Nanotechnology Research Directions for Societal Needs in 2020

RETROSPECTIVE AND OUTLOOK SUMMARY

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Summary of international report
STUDY ON NANOTECHNOLOGY RESEARCH DIRECTIONS

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The cover picture depicts the integration of various nanotechnology-based solutions in the design of a blended hybrid-wing-body concept for future subsonic commercial aircraft. Designed by NASA and MIT; the aircraft’s unique construction would enable it to carry 354 passengers while consuming 54% less fuel than a standard Boeing 777. It could be available for commercial use as early as 2030 (Courtesy of NASA and MIT).

This booklet is a summary of the report, Nanotechnology Research Directions for Societal Needs in 2020: Retrospective and Outlook, published in December 2010 by the World Technology Evaluation Center (WTEC) and Springer with sponsorship by the National Science Foundation. Further information about this study, as well as the complete text and image credits of the report can be found at http://www.wtec.org/nano2.
Nanotechnology Research
Directions for Societal Needs in 2020

RETROSPECTIVE AND OUTLOOK SUMMARY

Mihail C. Roco, Chad A. Mirkin, and Mark C. Hersam, Editors

NSF/WTEC report

The full report is published by Springer
Nanotechnology is the control and restructuring of matter at the atomic, molecular and supramolecular levels, in order to create materials, devices, and systems with fundamentally new properties and functions due to their small structure. A nanometer (10^{-9} meters) is the size of a small molecule.

Ten years have passed since the first U.S. National Science and Technology Council “Nano1” report\(^1\) on the prospects for nanotechnology. During the past decade, research and development in nanotechnology has made astonishing progress and has now provided a clearer indication of its potential. The recently completed “Nano2” report\(^2\) examines the last decade’s progress in the field and uncovers the opportunities for nanotechnology development in the United States and around the world in the next decade. This new report, of which this booklet is a summary, briefly describes the results of the investments made since 2000. It also describes the expected targets for nanotechnology R&D in the next decade and beyond, including how to achieve them in the context of societal needs and other emerging technologies.

The information in this booklet incorporates the views of leading experts from academia, industry, and government shared among U.S. representatives and those from over 35 other economies in four forums held between March and July 2010. These began with a brainstorming meeting in Chicago and included U.S.-multinational workshops in Hamburg, Germany (involving European Union and U.S. representatives); Tokyo, Japan (involving Japan, South Korea, Taiwan, and U.S. representatives); and Singapore (involving Singapore, Australia, China, India, Saudi Arabia, and U.S. representatives). Participants came from a wide range of disciplines, including the physical and biological sciences, engineering, medicine, social sciences, economics, and philosophy.

The study documents the progress made in nanotechnology from 2000 to 2010 and lays out a vision for progress in nanotechnology from 2010 to 2020, in four broad categories of interest: methods and tools of nanotechnology, safe and sustainable development, applications, and societal dimensions.


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**Figure 3.** Creating a new field and community in two foundational phases between 2000 and 2020 ("NS&E" is nanoscale science and engineering.)

- **2000**
  - Indirect measurements, Empirical correlations; Single principles, phenomena, tools; Create nanocomponents by empirical design

- **2020**
  - Direct measurements; Science-based design and processes; Collective effects; Create nanosystems by technology integration

**NS&E integration for general purposes technology**

- NANO1 (~2001) to NANO2 (~2011) to NANO3 (~2020)

**Figure 4.** Market of final products incorporating nanotechnology: the long-term vision for 2000-2020 (solid line, see Chapter on Long View) and outcomes in 2009 (survey by Lux Research, Chapter 13). The R&D focus evolves from fundamental discoveries to nanosystem integration in 2000-2010.
Over the last ten years, the viability and societal importance of nanoscale science, engineering, and technology applications have been confirmed, while extreme predictions, both pro and con, have receded.

Nanotechnology has been recognized as a revolutionary field of science and technology, comparable to the introduction of electricity, biotechnology, and digital information revolutions. Between 2001 and 2008, the numbers of discoveries, inventions, nanotechnology workers, R&D funding programs, and markets all increased by an average annual rate of 25 percent. The worldwide market for products incorporating nanotechnology reached about $254 billion in 2009.

Total worldwide nanotechnology R&D funding has grown from about $1.2 billion (of which $0.37 billion was in the U.S.) in 2000 to over $15 billion (of which $3.7 billion was in the U.S.) in 2008 with an average annual growth of 35 percent (33 percent in the U.S.).

The fraction of the U.S. Federal R&D investment in nanotechnology as compared to all Federal R&D expenditures grew from 0.39% in 2000 to about 1.5% in 2008. U.S. federal expenditures per capita on nanotechnology R&D has grown from about $1 in fiscal year 2000 to about $5.7 in 2008. Japan had about $7 per capita, and Korea about $6 per capita in 2008.

While government investment in the U.S. National Nanotechnology Initiative and similar government initiatives abroad has been considerable, the return on investment has been even greater. The market for products incorporating nanotechnology is about $250 billion worldwide in 2009.

Industry has recognized the importance of nanotechnology and the central role of government in the NNI R&D. The estimated market for products incorporating nanotechnology was about $91 billion in the United States alone as of 2009.

Some 60 countries have adopted nanotechnology research programs, making nanotechnology one of the largest and most competitive research fields globally.
**Figure 5.** Total number of nanotechnology patent applications in 15 leading patent depositories in the world from 1991–2008.

**Figure 6.** Estimation of the outcomes of U.S. Federal investment in nanotechnology R&D in 2009. The figure shows an annual balance between investments and outputs.
Current trends suggest that the number of nanotechnology workers and products worldwide will double every three years, reaching a $3 trillion market with 6 million jobs by 2020.

Systematic control of matter at the nanoscale using direct measurements, simulations and improved theories on nanoscale phenomena such as quantum and self-assembling, will lead to the creation of advanced materials, devices and nanosystems by design.

Nanotechnology is expected to be in widespread use by 2020. There is the potential to incorporate nanotechnology-enabled products and services into almost all industrial sectors and medical fields. The increasing integration of nanoscale science and engineering promises mass applications of nanotechnology in industry, medicine, and computing, and in conservation of nature. The benefits will include increased productivity, more sustainable development, and new jobs.

New applications expected to emerge in the next decade range from long-life photovoltaic devices to high performance batteries enabling competitive electric cars, novel computing systems, cognitive technologies, food and agricultural systems, quantum information systems, nanosystems and synthetic biology, and radical new approaches to diagnosis and treatment of diseases like cancer.

For illustration, nanotechnology applications will make solar energy conversion costs competitive by about 2015 in the United States and water desalination costs competitive by 2020–2025, depending on the region. Nanotechnology will continue to provide breakthrough solutions for over 50% of new projects on energy and water resources, as well as other sustainable development areas.

Continued investment in basic research in nanotechnology is needed, but additional emphasis should also be placed on application-driven research, innovation, commercialization, job creation, and societal “returns on investment,” with measures to ensure safety and public participation.

As nanotechnology is expected to satisfy essential societal needs and have mass applications by 2020, there is a need to institutionalize nanotechnology education, research, manufacturing, medical, EHS and ELSI programs.

Nanotechnology’s rapid development worldwide is a testimony to the transformative power of identifying a concept or trend and laying out a vision at the synergistic confluence of diverse scientific research areas.
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**Figure 8.** The percentage of manufacturing companies interested in introducing nanotechnology products (based on 2010 survey of 270 manufacturing companies by National Center for Manufacturing Systems).
Advances in the last ten years:

- Discovery of fundamental mechanical, optical, electronic, magnetic, and biological phenomena, properties, and processes at the nanoscale, and developing understanding of bionic-abiotic interfaces.

- New approaches such as ab-initio (from basic principles) electronic simulation frameworks, molecular dynamics simulations with chemical bonding, simulation of self-assembly of functionalized nanoparticles, and statistical analysis of complex nanostructures have been performed. The number of atoms simulated by classical molecular dynamics for 10 nanosecond time durations has increased from about 10 million in 2000 to nearly 1 billion in 2010. High-performance computing power, which enables more ambitious multiscale simulations, has increased by three orders of magnitude.

- Quantum effects were identified and measured in a series of nanostructures, such as quantum dots, nanotubes, and nanowires, and the first quantum device was built.

Vision for the next decade:

- Nanoscale modeling, numerical methods, and computational capability are expected to increase the speed of simulations by a factor of 10,000, leading to more ambitious projects and wider use of simulation in research and design. Theory, modeling, and simulation increasingly are critical tools that support nanotechnology.

- New theories on complexity for concurrent phenomena and system integration at the nanoscale will enable discovery and novel applications.

- General approaches to multiscale/multi-phenomena simulation for computational design materials, devices and systems from basic principles will be developed. Predictive simulation has the potential to greatly accelerate R&D in fields such as catalysis design, drug discovery and dynamics of complex systems. Broader use of multiscale and multi-phenomena simulation could also influence technology development directions. Nanoscience generates possibilities for new technologies, but it generates many more than can be experimentally explored.
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**Figure 10.** Hierarchy of theory, modeling and simulation methods relevant to nanoscale science and technology, along with some corresponding experimental methods, and the time and length scales over which each is applicable (2010).

**Figure 11.** New developments in the theory of molecular conduction have resulted in quantitative simulations of molecular junctions. A joint theory and experiment collaboration showed that electrical conductance of a bipyridine-Au molecular junction can be turned “on” or “off” simply by pushing or pulling on the junction.

**Figure 12.** Nanostructured materials are created for new applications. Right photovoltaic BH solar cells, left nanostructured morphology.
### Advances in the last ten years:

- Novel concepts and approaches have been created to provide a platform for a *new generation of nanoscale localized measurement tools.*

- There has been a dramatic expansion of the variety of properties that can be measured at the nanoscale. A *wide range of phenomena can now be accessed* with high-spatial-resolution scanning probe microscopy.

- New, cheap and accessible methods of nano-patterning, such as microcontact printing and imprint lithography, have allowed research and product development laboratories to easily *fabricate specialized complex devices* with which to explore new phenomena.

- Electron microscopy with aberration correction has achieved sub-nanometer spatial resolution and three-dimensional tomography.

- X-ray brilliance at measuring beam lines has increased five orders of magnitude between 2000 and 2010, enabling atomistic and dynamic measurements of three-dimensional nanostructures.

### Vision for the next decade:

- Tools will be developed *for simultaneous atomic resolution, three-dimensional imaging with chemical specificity and temporal resolution of the nanoscale phenomena.* We will see unanticipated new tools and discoveries of nanoscale phenomena along with new applications.

- *Generalized use of reference standard materials and measurement methods* in nanoelectronics, biomedical field, and nanomanufacturing and other areas.

- **Specific goals include:**
  - achieving atomic resolution of the three-dimensional internal structure of a single protein with chemical specificity
  - discovering of stable new compounds by manipulating atoms at room temperature
  - tracking electrons with sufficient speed to observe intermediate steps in chemical reactions
  - concurrent imaging of processes throughout an entire cell
  - new portable and inexpensive nanoscale instruments capable of operating in an industrial environment
  - developing *in situ* instrumentation for nanomanufacturing process control
  - developing easy to use instrumentation for non-specialists and education
Figure 13. (left) Lithography tools for nanoscale manufacturing. Imprint lithography produces sub-30nm resolution nanomaterials with less than 10 nm alignment over hundreds of millimeters (Molecular Imprints, Inc., Imprio® 300); (right) Imaging photo of current generation in an organic solar cell and current size of vector across an operating oxide device.

Figure 14. Faster increases in x-ray brilliance over the last 50 years in comparison to increase in computer processor speed.

Figure 15. Relation of advances in scanning probes to space, time and complexity. The future is in extending these probes into the regions in the center where spatial resolution, time resolution, and complexity can be simultaneously probed.
**SYNTHESIS, PROCESSING, AND MANUFACTURING OF COMPONENTS, DEVICES, AND SYSTEMS**

**Advances in the last ten years:**

- Nanotechnology has penetrated not only most disciplines in science and engineering, but also R&D for most of the production sectors of the economy. Nanotechnology has been used in commercial products, including coatings, industrial chemicals, cosmetics, textiles and magnetic storage devices, among many others.

- **Creation in the laboratory of a library of nanocomponents** such as particles, tubes, two- and three-dimensional structures, covering most of the chemical elements in the periodic table. There has been important basic research on toolkits for synthesis, fabrication, and patterning of nanostructures, in addition to bio-inspired synthesis and directed self-assembly.

- **Advances in nanofabrication** are illustrated by three-dimensional programmable polymeric structures, bi-inspired nanostructures, first molecular machines, graphene devices, metamaterials, (which have reverse diffraction index not encountered in nature), nanoscale printing by contact, and lithography based on scanning probes. Manufacturing has emerged with a myriad of focus areas and new approaches such as modular nanotechnology, scale-up synthesis of plasmonic materials, and nano-bio inspired and desk-top distributed methods.

**Vision for the next decade:**

- **Fundamental understanding of the pathways for atomic and molecular self-assembly** to develop a library of nanostructures (particle, wire, tubes, sheet, coatings, three-dimensional modular assemblies) of various chemical compositions in industrial-scale quantities.

- Achieve two- and three-dimensional macroscopic materials control in nanomanufacturing, with the ability to dictate where **building blocks are placed down to 1-nm resolution**.

- **Three illustrations:**
  - Power cables manufactured from carbon nanotubes for better efficiency and less weight
  - Recent research involving block copolymers as a platform to create self-assembled templates for nanoscale patterning for more efficient flash electronic memory devices
  - Manufacturing of metamaterials with nanostructures not encountered in nature
Figure 16. Examples of new synthesis and fabrication methods: (left) Precursor Janus dendrimers and dendrimersome with its cell-membrane-like bilayers of few nanometer thick first synthesized in 2010; (center) Large surface area nanopatterning using multiple probe technology; and positioning them with nanometer precision over large areas; (right) Random branching alumina nanotubes as an example of fractal nanomanufacturing (multiscale functional material architectures).

Figure 17. A major advance in the last decade: Roll-to-roll production of graphene for transparent conducting electrodes. This illustrates the broader area of carbon-based nanotechnology already leading to production of carbon cables and sheets.
Advances in the last ten years:

- Although exposure to engineered nanomaterials in the workplace, laboratory, home, and the environment is likely more widespread than previously realized, *no specific human disease or verifiable environmental mishap* has been ascribed to these materials to date. Public perceptions of engineered nanomaterials hazards have evolved from “small is dangerous” to a more realistic understanding that safety should be considered in terms of the specific-use contexts, applications and exposures.

- *Complex interdisciplinary programs and international community have been established.* The NSF established a research program solicitation with a focus on nanoscale processes in the environment in August 2000, and about 7% of its budget is currently for nano-EHS. The EPA has had a research program solicitation on nanotechnology EHS since 2003, and the National Institute for Environmental Health Sciences established one in 2004.

- The number of peer-reviewed publications on nano-EHS risk assessment has increased rapidly, amounting to over 250 papers in 2009, as compared to about 50 in 2004, *increasing faster than other publications in nanoscale science and engineering.* The research community has increasingly collaborated with industry, regulators and insurers to proactively address potential concerns of engineered, incidental and natural nanomaterials.

Vision for the next decade:

- The discovery and development of *predictive methods for engineered nanomaterials* for property–toxicology activity relationships, high-volume data sets, and computational methods used to establish knowledge domains, risk modeling, and nano-informatics capabilities to reliably assist decision-making.

- One goal for 2020 is to *develop validated hazard assessment methodologies and strategies* that consider the correct balance of in vitro and in vivo testing, of biologically relevant screening platforms, and of high-throughput methods. It includes further understanding of nano-biological interfaces.

- Another goal is to *develop risk reduction methodologies and strategies* that can be implemented through commercial nanoproduct data collection, regulatory activity, and EHS research directly linked to decision making.

- A key issue for academia, industry, and government is to effectively *communicate, inform and involve public participation* in the dialogue on the beneficial implications of nanotechnology, the potential for risk, and what is being done to ensure safe implementation of the technology.
Figure 18. This nano-information pyramid illustrates development of an incremental information-sharing collaboration between government, academia, industry, and public.

Figure 19. UC Center for Environmental Implications in Nanotechnology uses a predictive model for hazard ranking and risk profiling.
NANOTECHNOLOGY FOR SUSTAINABILITY: ENVIRONMENT, WATER, FOOD, MINERALS, AND CLIMATE

Advances in the last ten years:

- The global sustainability challenges facing the world are complex and involve multiple interdependent areas. Nanotechnology offers fundamentally new approaches for a clean environment, water resources, food supply, mineral resources, green manufacturing, habitat, transportation, and addressing climate change. We now have a better understanding of the planetary sustainability limits and how nanotechnology can help.

- Nanotechnology has provided solutions for more than half of the new projects on energy conversion, energy storage, and carbon encapsulation in the last decade. Discovery of high-porosity nanostructured materials has lead to metal organic frameworks, covalent organic frameworks, and zeolite imidazolate frameworks, for improved hydrogen storage and CO₂ sequestration.

- A broad range of polymeric and inorganic nanofibers and their composites for environmental separations and catalytic treatment have been synthesized. Nanocomposite membranes and nanosorbents have been developed for water purification, desalinization, oil spill cleanup, and environmental remediation.

Vision for the next decade:

A world in balance:

- A main goal is developing a coordinated approach to use nanotechnology innovation for breakthrough solutions in sustainable development. Nanotechnology applications are expected to significantly extend the limits of sustainability. For illustration, in water resources, the nanostructured membranes and materials with large surface areas discovered in the last decade will be optimized and scaled-up for a variety of applications, including water filtration and desalination, hydrogen storage, and carbon capture.

- Methods to better capture carbon and nitrogen using nanoscale processes will be developed for reuse at industrial scale. Nanotechnology has the potential to provide cost-effective sorbents for CO₂ separation from the flue gases of fossil-fuel-fired power plants and relevant industrial plants.

- Small-scale and ubiquitous sensors will be developed and deployed that will allow real time monitoring of environmental systems, including air, water, and soils.
Figure 21. Sustainability is at the intersection of environment, economic and social factors. Nanotechnology applications will have to balance the beneficial effects and potential negative effects on these interconnected factors.

Figure 22. Geoengineering concept for using magnetic nanodisks for sunlight reflection in upper atmosphere over the South pole. International projects will be developed to consider Earth cooling effects and environmental safety.
NANOTECHNOLOGY FOR SUSTAINABILITY: ENERGY CONVERSION, STORAGE, AND CONSERVATION

Advances in the last ten years:

- Rapid improvement has been made in efficiency and scalability of using nanotechnology for solar energy conversion. The power conversion efficiency of nanostructured organic cells has increased by about eight times since 2000. Nanostructuring has also been demonstrated as a viable means to increase the efficiency of current extraction by decreasing the distance charges have to travel, which would allow the use of lower cost, inorganic materials for photovoltaic applications without sacrificing performance.

- A number of research groups have been able to construct systems that emulate photosynthesis, converting sunlight into fuel in the laboratory.

- Alternative nanostructured materials incorporating cheap and available materials have increased the storage capability of electrical super capacitors.

Vision for the next decade:

- Application of nanotechnology will significantly lower costs and make economic solar energy conversion by about 2015 in the United States. Mass use of nanotechnology for energy conversion is envisioned after 2015-2016, when the cost of terawatt-scale solar energy generation will approach that of fossil energy. Crystalline silicon will be replaced with cheap and abundant alternative materials, such as iron disulfide, for photovoltaics. Use of nanoparticles and quantum dots will be applied in carrier multiplication and hot-carrier collection strategies to overcome the Shockley-Queisser 31% efficiency limit in thin-film photovoltaic devices.

- Nanostructured catalysts and thermoelectric materials will be designed to economically convert electricity and sunlight into chemical fuels.

- It is expected that nanotechnology will become a critical enabling technology for energy efficiency in buildings, transportation, mining, electricity generation and transmission, and battery power. The next decade will witness the development of new classes of nanostructured battery systems for electric vehicles with large range of action.
Figure 23. Goal for residential use of photovoltaic technologies estimated to become economic by about 2015 (DOE).

Figure 24. Nanotechnology and nanomaterials can impact all areas of the energy sustainability cycle.

Figure 25. Green building components.
Nanobiosystems and nanomedicine are two of the most exciting and fastest-growing areas in nanotechnology research. Nanomedicine has made significant breakthroughs in the laboratory, advanced rapidly in clinical trials, and made inroads in applications of biocompatible materials, diagnostics, and treatments. Advanced therapeutics have led to ten commercialized products based on nanotechnology, such as Abraxane, making a significant impact in treating several forms of cancer.

Development of diagnostic methods that are sensitive down to picomole and attomole levels and allow for multiple analytes to be assessed simultaneously by lab-on-a-chip approaches.

Five other nanotechnology outcomes: controlled development of molecules to promote tissue repair and regeneration in situ; achievement of partial nanoscale control in synthetic biology; products that are on track to meet the $1,000 genome challenge; the nano-enabled bio-barcode assay, which is a detection technology that provides significant sensitivity advantages over conventional methodologies; and FDA approvals for the first nanotherapeutics.

Many order-of-magnitude increased sensitivity, selectivity, and multiplexing capabilities at low cost will enable point-of-care diagnosis and treatment. They include noninvasive diagnostics based on breath and saliva nanoscale detection.

Overcome many challenges such as pharmacokinetics, biodistribution, targeting, and tissue penetration by drugs to support widespread adoption by industry of nanotherapeutics. At least 50% of all drugs used in 2020 will be enabled by nanotechnology. Many of these will be for diseases like glioblastoma, pancreatic cancer, and ovarian cancer, where patient prognosis is grim with current therapies. Adoption of nanomaterials by the pharmaceutical community will increase the effectiveness of chemotherapeutics while reducing toxic side effects. The potential is supported by the fact that in 2010 over 50 cancer-targeting drugs based on nanotechnology are in clinical trials in the United States alone.

Nanostructured implants with potential advantages over conventional materials can significantly enhance bone, cartilage, vascular, bladder, and nervous tissue regeneration. Widespread use by 2020 of nano-enabled tissue constructs is envisioned for repair of cardiac damage in heart attack victims. Widespread use by 2020 of nanotechnology-enabled stem-cell therapies is envisioned for spinal cord regeneration. Synthetic biology with control at the nanoscale will be used in regenerative medicine, biotechnology, and pharmaceuticals.
**Figure 26.** The cornerstones of nanomedicine.

**Figure 27.** Abraxane is a FDA-approved therapeutic which relies on albumin protein nanoparticles as a paclitaxel carrier for more efficient drug delivery to tumor sites.

**Figure 28.** Myocardial cells sheet engineering. Cell sheet technology is based on the use of thermo responsive polymers, poly(N-isopropylacrylamide), which are hydrophobic at 37°C, allowing primary tissue culture cells to lay down an ECM, which remains intact when the temperature of the culture dish is brought down to 20°C and the cell sheet released due to the fact that the polymer then becomes hydrophilic. Harvesting of numerous layers of myocyte cell sheets allows layering and the formation of a 3D spontaneously beating myocardial-like tissue construct that can be used for patching real-life myocardial defects as well as offering the possibility to reconstruct an entire myocardial tube.
## Advances in the last ten years:

- The semiconductor industry has doubled the number of field-effect transistors on a chip every 18–24 months, i.e. Moore’s Law. As a result, the number of products that use semiconductor chips has greatly expanded, from supercomputers to cell phones to toasters. Continuation of the Moore’s Law has led to scaling from devices at or above 100 nm to 30 nm dimensions. It includes an approximate 1 nm gate insulator, with monolayer accuracy across a 300 nm wafer, and transistors for logic and memory of about 15 nm. The industry has hit a record high of $300B in 2010, with 60 percent at the nanoscale, and the U.S. market share being approximately 50% of total.

- Discovery of the quantum spin Hall effect and demonstration of spin transfer torque, which enable direct control of electron spin and magnetic domains by electrical current. Research, design, and manufacturing of magnetic random access memory (MRAM) nonvolatile memory device.

- First fundamental experiments on quantum computing using small numbers of quantum bits.

## Vision for the next decade:

- Goals for nanoelectronics by 2020 include: achieving three-dimensional near-atomic-level control of reduced dimensional materials; combining lithography and self-assembly to pattern semi-arbitrary structures down to 1 nm precision; discovering devices for logic and memory that operate with greatly reduced energy dissipation; exploiting spin for memory, logic, and new functionality; integrating architecture and nanoscale device research for unique computation functionality; and increasing focus on emerging, non-IT applications.

- Increased R&D will focus on phenomena at 10 nm and below for all devices. There needs to be a paradigm shift in order to get beyond the traditional CMOS device to use the new physics offered at the nanoscale to increase device functionality. Discover and potentially use an alternative state variable for representing information instead of electron charge.

- Advances in the understanding of oxygen vacancy transport in metal oxides and other effects that can induce resistance changes in material stacks will find applications in resistive memory devices. One example is the “memristor” device that may be useful in memory, storage, and even circuits that mimic the synaptic functions of the human brain. Realize quantum computers for specific uses.
**Figure 29.** Nanoelectronics impact on society: Increase of computations per second for $1,000.

**Figure 30.** Schematic of spin-torque memory circuit, and a cross section of an individual 40 nm wide memory element (IBM).

**Figure 31.** Emerging multiscale information technology platform using nanotechnology (SRC).
APPLICATIONS: NANOPHOTONICS AND PLASMONICS

Advances in the last ten years:

- The young field of plasmonics has rapidly gained momentum, enabling exciting new fundamental science as well as groundbreaking real-life applications in terms of targeted medical therapy, ultrahigh-resolution imaging and patterning, and control of optical processes with extraordinary spatial and frequency precision.

- Many new technologies have emerged in which one uses plasmonics, including thermally assisted magnetic recording, thermal cancer treatment, catalysis and nanostructure growth, solar cells with quantum dots, and computer chips. High-dielectric-constant materials also can effectively be used as antennas, waveguides, and resonators, and their use deserves further exploration. First demonstrations of metamaterials (materials with reverse diffraction index) at visible and near-infrared wavelengths have been performed.

- Achievement of slowed light in solid state nanophotonic structures, which enables applications and information systems never before available to photonic systems, such as delaying and storing optical signals.

Vision for the next decade:

- Several goals for 2020 include: achieving integration with electronic circuits for ultrasmall, ultra-high speed information and communication applications; controlling light trapping and device integration for applications in the living world; using light to control the thermal and mechanical performance of materials; achieving control over the flow of light; and exploiting synergies between plasmonics, photonics, and electronics. Use plasmonic enhanced-emission and detection will allow controlled absorption and emission of light from single molecules.

- Nanophotonic structures and devices promise dramatic reductions in energies of device operation, densely integrated information systems with lower power dissipation, enhanced spatial resolution for imaging and patterning, and new sensors of increased sensitivity and specificity.

- Nanophotonics and plasmonics will have dramatic enabling capabilities for new medical therapies; low-power, high-bandwidth, and high-density computation and communications; high-spatial-resolution imaging and sensing with high spectral and spatial precision; efficient optical sources and detectors; and a host of profound scientific discoveries about the nature of light–matter interactions.
Future Technology for Photonics:
Next-generation information, communication, quantum processing, 3D photonic circuits, laser processing, display, lightings, high efficient solar cell, bio, sensing, etc.

Ultimate Control of Photons

A. On-demand photon control
I. Ultimate light confinement and dynamic control
II. Ultimate 3D photonic crystals

B. Toward industrial applications and energy issue contribution

C. Materials, nanotechnology and fundamentals
V. Nanophotonic materials and fabrication
III. Ultimate broad area coherent laser technology

IV. Highly efficient photon-electron conversion

Figure 32. Vision of silicon photonics for optical interconnects in future electronics (IBM).

Figure 33. Slowing the speed of light near metallic surfaces is used in the field of plasmonics defined after 2004.

Figure 34. Control of photons leads to diverse applications.

Figure 35. Quantum dots drive development of key technologies.
APPLICATIONS: CATALYSIS BY NANOSTRUCTURED MATERIALS

Advances in the last ten years:

- Rapid developments in spectroscopic tools and atomic-resolution electron microscopy have revolutionized scientists’ understanding of catalyst structures at the nanoscale. Computational catalysis has reached the stage in which it provides a complement to experimental research. Advances in computer processor speeds, large-scale parallel architectures, and more efficient theoretical and computational methods allow for complex simulations of catalytic reactions on solid surfaces.

- The global catalyst business is an $18–20 billion per-year enterprise for petroleum refining, chemicals processing, and environmental applications. Nanostructured catalysts introduced after 2000 represent 30–40% worldwide of all catalysts used in the oil and chemical industries. The broader, value-added impact of catalytic processing on the U.S. economy alone is estimated at several hundred billion dollars per year.

- Progress has been made in the synthesis of new nanostructured catalysts that can more efficiently and selectively convert low-grade hydrocarbons into higher-value fuels. Advances in instrumentation have made possible monitoring of catalysts in their working state.

Vision for the next decade:

- Although advances in theoretical descriptions of complex reactions and models that span multiple time and length scales have been realized, additional improvements will enable the predictive computational capabilities, especially in liquid phase systems. An overall goal is precise control of composition and structure of catalysts over length scales spanning 1 nm to 1 μm, allowing the efficient control of reaction pathways.

- Nanostructured catalysts will efficiently and selectively convert lower-grade hydrocarbons into higher-value fuels and chemical products, efficiently harness solar power, efficiently use of biomass and cellulosic materials for energy conversion, and redirecting energy selectively into driving thermodynamically uphill chemical processes.

- New nanostructured catalysts will cover at least 50 percent of the market worldwide by 2020.
**Figure 36.** Hierarchy of time and length scales in heterogeneous catalysis, and associated modeling methods.

![Hierarchy of time and length scales in heterogeneous catalysis, and associated modeling methods.](image)

**Figure 37.** Illustration of commercial nanotechnology: ExxonMobil, Chevron, Dow Chemicals, and other companies have used nanostructured catalysts developed since 2000 for more efficient upgrading of crude oil into transportation fuels and petrochemicals. Examples are redesigned aromatics and nanoporous silica materials such as MCM-41.

![Illustration of commercial nanotechnology: ExxonMobil, Chevron, Dow Chemicals, and other companies have used nanostructured catalysts developed since 2000 for more efficient upgrading of crude oil into transportation fuels and petrochemicals. Examples are redesigned aromatics and nanoporous silica materials such as MCM-41.](image)
Advances in the last ten years:

- Realization of bulk nanocomposites and coatings with predictable and unique properties based on monodisperse nanoscale building blocks (e.g., transparent conductors based on carbon nanotubes and graphene, and ductile high-strength metals).

- Nanotechnology has enabled the development of nanofluidic devices and systems, products using nanofibrous media, nanoscale sensors, lighter nanocomposites for use in aerospace, and numerous other multifunctional nanomaterials and nanoscale devices.

- The forest products industry has identified nanotechnology as a means to tap the enormous undeveloped potential of trees as photochemical “factories” that produce abundant sources of raw materials from sunlight and water. Cellulose wood fibers have been introduced in nanocomposite materials.

Vision for the next decade:

- Develop a complete library of monodisperse nanomaterials at industrial-scale quantities, and realize hierarchical nanostructured materials with independent tunability of previously coupled properties; that is, decoupling optical and electrical properties for photovoltaics used in display technology, and decoupling electrical and thermal properties for thermoelectrics using in energy conversion.

- Realize nanocomposites for structural components, for example enabling 40% weight reduction in airplane designs with better overall performance.

- Achieve scalable nanofluidic systems for processing in biotechnology, pharmaceuticals, and chemical engineering. Generally, the rational assembly of nanomaterials into nanocomposites and of nanocomponents into systems will yield high-performance products driving the development of previously unrealizable applications.
**Figure 38.** Fullerenes, atomic clusters, and larger inorganic crystals can be assembled to create materials and devices with tailored properties. Applications include photovoltaics (*top*), optical biosensors (*middle*) and electronics (*bottom*).

**Figure 39.** Examples of applications of nanostructured hybrid materials.

- **Improved transmission**—line and motor insulation
- **Skin care and UV protection**
- **Wear reduction in industrial conveyor belts**
Advances in the last ten years:

- In 2000, the NNI Implementation Plan recognized that nanoscale science and engineering education is vital to economic development, public welfare, and quality of life. Nanotechnology is now seen as a driving force for major industries worldwide and as playing a key role in solving challenges in energy, water, environment, health, information technology, and security.

- Establishment of over 150 interdisciplinary research centers and user facilities in the United States and many others worldwide, providing broad access to fabrication and characterization facilities. Creation of the Nanoscale Computation Network in 2002, redesign of the National Nanotechnology Infrastructure Network in 2003, and establishment of the Network for Informal Science Education in 2004, providing more democratic and global access to nanoscale science and engineering knowledge and tools.

- There were over half million nanotechnology researchers and workers in 2010 worldwide with an annual rate of increase of about 25 percent. Nanotechnology has emerged as a topic of interest on websites, in exhibits, and in educational programs at science museums around the world, including at Walt Disney World’s Epcot Center.

Vision for the next decade:

- Expand the breadth of interdisciplinary research and education center capabilities and extend the geographical distribution for more widespread access, and create open access centers and networks for discovery and development of innovative nano-enabled device and systems. Partnerships between countries, industries, and universities; and continued Federal support will be essential.

- Embed nanoscale science and engineering education in internationally benchmarked standards and curricula at all levels of education, but especially in the K–12 grades.

- To compete effectively in world markets, there must be continued attention to basic research, motivated and skilled entrepreneurs who can transition discovery into innovative technologies, state-of-the-art equipment for fabrication and characterization, well-trained workers, and well-informed, nanotechnology-literate citizens to sustain the workforce pipeline and public support.
**Figure 40.** The five DOE Nanoscale Science Research Centers.

**Key Education Networks**

**Figure 41.** U.S. nanotechnology infrastructure in 2010: Key education networks.
Advances in the last ten years:

- An international community has been established of nanotechnology professionals, with a sophisticated R&D infrastructure, and diverse manufacturing capabilities spanning the chemical, electronics, advanced materials, and pharmaceutical industries, as well as increasing attention to nanotechnology environmental, health and social implications. Developments in nomenclature, patents, standards, and standard materials have been initiated in national and international organizations.


- The vision of international collaboration and competition, including in multinational organizations, has been realized since the first International Dialogue on Responsible Development of Nanotechnology conference, held in the US in 2004.

Vision for the next decade:

- Knowledge, people, and regulatory capacity need to be prepared to address mass application of nanotechnology by 2020. Science-driven governance will be guided by societal needs to responsibly address broad societal challenges such as sustainability and health, and handling of the new generations of nanotechnology products.

- Emphasis is expected to increase on innovation and commercialization. Nanotechnology will become an enabling technology for many applications. Governance of nanotechnology will become institutionalized, and global coordination will be needed for international terminology, standards, reference materials, materials certification as well as environmental and health safety aspects.

- Public-private partnerships will integrate discovery and innovation programs, so that academics, industry managers, economists, and regulators are involved throughout the innovation process for societal benefit.
**Figure 42.** Key functions in nanotechnology governance: visionary, transformative, responsible and inclusive functions.

**Figure 43.** Products touched by nanotechnology generated $254 billion worldwide in 2009.
U.S. AND INTERNATIONAL WORKSHOPS
The study “Nanotechnology Research Directions for Societal Needs in 2020” received input from five brainstorming meetings titled “Long-term Impacts and Future Opportunities for Nanoscale Science and Engineering.” Public comments on the draft report were also considered.
Details are at http://www.wtec.org/nano2/

CHICAGO NATIONAL WORKSHOP
Chicago (Evanston), U.S. March 9-10, 2010
Hosted by WTEC
Sponsored by: NSF
96 participants
Agenda at http://www.wtec.org/nano2/docs/Chicago/Agenda.html

EUROPEAN UNION WORKSHOP
Hamburg, Germany. June 23-24, 2010
Hosted by Deutsches Elektronen-Synchrotron (DESY)
Sponsored by: European Commission (EC), DESY, and NSF
60 participants
Agenda at http://www.wtec.org/nano2/docs/Hamburg/Agenda.html

JAPAN, KOREA, AND TAIWAN WORKSHOP
Tokyo (Tsukuba), Japan. July 26-27, 2010
Hosted by the Japan Science and Technology Agency (JST).
Sponsored by: JST, MEST, NSC, and NSF
96 participants
Agenda at http://www.wtec.org/nano2/docs/Tokyo/Agenda.html

AUSTRALIA, CHINA, INDIA, SAUDI ARABIA, AND SINGAPORE WORKSHOP
Singapore. July 29-30, 2010
Hosted by Nanyang Technological University (NTU).
Sponsored by: Australia, China, India, Saudi Arabia, Singapore, and NSF
61 participants
Agenda at http://www.wtec.org/nano2/docs/Singapore

ARLINGTON FINAL WORKSHOP
Arlington, Virginia, U.S. September 30, 2010
Hosted by the National Science Foundation,
Sponsored by: NSF and USDA.
90 participants
Agenda at http://www.wtec.org/nano2/
Webcast at http://www.tvworldwide.com/events/NSFnano2/100930/

Public comments: received between September 30, and October 30, 2010
“Nanotechnology Research Directions for Societal Needs in 2020 is a wonderful piece of work. This book reflects the bible for nanotechnology for the next decades and for the whole world. Well done.”

—Professor Marcel van de Voorde, Delft University of Technology, Delft, November 2010

“The National Nanotechnology Initiative story could provide a useful case study for newer research efforts into fields such as synthetic biology, renewable energy or adaptation to climate change.”

—David Rejeski, Woodrow Wilson International Center for Scholars, September 2010

“This book provides a comprehensive vision and an overarching roadmap for the nanotechnology community. It comes at a great time as we move into the next decade of nano-enabled commercialization.”

—Vincent Caprio, Executive Director, NanoBusiness Commercialization Association, November 2010

“Some of these [nanotechnology] research goals will take 20 or more years to achieve. But that is why there is such a critical role for the federal government.”

—President Bill Clinton, Speech announcing NNI at Caltech, January 2000