properties.[27]

Collectively, the Goal 1 objectives provide a balanced approach for advancing the interdisciplinary foundational research that will lay the groundwork for future technologies, while also catalyzing strategic collaborations and activities in priority areas. The Federal nanotechnology portfolio is broad, with a wide range of materials, disciplines, and application areas, as well as the full spectrum of technology maturity levels. This broad approach ensures that progress in many areas continues unabated, while also supporting the high-risk/high-reward research that can provide breakthrough technical capabilities. The NNI agencies utilize their respective authorities to support programs and mechanisms for single investigators, multi-investigator awards, centers, institutes, networks, and collaborative activities.[28] World-class research is best supported by a highly trained and diverse

[22] https://physicsworld.com/a/discovery-of-magic-angle-graphene-that-behaves-like-a-high-temperature-superconductor-is-physics-world-2018-breakthrough-of-the-year/

[23] https://www.aps.org/programs/honors/prizes/prizerecipient.cfm?last_nm=Jarillo-Herrero&first_nm=Pablo&year=2020

[24] M. Yankowitz et al., 2019. Tuning superconductivity in twisted bilayer graphene. *Science* **363**, 1059-1064: https://doi.org/10.1126/science.abb8754.

[25] K.P. Nuckolls et al., 2020. Strongly correlated Chern insulators in magic-angle twisted bilayer graphene. *Nature* **588**, 610-615: https://doi.org/10.1038/s41586-020-3028-8.

[26] https://physicsworld.com/a/twistronics-for-photons-brings-tunable-diffraction-free-light-rays/

[27] https://physicsworld.com/a/magic-angle-graphene-doubles-up/

[28] See the annual NNI Supplement to the President's Budget for a more detailed reporting for funding programs, priorities, and progress. The fiscal year 2021 report is available at https://www.nano.gov/2021budgetsupplement.

workforce, and the NNI will place an increased emphasis on activities like NASA's MSI Fellowships program[29] that promote opportunities in all of America, particularly for people in communities that have traditionally been left behind.

The unique phenomena exhibited at the nanoscale can fuel progress across a breadth of priority technology and applications areas. The NASEM committee observed that "*…nanotechnology has been, and will continue to be, a highly interdisciplinary field of research (indeed, arguably the most interdisciplinary), with many discoveries and inventions awaiting. The early work has now advanced to a stage where nanotechnology is underpinning a rapidly growing range of economically important applications, including nanoelectronics, displays, catalysts, ultra-strong materials, energy storage, drug delivery systems, and so on, and is making important contributions to the technologies that underpin U.S. national security.*"[30] The COVID-19 pandemic has further demonstrated that nanotechnology can also play an indispensable role in addressing societal challenges. Strategies to rapidly advance progress in these high-impact-potential areas will include enhanced Federal coordination—both within the NNI and with synergistic activities and initiatives—and targeted activities to mobilize the nanotechnology community in pursuit of common goals.

Given the role that nanotechnology can play in supporting the industries of the future and providing the solutions to societal challenges, nanotechnology is an area of intense interest and activity around the world. Engaging internationally, from government-to-government conversations to researcher-led collaborations, can advance many of the NNI's research priorities and support U.S. foreign relations. For example, the Community of Research model has been a powerful tool that brings the research community together to support pre-competitive progress in priority areas by sharing best practices, developing standards, and facilitating international exchange. Representatives from the NNI also participate in and lead a wide variety of other international activities, from bilateral dialogues to multilateral engagements (e.g., through the Organisation for Economic Co-operation and Development or standards developing organizations) to building relationships with nanotechnology-focused organizations around the world. The NNI will prioritize continued collaboration with allies and partners in areas of mutual interest to advance nanotechnology and shared values while ensuring that the principles of research security[31] and integrity are embraced throughout the nanotechnology community.

The NNI's overarching strategy to ensure that the United States remains a world leader in nanotechnology research and development features support for a broad nanotechnology research portfolio that fuels new discoveries as well as the formation of strategic collaborations to build on this foundation and enable rapid progress in high-priority areas. Within the NNI, communities of interest will take lessons learned from the NSIs to support interagency discussion, stakeholder engagement, and the development of activities focused on specific nanotechnology topics such as nanosensors or the environmental implications of incidental nanoplastics. While the NNI has historically collaborated with other Federal activities, deliberate efforts to strengthen connections will include the establishment of Strategic Liaisons to bridge communities and leverage related activities. For example,

[29] https://nspires.nasaprs.com/external/solicitations/summary.do?solId=%7B636A2034-47D4-8664-8510-709E246A3BA6%7D&path=&method=init

[30] National Academies of Sciences, Engineering, and Medicine, 2020. *A Quadrennial Review of the National Nanotechnology Initiative: Nanoscience, Applications, and Commercialization.* Washington, DC, The National Academies Press: https://doi.org/10.17226/25729.

[31] National Science and Technology Council, 2021. *Recommended Practices for Strengthening the Security and Integrity of America's Science and Technology Research Enterprise*. Washington, DC.

there are strong intersections among nanotechnology, quantum information sciences, microelectronics, and information technologies. The newly formed NSTC Subcommittee for Microelectronics Leadership is co-chaired by the NNCO Director. The directors of the Networking and Information Technology Research and Development National Coordination Office and the National Quantum Coordination Office are members of the Subcommittee, and staff support for the Subcommittee is provided by members of each of the coordination offices. In this case, the directors of the coordination offices serve as liaisons between the initiatives. For the incorporation of IDEA principles and practices across the nanotechnology community, the NNI will identify an IDEA Liaison to interface with the Federal groups leading the government-wide conversations about how to best improve IDEA in STEM to implement the latest opportunities and practices within the nanotechnology community. The establishment of Strategic Liaisons will further strengthen ties and ensure that the NNI is well aligned with Administration priorities.

Applying nanomedicine lessons to agriculture

Advances in one field of nanotechnology can inform creative solutions in other fields, emphasizing the importance of building a broad and robust nanotechnology research community. For example, discoveries in nanomedicine and precision drug delivery for cancer treatment have led to the development of novel nanotechnology-enabled pesticide delivery systems. These pesticide nanocarriers can maximize the efficacy of the pesticide while minimizing the environmental impact of agrochemicals, just as nanomedicine drug formulations help avoid systemic toxicity of certain drug formulations.

"We're taking concepts we've learned from nanomedicine, where we're developing nanoparticles for targeted drug delivery, and applying them to agriculture" (Professor Nicole Steinmetz). Credit: David Baillot/UC San Diego Jacobs School of Engineering.

Traditional pesticide formulations require the input of a high volume of pesticide to control pests deep in the soil, releasing pesticide as runoff into surrounding ecosystems. Scientists at the University of California-San Diego are using lessons learned from nanomedicine to leverage a nanoparticle found in nature, tobacco mild green mosaic virus, as a pesticide nanocarrier. This pesticide nanocarrier system can carry a small amount of pesticide deep into the soil and deliver it to its intended target, while minimizing the effect on its surrounding environment. The virus is also safe for most plants and can only be transmitted by physical contact between plants. After testing different nanocarriers with different shapes and chemical formulations, the researchers found that nanocarriers with skinny, tubular shapes and diverse surface chemistry, such as the tobacco mild green mosaic virus, can more easily navigate through the soil, which is similar to what is observed with nanocarriers for medical applications. This work was supported by NSF, NIH, and USDA's National Institute of Food and Agriculture (NIFA).

As introduced above, the NNI is launching a new mechanism, National Nanotechnology Challenges (NNCs), to mobilize the nanotechnology R&D community and connect it with broader efforts addressing significant world challenges (e.g., pandemic response, climate change, etc.). The NNI will work with the community to identify high-impact NNC topics. NNI agencies will use their respective authorities and programs to support research and development in these areas, and NNCO will convene and foster collaborative activities and deliberately connect the nanotechnology community to synergistic efforts in each of the NNC areas.

In the international arena, the NNI agencies and NNCO leadership will strengthen engagement with international counterparts and nanotechnology-focused organizations to share information, learn

from each other, and monitor emerging trends. The Standards and Global Issues Coordinators will serve as the NNI points of contact in their respective areas, coordinate relevant activities across the NNI, keep abreast of developments, and provide regular updates to the Federal NNI community. Building on the success of the nanoEHS CORs over the last decade, NNCO will continue to facilitate these groups and will expand the COR model to other areas as appropriate.

Select Federal actions that support Goal 1:

- NNI agencies will utilize and leverage their full authorities to support and conduct nanotechnology research and development including single-investigator and multi-investigator awards, centers and networks, and public-private partnerships.
- NNI agencies will support long-term advancements by sustaining core programs that include support for nanoscience.
- The NNI will establish and facilitate communities of interest to support interagency collaboration in targeted areas, including sensors and water.
- The NNI will identify Strategic Liaisons to explicitly connect with related Federal activities. The Strategic Liaisons will be named in the annual NNI Supplement to the President's Budget.
- The NNI will identify Coordinators to facilitate interagency collaboration in their respective areas, including Standards and Global Issues. The Coordinators will be named in the annual NNI Supplement to the President's Budget.
- The NNI will launch National Nanotechnology Challenges to mobilize the community to address global issues.
- NNCO will facilitate and expand the international Community of Research model.
- NNCO will convene and connect the nanotechnology community through targeted workshops, webinars, and embedded programs in conferences where the community gathers.
- NNCO will promote opportunities for and share highlights from the nanotechnology research and development community.

Opportunities for the NNI community to participate and engage:

- The NNI community is welcome to participate in and advance the Communities of Research and National Nanotechnology Challenges.
- The NNI community is encouraged to share highlights and accomplishments with NNCO and the broader public.

Goal 2. Promote commercialization of nanotechnology R&D.

Objectives:

Train, strengthen, and support the nanotechnology entrepreneurship community.

Engage with and enhance connections among regional innovation ecosystems to support nanotechnology commercialization in every part of the country.

Raise awareness of and coordinate Federal activities that support later stages of the technology development pathway.

Establish and expand public-private partnerships in targeted areas.

Highlight the significance of nanotechnology in the market.

The translation of nanotechnology innovations has had a profound effect on society and the economy, from the vivid displays that inform and entertain to the lipids that deliver life-saving medicine. For example, nanotechnology emerged as a key tool in the fight against COVID-19. Innovators are

leveraging decades of investments in nanotechnology research to develop vaccines and other prophylactics, diagnostics and surveillance tools, therapeutics, disinfectants and coatings, and protective equipment.[32] Continued nanotechnology innovations will help America build back better. Nanotechnology will contribute to vehicle batteries that charge faster and run longer, building and construction materials that save energy and are produced with a smaller CO_2 footprint, and various applications in water filtration, sensing, and pollution mitigation.

As recommended by the NASEM committee, the NNI and participating agencies will place a renewed emphasis on activities that promote nanotechnology commercialization. Taking basic research to commercialization has to be intentional. It requires strong interfaces between academia, where the seeds of innovation are conceived, and industry, where the benefits of new technologies are reaped when they change the way we live. This phase of technology maturation can take time. The Federal Government has many mechanisms available to support companies along the entire nanotechnology development pathway, including setting research priorities, providing funding, supporting infrastructure, and providing technical expertise, regulatory guidance, and health and safety leadership. The Goal 2 objectives articulate a cohesive framework that will empower American workers and businesses by providing essential resources and fostering effective collaborations and partnerships. As discussed in more detail below, the NNI will leverage synergies with the Manufacturing USA institutes. The efforts outlined here align with the goals of the Strategy for American Leadership in Advanced Manufacturing.[33]

The NNI will continue to catalyze and facilitate interagency collaboration to support later stages of the nanotechnology development pathway in high-priority areas of mutual interest. As specific needs are identified, the NNI will establish "Tiger Teams" to rapidly assemble and address challenges by, for example, producing a technical roadmap or other relevant output. This mechanism will allow NNI agencies to work together to quickly identify key R&D gaps and the means to address them.

Entrepreneurs play a critical role in the nanotechnology ecosystem, nurturing ideas and bringing them to market. The NNI agencies provide a host of training opportunities to help entrepreneurs, including I-Corps,[34] NIH's Concept to Clinic: Commercializing Innovation Program,[35] and entrepreneurship activities associated with the DOE National Labs such as Cyclotron Road.[36] Many colleges and universities now offer courses or training programs in entrepreneurship, including efforts focused on nanotechnology.[37] The NSF-funded NNCI has recently expanded these efforts in nanoentrepreneurship and added an Associate Director focused on this effort to provide opportunities across all of America. In addition to these training programs, opportunities for internships in small companies and start-ups could provide valuable experience to students interested in following this path. While entrepreneurs growing nanotechnology businesses face the same challenges all entrepreneurs face, they may encounter some issues unique to nanotechnology, such as a need to access expensive tools or safe handling procedures for nanomaterials. To share resources and best practices from those who have successfully traversed the nanotechnology development pathway, NNCO facilitates the Nanotechnology Entrepreneurship Network. The NNI will support the nanotechnology

[32] E.V.R. Campos et al., 2020. How can nanotechnology help to combat COVID-19? Opportunities and urgent need. *Journal of Nanobiotechnology* **18**, 125: https://doi.org/10.1186/s12951-020-00685-4.

[33] National Science and Technology Council, 2018. *Strategy for American Leadership in Advanced Manufacturing*. Washington, DC.

[34] https://www.nsf.gov/news/special_reports/i-corps/

[35] https://www.nibib.nih.gov/research-program/c3i-program

[36] https://cyclotronroad.lbl.gov/

[37] For example, the Nanotechnology Entrepreneurship Challenge program at Virginia Tech: https://vtx.vt.edu/articles/2018/03/ictas-nanoentrepreneurs.html.

entrepreneurship community—engaging broadly across racial, gender, economic, and geographical lines—and will focus on expanding activities and growing this network.

Effectively navigating the nanotechnology development pathway requires a diverse set of resources, from funding to access to appropriate instrumentation to regulatory guidance. Nano.gov has been expanded to provide additional information for industry, highlighting many resources in each of these areas, including current intelligence bulletins and targeted content from regulatory agencies. NNI agencies offer a broad portfolio of funding opportunities that support later-stage development and transition to the market. For example, the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs[38] serve as America's seed fund and encourage domestic small businesses to engage in Federal R&D with the potential for commercialization. Other programs the agencies use to meet their mission needs and support the community include NSF's Partnerships for Innovation Program,[39] the DOE Technology Commercialization Fund,[40] and the Defense Production Act Title III.[41] The NNI will explore expanding the use of additional, agile funding mechanisms such as Other Transactional Authority, government-funded venture capital, and associated foundations. The establishment of a Lab2Market Liaison will help connect the nanotechnology community with the broad array of Federal programs that support the commercialization of advanced technology.

Saving energy and reducing carbon emissions with nanotechnology-enabled smart windows

Building with nanotechnology-enabled smart glass windows in New York City. Credit: View, Inc.

Smart windows are an example of nanotechnology in commercial applications that are making a difference at scale. Residential and commercial buildings are responsible for roughly 40% of U.S. energy consumption.[42] Enhancing building energy efficiency has the potential to significantly decrease CO_2 emissions. Researchers supported by the DOE's National Renewable Energy Laboratory have developed a nanofilm that can be incorporated into windows made of electrochromic nanomaterials that can absorb or deflect sunlight.[43] By transmitting the sun's rays (infrared energy) indoors in colder months and deflecting it in warmer months, dynamic windows provide an energy-efficient solution to managing internal building temperatures and reducing energy consumption by up to 20%. A Cornell study found that electrochromic windows also reduced headaches, drowsiness, and eyestrain by 63, 56, and 51%, respectively.[44] Nanotechnology-enabled windows have been installed in the Dallas (DFW) and Atlanta (ATL) airports and new buildings in New York City, Boston, and Las Vegas in addition to a host of other buildings across the Nation.

The maturation of nanotechnology into end-products or as intermediates of other technologies is a complex undertaking, often requiring sophisticated equipment and technical expertise that can be found in an ecosystem anchored by research institutions, high-technology companies, and/or Federally

[38] https://www.sbir.gov/
[39] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504790
[40] https://www.energy.gov/technologytransitions/technology-commercialization-fund
[41] https://www.businessdefense.gov/Programs/DPA-Title-III/
[42] https://www.eia.gov/tools/faqs/faq.php?id=86&t=1
[43] https://view.com/product/how-it-works
[44] https://view.com/sites/default/files/documents/research-brief-daylight-and-the-workplace.pdf

funded user facilities. As discussed in Goal 3, the NNI supports nanotechnology user facilities that provide researchers and industry with access to tools and equipment for the fabrication and characterization of nanomaterials and devices. Networks of facilities supported by NSF and DOE are distributed across America. At later stages of development, testbeds and prototyping facilities can become a critical need. For example, the facilities required to transition from "lab to fab" in advanced electronics have been highlighted in recent legislation.[45] The NNI will pursue opportunities, in collaboration with the private sector as appropriate, to develop and provide access to advanced prototyping facilities for nanotechnologies and nanotechnology-enabled devices and systems.

Strategic collaborations to advance nanotechnology commercialization

The Manufacturing USA Institutes play an important role in the advanced manufacturing ecosystem. Manufacturing USA is a national network of institutes created to secure U.S. global leadership in advanced manufacturing through large-scale public-private collaboration on technology, supply chain, and workforce development. The 16 manufacturing innovation institutes are facilitating innovation and commercialization by bringing together member organizations from manufacturers of all sizes, academia, and government to work on major research and development projects relevant to industry, and to train people in advanced manufacturing skills. Each site has a unique technological concentration, several of which intersect with nanotechnology. For example, an AFOSR-sponsored team utilized AIM Photonics[46] facilities to fabricate a silicon photonics-based 2-bit comparator that outperforms the current transistor-based electronic comparators in terms of both computational speed and power efficiency.[47] In support of Goal 2, the NNI plans to more deliberately engage with Manufacturing USA and facilitate connections between the institutes and resources, such as the National Nanotechnology Coordinated Infrastructure, that support industry's earlier-stage fabrication and characterization needs.

Researchers inspect a sample in a cleanroom. Credit: NextFlex.

There are many activities to support the commercialization of advanced technologies, both within the Federal Government, including those mentioned above, and across external organizations. It is imperative that the NNI forge stronger ties to these activities to ensure that the latest opportunities and resources from across the technology transfer communities are shared with nanotechnology developers. Regional innovation ecosystems are uniquely positioned to foster an interdisciplinary community of developers and serve as accessible resources to support the commercialization of advanced technologies. The NNI will enhance connections among the organizations that contribute to regional ecosystems. For example, NNCO will periodically convene representatives from the NNI user facilities and the Manufacturing USA institutes to facilitate and strengthen connections across these vital communities. Connections will also be established between the NNI and incubators and innovation hubs, melding initiatives put forth by the U.S. Economic Development Administration and local activities where academia, business, and government join to accelerate research and bring breakthrough ideas to market. Particular attention will be given to building connections to and nurturing communities that have traditionally been left behind.

[45] For example, Title XCIX of the National Defense Authorization Act for Fiscal Year 2021 ("CHIPs"), USICA.

[46] https://www.aimphotonics.com/

[47] C. Feng et al., 2021. Toward high-speed and energy-efficient computing: A WDM-based scalable on-chip silicon integrated optical comparator. *Laser & Photonics Review* **15**: https://doi.org/10.1002/lpor.202000275.

Facilitated by the Standards Coordinator, NNI agencies work together on a broad range of nanotechnology standards, which can greatly impact the commercialization of nanotechnology, from unifying terms and facilitating regulatory review and acceptance to developing reference materials and setting performance standards. NNI agencies actively participate and engage with industry and international stakeholders to identify appropriate standards for development through organizations such as the International Organization for Standardization Technical Committee 229, ASTM International Committee E56, and the OECD Working Party on Manufactured Nanomaterials. The NNI will conduct targeted outreach to help make American businesses aware of opportunities to participate in standards activities that will shape their industries.

Public-private partnerships can be effective mechanisms to leverage knowledge and resources and generate commercialization pathways. These collaborative programs provide funding agencies with valuable insights into industry's needs. NNI agencies have a rich history of establishing partnerships to advance development in specific areas, including nanoelectronics (e.g., the Nanoelectronics Research Initiative and the Joint University Microelectronics Program) and cellulosic nanomaterials (P^3Nano). PPPs bring together researchers and developers actively working on a specific topic with constant communication of new discoveries and needs, creating a virtuous loop of fundamental and applied research to accelerate innovation. Furthermore, PPPs can give students the opportunity to learn how industry approaches research, providing a valuable training path for the future R&D workforce. The NNI will continue to use this mechanism in targeted application areas.

The NNCO Industry and Regional Liaison (IRL) will foster relationships with and serve as a resource for the commercialization community by providing information on Government resources, including funding mechanisms, nanoEHS best practices, and regulatory authorities and processes. Further, the IRL will track industry trends and communicate successes, needs, and concerns with the Federal community. The NNI will engage with organizations that support science and technology hubs in every part of the country to ensure that nanotechnology innovators from all backgrounds and groups can access the resources they need to be successful.

While nanomaterials are already being used in a wide range of everyday items and advanced applications, such as medical devices, environmental sensors, window coatings, lightweight materials, and even in space, the role of nanotechnology and the impact of past NNI investments is often not clear to stakeholders. The NNI will enhance efforts to share how Federal investments lead to innovative nanotechnology-enabled products that impact Americans and help address global challenges. NNCO will work with NNI agencies and external entities as appropriate to identify and better highlight NNI success stories.

Select Federal actions that support Goal 2:

- NNI agencies will use their respective authorities to support translational research and small businesses through programs such as SBIR, STTR, etc.
- NNI agencies will continue and establish new public-private partnerships in high-priority technical areas to accelerate commercialization.
- NNI agencies will support research development and demonstration projects to advance nanotechnology applications.
- NNI agencies will explore innovative and more agile funding mechanisms to support nanotechnology commercialization.
- NNI agencies will utilize boot camps and other programs to provide education and awareness of opportunities for entrepreneurs.

- The NNI will establish and support "Tiger Teams" to rapidly address specific development or application challenges and/or develop technical roadmaps.
- The NNI will identify a Lab-to-Market (L2M) Liaison and engage fully with the NSTC L2M Subcommittee.
- NNCO will establish and facilitate a network that brings together regional nanotechnology efforts.
- NNCO will enhance and expand the Nanotechnology Entrepreneurship Network.
- NNCO will identify an Industry and Regional Liaison who will engage and share resources with the nanotechnology development community.
- NNCO, in collaboration with NNI regulatory agencies, will develop and disseminate resources to the nanotechnology development community on how to navigate the regulatory process.
- NNCO will develop and share informational packets regarding nanotechnology resources for small and medium-sized enterprises with regional innovation organizations, including the Manufacturing Extension Partnerships.
- NNCO will periodically convene representatives from NNI user facilities and Manufacturing USA institutes to better enable the seamless transition of technologies among facilities along the technology development pathway.
- NNCO will convene and connect the nanotechnology development community through targeted workshops, webinars, and embedded programs in conferences.
- NNCO will promote opportunities for the nanotechnology development community and share highlights of how nanotechnology is used in commerce.

Opportunities for the NNI community to participate and engage:

- The NNI community is welcome to participate in the Nanotechnology Entrepreneurship Network and regional nanotechnology network.
- The NNI development community is encouraged to share highlights and accomplishments with NNCO and the broader public.

Goal 3. Provide the infrastructure to sustainably support nanotechnology research, development, and deployment.

Objectives:

Coordinate Federal efforts that support nanotechnology R&D infrastructure.

Support the development and acquisition of critical nanotechnology infrastructure.

Promote access to nanotechnology research and development infrastructure across America and for all Americans.

Encourage the sharing of nanotechnology data by promoting database interoperability and best practices.

Raise awareness of and facilitate pathways to transition from research user facilities to prototype, testing, and manufacturing resources.

Develop testbeds and prototyping facilities in targeted technology areas.

Provide and promote opportunities for education, training, and workforce development leveraging the specialized nanotechnology infrastructure.

Advances in instrumentation that enable the ability to image and control matter at the atomic and molecular level have opened up the world of nanotechnology. A hallmark of the NNI has been the physical and cyber infrastructure, which not only democratizes nanoscience across the ecosystem but also serves as a platform to educate and train students who will become the next generation of instrument users, designers, and builders.

The NNI agencies have collaboratively and synergistically sought to remove barriers to access critical instrumentation by funding equipment acquisition at institutions across the United States and have established world-class facilities, including networks of user facilities such as the NSF-funded National Nanotechnology Coordinated Infrastructure and DOE-funded Nanoscale Science Research Centers (NSRCs). These user facilities enable researchers from colleges, universities, government labs, and small and large companies to utilize specialized equipment they otherwise would not have access to or be unable to afford. Through the interdisciplinary nature of nanotechnology and shared research environments, the user facilities serve as powerful innovation platforms that bring together diverse researchers and developers and support collaboration.

For example, the Nanotechnology Characterization Laboratory (NCL), established by the NIH National Cancer Institute in concert with FDA and NIST, provides expert staff scientists and multidisciplinary settings to support the translation of nanomedicines from the lab bench to the patient's bedside. Furthermore, facilities that support mid-scale prototype fabrication and testing fill a crucial gap between lab-scale fabrication and mass production. The physical and cyber infrastructure remains an integral piece of the nanotechnology enterprise, and the NNI will continue to expand opportunities to share these resources widely.

The next generation of cutting-edge fabrication, characterization, metrology, modeling, design, simulation, and analysis tools and capabilities will further push the boundaries of understanding of nanoscale phenomena and enable additional groundbreaking scientific discoveries. Funding programs that support the development and acquisition of critical instrumentation, such as the Major Research Instrumentation Program at NSF,[48] are crucial to advancing the frontiers in nanoscale science and engineering research. Beyond access to state-of-the-art tools, updating and maintaining the infrastructure, especially "workhorse" tools like scanning electron microscopes, are vital components to sustaining a world leadership position in nanoscience and nanotechnology.

Data drives the integration of the physical instrumentation and cyber tools (e.g., computational, modeling); these systems, working together harmoniously, can catalyze scientific and technological breakthroughs. Improving the accessibility and quality of data will not only aid this harmonization but will also enhance the integration of artificial intelligence in nanotechnology development. The value of the data generated by both physical instrumentation and modeling tools is multiplied significantly when that data can be shared effectively with researchers beyond the original team. As noted by NIH, "Sharing scientific data helps validate research results, enables researchers to combine data types to strengthen analyses, facilitates reuse of hard to generate data or data from limited sources, and accelerates ideas for future research inquiries."[49] The Materials Genome Initiative has illustrated how access to high-quality data enables the validation of predictive models or provides the necessary inputs

[48] https://www.nsf.gov/pubs/2018/nsf18513/nsf18513.htm

[49] https://osp.od.nih.gov/scientific-sharing/nih-data-management-and-sharing-activities-related-to-public-access-and-open-science/

NNI user facilities advance nanotechnology R&D, innovation, education, and outreach

One of the hallmarks of the NNI is the user facilities that provide researchers and developers access to the critically enabling tools required to create, characterize, and understand nanomaterials and nanotechnology-enabled components, devices, and systems. NNI participating agencies have developed a suite of user facilities that provide unique capabilities for the nanotechnology community, including the NSF-funded National Nanotechnology Coordinated Infrastructure,[50] the DOE-funded Nanoscale Science Research Centers,[51] the NIST Center for Nanoscale Science and Technology NanoFab,[52] the Nanotechnology Characterization Laboratory,[53] and the Network for Computational Nanotechnology (NCN)—nanoHUB.org.[54]

A researcher uses equipment at a DOE Nanoscale Science Research Center. Credit: DOE.

NNCI is a network of 16 university-based nanofabrication and characterization sites, located across the Nation, that provides access to 69 distinct facilities and more than 2,000 tools. These resources are accessed by over 13,000 users annually from 250 U.S. academic institutions, more than 900 small and large companies, and approximately 60 government and non-profit institutions. Researchers from a variety of disciplines and at different stages of the technology development pathway utilize this network. These university-based facilities anchor the surrounding innovation ecosystem and serve as a platform for education and outreach. The NSF investment in the NNCI network has been significantly leveraged with user fees and contributions from university collaborators, industry, local governments, and other Federal agencies. For example, in one year the $16 million NSF investment was leveraged by nearly $44 million in other contributions.

The DOE-funded NSRCs house the most advanced facilities for nanoscience research and employ world-class scientists and experts to help guide and support researchers in experimental design and execution. These facilities are strategically located in DOE National Laboratories and are co-located with other major user facilities such as neutron or synchrotron light sources. Any researcher can apply to use these facilities. Projects are selected via a peer-review process.

The National Cancer Institute, in collaboration with NIST and FDA, established NCL to perform preclinical efficacy and toxicity testing of nanoparticles. NCL serves as a national resource and knowledge base for all cancer researchers to facilitate the regulatory review of nanotechnologies intended for cancer therapies and diagnostics. By providing critical infrastructure and characterization services to nanomaterial providers, NCL accelerates the transition of nanoscale particles and devices into clinical applications.

In addition to the physical infrastructure, the NCN at nanoHUB.org provides over 320 simulation and modeling tools accessible by the entire nanotechnology research community and serves over 1.6 million visitors annually. From the university-based facilities to the National Laboratory-based research centers and the cyber infrastructure afforded by nanoHUB, the combined power of the NNI user facilities fuels a vibrant ecosystem that offers researchers, developers, educators, students, and entrepreneurs access to a suite of critical tools and capabilities.[55]

[50] https://www.nnci.net
[51] https://nsrcportal.sandia.gov/
[52] https://www.nist.gov/cnst
[53] https://ncl.cancer.gov/
[54] https://www.nanohub.org/
[55] For more information on the NNI user facility network, see www.nano.gov/userfacilities.

for simulation.[56] In all cases, efforts to improve database interoperability will further increase the utility of data collected and enable the application of machine learning/artificial intelligence tools that can make effective use of large, complex datasets.

The physical and cyber infrastructure can only be capitalized upon when researchers and developers can access and afford it. Innovators with a promising idea, regardless of geographic location, disability status, and gender, racial, or ethnic identity, should have equitable access to the tools and resources available to bring that idea to fruition. The NNI has intentionally distributed user facilities across all of America; for example, the NNCI sites are located in 17 states and involve 29 universities and other partner organizations. The NNI user facilities also employ innovative access models, such as remote access (e.g., Remote Access Instrumentation for Nanotechnology—RAIN) and traveling laboratories (e.g., the Nebraska Nanoscale Facility's traveling museum), not only to increase access to communities traditionally left behind but also as education and outreach tools. Similarly, NanoHUB provides access to an exceptional range of modeling tools for the entire community.

As technologies mature, innovators need to be able to access the research user facilities and then seamlessly transition to facilities that support later-stage development, such as the Manufacturing USA institutes. When the pathways between research facilities and scale-up and manufacturing facilities are clear and accessible, developers can more easily transition their ideas from the lab to the marketplace. The NNI strives to eliminate barriers to infrastructure utilization by enhancing awareness of available resources and pathways to transition between facilities, and will increase focus on this issue over the next five years.

The breadth of NNI-supported infrastructure enables not only the nanotechnology community but also related disciplines including quantum science, advanced microelectronics, and bioengineering. For example, Figure 2 illustrates how NNCI has supported research across a broad array of high-priority research areas. Coordination and collaboration across the Federal Government is imperative to leverage synergies with related Federal efforts such as the National Quantum Initiative that benefit from similar equipment. Furthermore, the nanotechnology community benefits from and leverages related resources, such as the Materials Research Facilities Network.[57] The Goal 3 objectives build upon the existing infrastructure to enhance and expand an agile, robust, and democratized system, across all of America, that advances nanotechnology R&D, trains the future workforce, and facilitates the commercialization of new technologies.

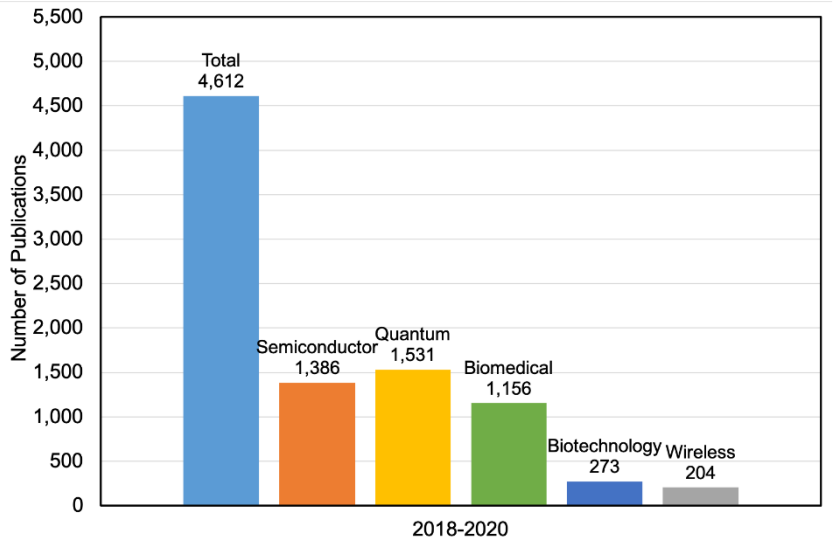


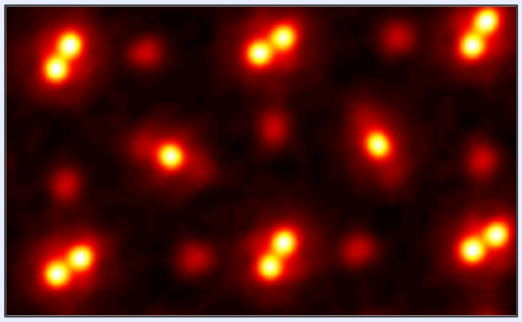
Figure 2. Number of publications between 2018–2020 according to a Google Scholar full text search (performed July 2021) that reference any of the original NNCI award numbers from 2015 and one of the following key words: semiconductor, quantum, biomedical, biotechnology, or wireless. Credit: NNCI Coordinating Office, Georgia Institute of Technology.

[56] https://www.mgi.gov/activities
[57] https://www.mrfn.org/

Deliberate mechanisms, programs, and activities will be employed by the NNI and participating agencies to achieve the overarching vision to build, sustain, and leverage the physical and cyber infrastructure. NNI agencies will use their respective authorities to establish funding mechanisms to replace, maintain, and update "workhorse" tools while also supporting the development and acquisition of new, cutting-edge instruments. The NNI will collect and disseminate best practices for data collection, archiving, and sharing. These efforts will leverage conversations across diverse nanotechnology communities, including the user facilities and relevant Federal working groups, to better address issues such as database management and protection of proprietary information. An Infrastructure Coordinator will facilitate communication and engagement across U.S. Government programs in support of this goal. NNI agencies will work with the private sector as appropriate to establish prototyping and testing facilities in priority applications areas.

Imaging atoms with unprecedented resolution

Researchers from the Kavli Institute at Cornell for Nanoscale Science, the Department of Energy's Argonne National Laboratory, and international collaborators built an electron microscope pixel array detector that set a new world record by doubling the resolution of state-of-the-art electron microscopes.[58] *The detector enables researchers to locate individual atoms in all three dimensions. Thanks to this detector, the resolution of an electron microscope can be so fine-tuned that the only blurring that remains is the thermal vibration of the atoms themselves.*



An electron ptychographic reconstruction of a praseodymium orthoscandate ($PrScO_3$) crystal, zoomed in about 100 million times to a field of view of 1 nm. Credit: Zhen Chen and David Muller, Cornell University.

This scientific advance is the result of 15 years of research, in which the researchers painstakingly improved the performance of the electron microscope, so it can record a wide range of intensities—from detecting a single electron to intense beams containing hundreds of thousands, or even a million, electrons. To ensure that researchers have access to this technology the invention has been licensed to a leading manufacturer of electron microscopes and is also available for use in Cornell's user facility. The university is also home to an NNCI node, the Cornell Nanoscale Science and Technology Facility.

The user facilities will develop and expand innovative access models (e.g., remote access) and target efforts to engage populations that have historically been left behind. To improve accessibility to all stages of the technology development pathway, NNCO will enhance connections among resources, including research user facilities and manufacturing institutes, to facilitate technology transition from the lab to the market. Community engagement efforts will span the entire country, reaching rural and urban areas and leveraging regional innovation hubs, to increase awareness of existing resources and promote access for all of America. As further described under Goal 4, the NNI will leverage the physical and cyber infrastructure to develop essential technical skills and competencies for the future nanotechnology workforce through programs such as NIST Summer Undergraduate Research

[58] Y. Jiang et al., 2018. Electron ptychography of 2D materials to deep sub-ångström resolution. *Nature* **559**, 343–349: https://doi.org/10.1038/s41586-018-0298-5. Z. Chen et al., 2021. Electron ptychography achieves atomic-resolution limits set by lattice vibrations. *Science* **372**, 826–831: https://doi.org/10.1126/science.abg2533.

Fellowship,[59] DOE-hosted summer internship,[60] and NSF-funded Research Experiences for Undergraduates[61] programs.

Select Federal actions that support this goal:

- NNI agencies will utilize their respective authorities to establish and sustain funding mechanisms to replace, maintain, and update "workhorse" (productivity) tools, as well as support the development and acquisition of new, cutting-edge tools.
- NNI agencies will utilize their respective authorities to establish and sustain development of and access to state-of-the-art design, modeling, and simulation tools.
- NNI agencies will work with the private sector to develop and provide equitable access to prototyping and testing facilities in priority application areas.
- NNI agencies will explore mechanisms to provide funds to offset infrastructure access costs.
- The NNI will establish the Infrastructure Coordinator role to ensure that Federal nanotechnology infrastructure activities are aligned and fully leveraged. The Infrastructure Coordinator will be named in the annual NNI Supplement to the President's Budget.
- NNI user facilities will develop and expand innovative access models, including remote access, to provide broader and more equitable access across America.
- NNI user facilities will leverage their infrastructure to develop essential technical skills and competencies of the future nanotechnology workforce and train future tool developers.
- NNCO will enable the seamless transition of research and technology development among facilities, with actions including periodically convening representatives from NNI user facilities and Manufacturing USA institutes.
- NNCO will develop and broadly share information regarding the full suite of NNI infrastructure with research, development, and education communities.
- NNCO will provide and continuously update relevant information about the NNI infrastructure on Nano.gov.

Opportunities for the NNI community to participate and engage:

- The NNI community is encouraged to share infrastructure needs with NNCO.

Goal 4. Engage the public and expand the nanotechnology workforce.

Objectives:

Use nanotechnology to inspire students to pursue science, technology, engineering, and mathematics degrees and career paths.

Provide teacher training and promote access to nanotechnology teaching resources.

Promote and expand opportunities for student research, internships, exchanges, and international experiences.

Provide and promote opportunities for education, training, and workforce development leveraging the specialized nanotechnology infrastructure.

Prepare workers for high-quality jobs in emerging technologies enabled by nanotechnology.

[59] https://www.nist.gov/surf
[60] https://www.energy.gov/eere/education/find-internships
[61] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5517

Expand and diversify the nanotechnology workforce.

Inform and engage with the public on issues related to the science, applications, and implications of nanotechnology.

Science, technology, engineering, and mathematics have been the foundation for discovery and technological innovation throughout American history. The United States' position as a world leader in nanotechnology innovation relies on STEM talent and a highly skilled workforce for every aspect of the R&D continuum. The NNI has supported outreach, education, and workforce development activities as part of its primary goals for the past 20 years, and fostering the growth of a globally competitive and diverse nanotechnology workforce is a strategic objective of the NNI.[62] In recognition of the importance of education, workforce development, and public engagement to the entire nanotechnology ecosystem, these efforts are now a stand-alone NNI goal. The NSTC Committee on STEM Education developed a comprehensive strategic plan that serves as a valuable guide for education and outreach efforts.[63]

A basic understanding of and comfort with STEM and STEM-enabled technology has become vital for full participation in modern society. The wonder of nanoscience and unique nanoscale phenomena can provide the spark to inspire students' deeper interest in STEM topics and career paths. Nanotechnology's potential to provide solutions to pressing societal needs can also be used to attract students motivated to make a difference in their communities. NNI participating agencies employ a broad spectrum of formal and informal programs to nurture students' curiosity and build confidence in STEM and nanotechnology. For example, the NSF-funded NNCI sites sponsor many activities such as open houses and laboratory tours, outreach, contests, and the establishment of age-appropriate nanotechnology content, including *Nanooze*,[64] a magazine designed to get middle school students excited about science and nanotechnology. To further catalyze students' interest in nanotechnology and STEM, the NNI will widely promote and celebrate community-led activities such as National Nanotechnology Day.[65]

Diverse perspectives and approaches are known to spark innovation,[66] and the NNI will focus efforts to build a vibrant interdisciplinary community that reflects the broad diversity of American people from all backgrounds. The NNI and participating agencies will promote just and equitable routes to enter the nanotechnology workforce by engaging with, creating opportunities for, and enhancing retention of people from underrepresented groups—across racial, gender, socioeconomic, physical ability, and geographic lines. For example, NIST scientists and academic collaborators developed and deployed a program to introduce blind and visually impaired students to nanoscale science.[67] USDA/NIFA has encouraged proposals in its higher education programs to build capacity in minority-serving institutions and Tribal colleges and universities. NSF has developed programs to increase

[62] L.E. Friedersdorf, 2020. Developing the workforce of the future: How the National Nanotechnology Initiative has supported nanoscale science and engineering education in the United States. *IEEE Nanotechnology Magazine* **14**, 4: https://ieeexplore.ieee.org/document/9109641.

[63] National Science and Technology Council, 2018. *Charting a Course for Success: America's Strategy for Stem Education*. Washington, DC.

[64] https://www.nanooze.org/

[65] https://www.nano.gov/nationalnanotechnologyday

[66] L. Hong and S.E. Page, 2004. Groups of diverse problem solvers can outperform groups of high-ability problem solvers. *PNAS USA* **46**, 16385-16389: https://doi.org/10.1073/pnas.0403723101.

[67] https://www.nist.gov/news-events/news/2013/09/nist-center-nanoscale-science-and-technology-researchers-introduce-blind

nanotechnology efforts in HBCUs,[68] Hispanic-Serving Institutions,[69] and Tribal colleges,[70] encouraging them to establish and maintain close connections with existing cutting-edge nanotechnology research laboratories and institutions of higher education. Efforts to expand and diversify the nanotechnology workforce will also be pursued through collaborations with organizations that have established trusted relationships with underserved communities, including rural and racial-minority students. Beyond equitable access to STEM education and careers, the NNI and participating agencies will facilitate and enhance efforts to foster inclusive working and educational environments for all nanotechnology students and professionals through programs such as the NSF Louis Stokes Alliances for Minority Participation program, which takes a comprehensive approach to the development and retention of historically underrepresented STEM students.

Inspiring students to pursue STEM by opening their imaginations to the nanotechnology world

Middle school students participating in the 4-H Career Exploration STEM event at Cornell. Credit: Cornell NanoScale Science and Technology Facility.

The NNI-supported National Nanotechnology Coordinated Infrastructure sites at land grant universities have partnered with 4-H[71] to provide nanotechnology learning opportunities to students at the National 4-H Youth Summit. In collaboration with 4-H, the Nebraska Nanoscale Facility invited middle schoolers from 14 schools and programs in Omaha to attend the Engineering with Nano Power program. The students were able to analyze environmental samples using the remote access capabilities of the NSF-funded Remotely Accessible Instruments for Nanotechnology (RAIN) network. In those remote sessions, students were able to use an x-ray fluorescence instrument to understand what the samples are made of, learn why analyzing samples is important, and interact with researchers to understand what nanoscientists do and how to pursue that career path. Every summer, the Cornell NanoScale Science and Technology Facility (CNF) participates in the 4-H Career Exploration, bringing around 500 middle school students across New York State to the Cornell campus to participate in hands-on STEM activities. CNF also supports annual workshops at Cornell for 4-H leaders.

The NNI has supported the development of scores of educational resources, including the physical and cyber infrastructure that provides an unparalleled resource of world-class specialized nanotechnology tools to train the future STEM workforce through authentic and hands-on learning experiences. Programs embedded in the NNI infrastructure, such as NSF's Engineering Research Centers and DOE's National Alliance for Water Innovation, prepare students and workers for high-quality jobs by leveraging cutting-edge tools and industry collaborations and providing students with tangible real-world examples. As discussed in Goal 3, the physical and cyber infrastructure provides interdisciplinary environments that enrich and expand a learner's educational and career journey. For example, the National Cancer Institute Alliance for Nanotechnology in Cancer, in collaboration with Center for Cancer Training, supports Cancer Nanotechnology Training Centers to engage academic researchers and their students in the development of innovative research training opportunities across a broad spectrum of cancer research disciplines and for individuals at all stages of their career development. The NNI will explore opportunities to further leverage the physical and cyber infrastructure to expand research capacity and advance training and workforce development programs.

[68] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5481
[69] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505512
[70] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5483
[71] https://4-h.org/

Immersive educational experiences provide opportunities for students to work with a broad array of people and cultures across geographical lines and institution types while also developing the skills to excel in a wide range of environments. NNI agencies employ internship, fellowship, and international exchange programs to provide immersive research and real-world experiences for students. For example, NSF provides both domestic and international research experiences for undergraduate students.[72,73] America benefits from strategic partnerships that align what is taught and learned with what is needed at work and in the community. Partnerships across academia, industry, and government, such as NASA's Established Program to Stimulate Competitive Research,[74] facilitate industry internships to expose STEM students to business and commercialization pathways while also preparing them for high-quality jobs. Cross-sectoral training and educational partnerships also provide a mechanism to strengthen communication across academia, industry, and government and better communicate industry needs with training and education programs. In addition to research training, the NSF Skills Training in Advanced Research & Technology program[75] provides technical training for a critical segment of our STEM-capable workforce, technicians. The NNI will leverage collaborations with internal and external entities to provide robust training opportunities and equip students with the necessary tools to successfully enter the nanotechnology workforce.

Educators play a foundational role in sparking students' curiosity and equipping them with the tools to be engaged, life-long learners. The NNI agencies provide a wealth of educational resources and training materials for teachers that can support K-12 nanotechnology curriculums. NSF has supported a series of workshops on nanoscale science and engineering education to develop educational resources for K-12 teachers. These resources formed the basis for a searchable database now available on nanoHUB, which also includes lesson plans and demonstrations developed through the NSF Research Experiences for Teachers[76] program. Although the NNI and participating agencies have developed thousands of resources for K-12 teachers, crowded curricula with competing topics make it challenging for teachers to prioritize nanotechnology content. The NNI strives to provide accessible and easy-to-use nanotechnology examples for teachers to excite students about nanotechnology and STEM broadly. The NNI will engage with educators where they already convene by participating in teacher association meetings and conferences. NIST has included nanotechnology as a topic at its annual Summer Institute for Middle School Science Teachers.

Public trust in nanoscience and technology is critical for the potential of nanotechnology innovations to be realized. The NNI and participating agencies will promote trust and transparency by sharing information on scientific advances and applications, as well as the potential environmental, health, and safety implications of nanotechnology. Podcasts are one way to share nanotechnology stories and information. NNCO produces three podcast series—*Stories from the NNI, Nanotechnology Entrepreneurship Network,* and *NanoMatters*—that target researchers, entrepreneurs, and the general public.[77] The NNI will collaborate with media organizations and social media content creators to develop programming that highlights the impact nanotechnology has on everyday life. Existing communication platforms such as webinars and Nano.gov, as well as informal educational experiences, also will be utilized to share information with the public and targeted audiences.

[72] https://www.nsf.gov/crssprgm/reu/
[73] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505656
[74] https://www.nasa.gov/stem/epscor/home
[75] https://www.nsf.gov/pubs/2021/nsf21076/nsf21076.jsp?WT.mc_id=USNSF_25&WT.mc_ev=click
[76] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505170
[77] https://www.nano.gov/podcast

Revolutionizing micro- and nanotechnology technician education

An NSF-funded program is helping revolutionize micro- and nanotechnology technician training by aligning industry needs with training and education curriculum development. An industry-wide Semiconductor Workforce Certification Program building on the U.S. Department of Labor competency model is being piloted at 16 technician education programs at two-year and four-year colleges, technical high school programs, and with newly transitioned veterans at Fort Drum, NY. The pilot program will then be expanded to Oregon and North Carolina. Industry helps develop talent competency models based on skills needed by the semiconductor and advanced manufacturing industries. SUNY Polytechnic uses that information to build course curriculum for community colleges and mechatronics programs. Participating students receive a technician certification. By the end of the pilot project, the organizers expect that approximately 400 students will have completed their technician certification. This technician training approach can serve as a model in other industries.

Veterans participating in an NSF-funded Northeast Advanced Technological Education Center workshop, part of the SEMI Works-SUNY Poly program. Credit: Kathleen Alcott, SUNY Poly.

The NNI will leverage Federal activities and work within the framework articulated by the NSTC STEM strategic plan. The Goal 4 objectives provide a holistic approach to enhance educational efforts at all educational levels, by growing, strengthening, and diversifying the STEM talent pool, supporting educators, and engaging members of the public where they are. The NNI will support and invigorate outreach and education efforts by amplifying the reach of new and existing activities, broadening collaborations with relevant organizations, and leveraging existing social media campaigns (e.g., #BlackInScience). Advances in virtual learning will be leveraged to remove geographical barriers and expand outreach. The NNI agencies also will enhance existing and develop new higher education, technical, retraining, and veteran training programs that support the expansion of U.S. industries, enabling the Nation to build back better. Early teacher engagement will be encouraged to ensure that new educational materials are tailored to classroom and teacher needs. An Education Coordinator will be identified to coordinate activities and resource development with other Federal activities.

Select Federal actions that support Goal 4:

- NNI agencies will use their respective authorities to support education, training, and outreach opportunities, including targeted efforts for veterans and underrepresented communities.
- NNI agencies will support, promote, and advance immersive educational experience opportunities and leverage the NNI infrastructure to provide hands-on training opportunities.
- NNI agencies will pursue opportunities for collaborative workforce development and training activities. STEM engagement at NASA could serve as a model for such programs.
- NNI agencies and NNCO will collaborate with relevant organizations to expand the reach of and leverage activities to inspire students and enhance diversity of the nanotechnology workforce.
- The NNI will establish an Education Coordinator to facilitate collaborative activities and resource development with other Federal activities. The Education Coordinator will be named in the annual NNI Supplement to the President's Budget.

- NNCO will work with academia to support networks for students (e.g., NextTech[78]) and teachers.
- NNCO will promote awareness of nanotechnology-related educational resources, including through a centralized database on NanoHUB and at venues where teachers already gather.
- NNCO will actively promote opportunities and raise awareness of resources among underrepresented communities through collaboration and engagement with relevant organizations. See the IDEA call-out box on page 5 for additional information.
- NNCO will highlight nanotechnology advancements, applications, and implications through varied communication and outreach mechanisms, including National Nanotechnology Day.
- NNCO will develop and distribute engaging information about nanotechnology through a variety of mechanisms, including podcasts, webinars, newsletters, infographics, presentations, social media, and dynamic content on Nano.gov.

Opportunities for the NNI community to participate and engage:

- The nanotechnology research community is encouraged to utilize programs such as NSF's Research Experiences for Undergraduates and Research Experiences for Teachers to expand nanotechnology-related opportunities for teachers and students.
- Teachers and students are encouraged to participate in the networks facilitated by NNCO and apply for research opportunities.
- The NNI community is encouraged to share highlights and accomplishments with NNCO and the broader public.

Goal 5. Ensure the responsible development of nanotechnology.

Objectives:

Coordinate Federal activities related to the responsible development of nanotechnology.

Advance and broadly share the scientific understanding of nanoEHS.

Support the incorporation of responsible development principles into the research, development, and commercialization of nanomaterials and nanotechnology-enabled products.

Encourage incorporation of responsible development principles into education and training programs.

Enhance international engagement in support of the responsible development of nanotechnology.

The responsible development of nanotechnology has been an integral pillar of the NNI since its inception, and the initiative has proactively considered potential implications and technology applications concurrently. This approach was acknowledged in the 2020 NASEM quadrennial review of the NNI, which noted that "*the NNI has performed exceptionally well and is recognized internationally for its leadership in responsible nanotechnology development*." Just as scientific understanding of nanomaterials has deepened and matured since the beginning of the NNI, the understanding of responsible development also has evolved. The responsible development framework articulated in this plan builds on concepts the NNI traditionally included in responsible development—such as nanoEHS considerations to protect human health and the environment and ELSI—and embraces the new ideas that have emerged, including an emphasis on IDEA and the responsible conduct of research. Another

[78] https://www.nexttechnetwork.org/

key facet of responsible development is transparent public engagement to promote trust and equip consumers with the knowledge to make informed decisions.

When taken as a whole, the elements of the responsible development framework underpin each of the NNI's other four goals, and provide a comprehensive foundation to safely and responsibly conduct research and develop products that will drive American prosperity and security. Key topics such as scientific rigor, integrity, and reproducibility are essential components of research excellence. Research integrity is linked to research security, and open environments must be balanced with the protection of intellectual property and the responsible management of U.S. taxpayer dollars.[79] As discussed throughout this document, a more diverse nanotechnology workforce will advance more creative innovation and expand the technical capacity of the United States. Equitable access to resources and inclusive education, training, and funding are key components that facilitate the inclusion of historically marginalized communities across racial, gender, economic, and geographic lines. Product stewardship builds on the foundation of nanoEHS knowledge to evaluate and mitigate potential risks to consumers and the environment across the product lifecycle, facilitating public confidence and technology adoption. Further, the growing emphasis on a circular economy will only intensify the need to better understand and manage product lifecycles.

Sharing nanoEHS lessons learned

The nanoEHS understanding of nanomaterial behavior has vastly expanded over the past 20 years, yet the broader nanotechnology research and development community is often not fully aware of these advances. The NNI Environmental, Health, and Safety Research Strategy, published ten years ago, identified six core research categories, each with detailed research needs. Significant progress has been made in each of these categories, and the current state of understanding is being shared with the broader nanotechnology community through a series of public webinars. The 2021 NNI webinar series, What we know about nanoEHS*, brings together expert panelists to discuss progress on key questions posed in the research strategy and share the state of the science and lessons learned. Recordings of the webinars can be found at* www.nano.gov/publicwebinars.

Selection of panelists in the 2021 NNI webinar series, *What we know about nanoEHS*. Clockwise from top left: John Howard (NIOSH), Janet Carter (OSHA), Greg Lowry (Carnegie Mellon University), Vicki Colvin (Brown University), Gavin West (CPWR), and Patricia Holden (University of California, Santa Barbara). Credit: NNCO.

Strong coordination across the nanoEHS community has been a hallmark of the NNI, with the NEHI Working Group providing an invaluable forum for information sharing, program planning, and flexibly responding to new considerations (e.g., nanomaterial use in additive manufacturing) as they arise. Research efforts have resulted in the development of numerous tools,[80] guidances,[81] and other

[79] National Science and Technology Council, 2021. *Recommended Practices for Strengthening the Security and Integrity of America's Science and Technology Research Enterprise*. Washington, DC.

[80] See, for example, NIOSH's *Controlling Health Hazards When Working with Nanomaterials: Questions to Ask Before You Start* poster: https://www.cdc.gov/niosh/docs/2018-103/default.html.

[81] For example, guidances from FDA are summarized in the 2020 report: *Nanotechnology—Over a Decade of Progress and Innovation*: https://www.fda.gov/media/140395/download.

resources,[82] as well as a robust foundation of knowledge about the properties, transformations, and potential implications of nanomaterials and nanotechnology-enabled products.[83] As nanomaterials become increasingly complex and are more widely incorporated into commercial products, advancing the understanding of nanoEHS and ELSI remains central to responsible development. Core agency programs, such as NSF's Nanoscale Interactions program[84] or NIFA's Agriculture and Food Research Initiative[85] continue to fund this important work. The increasing complexity of forms and media of engineered nanomaterials requires continued focus on advancing tools and capabilities for nanoEHS research, including toxicology, fate and transport, and risk assessment and management. Additionally, efforts to understand and mitigate the impacts of incidental nanomaterials (e.g., nanoplastics) in the environment will be driven by the tools and supported by the EHS knowledge developed for engineered nanomaterials.

Credit: NNCO.

Strategies to support broader responsible development themes will focus on facilitating the incorporation of best practices across the nanotechnology community by leveraging existing activities, sharing information, and providing training opportunities. Many of the issues related to the responsible conduct of nanotechnology research apply across the research enterprise, and it is incumbent on the NNI to coordinate with other Federal activities providing leadership in these priority areas, such as the Scientific Integrity Fast-Track Action Committee.[86] Agency programs to foster diversity, as described throughout this document, can provide the critical resources to support IDEA efforts in the nanotechnology community. The Federal community has created a breadth of responsible development information, training, and best practices, as well as approaches to improving IDEA[87] across the STEM ecosystem. Agency websites on the responsible and ethical conduct of research[88] provide rich resources. Information sharing in support of responsible development extends beyond sharing best practices to include sharing the state of nanoEHS science with the innovation community and transparently communicating the potential risks and benefits of new innovations with the public. Finally, the long-term incorporation of responsible development principles and best practices is supported by widespread and easily accessible training opportunities. NIH[89] and NSF[90] each require that grantees participate in responsible conduct of research training and provide extensive information on example programs and resources.

---

[82] See, for example, NIOSH's *Current Intelligence Bulletin 70: Health Effects of Occupational Exposure to Silver Nanomaterials*: https://www.cdc.gov/niosh/docs/2021-112/pdfs/2021-112.pdf.

[83] L.E. Friedersdorf et al., 2019. Fifteen years of nanoEHS research advances science and fosters a vibrant community. *Nature Nanotechnology* **14**, 996–998: https://doi.org/10.1038/s41565-019-0574-z.

[84] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505696

[85] https://nifa.usda.gov/program/agriculture-and-food-research-initiative-afri

[86] https://www.federalregister.gov/documents/2021/06/28/2021-13640/request-for-information-to-improve-federal-scientific-integrity-policies

[87] For example, NIST's Diversity, Equity, and Inclusion page (https://www.nist.gov/diversity-equity-and-inclusion) or the FDA Diversity And Inclusion Strategic Plan 2018 – 2021 (https://www.fda.gov/media/107939/download).

[88] See, for example, resources available from NIH (https://oir.nih.gov/sourcebook/ethical-conduct/responsible-conduct-research-training), NSF (https://www.nsf.gov/od/recr.jsp), or NIFA (https://nifa.usda.gov/responsible-and-ethical-conduct-research).

[89] https://oir.nih.gov/sourcebook/ethical-conduct/responsible-conduct-research-training

[90] https://www.nsf.gov/bfa/dias/policy/rcr.jsp

Using nanocatalysts to help address the growing problem of plastic waste

Credit: pixabay.com.

Currently in the United States less than 10% of discarded plastics are recycled, but scientists are working hard to develop alternative solutions to the plastics problem. Researchers supported by DOE are exploring two approaches to tackling plastic waste: developing circular plastics and upcycling existing plastics.[91] Circular plastics can repeatedly be broken down into their components and put back together, while upcycling plastic waste turns it into products with high value, such as transportation fuels, waxes, lubricants, or new materials. A 2019 Argonne National Laboratory study utilized a catalyst composed of platinum nanoparticles immobilized on perovskite nanocuboids to bind and break down plastic.[92] In 2020, scientists at the University of California, Santa Barbara demonstrated a low-temperature catalytic method that upcycles polyethylene into high-value alkylaromatic molecules that are the basis of many industrial chemicals and consumer products.[93] The platinum nanoparticle catalyst is combined with alumina to both break down and rearrange the polymer's molecular "skeleton," and the researchers were able to transform almost 70% of a plastic bag into a mixture of liquid and waxes. Catalysts that can convert waste plastics into useful materials will help transition to a more circular economy where one person's waste is another person's feedstock.

International engagement supports all five NNI goals but is particularly valuable when related to responsible development efforts. Areas of mutual interest such as nanoEHS data sharing and protocol development are especially ripe for collaboration as these efforts promote research reproducibility and reliability and fully leverage existing and growing nanoEHS knowledge.[94] NNI agencies have supported international research dialogues on topics such as sustainable nanotechnology,[95] and representatives from across the NNI have actively contributed to nanotechnology conversations through multilateral fora such as the Organisation for Economic Co-operation and Development and the World Health Organization to share resources, explore synergies, and shape the global dialogue. NNCO has established strong relationships with governments and organizations around the world and has supported a robust research dialogue through the U.S.-EU NanoEHS Communities of Research. These efforts will continue to be an important part of the NNI portfolio and will expand as appropriate to address emerging topics of mutual interest.

The NNI will implement a holistic set of activities and mechanisms to support the responsible development of nanotechnology, from supporting the foundational development of knowledge and best practices to sharing information widely and collaborating strategically. The NNI agencies will continue to support fundamental nanoEHS research and the development of new tools. Key nanoEHS

[91] https://www.energy.gov/science/articles/transforming-plastics-recycling-discovery-science

[92] https://www.anl.gov/article/rethinking-the-science-of-plastic-recycling

[93] F. Zhang et al., 2020. Polyethylene upcycling to long-chain alkylaromatics by tandem hydrogenolysis/aromatization. *Science* **370**, 437-441: https://doi.org/10.1126/science.abd4441.

[94] J.J. Scott-Fordsmand et al., 2021. Bridging international approaches on nanoEHS. *Nature Nanotechnology* **16,** 608–611: https://doi.org/10.1038/s41565-021-00912-5. E.J. Petersen et al., 2021. New guidance brings clarity to environmental hazard and behaviour testing of nanomaterials. *Nature Nanotechnology* **16,** 482–483: https://doi.org/10.1038/s41565-021-00889-1.

[95] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1740327

interagency conversations will be facilitated under the NEHI Working Group, and communities of interest will be used as a dynamic mechanism to foster conversations on more targeted topics such as nanoplastics and nanoEHS databases. NNI representatives will work with stakeholders, both domestic and international, to coordinate data-sharing practices and integrate data with cyber tools. The NNI will develop and share best practices, protocols, and nanoEHS information with industry, developers, and entrepreneurs through coordinated efforts with relevant entities, and NNCO will use a variety of outreach mechanisms to broadly share the scientific understanding of nanoEHS with the public and will continually explore new approaches and activities to reach new audiences.

The NNI and NNCO will encourage the incorporation of responsible development principles and practices by sharing the wealth of information and resources from across the Federal Government with the nanotechnology research community. NNI agencies will continue to support training programs so that the researchers driving tomorrow's nanotechnology breakthroughs and technological advances are equipped with a robust understanding of how to advance their work ethically and responsibly.

Select Federal actions that support Goal 5:

- NNI agencies will use their respective authorities to support nanoEHS research, methodology, standards (voluntary and reference), and tool development.
- NNI agencies will enhance IDEA throughout the nanotechnology community with a variety of programs and activities. See the IDEA call-out box on page 5 for additional information.
- NNI agencies will offer programs and resources that support training related to the responsible conduct of research and promote this content to the nanotechnology community.
- NNI agencies and NNCO will disseminate information, resources, and best practices related to responsible development, including nanoEHS.
- The NNI will coordinate Federal nanoEHS activities through the NEHI Working Group.
- The NNI will establish an IDEA Liaison to interface with Federal groups leading these important discussions and share resources, opportunities, and best practices with the nanotechnology community. The IDEA Liaison will be named in the annual NNI Supplement to the President's Budget.
- The NNI will utilize the community of interest model to support interagency collaboration in priority areas, including nanoplastics and nanoEHS database interoperability.
- The NNI will leverage interagency resources and activities to support the data infrastructure, data sharing, and interoperability.
- NNCO will facilitate international nanoEHS Communities of Research to support robust dialogue and collaborative activities that advance shared interests and values.
- NNCO, in collaboration with NNI regulatory agencies, will develop and disseminate resources to the nanotechnology development community on how to navigate the regulatory process.

Opportunities for the NNI community to participate and engage:

- The NNI community is welcome to participate in the international nanoEHS Communities of Research.
- The responsible development community is encouraged to share highlights and best practices with NNCO.
- The nanoEHS community is encouraged to communicate the current understanding of nanoEHS issues with the broader nanotechnology development community.

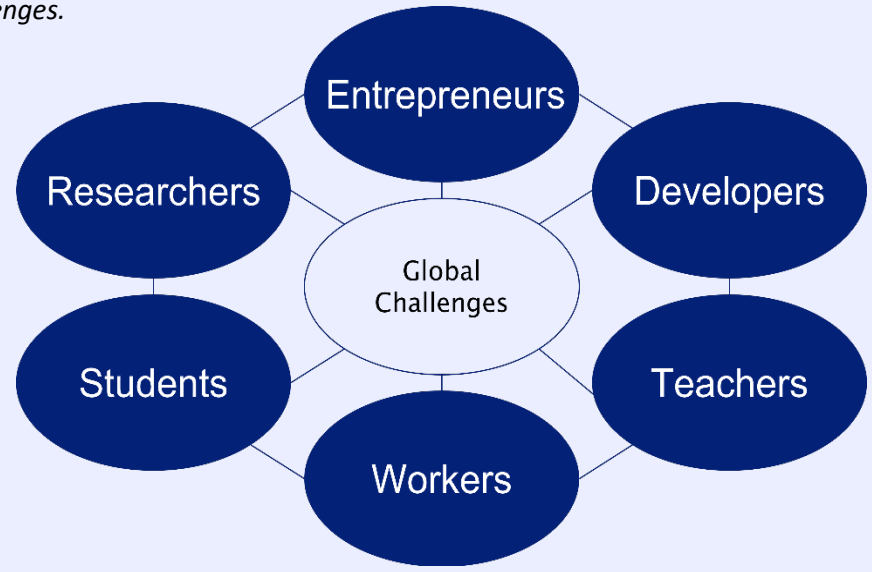
The Path Forward

With the release of the 2021 NNI Strategic Plan in conjunction with National Nanotechnology Day (October 9, to represent the nanoscale, 10^{-9}), the Office of Science and Technology Policy and the NNI agencies are launching the next phase of the National Nanotechnology Initiative. This plan outlines a new framework along with goals, objectives, and actions over the next five years to engage all of America and to ensure that the United States remains not only the place where nanoscience discoveries are made, but also where these discoveries are translated and manufactured into products to benefit society.

The framework presented in this document intentionally connects the many elements of the nanotechnology innovation ecosystem to meet the current and future needs of the nanotechnology community, ensuring that the impact of the NNI is greater than the sum of its parts. The NNI is not just a collection of individual agency activities, but a dynamic and vibrant community that advances the understanding of nanoscience and uses the novel properties at the nanoscale to inspire and educate; develop complex materials, devices, and systems; and address critical global challenges. All are welcome; reach out to NNCO to join the conversation.

Expanding the nanoNE(x)US

A key message expressed throughout the strategic planning process was that the strength of the NNI lies in the broad and innovative nanotechnology community and the rich interdisciplinary research culture that the initiative has nurtured. This plan builds on these strengths and emphasizes efforts to form and expand strategic connections and networks with intention. The NNI will utilize existing activities (e.g., NNI Coordinators) and newly articulated mechanisms (e.g., National Nanotechnology Challenges) to focus efforts from across the nanotechnology ecosystem in pursuit of shared interests and goals. As part of the redesign of Nano.gov and related outreach efforts, the nanoNE(x)US (Nanotechnology Networks Enabling and Empowering (x) across the United States) will be used to communicate the important role of networks in the NNI. For example, the NextTech network empowers students across the United States, or the National Nanotechnology Challenges will enable solutions to global challenges.



Appendix A. 2021 NNI Strategic Planning Stakeholder Workshop Synopsis

Over the past 20 years, the National Nanotechnology Initiative has played a pivotal role in fostering and advancing a dynamic nanotechnology ecosystem and driving significant scientific and technological breakthroughs. To better understand the current and future needs of the community, the NNI organized the virtual 2021 NNI Strategic Planning Stakeholder Workshop: Charting the Path Forward[96] on January 11–13, 2021, to inform the 2021 NNI Strategic Plan. The event convened over 200 representatives from across the nanotechnology community, including academia, industry, the Federal Government, state governments, and non-governmental organizations. The workshop featured plenary panel discussions and breakout sessions to discuss effective approaches to advance research and development, communication strategies, and priority topics for the NNI. Conversations also addressed potential metrics to evaluate research progress. Key themes that emerged from the workshop are highlighted below. The workshop agenda and archived videos are available at www.nano.gov/2021stakeholderworkshop.

Key themes identified by the nanotechnology community:

- The value of bringing the community together was a prominent theme of the event. The NNI plays an important convening role through events such as workshops to improve awareness of opportunities, resources, and best practices.
- Enhanced collaboration among academia, industry, and government can provide powerful educational experiences and opportunities to advance commercialization.
- Educational activities are important for all aspects of the nanotechnology ecosystem, including entrepreneurship, workforce development, and responsible development.
- NNI infrastructure and expertise play an important role in responding to the coronavirus pandemic.
- The NNI infrastructure democratizes nanotechnology R&D, serves as an educational platform, and provides an environment for interdisciplinary research teams.
- Funding for "workhorse" tools and infrastructure support staff is a challenge. The importance of sustained funding for infrastructure was emphasized.
- "Translators" are needed across disciplines and sectors to strengthen communication among various nanotechnology communities and to broaden opportunities.
- A range of high-priority topics were identified, including food, water, environment, and healthcare.

[96] https://www.nano.gov/2021stakeholderworkshop

Appendix B. Strategic Planning Team Members

Affiliations are as of June 2021

Goal 1/World-Class Research

Heather Evans, NIST
Lisa Friedersdorf, NNCO/OSTP
Jaclyn Kellon, AAAS S&T Policy Fellow, NNCO
Antti J. Makinen, DOD
Andrew R. Schwartz, DOE
Seila Selimovic, BARDA
Shahab Shojaei-Zadeh, NSF
Stacey Standridge, NNCO
David M. Stepp, DOD
Xiaojing (John) Zhang, NSF

Goal 2/Commercialization

John Bittman, NIST
Khershed Cooper, NSF
Lisa Friedersdorf, NNCO/OSTP
Chuck Geraci, NIOSH
Ilana Goldberg, NIH
Candi Hudson, DOI/BSEE
Tina M. Kaarsberg, DOE
Jaclyn Kellon, AAAS S&T Policy Fellow, NNCO
Gene E. Lester, USDA ARS
Lynnette Madsen, NSF
Antti J. Makinen, DOD
Elizabeth R. Nesbitt, USITC
World L.-S. Nieh, USDA FS
Anil Patri, FDA
Victor Pugliano, DOD
Dan Ryman, USPTO
Andrew R. Schwartz, DOE
Seila Selimovic, BARDA
Mia Siochi, NASA
Stacey Standridge, NNCO
Treye A. Thomas, CPSC
Tiffany S. Williams, NASA
Xiaojing (John) Zhang, NSF

Goal 3/Physical and Cyber Infrastructure

Jim Burgess, DOD
Lisa Friedersdorf, NNCO/OSTP
Lawrence S. Goldberg, NSF
Jaclyn Kellon, AAAS S&T Policy Fellow, NNCO
J. Alexander Liddle, NIST
Pat Looney, OSTP
Antti J. Makinen, DOD
George Maracas, DOE
Andrew R. Schwartz, DOE
Stacey Standridge, NNCO
Xiaojing (John) Zhang, NSF

Goal 4/Education and Workforce

Lisa Friedersdorf, NNCO/OSTP
Jaclyn Kellon, AAAS S&T Policy Fellow, NNCO
Lynnette Madsen, NSF
Antti J. Makinen, DOD
Dan Ryman, USPTO
Andrew R. Schwartz, DOE
Stacey Standridge, NNCO

Goal 5/Responsible Development

Lisa Friedersdorf, NNCO/OSTP
Chuck Geraci, NIOSH
Andrea Hindman, AAAS Fellow, DOD
Jaclyn Kellon, AAAS S&T Policy Fellow, NNCO
Lynnette Madsen, NSF
Antti J. Makinen, DOD
Andrew R. Schwartz, DOE
Stacey Standridge, NNCO
Treye A. Thomas, CPSC

National Nanotechnology Coordination Office

2415 Eisenhower Avenue

Alexandria, Virginia 22314