REPORT TO THE PRESIDENT AND TO CONGRESS

The Seventh Assessment of the National Nanotechnology Initiative

Executive Office of the President

President's Council of Advisors on Science and Technology

August 2023

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Executive Summary

Nanotechnology sparked a new phase of scientific discovery, producing groundbreaking innovations over the last 30 years. Microelectronics, mRNA vaccines, and next generation energy technologies are examples of the social and economic benefits of nanotechnology to the American people. The ingenuity of scientists and engineers in the United States and the leadership of the federal government across five administrations nurtured an emerging technology into an established advanced technology that continues to provide solutions to American and global challenges.

The National Nanotechnology Initiative (NNI) was a driving force behind these accomplishments. Launched in 2003 as a dedicated whole-of-government R&D program, the NNI was instrumental in coordinating federal activities for nascent nanotechnology research and funding. The 2003 21st Century Nanotechnology R&D Act that authorized the NNI directed a National Nanotechnology Advisory Panel (NNAP) to review periodically the status of the NNI. Nanotechnology is now fully established in numerous research and commercial initiatives across the federal government and private sector. In this 2023 report, the President's Council of Advisors on Science and Technology (PCAST), designated as the NNAP by Executive Order, provides three recommendations on federal nanotechnology coordination that reflect the success of the initiative and the maturity of the field.

Recommendations

Recommendation 1: PCAST recommends the President work with Congress to sunset or substantially revise the 21st Century Nanotechnology Research & Development Act.

Recommendation 2: PCAST recommends the Director of the Office of Science and Technology Policy (OSTP) work with the Executive Director of the National Science and Technology Council (NSTC) to direct the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee to continue leadership for federal coordination of nanotechnology strategic planning, implementation, and outreach.

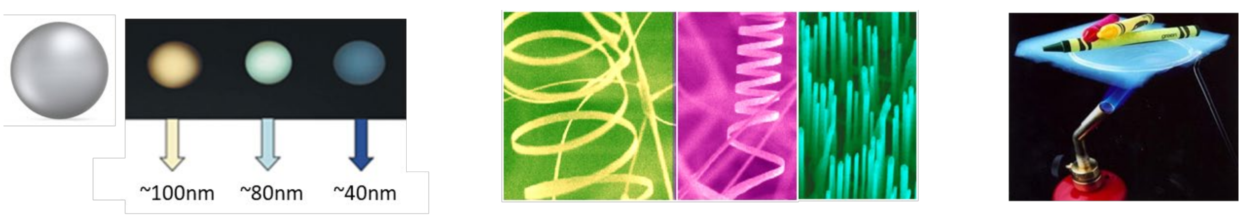
Recommendation 3: PCAST recommends the NSET Subcommittee enhance experiential learning programs for nanotechnology students and scientists to create the collaborative, multi-disciplinary workforce needed for nanotechnology and other advanced technologies.

The Seventh Assessment of the National Nanotechnology Initiative

Nanotechnology for the Nation

Nanoscale science catalyzed a revolution in scientific research and development that sparked a new phase of discovery. Nanoscale particles—most often below 100 nanometers (nm) in size—display new capabilities that have led to the rapid development of innovative technologies, created new industries, and fostered social and economic benefits. Nanotechnology research has showcased American ingenuity, innovation, and leadership.[1] The President's Council of Advisors on Science and Technology (PCAST), appointed by the President to serve as the congressionally mandated National Nanotechnology Advisory Panel (NNAP), is providing the seventh assessment of the National Nanotechnology Initiative (NNI). In this assessment, PCAST considered whether and how the NNI continues to advance nanoscale science and technology and what federal organizational structure would continue to facilitate nanotechnology achievements.

For over 30 years, the United States has charted the course for nanoscale research that expanded our understanding of and ability to control matter at the nanoscale through the collective efforts of countless scientists and engineers across the country's universities, private industries, federal agencies, and the National Laboratories (Figure 1).



Left image: Silver particles appear gold, green, and blue at 100, 80, and 40 nm, respectively
Middle image: Shape changes the electrical properties of nanoscale materials with the same chemical composition
Right image: Nanomaterial composites may display high resistance to extreme heat

Figure 1. Examples of Novel Material Properties That Occur at the Nanoscale

These efforts have addressed some of the most pressing challenges of our time. Nanotechnologies have accelerated the United States' path to becoming carbon-neutral by 2050 by dramatically reducing the cost of solar energy[2] and improving the performance of batteries for electric vehicles.[3] Nanotechnologies have been employed in life-saving treatments, including the lipid nanoparticles

[1] Subcommittee on Nanoscale Science, Engineering, And Technology. (2023 February). The National Nanotechnology Initiative Supplement to the President's 2023 Budget. https://www.nano.gov/sites/default/files/pub_resource/NNI-FY23-Budget-Supplement.pdf
[2] Ghasemzadeh, F., & Esmaeili Shayan, M. (2020 February 25). Nanotechnology in the Service of Solar Energy Systems. In *Nanotechnology and the Environment*. https://www.intechopen.com/chapters/73145
[3] Amarakoon, S., Smith, J., & Segal, B. (2012 April 26). Lithium-ion Batteries and Nanotechnology for Electric Vehicles: A Life Cycle Assessment. EPA. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100FT8E.PDF?Dockey=P100FT8E.PDF

that made COVID-19 vaccines possible,[4] as well as the many nanotechnology-dependent precision cancer therapies available to patients today.[5] Research on nanoscale particulates has informed safety standards to protect workers and consumers using products containing nanomaterials.[6] These wide-ranging technological accomplishments have helped drive economic growth in the United States, generating significant returns on research investments for the American people. In 2017,[7] over 3,700 companies that identified as nanotechnology enterprises employed more than 171,000 workers and reported $42 billion in revenue (Figure 2). These companies' products supported and enabled a plethora of other industries.[8,9]

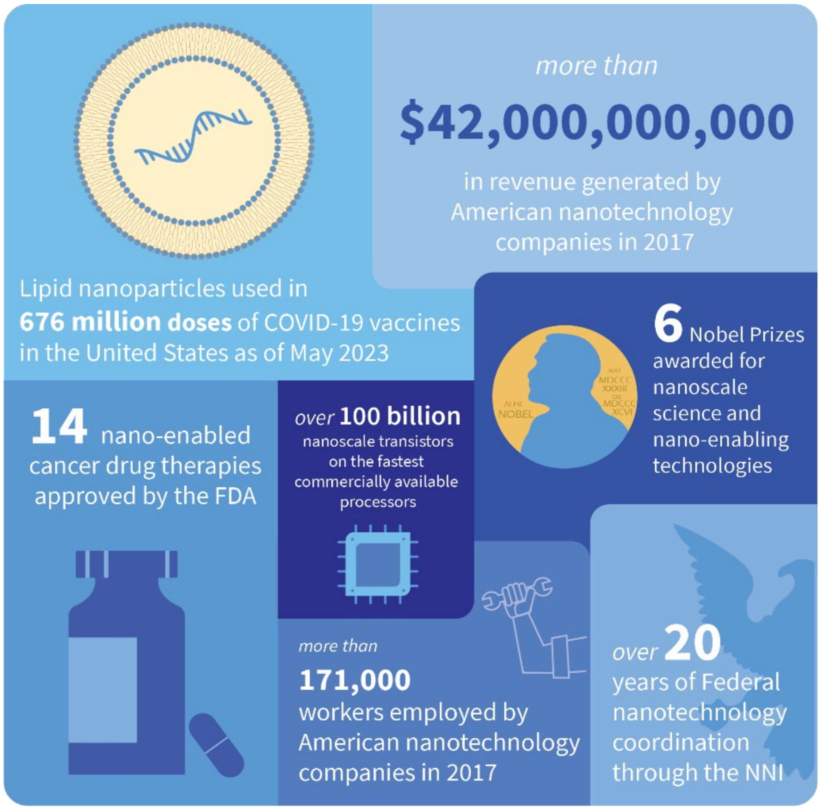


Figure 2. Achievements in Nanotechnology Research

Sources (clockwise, starting top left): *CDC COVID Data Tracker: COVID-19 Vaccinations in the United States (2023), National Nanotechnology Initiative - Impact of the NNI on the U.S. economy: at least $42 billion in one year! (2022), The Nobel Prize - All Nobel Prizes (2022), National Nanotechnology Initiative - Supplement to the President's 2023 Budget (2023), National Nanotechnology Initiative - Impact of the NNI on the U.S. economy: at least $42 billion in one year! (2022), National Cancer Institute - Current Nanotechnology Treatments (2017), Shankland, S. - Apple's M1 Ultra Shows the Future of Computer Chips. CNET. (2022).*

The six Nobel Prizes include the 2007, 2010, and 2014 Nobel Prizes in Physics and the 1996, 2014, and 2016 Nobel Prizes in Chemistry. These prizes were identified through subject matter expert review as directly related to nanoscale research, but PCAST recognizes other Nobel prizes might involve nano-enabled science or technology.

The federal government played a critical role in the development of these accomplishments. Key federal leaders and scientific

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[4] Jain, S., Venkataraman, A., Wechsler, M. E., & Peppas, N. A. (2021 October 9). Messenger RNA-based vaccines: Past, present, and future directions in the context of the COVID-19 pandemic. *Advanced Drug Delivery Reviews*. 179: 114000. https://www.sciencedirect.com/science/article/pii/S0169409X21003938?via%3Dihub

[5] National Cancer Institute. (n.d.). Cancer and Nanotechnology. https://www.cancer.gov/nano/cancer-nanotechnology

[6] National Research Council. (2009). Review of the Federal Strategy for Nanotechnology-Related Environmental, Health, and Safety Research. https://nap.nationalacademies.org/catalog/12559/review-of-the-federal-strategy-for-nanotechnology-related-environmental-health-and-safety-research

[7] The last year for which complete data are available is 2017.

[8] These numbers represent only nanotechnology-specific companies and do not include the many companies that employ nanotechnology as part of their broader business portfolio. See: Kiley, M. (2022 November 28) Impact of the NNI on the U.S. Economy: At Least $42 Billion in One Year!. https://www.nano.gov/node/5257

[9] Documented through the NNI's annual Supplement to the President's Budget, federal nanotechnology investment has remained steady at $1.8-1.9 billion each year since Fiscal Year (FY) 2020. See: https://www.nano.gov/2023BudgetSupplement

visionaries recognized in the late 1990s that nanotechnology would be essential to grow our economy and strengthen our global competitiveness. The 1998 federal report *Shaping the World Atom by Atom* led to the NNI, a dedicated whole-of-government R&D effort for nanoscale science, engineering, and technology.[10] Congress authorized the NNI through the 21st Century Nanotechnology Research and Development Act of 2003 and directed the executive branch to create a governance infrastructure that would coordinate activities that support nanotechnology research and funding (detailed in Appendix B).

In response, federal agencies created an extensive research infrastructure to advance nanotechnology R&D. The NNI agencies (Appendix C) funded research through nanotechnology-specific grants and applications-specific grants.[11] The NNI agencies established research centers and laboratory networks that provide federal, academic, and private scientists access to the critical equipment and expertise needed for nanoscale research. For example, in FY2022, researchers logged nearly 1 *million* facility hours across the 16 primary sites of the National Nanotechnology Coordination Infrastructure (NNCI), with users external to the NNCI accounting for 25% of these hours.[12] The NNI agencies, individually and collectively through the National Science and Technology Council (NSTC) Nanoscale Science, Engineering, and Technology (NSET) Subcommittee[13] provide leadership in the field by publishing strategic research plans, funding research initiatives, and convening fora for scientific exchange. The congressionally established National Nanotechnology Coordination Office (NNCO) provides administrative and technical support to carry out these activities.

Through the NNI, the United States established itself as a global leader in nanotechnology. In 2001 the United States was one of the first countries to create a national initiative on nanotechnology, and by 2011, over 49 countries had followed suit.[14] Scientists at U.S. research institutions and companies have led the world in producing highly cited papers and patents while the federal government has established frameworks to enable international cooperation, a shared understanding of the risks and benefits of nanotechnology, and a global marketplace for nanotechnology goods and services.

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[10] NSTC Interagency Working Group on Nanoscience, Engineering and Technology. (1999 September). Nanotechnology: Shaping the World Atom by Atom. https://www.nanowerk.com/nanotechnology/reports/reportpdf/report23.pdf

[11] Subcommittee on Nanoscale Science, Engineering, And Technology. (2022 March). The National Nanotechnology Initiative Supplement to the President's 2022 Budget. https://www.nano.gov/sites/default/files/NNI-FY22-Budget-Supplement.pdf

[12] NNCI Coordinating Office. (2022 February 16). NNCI Coordinating Office Annual Report (Year 6). https://nnci.net/sites/default/files/inline-files/NNCI%20CO%20Annual%20Report%202022%20Final%20for%20Web.pdf

[13] The NSTC is described in Appendix D.

[14] These data were gathered from publicly available sources in 2014; the initiatives in other countries may no longer be active. See: Clunan, A. & Rodine-Hardy, K. (2014 June). Nanotechnology in a Globalized World: Strategic Assessments of an Emerging Technology. https://calhoun.nps.edu/bitstream/handle/10945/43101/2014%20006%20Nanotechnology%20Strategic%20Assessments.pdf?sequence=1&isAllowed=y

Positioning U.S. Nanotechnology for the Future

Nanotechnology continues to hold immense potential for solving critical challenges of the coming decade. Revolutionary nanomaterials may be the key to creating economically viable carbon capture and sequestration tools to curb the effects of climate change.[15] Next generation nanoscale materials and fabrication technologies will advance semiconductor performance and enhance domestic manufacturing capabilities.[16] They may supplement or eventually replace rare critical minerals, thereby strengthening our economic and national security (additional examples are located in Appendix F).[17,18,19] Sustained federal investment will continue to be critical in advancing nanoscale science, engineering, and technologies. But the current field of nanotechnology requires a different form of federal coordination than when the NNI was launched in 2003.

Today, agency calls for proposals are more likely to request research that addresses an agency goal for which nanotechnology may provide one possible solution, rather than calls for research on specific aspects of nanotechnology, an observation confirmed in PCAST discussions with NNI agencies. Researchers are more likely to study nanoscale properties and materials in the context of a broader research problem or to incorporate nanoscale research with other fields and technologies. For example, fundamental research on nanomaterials is now being performed to develop components for quantum computers or lightweight heatshields for spacecraft. Knowledge about interactions between molecules and proteins at the nanoscale is now being used to better understand biochemical processes and optimize drug development. These trends are reflected in current nanotechnology reports, such as the 2021 *NNI Strategic Plan*[20] and FY2022 National Science Foundation (NSF) budget request for nanotechnology,[21] which recognize the importance of the field of nanotechnology but note nanotechnology's diffusion and integration into other fields.

Through PCAST's review of the NNI and discussions with NNI agencies and external stakeholders (Appendix A), there is a general consensus that the federal coordination structure required for the

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[15] Saleh, T. (2022 August 24). Nanomaterials and hybrid nanocomposites for CO_2 capture and utilization: environmental and energy sustainability. *RSC Advances*. 12 (37): 23869–23888. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9400618/

[16] Subcommittee on Nanoscale Science, Engineering, And Technology. (2023 February). The National Nanotechnology Initiative Supplement to the President's 2023 Budget. https://www.nano.gov/sites/default/files/pub_resource/NNI-FY23-Budget-Supplement.pdf

[17] Burton, J. (2022 February 22). U.S. Geological Survey Releases 2022 List of Critical Minerals. United States Geological Survey. https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals

[18] Arvidsson, R. & Sandén, B. (2017 July 10). Carbon nanomaterials as potential substitutes for scarce metals. *Journal of Cleaner Production*. 156: 253–261. https://www.sciencedirect.com/science/article/pii/S0959652617307564?via%3Dihub

[19] Gielen, D. (2021). *Critical minerals for the energy transition*. International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Technical-Papers/IRENA_Critical_Materials_2021.pdf

[20] Subcommittee on Nanoscale Science, Engineering, and Technology. (2021 October). National Nanotechnology Initiative Strategic Plan. https://www.nano.gov/sites/default/files/pub_resource/NNI-2021-Strategic-Plan.pdf

[21] National Science Foundation. (2021 May 28). FY 2022 NSF Budget Request to Congress – National Nanotechnology Initiative. https://www.nsf.gov/about/budget/fy2022/pdf/27_fy2022.pdf

emergence of nanotechnology in the early 2000s needs to evolve to reflect nanotechnology's maturation and broad relevance in many science and technology fields. Agencies confirmed that the NSET Subcommittee and NNCO's efforts to coordinate emerging nanotechnology were critical to its maturation (Appendix E). The agencies also noted the NNI's current primary utility as a mechanism to facilitate interagency discussions and collaborations. These findings indicate that the federal organizational structure that was effective in the early 2000s for nanotechnology as an emerging technology should be reconsidered in the context of nanotechnology as a mature field. Evolution of the federal support structure to current science and technology (S&T) requirements would ensure that U.S. nanotechnology research remains forward looking, agile, and innovative.

Recommendations

Recommendation 1: PCAST recommends the President work with Congress to sunset or substantially revise the 21st Century Nanotechnology Research & Development Act.

The NNI has played a key role in the field's maturity, especially in the early phases of nanoscale research: the NNI defined the emerging field, served as the nexus for disparate research efforts, and demonstrated the federal government's commitment to the field. Because of this maturation, nanotechnology no longer needs the significant management required by the NNI. The federal government should consider sunsetting the 21st Century Nanotechnology Research and Development Act[22] or streamlining the directives listed in the legislation. This could include, for example, ending the mandated reviews—each of which can cost an estimated $1.5–2 million—and the annual Supplement to the President's Budget.

Recommendation 2: PCAST recommends the Director of the Office of Science and Technology Policy (OSTP) work with the Executive Director of the National Science and Technology Council (NSTC) to direct the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee to continue leadership for federal coordination of nanotechnology strategic planning, implementation, and outreach.

Since its establishment, the NSET Subcommittee has effectively achieved its legislatively prescribed activities, such as establishing and updating a nanotechnology strategic plan every three years, awarding grants, establishing research centers, and promoting adoption of nanotechnology in the private sector. In the process, the NSET Subcommittee has become an invaluable coordination and communication tool. PCAST commends the Subcommittee's significant efforts and recommends the Subcommittee continue its leadership for federal nanotechnology coordination and corresponding administrative activities. More fully utilizing the NSTC subcommittee mechanism would simplify and

[22] The 21st Century Nanotechnology Research and Development Act was amended in 2017 through the American Innovation and Competitiveness Act (P.L. 114-329). The most up-to-date version of NNI-related legislation can be found in 15 USC §7501-7509 (See: https://uscode.house.gov/view.xhtml?path=/prelim@title15/chapter101&edition=prelim). Appendix B contains additional details on NNI legislative history.

streamline federal nanotechnology coordination while continuing the benefits of nanotechnology for the American people.

Recommendation 3: PCAST recommends the NSET Subcommittee enhance experiential learning programs for nanotechnology students and scientists to create the collaborative, multi-disciplinary workforce needed for nanotechnology and other advanced technologies.

The nanotechnology laboratory—whether academic or industrial—is becoming increasingly multi-disciplinary[23] with teams composed of engineers, mathematicians, biologists, chemists, and physicists, all of whom are familiar with different methods, techniques, and properties relevant to nanomaterials.[24] Each scientific discipline has a technical vocabulary that may not be readily understood by those in other disciplines. Students and scientists need opportunities to *learn* and to *practice* the multi-disciplinary science languages required for the many applications of nanotechnology today. The agencies in the NSET Subcommittee should enhance and expand programs that offer multi-disciplinary coursework, laboratory rotations, apprenticeships, and re-skilling options across high schools, community colleges, universities, and industry. This type of multi-disciplinary training is important for the continued impact of nanotechnology across many fields and industries, but is also valuable for developing the workforce for almost every technical field. The NSET agencies should also provide targeted funding for undergraduate, graduate, and post-doctoral students to perform multi-disciplinary laboratory research that includes nanotechnology. Specific consideration should be given to students at Historically Black Colleges and Universities and other Minority-Serving Institutions. These educational and training activities would catalyze the country's continued investments in nanoscale science and technology while building a skilled domestic workforce.

[23] Multi-disciplinary is defined as "combining or involving more than one discipline or field of study" by Merriam-Webster. In this context, we use the term multi-disciplinary to describe the ability for individuals to communicate and collaborate using the skills and languages from different disciplines to solve a research problem.

[24] For example, materials scientists now need to interface with quantum scientists and mathematicians to create the materials and measurements necessary for future quantum computers, and geneticists and chemists must collaborate with regulators and epidemiologists to develop new nano-enabled vaccines.

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Appendix A. External Experts Consulted

PCAST sought input from a diverse group of additional experts and stakeholders. PCAST expresses its gratitude to those listed here who shared their expertise. They did not review drafts of the report, and their willingness to engage with PCAST on specific points does not imply endorsement of the views expressed herein. Responsibility for the opinions, findings, and recommendations in this report and for any errors of fact or interpretation rests solely with PCAST.

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Appendix B. History and Statutory Authorities of the NNI

In the 1990s, U.S. research on nanotechnology increased in complexity and effort, with funding generated across multiple federal research agencies and federally supported research institutes. On the international stage, with countries like Japan and Germany making strategic investments in nanotechnology, nations and regions began competing for global leadership. To compete effectively and garner the benefits of nanotechnology for the American people, the United States determined that a coordinated national effort was needed to keep pace with—and even outpace—global competition. Within this context, a national initiative was proposed to establish a broad foundational research framework that would coordinate the disparate agency missions and accelerate research progress. This initiative—the National Nanotechnology Initiative (NNI)—emphasized U.S. commitment to nanotechnology as a scientific priority and harmonization of nanotechnology-related activities across the federal government.

In 2000, President Clinton announced the launch of the NNI to "coordinate Federal R&D efforts and promote U.S. competitiveness in nanotechnology" with a budget of $422 million granted by Congress. Under President G. W. Bush, the NNI was officially authorized in the 21st Century Nanotechnology Research and Development Act (P.L. 108-153), which established multiple key aspects of the NNI including the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee under the Committee on Technology (CoT) of the National Science and Technology Council (NSTC); the National Nanotechnology Coordination Office (NNCO); and the National Nanotechnology Advisory Panel (NNAP).[25]

The Act also established the two review requirements of the NNI: (1) The National Research Council of the National Academy of Sciences (now known as the National Academies of Sciences, Engineering, and Medicine [NASEM]) was directed to conduct a review of NNI in coordination with the NNCO on a triennial basis, and (2) The NNAP was created for the purpose of conducting a biennial review of the NNI and advising the President and the NSTC on future directions. In 2004, President Bush appointed the President's Council of Advisors on Science and Technology (PCAST) to serve as the NNAP in Executive Order 13349. In 2021, President Biden renewed PCAST's designation as the NNAP in Executive Order 14007. Since the establishment of the NNI, there have been 12 reviews: 6 by NASEM (2002, 2006, 2009, 2013, 2016, 2020) and 6 by PCAST (2005, 2008, 2010, 2012, 2014, 2017). Congress reduced the number of NASEM's and PCAST's reviews to every 4 years in the 2017 American Innovation and Competitiveness Act (P.L. 114-329). Accordingly, PCAST and NASEM now aim to release their reviews of NNI every 4 years such that they alternate release every 2 years. A copy of each review is transmitted by the NNCO to Congress. This report is the 13th NNI review and 7th by PCAST. An overview of the organization of the NNI and the relevant reviewing entities are outlined in Figure B-1.

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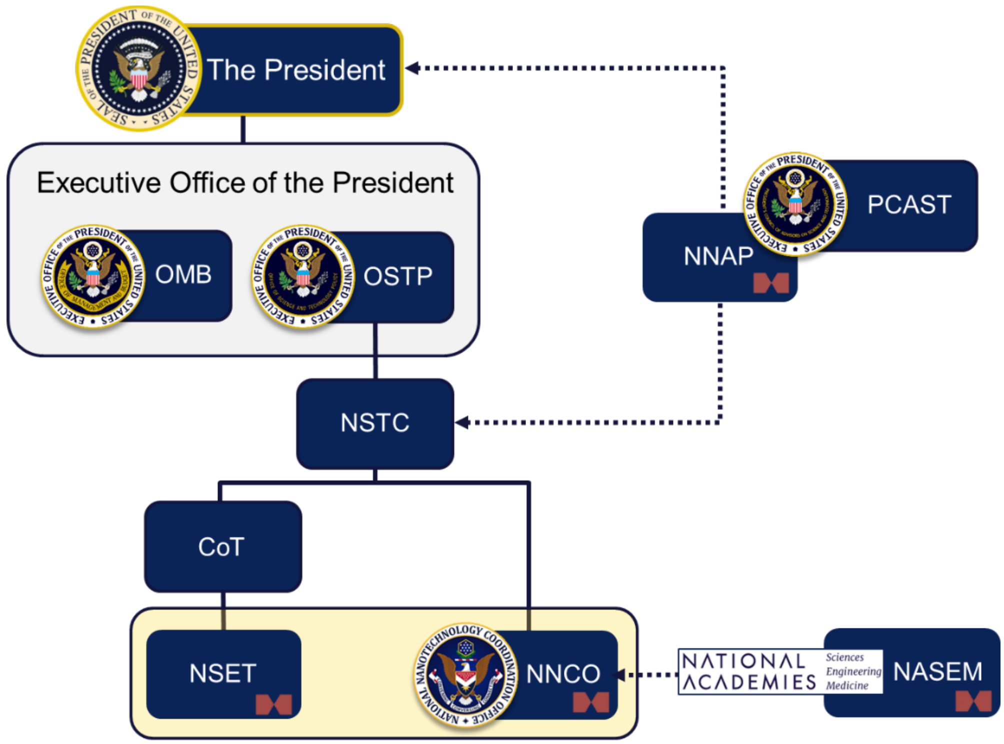
[25] 108th Congress. (2003 December 3). Public Law 108-153, 21st Century Nanotechnology Research and Development Act. https://www.govinfo.gov/content/pkg/PLAW-108publ153/pdf/PLAW-108publ153.pdf



indicates the entity was named in the 21st Century Nanotechnology Research and Development Act. Yellow box indicates entities directly involved in the NNI. Reviews are indicated by the dotted arrows.

Abbreviations: Office of Management and Budget (OMB); Office of Science and Technology Policy (OSTP); President's Council of Advisors on Science and Technology (PCAST); National Nanotechnology Advisory Panel (NNAP); National Science and Technology Council (NSTC); Committee on Technology (CoT); Nanoscale Science, Engineering, and Technology (NSET) Subcommittee; National Nanotechnology Coordination Office (NNCO); National Academies of Science, Engineering, and Medicine (NASEM)

Figure B-1. NNI Organizational Chart

Appendix C. Federal Entities of the National Nanotechnology Initiative

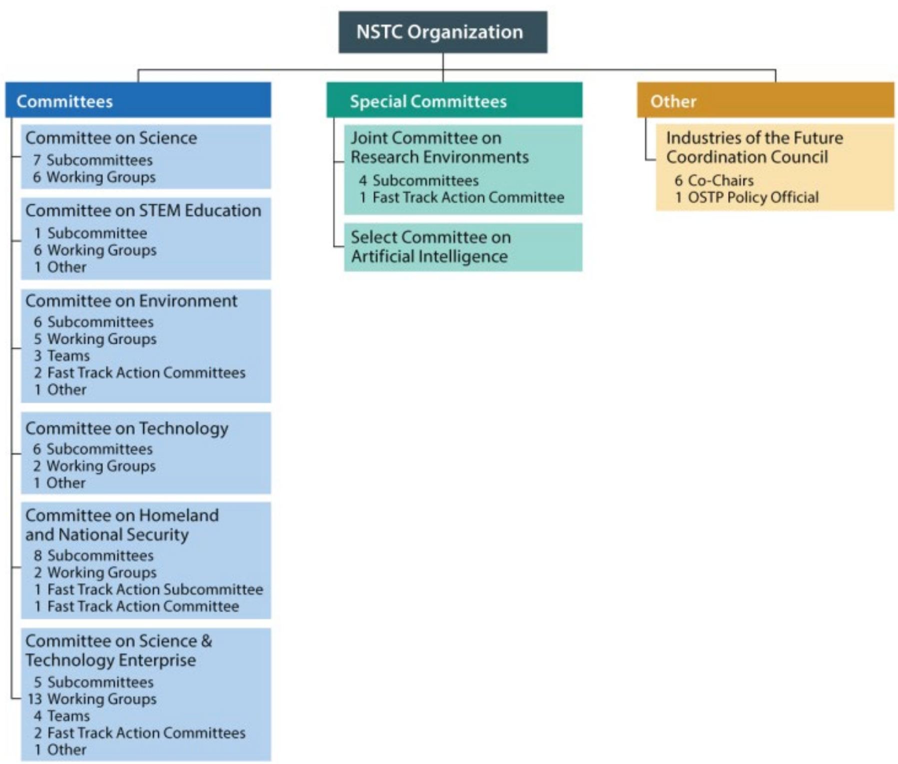
Note: List taken from the NNI 2023 Supplement to the President's Budget; asterisks denote agencies who participated in the PCAST discussions.

NNI Participating Entities

- Consumer Product Safety Commission (CPSC)*
- Department of Agriculture (USDA)
  - Agricultural Research Service (ARS)*
  - Forest Service (FS)
  - National Institute of Food and Agriculture (NIFA)*
- Department of Commerce (DOC)
  - Bureau of Industry and Security (BIS)
  - Economic Development Administration (EDA)
  - International Trade Administration (ITA)
  - National Institute of Standards and Technology (NIST)
  - Patent and Trademark Office (USPTO)
- Department of Defense (DOD)
- Department of Education (ED)
- Department of Energy (DOE)*
- Department of Health and Human Services (HHS)
  - Agency for Toxic Substances and Disease Registry (ATSDR)
  - Biomedical Advanced Research and Development Authority (BARDA)
  - Food and Drug Administration (FDA)*
  - National Center for Environmental Health (NCEH)
  - National Institute for Occupational Safety and Health (NIOSH)*
  - National Institutes of Health (NIH)*
- Department of Homeland Security (DHS)*
- Department of the Interior (DOI)
  - Bureau of Reclamation (USBR)
  - Bureau of Safety and Environmental Enforcement (BSEE)
  - United States Geological Survey (USGS)
- Department of Justice (DOJ)
  - National Institute of Justice (NIJ)*
- Department of Labor (DOL)
  - Occupational Safety and Health Administration (OSHA)*
- Department of State (State)
- Department of Transportation (DOT)
  - Federal Highway Administration (FHWA)
- Department of the Treasury (Treasury)
- Environmental Protection Agency (EPA)*
- Intelligence Community (IC)
- International Trade Commission (USITC)
- National Aeronautics and Space Administration (NASA)*
- National Science Foundation (NSF)*
- Nuclear Regulatory Commission (NRC)*

Appendix D. National Science and Technology Council

The National Science and Technology Council (NSTC) was established by Executive Order 12881 by President Clinton in order to coordinate science and technology efforts across the federal agencies and ensure that science and technology are considered in developing federal policies and programs.[26] The NSTC is made up of the Vice President, the Director of OSTP, Cabinet Secretaries, and Agency Heads with significant science and technology responsibilities. As of March 2023, the NSTC has six primary committees: Science, STEM Education, Environment, Technology, Homeland and National Security, and Science & Technology Enterprise. The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee is under the Committee on Technology. The Council also houses the Joint Committee on Research Environments, the Select Committee on Artificial Intelligence, and the Industries of the Future Coordination Council (Figure D-1). Each of these councils has a variety of subcommittees, working groups, and teams. The NSTC also oversees the National Coordination Offices including the National Nanotechnology Coordination Office (NNCO), the Networking & Information Technology Research & Development (NITRD) Coordination Office, and the U.S. Global Change Research Program (USDCRP).



Source: Reprinted from Congressional Research Service, The Office of Science and Technology Policy (OSTP): Overview and Issues for Congress, R47410; February 7, 2023.

Figure D-1. National Science and Technology Council Organizational Chart

[26] The White House. (n.d.). National Science and Technology Council. https://www.whitehouse.gov/ostp/nstc/

Appendix E. Nanotechnology as a Mature Science and Technology

For their 2023 quadrennial review of the National Nanotechnology Initiative (NNI), the President's Council of Advisors for Science and Technology (PCAST) NNI working group asked whether the federal coordination structure established through the 2003 21st Century Nanotechnology R&D Act aligns with current federal nanotechnology research needs. This appendix summarizes data evaluating whether nanotechnology has transitioned from an emerging technology to a maturing technology and draws on data in a STPI report commissioned by the National Institute of Standards and Technology entitled "Assessment of the Role of Federal Government in the Emergence and Maturation of Nanotechnology." The data are used here with the permission of NIST.

Approach

Although there are multiple ways to assess the maturity of a science and technology (S&T) field, STPI used the general characteristics of an emerging technology (Figure E-1) and examined indicators that are associated with federal involvement along this time course; specifically, the history and current status of federal funding, research projects, and associated publications. These findings also include perspectives and insight provided by Nanoscale Science, Engineering, and Technology (NSET) Subcommittee agency representatives and subject matter experts.[27]

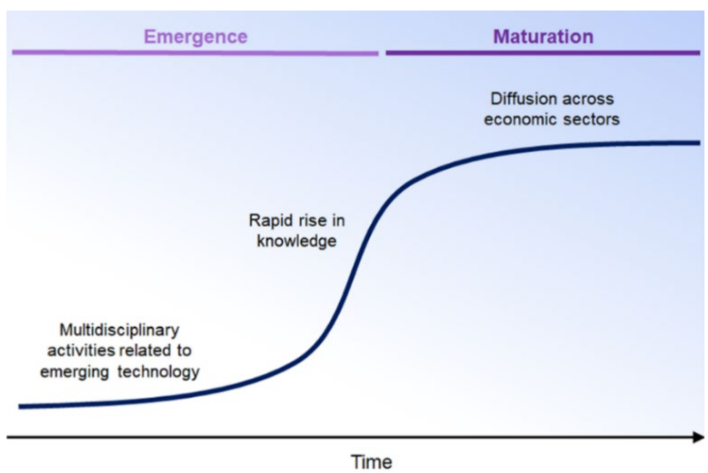


Figure E-1. Generalized Time Course for Emerging Technology Maturation

Evidence for Nanotechnology as an Emerging Technology

Nanotechnology was recognized as an emerging technology in the 1980s and 1990s with nanotechnology research occurring primarily in chemistry, physics, and engineering departments. At this time, it was just starting to become clear that materials exhibited fundamentally different

[27] PCAST conducted 12 interviews with NSET subcommittee agencies: CPSC, USDA, DOE, HHS/FDA, HHS/NIOSH, HHS/NIH, DHS, DOJ/NIJ, DOL/OSHA, EPA, NASA, and NRC).

properties than their bulk counterparts but there was very little understanding around why this happened or what these properties were. Nanotechnology began to coalesce into a distinct field in the late 1990s as nanotechnology research focused on the unique properties of materials at the nanoscale—most often below 100 nanometers (nm) in size. Prior to the establishment of the NNI in 2003, there was a consistent, slowly increasing level of federal nanotechnology activity. While there are no publicly available data for all NNI agency research projects, PCAST tracked the number of research projects, investments, and publications by year for the agencies reporting the largest nanotechnology investments–NSF and NIH. Analysis of publicly available data from NIH and NSF, demonstrates that each agency funded 100 or fewer research projects per year from 1985 to 1990 (Figure E-2), with an approximate budget of $50 million per year for each agency (Figure E-3). Research activities from 1991 to 1999 signaled the beginning of the rapid rise in knowledge and information as the number of agency projects per year rose to about 400–500 projects, and nanotechnology budgets reached $100–200 million. This significant growth in funding and projects is characteristic of emerging technologies.

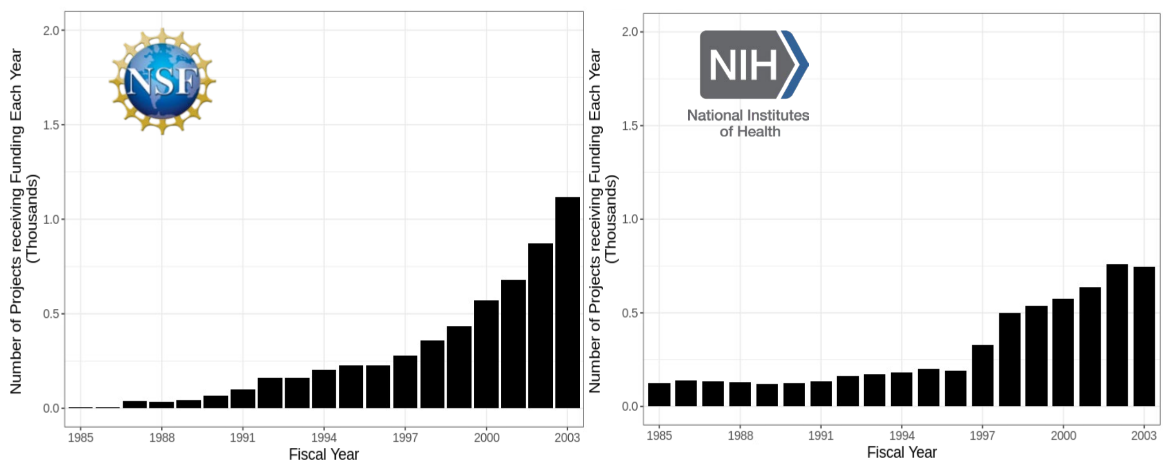
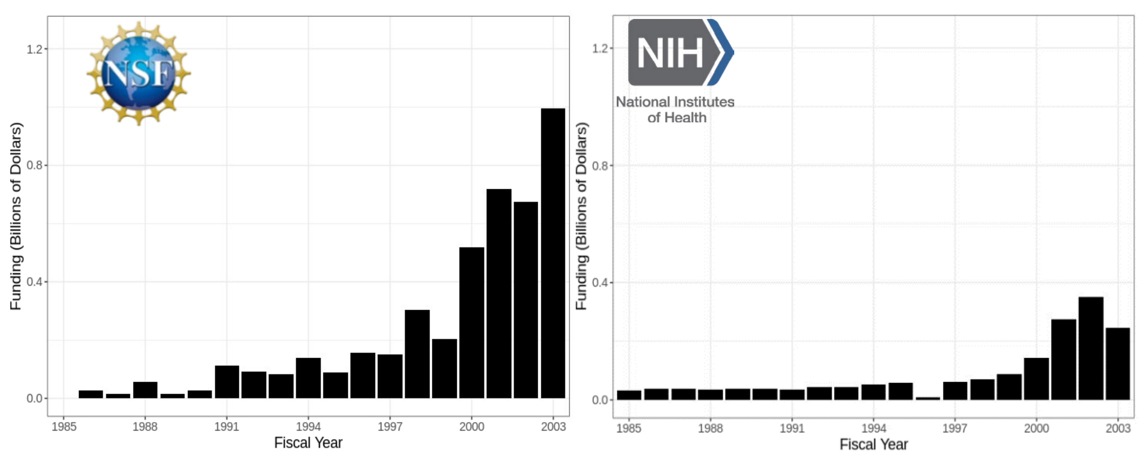


Figure E-2. NSF and NIH sponsored Nanotechnology Projects Each Year from 1985 to 2003



Note: All dollar amounts are adjusted to 2021 U.S. dollars.

Figure E-3. NSF (left) and NIH (right) Nanotechnology Funding Each Year from 1985 to 2003

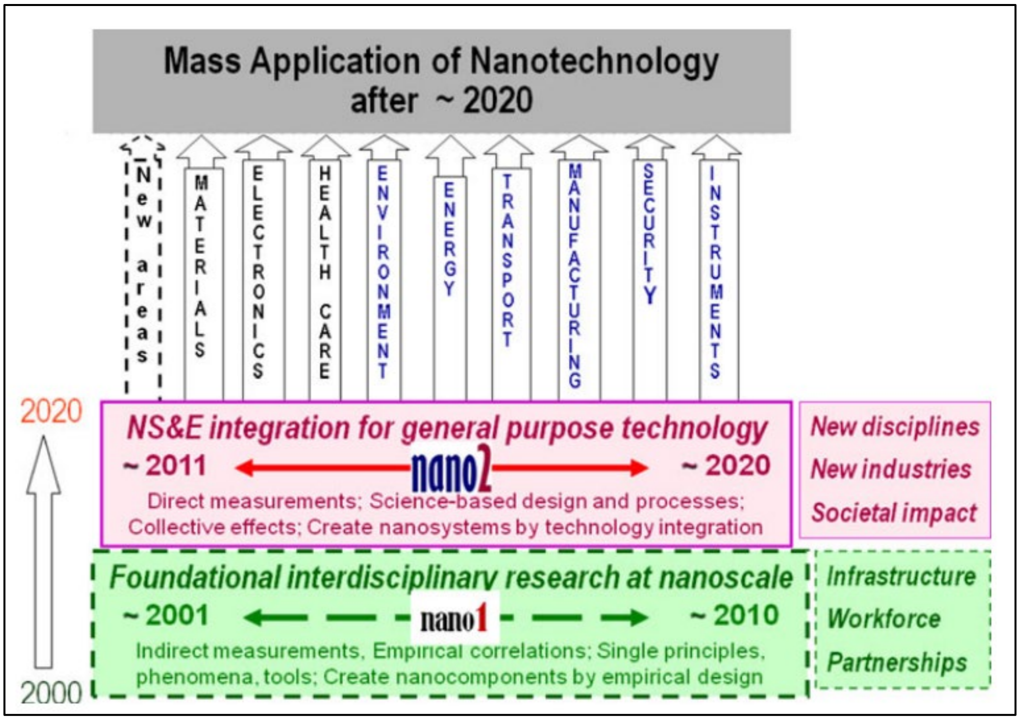
Evidence for Nanotechnology as a Mature Technology

Acknowledging Predictions of Nanotechnology Maturity

The transition of nanotechnology—from an emerging technology to a mature technology that has diffused across scientific and economic sectors—was predicted by the early federal nanotechnology leaders and policymakers. A 2011 projection of the trajectory of nanoscale research predicted the research would occur in three primary phases:[28]

- Between 2001 and 2010, inter-disciplinary research at the nanoscale would result in the "discovery of new phenomena, properties, and functions at the nanoscale; synthesis of a library of components as building blocks for potential future applications; tool advancement; and improvement of existing products by incorporating relatively simple nanoscale components"
- Between 2011 and 2020, research would focus on "nanoscale science and engineering integration, . . . science-based design of fundamentally new products, and general-purpose and mass use of nanotechnology" with a "shift toward more complex nanosystems."
- After 2020, "nanotechnology R&D is projected to develop closely with other emerging and converging technologies, creating new science and engineering domains and manufacturing paradigms."

[28] Roco, M. (2011 February 12). The long view of nanotechnology development: the National Nanotechnology Initiative at 10 years. *Journal of Nanoparticle Research*. 13: 427-445. https://link.springer.com/article/10.1007/s11051-010-0192-z



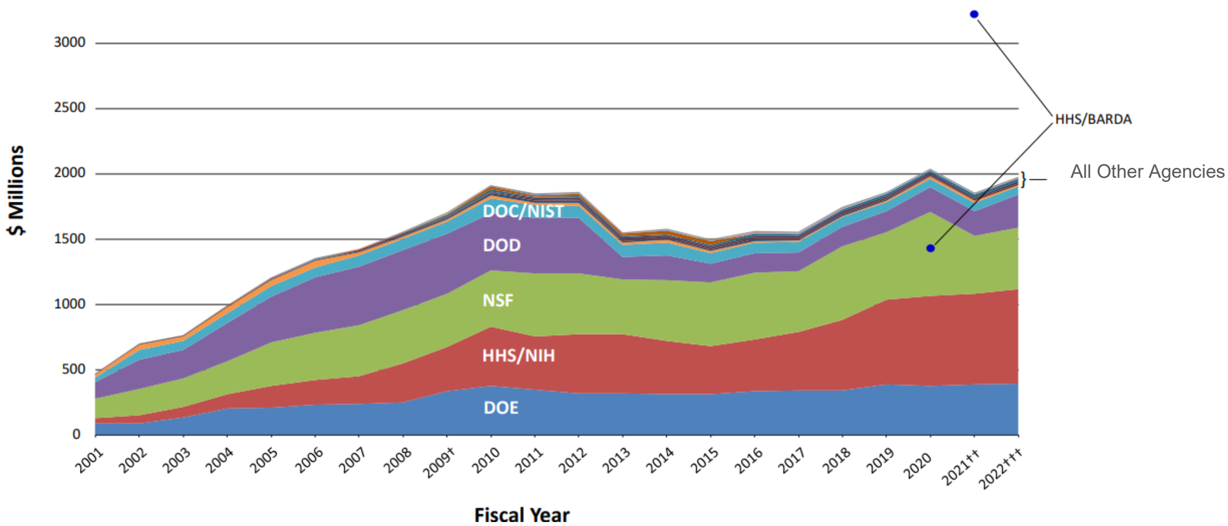
Source: Reprinted from Roco "The long view of nanotechnology development: the National Nanotechnology Initiative at 10 years" (2011).

Figure E-4. Roco's Projected Nanotechnology Development Timeline

Assessing Maturity Through Research and Investment

The 2003 21st Century Nanotechnology R&D Act directed the executive branch to establish the NSTC NSET Subcommittee and the NNCO, collaborate on research directions and investment, and report progress annually to Congress. This effort successfully coordinated federal research across prioritized research areas, investment, and policy. Although there are multiple ways to assess the maturity of a S&T field, PCAST used the history and recent status of federal funding and research projects and their associated publications as measures that are directly influenced by the federal government. As a reminder, the information provided here is not intended to be comprehensive but to provide sufficient information to understand these parameters of federal support for nanotechnology R&D.

The cumulative 20-year federal investment in nanoscale R&D has been $40.7 billion dollars, and as reported in the annual Supplement to the President's Budget, the annual investment has been greater than $1.5 billion per year since FY2008 (Figure E-5). Consistent with an emerging technology, there was a rapid rise in investment from Fiscal Year (FY) 2001 to FY2010 from ~$0.5 billion to ~$1.8 billion and, consistent with a maturing technology, a plateau from FY2019 to FY2022 at $1.8-1.9 billion.



† 2009 figures do not include American Recovery and Reinvestment Act funds for DOE, NSF, NIH, and NIST.

†† 2020 figures do not include one-year supplemental HHS/Biomedical Advanced Research and Development Authority funding for Covid vaccines.

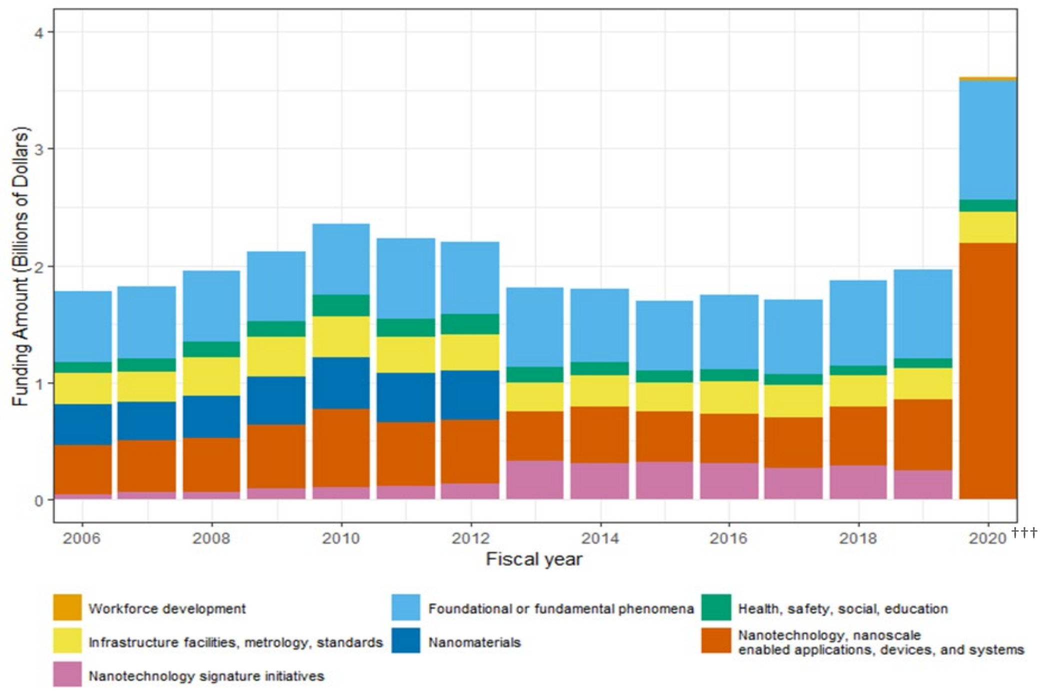
††† 2021 estimated based on appropriated levels.

Note: The funding in this figure is not adjusted to 2021 U.S. dollars.

Source: The NNI Supplement to the President's FY2022 Budget

Figure E-5. NNI Funding by Year (FY2001–2022)

Although the original NNI six nanotechnology research areas—called Program Component Areas—were consolidated to five in 2013, investment in the PCAs has remained relatively stable, thus demonstrating continuing agency commitment to the critical components of nanotechnology research (Figure E-6).



††† 2020 figures include one-year, ~$1 Billion, supplemental HHS/Biomedical Advanced Research and Development Authority funding for COVID-19 vaccines.

Note: All dollar amounts are adjusted to FY2021 dollars.

Source: NNI Supplement to the President's Budget FY2022

Figure E-6. NNI Funding by Program Component Areas (FY2001–2019)

The number of research projects from NSF and NIH increased in proportion to federal investment (Figure E-7). For example, the number of NSF projects per year has remained fairly level since 2011, while NIH projects display a contraction, then a second increase that more closely tracks its funding (Figure E-8).

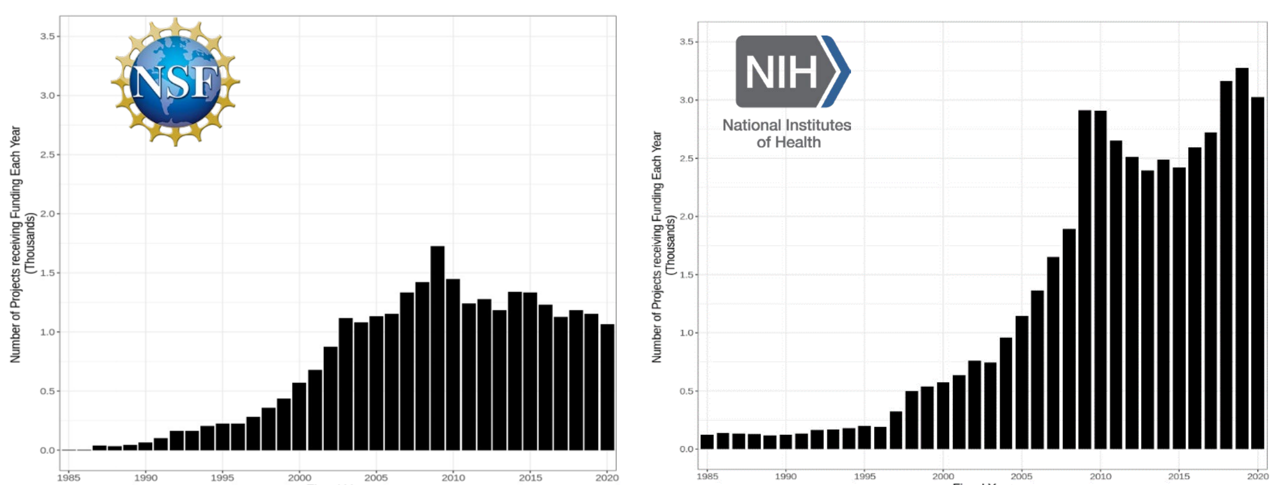
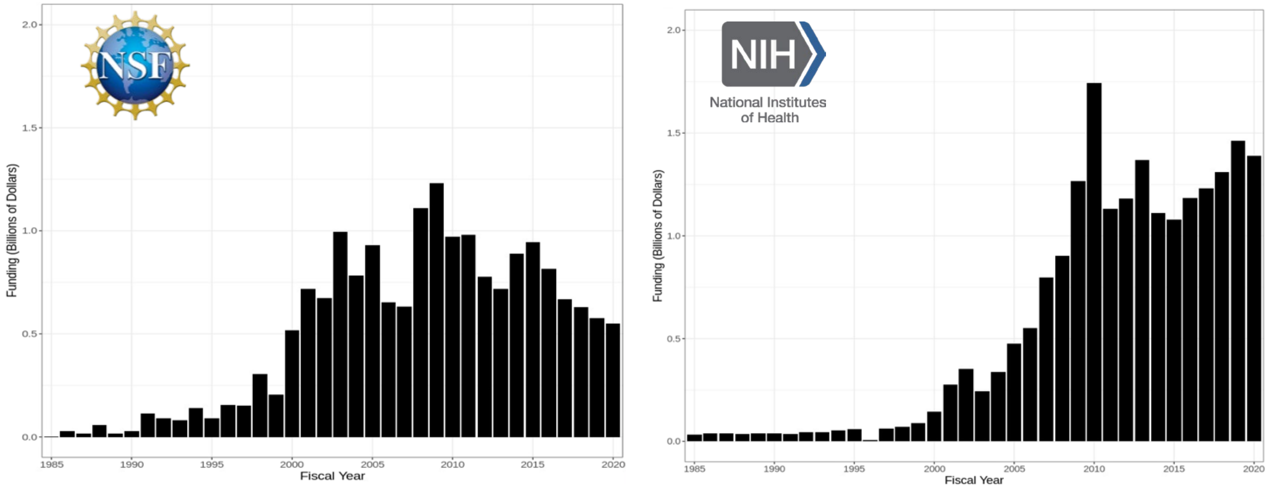


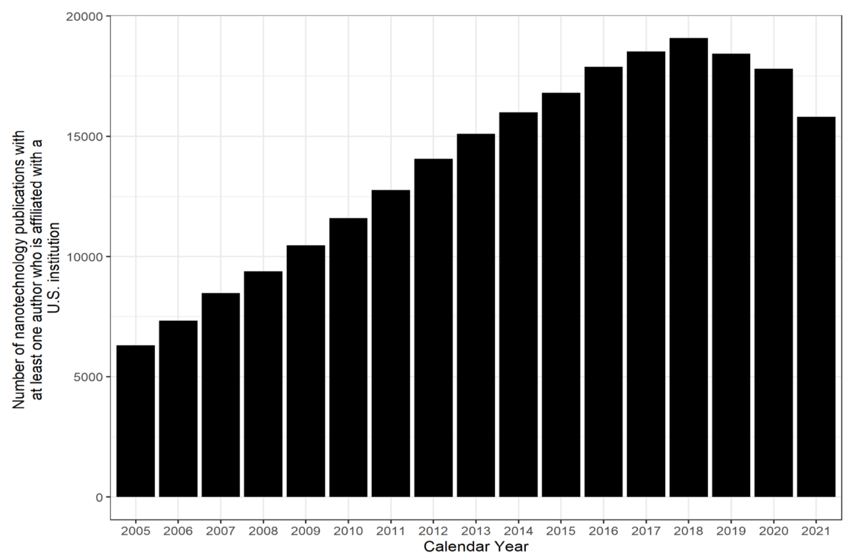
Figure E-7. NSF (left) and NIH (right) Nanotechnology Projects Each Year from 1985 to 2020



Note: All dollar amounts are adjusted to FY2021 dollars.

Figure E-8. NSF and NIH Nanotechnology Funding Each Year from 1985 to 2020

Based on a key word search of the Web of Science publications database, PCAST also assessed the number of U.S. nanotechnology publications and tracked the increase in nanotechnology publications with at least one author affiliated with a U.S. institution. Approximately 6,000 publications were identified in 2005, rising to over 180,000 in 2018, with some indications of a possible plateau from 2017 to 2019 (Figure E-9). Due to the possible effect of the COVID-19 pandemic on research and publications rates in FY2020 and FY2021, data from these years are not included in this assessment.



Source: Results based on STPI analysis of proprietary data from Web of Science.

Figure E-9. Nanotechnology Publications per year (2005-2022)

Assessing Nanotechnology Diffusion Across Scientific Fields and Economic Sectors

Nanotechnology's maturation can also be understood through its diffusion and deep integration into other science and technology domains. Research and development—and advances associated with them—are increasingly less dedicated solely to nanotechnology but are instead becoming focused on how the understanding of nanoscale properties and nanomaterial discoveries can be used to advance other fields and technologies. Examples include semiconductors and other nanoscale electronics, quantum technologies, and biologics and other advanced medicines. While nanotechnology may be becoming more diffuse and less novel, much about the nanoscale remains unknown. For instance, advances in understanding nano-bio interactions are still lacking, which has contributed to underwhelming development of nanomedicines compared to the visions presented in the late 1990s and early 2000s.[29] Products and other applied uses of nanotechnology continue to advance to this day. In 2017, the Consumer Product Safety Commission noted that they expect the number of consumer products containing nanomaterials to increase considerably by 2027.[30]

There are many visions for the future of nanotechnology. The latest NNI strategy, updated in 2021, suggests the continued diffusion and convergence of nanotechnology and emphasizes transitioning nanotechnology discoveries into commercial nanotechnology products.[31] Consistent with predictions for nanotechnology in 2011, this view has been expanded on, suggesting that nanotechnology will eventually be integrated into almost every system and product.[32] This suggests nanotechnology may be increasingly used and interpreted as a general use product, rather than having single applications.

Incorporating NSET Agency Insight

Agency representatives from 12 NSET Subcommittee agencies were interviewed between June 14 and July 5, 2023 and responded to open-ended interview questions about the relationship of nanotechnology to their agency missions, their role in the NNI, and the benefits derived from NSET and NNCO.

During discussions with NSET Subcommittee members, there was consensus that nanotechnology has reached a phase of maturity where nanoscience is increasingly applied across disciplinary boundaries, serving as a tool for advancing materials research across fields from precision agriculture to microelectronic devices. Agency representatives focused less on nanotechnology research per se and more on nanotechnology as a research and development solution.

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[29] Nature Nanotechnology Editorial Board. (2020 November 27). Nanomedicine and the COVID-19 vaccines. *Nature Nanotechnology*. 15: 963. https://www.nature.com/articles/s41565-020-00820-0

[30] U.S. Consumer Product and Safety Commission. (2017 January). Potential Hazards Associated with Emerging and Future Technologies. https://www.cpsc.gov/content/Potential-Hazards-Associated-with-Emerging-and-Future-Technologies

[31] NSTC Subcommittee on Nanoscale Science, Engineering, and Technology. (2021 October). National Nanotechnology Initiative Strategic Plan. https://www.nano.gov/2021strategicplan

[32] Omni Nano. (2019 May). Exclusive Interview with Dr. Mike Roco of the U.S. NSF. https://omninano.org/exclusive-interview-with-dr-mike-roco-of-the-u-s-nsf/

In response to questions about the NNI, agency representatives most often cited the NSET Subcommittee's facilitation of interagency communication, coordination, and collaboration, especially between agencies who would otherwise not interact. These actions were considered the strength of the NNI. The NNCO was noted for the importance of their administrative support, noting that other subcommittees who do not have the same level of coordination staff are less effective.

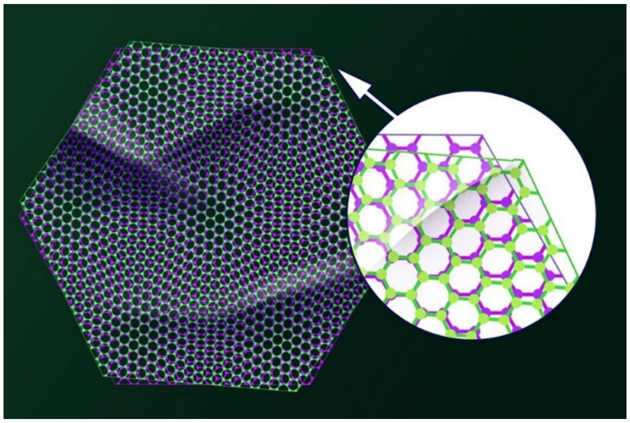
Appendix F. Nanotechnology Vignettes

Source: NIFA

Nanotechnology-enabled precision agriculture. The National Institute of Food and Agriculture's (NIFA) Agriculture and Food Research Initiative's (AFRI) program supports nanotechnology for a wide range of issues facing agricultural and food systems.[33] Nano-encapsulated versions of traditional fertilizers, insecticides, and herbicides enable the precise distribution of nutrients and agrochemicals. Because of their unique properties plants react differently to nanoparticles regarding their growth and metabolic activities, therefore nanoencapsulation is a powerful tool for precision agriculture.[34] Affordable technologies and manufacturing that can be translated to commercial markets are particularly relevant to the food and agriculture sectors and promoting biosecurity. There is also effort taken to explore nanotechnology applications for improving the quality and quantity of agriculture and water resources. The advanced food manufacturing program includes nanotechnologies to improve productivity, product quality, and safety—extending food shelf life and minimizing food waste and environmental footprints. These technologies also have impacts on enhancing the nutritional value of foods through improved absorption, nanoscale delivery, and the multidirectional impact of food composition and structure.[35]

Twisted graphene. Twistronics is the study of how the angle, or twist, between layers of two-dimensional materials can change their electrical properties. The field can be traced back to the isolation of single-layer graphene sheets by Novoselov and Geim in 2004,[36] work that led to their award of a Nobel Prize in Physics in 2010. Building off theoretical work by several groups,[37] Jarillo-Herrero and colleagues presented experimental results showing twisted bilayer graphene as a

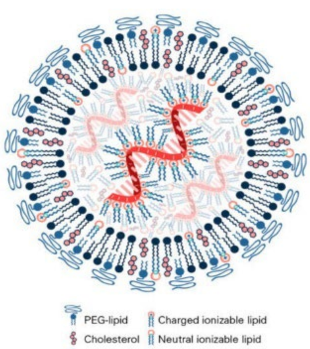
[33] USDA National Institute of Food and Agriculture. (n.d.). Nanotechnology Program. https://www.nifa.usda.gov/grants/programs/food-science-technology-programs/nanotechnology-program
[34] Samreen, T., Rasool, S., Kanwal, S., Riaz, S., Tul-Muntaha, S., & Zulquernain Nazir, M. (2022 December 20). Role of Nanotechnology in Precision Agriculture. *Environmental Sciences Proceedings*. 23(1): 13. https://www.mdpi.com/2673-4931/23/1/17
[35] Subcommittee on Nanoscale Science, Engineering, And Technology. (2023 February). The National Nanotechnology Initiative Supplement to the President's 2023 Budget. https://www.nano.gov/sites/default/files/pub_resource/NNI-FY23-Budget-Supplement.pdf
[36] Novoselov, K. S., Geim, A. K., Morozov, S. V., Jiang, D., Zhang, Y., Dubonos, S. V., Grigorieva, I. V., & Firsov, A. A. (2004 October 22). Electric Field Effect in Atomically Thin Carbon Films. *Science*. 306 (5696): 666-669. https://www.science.org/doi/10.1126/science.1102896
[37] Andrei, E.Y. & MacDonald, A.H. (2020 November 18). Graphene bilayers with a twist. *Nature Materials*. 19, 1265–1275. https://doi.org/10.1038/s41563-020-00840-0



Source: MIT News

precisely tunable, purely carbon-based, two-dimensional superconductor.[38] This break-through led to the field of twistronics, with many new researchers seeking to develop novel electronic devices. The novelties in the applications of the properties available due to twistronics have the potential to represent a significant leap in the transport and control of energy and information.[39] The federal government, coordinated through the NNI, was critical to funding this work—specifically, the NSF STC Center for Integrated Quantum Materials, NSF Materials Research Science and Engineering Center Shared Experimental Facilities, and NSF Center for Nanoscale Systems at Harvard provided essential funding.

Lipid nanoparticles. Messenger RNA (mRNA) has emerged as a novel and effective therapeutic agent; however, it requires a specific delivery method to protect the nucleic acid from degradation in vivo while still allowing the mRNA to release from the protection to achieve its therapeutic benefit. Lipid nanoparticles serve as this delivery vehicle to coat the delicate mRNA strands.[40] The use of lipid nanoparticles for delivery of mRNA in vaccines for COVID-19 marked a milestone for mRNA therapeutics. These were the first FDA-approved lipid nanoparticle encapsulated mRNA vaccines.[41] Both the Moderna and BioNTech/Pfizer vaccines were developed through sustained public and private investment and the U.S. government's advance purchase of the vaccines.[42] There are now an array of lipid nanoparticle formulations under clinical evaluation for the prevention and treatment of other viral



Source: https://www.mdpi.com/2076-393X/9/1/65

[38] Cao, Y., Fatemi, V., Fang, S., Watanabe, W., Taniguchi, T., Kaxiras, E., & Jarillo-Herrero, P. (2018 March 5). Unconventional superconductivity in magic-angle graphene superlattices. *Nature*. 556: 43-50. https://www.nature.com/articles/nature26160

[39] Jorio, A. (2022 July 27). Twistronics and the small-angle magic. *Nature Materials.* 21: 844–845. https://www.nature.com/articles/s41563-022-01290-6

[40] Pardi, N., Hogan, M. J., Porter, F. W., & Weissman, D. (2018 January 12). mRNA vaccines — a new era in vaccinology. *Nature Reviews Drug Discovery.* 17(4): 261–279. https://www.nature.com/articles/nrd.2017.243

[41] For a detailed history of mRNA and lipid nanoparticle development, see: Hou, X., Zaks, T., Langer, R., & Dong, Y. (2021 August 10). Lipid nanoparticles for mRNA delivery. *Nature Reviews Materials.* 6: 1078-1094. https://www.nature.com/articles/s41578-021-00358-0

[42] Jain, S., Venkataraman, A., Wechsler, M. E., & Peppas, N. A. (2021 October 9). Messenger RNA-based vaccines: Past, present, and future directions in the context of the COVID-19 pandemic. *Advanced Drug Delivery Reviews*. 179: 114000. https://www.sciencedirect.com/science/article/pii/S0169409X21003938?via%3Dihub

infections, cancers, and genetic diseases.[43] For examples, lipid nanoparticles are currently under clinical investigation to be used in vaccines to treat autoimmune disorders.[44]

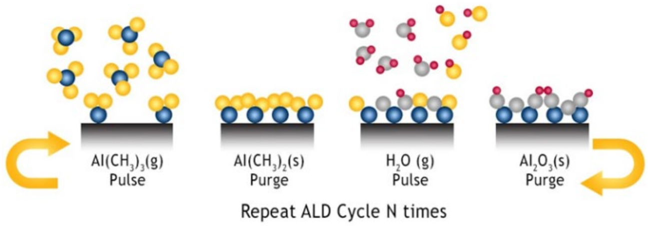
Nanotechnology-enabled prosthetics. The use of nanomaterials in prosthetic devices has increased their performance and significantly improved the quality of life for their users.[45] Research shows that artificial limbs made of traditional materials are stiff, expensive, and not easy to handle. As a result, the risk of falling is increased, and the activity ability is limited. Advanced nanomaterials—such as plastics, ceramics, metals, and graphene—have led to better performing prosthetics that are also better tolerated by the user.[46] Numerous prosthetic devices have been made for various prosthetic limbs using the biosensing properties of nanomaterials. These effectively improve the sense of use of the disabled and allow for greater functionality of the limbs. Prosthetic limbs made of nanocomposites enable patients to engage in more demanding recreational activities such as running.[47]

Source: U.S. Army/Tim Hipps

Precision surface coatings. Atomic Layer Deposition (ALD) describes a process for controlled deposition of atoms onto the surface of a material. Surfaces treated through ALD have fewer surface defects (holes in the coating) than other deposition processes such as chemical vapor deposition.[48,49] Because of these advantages, ALD has become critical in multiple industries—including the semiconductor and solar energy industries for which the ability to collect or block the flow of electrical charge (capacitor and insulator, respectively) is an essential design element. ALD has been adopted in semiconductor development because of its high level of precision and fine tunability to

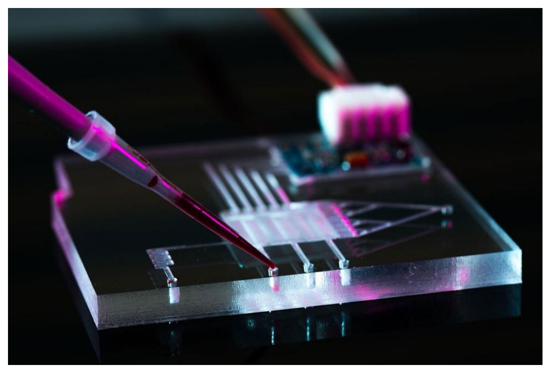
[43] Hou, X., Zaks, T., Langer, R., & Dong, Y. (2021 August 10). Lipid nanoparticles for mRNA delivery. *Nature Reviews Materials*. 6(12): 1078–1094. https://www.nature.com/articles/s41578-021-00358-0
[44] Henderson, E. (2023 February 17). LLNL licensee and collaborators develop novel medicines to combat autoimmune diseases. https://www.news-medical.net/news/20230217/LLNL-licensee-and-collaborators-develop-novel-medicines-to-combat-autoimmune-diseases.aspx
[45] Tan, Q., Wu, C., Li, L., Shao, W., & Luo, M. (2022 March 31). Nanomaterial-Based Prosthetic Limbs for Disability Mobility Assistance: A Review of Recent Advances. *Journal of Nanomaterials*. ID: 3425297. https://www.hindawi.com/journals/jnm/2022/3425297/
[46] Brooks, C. (2022 May 31). 3 Key Areas Where Nanotechnology Is Impacting Our Future. *Forbes*. https://www.forbes.com/sites/chuckbrooks/2022/05/31/3-key-areas-where-nanotechnology-is-impacting-our-future/?sh=8cca4166741a
[47] Tan, Q., Wu, C., Li, L., Shao, W., & Luo, M. (2022 March 31). Nanomaterial-Based Prosthetic Limbs for Disability Mobility Assistance: A Review of Recent Advances. *Journal of Nanomaterials*. ID: 3425297. https://www.hindawi.com/journals/jnm/2022/3425297/
[48] George, S. M. (2009 November 30). Atomic Layer Deposition: An Overview. *Chemical Reviews.* 110(1): 111–131. https://pubs.acs.org/doi/10.1021/cr900056b
[49] Weimer, A. W. (2019 January 4). Particle atomic layer deposition. *Journal of Nanoparticle Research.* 21(9). https://link.springer.com/article/10.1007/s11051-018-4442-9

create uniform surface coatings with high dielectric constants,[50] particularly SiO_2.[51] The opposite of ALD, atomic layer etching—which involves *removal* of atomic layers of a coating—has also been applied in semiconductor production.[52] ALD has also demonstrated potential application for depositing perovskite materials in thin films to increase efficiency of solar cells.[53]



Source: Forge Nano

Device engineering. Nanotechnologies have led to advancements in device engineering that feature more compact and capable computers. Smartphones exemplify how far the science has come in device engineering.[54] Over the past few decades, the transistor has been continually miniaturized. Modern integrated circuits incorporate transistors with features as small as a few tens of nanometers. Nanotechnology broadly includes all technologies that handle nanoscale materials, and in a narrow sense, technologies that handle unique phenomena that arise in the 10-to-100-nm size range. The microelectronics industry now falls under both definitions, having components that are in the nanoscale range and leveraging nanoscale materials' unique properties.[55] The study and application of nanotechnology has allowed for devices to shrink orders of magnitude in size with increased performance



Source: Forbes

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[50]As the dielectric constant increases, the electric flux density increases, if all other factors remain unchanged. This enables objects of a given size, such as sets of metal plates, to hold their electric charge for long periods of time, and/or to hold large quantities of charge.

[51] Johnson, R. W., Hultqvist, A., & Bent, S. F. (2014 June). A brief review of atomic layer deposition: from fundamentals to applications. *Materials Today*. 17(5): 236–246. https://www.sciencedirect.com/science/article/pii/S1369702114001436j

[52] Kanarik, K. J., Lill, T., Hudson, E. A., Sriraman, S., Tan, S., Marks, J., Vahedi, V., & Gottscho, R. A. (2015 March 5). Overview of atomic layer etching in the semiconductor industry. *Journal of Vacuum Science & Technology A*. 33(2): 20802. https://pubs.aip.org/avs/jva/article/33/2/020802/246821/Overview-of-atomic-layer-etching-in-the

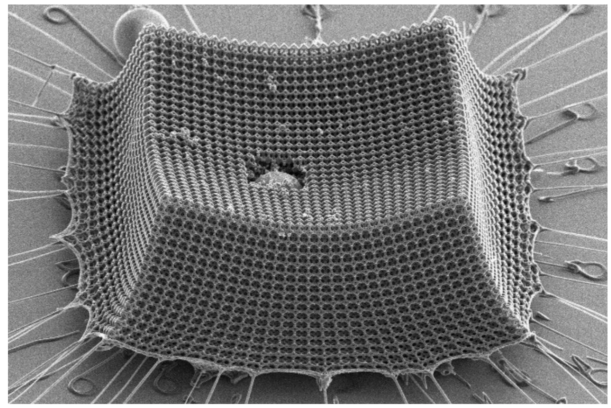
[53] Raiford, J. A., Oyakhire, S. T., & Bent, S. F. (2020 May 5). Applications of atomic layer deposition and chemical vapor deposition for perovskite solar cells. *Energy & Environmental Science*. 13(7): 1997–2023. https://pubs.rsc.org/en/content/articlelanding/2020/ee/d0ee00385a

[54] Brooks, C. (2022 May 31). 3 Key Areas Where Nanotechnology Is Impacting Our Future. *Forbes*. https://www.forbes.com/sites/chuckbrooks/2022/05/31/3-key-areas-where-nanotechnology-is-impacting-our-future/?sh=8cca4166741a

[55] Tamirat Y. (2017 September 5). The Role of Nanotechnology in Semiconductor Industry: Review Article. *Journal of Materials Science & Nanotechnology*. 5(2): 202. https://www.annexpublishers.co/articles/JMSN/5202-The-Role-of-Nanotechnology-in-Semiconductor-Industry-Review-Article.pdf

and intelligence capabilities. By manipulating the size and shape of manufactured nanomaterials, researchers are able to adjust the energy and optical transitions of nanoengineered semiconductors.[56]

Defense armor strengthened by nanomaterials. Developing advanced body armor to protect the defense forces has been a priority research area in academia and industry. Soft body armors with multilayered high-performance fabrics and hard body armors reinforced with stiff metal, ceramics, or polymer plates are widely used by soldiers, law enforcement officers, and other security personnel. The application of nanomaterials has been highly effective at making this body armor easier to use and safer.[57]



Source: Nature Materials

Nanomaterials are the strongest materials known to science. The high strength-to-weight ratios and superior energy absorption of nanomaterials makes them an ideal material to use in defense body armor. Various fabrication methods (e.g., compression molding, impregnation, hand lay-up) can be adopted to make nanocomposites in different forms and structures to be used on different pieces of armor. Beyond anti-ballistic materials, this application of nanotechnology also has uses for other anti-impact materials.[58]

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