CHANGING RESEARCH PRIORITIES
IN NANOSCALE SCIENCE AND ENGINEERING

Mike Roco
National Science Foundation and National Nanotechnology Initiative

Virginia Tech, April 26, 2012
Topics

• Nanotechnology timeline: 2000-2020
• Main outcomes at 10 years
• Changing R&D priorities
• Outlook for the future

Related publications
“Nanotechnology: From Discovery to Innovation and Socioeconomic Projects” 2010-2020 (2011)
“The Long View of Nanotechnology development: the NNI at 10 Years” (2011)
“Nanotechnology Research Directions for Societal Needs in 2020” (2011)
10-year vision documents, 3-year strategic plans, 1-year plans and topical workshops: www.nsf.gov/nano; www.nano.gov
Nanotechnology at the core of convergence of new emerging technologies (foundational tools)

Examples of emerging technologies and corresponding U.S. long-term S&T projects

Justified mainly by societal/application factors (examples)

- Manhattan Project, WW2 (centralized, goal focused, simultaneous paths)
- Project Apollo (centralized; goal focused)
- AIDS Vaccine Discovery ("big science" model, Gates Foundation driven)
- IT SEMATECH (Roadmap model, industry driven)

Justified mainly by science and technology potential, following a competitive process

- National Nanotechnology Initiative (bottom-up, science opportunity-born for a general purpose technology)
Nanotechnology Definition for the R&D program

Working at the atomic, molecular and supramolecular levels, in the length scale of ~ 1 nm (a small molecule) to ~ 100 nm range, in order to understand, create and use materials, devices and systems with specific, fundamentally new properties and functions because of their small structure (natural threshold)

NNI definition encourages new R&D that were not possible before:

- the ability to control and restructure matter at nanoscale
- collective effects → new phenomena → novel applications
- integration along length scales, systems and applications
“Vision for nanotechnology in the next decade”, 2001-2010
based on R&D definition focused on behavior

Systematic control of matter on the nanoscale will lead to a revolution in technology and industry
- Change the foundations from micro to nano
- Create a general purpose technology (similar IT)

More important than miniaturization itself:
Novel properties/ phenomena/ processes/ natural threshold
Unity and generality of principles
Most efficient length scale for manufacturing, biomedicine
Show transition from basic phenomena and components to system applications in 10 areas and 10 scientific targets

Periodic table

Atom diameters
- ~ 0.1 nm Hydrogen, Carbon
- ~ 0.5 nm Gold, Platinum

A small molecule
about 1 nm
Natural and synthetic nanoscale modules ~1 to 100 nm

Examples for first level of organization of atoms and molecules with a large variety of structures, properties and functions.
Nanoproducts and Nanomanufacturing

- Fragmentation
- Patterning
- Restructuring of bulk
- Lithography, ..

- Interfaces, field & boundary control
- Positioning assembly
- Integration, ..

- System engineering
- Device architecture
- Integration, ..

- Nanosystem biology
- Emerging systems
- Hierarchical integration..

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From Nanoscale Modules

Assembling

- Directed selfassembling,
- Templating,
- New molecules

- Multiscale selfassembling,
- In situ processing, ..

- Eng. molecules as devices,
- Quantum control,
- Synthetic biology..

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PASSIVE NANOSTRUCTURES - ACTIVE NANOSTR. - SYSTEMS OF NANOSYSTEMS - MOLECULAR NANOSYSTEMS

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Timeline for beginning of industrial prototyping and nanotechnology commercialization

1st: Passive nanostructures (1st generation products)
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

2nd: Active nanostructures
Ex: 3D transistors, amplifiers, targeted drugs, actuators, adaptive structures

3rd: Nanosystems
Ex: guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary

4th: Molecular nanosystems
Ex: molecular devices ‘by design’, atomic design, emerging functions

Converging technologies
Ex: nano-bio-info from nanoscale, cognitive technologies; large complex systems from nanoscale

CREATING A NEW FIELD AND COMMUNITY IN TWO FOUNDATIONAL STEPS (2000 ~ 2020)

Mass Application of Nanotechnology after ~ 2020

NS&E integration for general purpose technology
~ 2011 to ~ 2020
Direct measurements; Science-based design and processes; Collective effects; Create nanosystems by technology integration

Foundational interdisciplinary research at nanoscale
~ 2001 to ~ 2010
Indirect measurements, Empirical correlations; Single principles, phenomena, tools; Create nanocomponents by empirical design

New disciplines
New industries
Societal impact

Infrastructure
Workforce
Partnerships

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Nanotechnology: from discovery to innovation and socioeconomic projects (2000-2020)

**nano1** (2000-2010)

**nano2** (2010-2020)

NSF/WTEC, www.wtec.org/nano2/
NNI timeline
(2000-2020)

- Interagency group (11/1996); NNI is proposed at WH (3/1999); Competition OMB (10/1999); PCAST supports NNI (12/1999); President Clinton announces NNI in 1/2000

- NNI/NSTC subcommittee established (8/2000); NNI begins (10/2000); MOU for NNI coordination and NNCO (1/2001); NanoBusiness Alliance

- President Bush signs 21st Century Nanotechnology R&D Act (12/2003); International Dialogue initiated by NNI (6/2004), followed by OECD, ISO

- President Obama approves PCAST (2010) vision for NNI to 2020

- NNI Signature Initiatives (2011-2015) for creating nanosystems

- Institutionalize NSE (2016-2020) for general purpose technology
National Nanotechnology Initiative

Collaborative, multi-agency, cross-cut program among 25 Federal agencies with a range of research, industry, trade, educational and regulatory roles and responsibilities.
Estimates show an average quasi-exp growth rate of key nanotechnology indicators of 16% - 33%.

<table>
<thead>
<tr>
<th>World (US)</th>
<th>People -primary workforce</th>
<th>SCI papers</th>
<th>Patents applications</th>
<th>Final Products Market</th>
<th>R&amp;D Funding public + private</th>
<th>Venture Capital</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2000</strong> (actual)</td>
<td>~ 60,000 (25,000)</td>
<td>18,085 (5,342)</td>
<td>1,197 (405)</td>
<td>~ $30 B ($13 B)</td>
<td>~ $1.2 B ($0.37 B)</td>
<td>~ $0.21 B ($0.17 B)</td>
</tr>
<tr>
<td><strong>2010</strong> (actual)</td>
<td>~ 600,000 (220,000)</td>
<td>78,842 (17,978)</td>
<td>~ 20,000 (5,000)</td>
<td>~ $300 B ($110 B)</td>
<td>~ $18 B ($4.1 B)</td>
<td>~ $1.3 B ($1.0 B)</td>
</tr>
<tr>
<td><strong>2000 - 2010 average growth</strong></td>
<td>~ 25% (~23%)</td>
<td>~ 16% (~13%)</td>
<td>~ 33% (~28%)</td>
<td>~ 25% (~24%)</td>
<td>~ 31% (~27%)</td>
<td>~ 30% (~35%)</td>
</tr>
<tr>
<td><strong>2015</strong> (estimation in 2000)</td>
<td>~ 2,000,000 (800,000)</td>
<td>~ $1,000B ($400B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2020</strong> (extrapolation)</td>
<td>~ 6,000,000 (2,000,000)</td>
<td>~ $3,000B ($1,000B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2020 - 2010 average growth:
- People -primary workforce: ~ 35%
- SCI papers: ~ 16%
- Patents applications: ~ 55%
- Final Products Market: ~ 25%
- R&D Funding public + private: ~ 31%
- Venture Capital: ~ 30%

Evolving Topics:
2000-2010
Changing international context:
federal/national government R&D funding (NNI definition)

R&D FUNDING (million $ / year)

- W. Europe
- Japan
- USA
- Others
- Total

Industry $ > Public $

Seed funding 1991 - 1997
NNI Preparation vision/benchmark
1st Generation products passive nanostructures
2nd Generation active nanostructures
3rd Generation nanosystems

Rapid, uneven growth per countries

--- | --- | ---
USA | ~ 1,781 | ~ 5.8
EU-27 | ~ 2,200 | ~ 5.9
Japan | ~ 950 | ~ 7.3
China | ~ 550 | ~ 0.5
Korea | ~ 310 | ~ 6.0
Taiwan | ~ 110 | ~ 4.5

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Nanoscale Science and Engineering
FY 2012 C.P.: $426M across NSF

- **Fundamental research and innovation** in all areas of science and engineering: ~5,000 active projects in all 50 states in 2011
- **Training and education**: >10,000 students and teachers/y; ~$30M/y
- **Infrastructure**: 30 large centers, 2 large user facilities (NNIN and NCN), ~100 universities with major equipment and NSE teams
NANOTECHNOLOGY OUTPUTS AT 10 YEARS

Nanotechnology publications in the Science Citation Index (SCI) 1990 - 2011

Data was generated using “Title-abstract” search in SCI database for nanotechnology by keywords (Chen and Roco, NRC, 2012)

Rapid, uneven growth per countries

2000-2011 Worldwide annual growth rate - 16%

MC Roco, April 26, 2012

Data was generated using “Title-abstract” search in SCI database for nanotechnology by keywords (Chen and Roco, NRC, 2012)

USA ~ 65% in 2011

U.S. maintain the lead in highly cited publications
WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY
(Estimation made in 2000 after international study in > 20 countries)

Passive nanostructures
Active nanostructures
Nanosystems by design

World annual rate of increase ~ 25%; Double each ~ 3 years

~ $40B
~ $120B
~ $250B
~ $91B, U.S.
$1T by 2015
$3T by 2020

Final products incorporating nanotechnology in the world

Reference: Roco and Bainbridge, Springer, 2001
Percentage of nanotechnology content in NSF awards, ISO papers and USPTO patents (1991-2011)
(update after Encyclopedia Nanoscience, 2012)

Documents searched by keywords in the title and abstract/claims

Top 20 Journals' Nano Paper Percentage
3 Selected Journals' Nano Paper Percentage
Title-claim Search's Nano Patent Percentage
NSF Nano New Award Percentage

2011 Top nano J. ~ 13%
2011 NSF grants ~ 11%
2011 All journals ~ 5%
2011 USPTO patents ~ 1.9%
2011 Market /US GDP ~ 0.8%

Similar, delayed penetration curves: for R&D funding /papers /patents /products /ELSI
MC Roco, April 26 2012
Main nanotechnology outcome at 10 years

- **Foundational knowledge of nature** by control of matter at the nanoscale
- **Global interdisciplinary community** (~ 600,000) for R&D, nano-EHS and ELSI
- **Science & technology (S&T) breakthroughs**
- **Novel methods and tools**
- **Extensive multi-domain infrastructure**
- **New education & innovation ecosystems**
- **New industries** with increased added value
- **Solutions for sustainable development**
Remarkable scientific discoveries than span better understanding of the smallest living structures, uncovering the behaviors and functions of matter at the nanoscale, and creating a library of 1D - 4D nanostructured building blocks for devices and systems; Towards periodical table for nanostructures.

New S&E fields have emerged such as: spintronics (2001), plasmonics (2004), metamaterials, carbon nanoelectronics, molecules by design, nanofluidics, nanobiomedicine, nanoimaging, nanophotonics, opto-genetics, synthetic biology, branches of nanomanufacturing, and nanosystems.

Technological breakthroughs in advanced materials, biomedicine, catalysis, electronics, and pharmaceuticals; expansion into energy resources and water filtration, agriculture and forestry; and integration of nanotechnology with other emerging areas such as quantum information systems, neuromorphic engineering, and synthetic and system nanobiology.
Example: Emergence of Plasmonics after 2004

Plasmonics: Merging photonics, electronics and materials at nanoscale dimensions

![Number of NSF Awards Graph](image)

![Published Items in Each Year](image)

![Citations in Each Year](image)

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The simplest quantum states of motion with a vibrating device was measured (the board of aluminum is as long as a hair is wide). It can absorb and emit energy only in quanta proportional to the beam’s frequency; continuously in motion about a zero-point motion; two states (Aaron O'Connell and Andrew Cleland, UCSB, 2010)
Discovery of Nanoscale Repulsion
Federico Capasso, Harvard University

A repulsive force arising at nanoscale was identified similar to attractive repulsive Casimir-Lifshitz forces.

As a gold-coated sphere was brought closer to a silica plate - a repulsive force around one ten-billionth of a newton was measured starting at a separation of about 80 nanometers.

For nanocomponents of the right composition, immersed in a suitable liquid, this repulsive force would amount to a kind of quantum levitation that would keep surfaces slightly apart.
Example: Mechanism of self-assembling of a carbon nanotube

Nanotubes Spin as They Grow on a Catalyst

Field-emission microscopy demonstrates rotation of a growing tube. The atomic wall-tapestry of nanotubes depends on the rate of this rotation (B. Yacobson et al, PNAS, 2009)
How to Teleport Quantum Information from One Atom to Another

Chris Monroe, University of Maryland, NSF 0829424

Teleportation to transfer a quantum state over a significant distance from one atom to another was achieved.

Two ions are entangled in a quantum way in which actions on one can have an instant effect on the other.

Teleportation carries information between entangled atoms.

Experiments have attempted to teleport states tens of thousands of times per second. But only about 5 times in every billion attempts do they get the simultaneous signal at the beam splitter telling them they can proceed to the final step.
Examples:

- *Programmable nanoscale machines* achieved by DNA Self-assembly

- A *two-armed nanorobotic device* that can manipulate molecules within a device made of DNA
IBM magnetic storage is at 100 times denser than hard disk drives and solid state memory chips.

Antiferromagnetic order in an iron atom array on copper nitrate revealed by spin-polarized imaging with a scanning tunneling microscope - area 4 x 16 nm (Bistability in Atomic-Scale Antiferromagnets, Loth, Baumann, C Lutz, Eigler and Heinrich: Science Jan 2012)
Silicon Nanophotonics - chip with three layers

Yurii Vlasov, IBM
Graphite + water = high density energy storage
(G. Jiang, 2011)

Keeping graphene moist – in gel form – provides repulsive forces between the sheets and prevents re-stacking, making it ready for energy storage applications.
FDA-approved and commercially available point-of-care diagnostic methods can enable early disease detection based on blood analysis.

The Verigene® System

Up to six orders of magnitude more sensitive than current approach ELISA for proteins.
Advanced Nanomanufacturing

Roll-to-roll production of graphene for transparent conducting electrodes


U. Texas Austin

Korea/Japan/Singapore Collaboration
Example for hierarchical self-fassembling - 4th NT generation (in research)

Example: Designing new molecules with engineered structures and functionalities

EX: - *Biomaterials for human repair*: nerves, tissues, wounds (Sam Stupp, NU)

- New nanomachines, robotics - DNA architectures (Ned Seeman, Poly. Inst.)
- Designed molecules for *self-assembled porous walls* (Virgil Percec, U. PA)
- Self-assembly processing for *artificial cells* (Matt Tirrell, UCSB)
- Block co-polymers for *3-D structures on surfaces* (U. Mass, U. Wisconsin)
- Polymeric surfaces with *3-D folding* (U. Maryland)
Quantum information science (IT; Nano and subatomic physics; System approach for dynamic/probabilistic processes, entanglement and measurement)

Eco-bio-complexity (Bio; Nano; System approach for understanding how macroscopic ecological patterns and processes are maintained based on molecular mechanisms, evolutionary mechanisms; interface between ecology and economics; epidemiological dynamics)

Neuromorphic engineering (Nano, Bio, IT, neurosc.)

Cyber-physical systems (IT, NT, BIO, others)

Synthetic & system biology (Bio, Nano, IT, neuroscience)

Cognitive enhancers (Bio, Nano, neuroscience)
(B) 2000-2010: Novel Methods and Tools

- **Femtosecond measurements** with atomic precision in domains of biological and engineering relevance
- **Sub-nanometer measurements** of molecular electron densities
- **Single-atom and single-molecule** characterization methods
- **Scanning probe tools for printing**, sub-50 nm “desktop fab”
- **Simulation** from basic principles has expanded to **assemblies of atoms 100 times larger than in 2000**
- **New measurements**: negative index of refraction in IR/visible wavelength radiation, Casimir forces, quantum confinement, nanofluidics, nanopatterning, teleportation of information between atoms, and biointeractions at the nanoscale. Each has become the foundation for new domains in science and engineering
4D Microscope Revolutionizes the Way We Look at the Nano World

A. Zewail, Caltech, and winner of the 1999 Nobel Prize in Chemistry

Use of ultra short laser flashes to observe fundamental motion and chemical reactions in real-time (timescale of a femtosecond, $10^{-15}$ s), with 3D real-space atomic resolution.

Allows for visualization of complex structural changes (dynamics, chemical reactions) in real space and real time. Such visualization may lead to fundamentally new ways of thinking about matter.

Nanodrumming of graphite, visualized with 4D microscopy.

http://ust.caltech.edu/movie_gallery/
Infrastructure
- Developed an **extensive infrastructure** of interdisciplinary research of
  ~ 100 large centers, networks and user facilities
- **Educate and train > 10,000 students and teachers** per year
  ~ 1,000 new curricula in accredited research universities ;
  ~ 30 associate degree nanotechnology programs
- **Established networks for ELSI and public awareness**

R&D&I Results
With ~22% of global government investments, U.S. accounts for
~ 70% of startups in nanotechnology worldwide
> 2,500 U.S. nanotech companies with products in 2010, with
$110B (~38% of the world) products incorporating nano parts
About 100 major NNI centers, networks, user facilities

Alaska is shown at approximately half its size, and Hawaii's size is approximately doubled.

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Nationwide Impact

Ten Nanoscale Science and Engineering networks with national outreach

**TOOLS**

Network for Computational Nanotechnology (2002-) > 180,000 users/ 2011
National Nanotechnology Infrastructure Network (2003-) ~ 7,000 users/ 2011

**TOPICAL**

Nanotechnology Center Learning and Teaching (2004-2011)
Nanoscale Informal Science Education Network (2005-) >200 sites/ 5yr
Network for Nanotechnology in Society (2005-) Involves academia, public, industry
National Nanomanufacturing Network (2006-) 4 NSETs, DOD centers, and NIST
Environmental Implications of Nanotechnology (2008-) with EPA

**GENERAL RESEARCH AND EDUCATION**

NSEC Network (2001-) 19 research and education centers
MRSEC Network (2001-) about 2/3 cover NSE
National Nanomanufacturing Network (2006- )
Its core: Four Nanomanufacturing NSECs

- **Center for Hierarchical Manufacturing (CHM)**
  - U. Mass Amherst/UPR/MHC/Binghamton

- **Center for High-Rate Nanomanufacturing (CHN)**
  - Northeastern/U. Mass Lowell/UNH

- **Center for Scalable and Integrated Nanomanufacturing (SINAM)**
  - UC Berkeley/UCLA/UCSD/Stanford/UNC Charlotte

- **Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS)**
  - UIUC/CalTech/NC A&T

Open-access network
www.nanomanufacturing.org  beta.internano.org

Director: Mark Tuominen
MC Roco, April 26, 2012
nanoHUB.org is a resource for the global Nanotechnology Community. The map below indicates a red-peg for every nanoHUB user on the planet.

http://www.nanoHUB.org est. 190,000 users / 2012 NSF ~ $20 / user

Support global eco-systems via COLLABORATION
National Nanotechnology Infrastructure Network (NNIN)

An integrated national network of 14 user facilities providing researchers open access to resources, instrumentation and expertise in all domains of nanoscale science, engineering and technology

http://www.NNIN.org

Est. 6,800 users / 2011

NSF ~$2,500 / user
Five DOE Nanoscale Science Research Centers (NSRCs)

Center for Nanoscale Materials
Argonne National Laboratory

Molecular Foundry
Lawrence Berkeley National Laboratory

Center for Functional Nanomaterials
Brookhaven National Laboratory

Center for Nanophase Materials Sciences
Oak Ridge National Laboratory

Center for Integrated Nanotechnologies
Los Alamos National Laboratory &
Sandia National Laboratory
NCI Nanotechnology Alliance – Center and Platform Awards

**Centers of Cancer Nanotechnology Excellence (8)**

- Nanotechnology Platform for Targeting Solid Tumors, The Sidney Kimmel Cancer Center, San Diego, Calif.
- Novel Cancer Nanotechnology Platforms for Photodynamic Therapy and Imaging, Roswell Park Cancer Institute, Buffalo, N.Y.
- Multifunctional Nanoparticles in Diagnosis and Therapy of Pancreatic Cancer, State University of New York, Buffalo, N.Y.
- Hybrid Nanoparticles in Imaging and Therapy of Prostate Cancer, University of Missouri, Columbia, Mo.
- DNA-linked Dendrimer Nanoparticle Systems for Cancer Diagnosis and Treatment, University of Michigan, Ann Arbor, Mich.
- Metallofullerene Nanoplatform for Imaging and Treating Infiltrative Tumor, Virginia Commonwealth University, Richmond, Va.
- Photodestruction of Ovarian Cancer: ErbB3 Targeted Aptamer-Nanoparticle Conjugate, Massachusetts General Hospital, Boston, Mass.
- Carolina Center of Cancer Nanotechnology Excellence, University of North Carolina, Chapel Hill, N.C.

**Cancer Nanotechnology Platform Partnerships (12)**

- Nanotechnology Platform for Targeting Solid Tumors, The Sidney Kimmel Cancer Center, San Diego, Calif.
- Near-Infrared Fluorescence Nanoparticles for Targeted Optical Imaging, University of Texas M. D. Anderson Cancer Center, Houston, Texas.
- Emory-Georgia Tech Nanotechnology Center for Personalized and Predictive Oncology, Atlanta, Ga.
- DNA-linked Dendrimer Nanoparticle Systems for Cancer Diagnosis and Treatment, University of Michigan, Ann Arbor, Mich.
- Hybrid Nanoparticles in Imaging and Therapy of Prostate Cancer, University of Missouri, Columbia, Mo.
- Metallofullerene Nanoplatform for Imaging and Treating Infiltrative Tumor, Virginia Commonwealth University, Richmond, Va.
- Photodestruction of Ovarian Cancer: ErbB3 Targeted Aptamer-Nanoparticle Conjugate, Massachusetts General Hospital, Boston, Mass.
- Carolina Center of Cancer Nanotechnology Excellence, University of North Carolina, Chapel Hill, N.C.
NCL is a formal collaboration between NCI, FDA and NIST
Collaborations within NIH, and with FDA, NIST, NIEHS NTP, EPA and others
24 efficacy/tox/PK studies per year
Key NSF/NNI education networks in 2010

- Oregon Museum of Science and Industry
- Exploratorium
- Lawrence Hall of Science
- UC Santa Barbara
- The Maricopa Community Colleges
- U Texas El Paso
- U Wisconsin-Madison
- Northwestern Univ.
- U Illinois Chicago Argonne Nati Labs
- U Michigan
- Pennsylvania State Univ
- Sciencenter
- Museum of Science
- New York Hall of Science
- The Franklin Institute
- Hampton Univ
- Morehouse College
- U Puerto Rico
- Children's Museum of Houston
- host node

(college centers)

National Centers for Learning and Teaching in Nanoscale Science and Engineering (core partners)

NANOCENTER
NCLT
NISE network

(host node)

nanoHUB
CNS

The Centers for Nanotechnology in Society

“Nanotechnology Research Directions for ..2020”, 2010, p. XVIII
NSF investment in nanoscale science and engineering education, moving over time to broader and earlier education and training

- **2000**: Graduate Education Programs (curriculum development)
- **2002**: Undergraduate Education Program
- **2003**: High School Education Programs
- **2004-2005**: K-12 and Informal (museum)
- **2006**: Technological Education Network

“Nanotechnology Research Directions for 2020” , 2010, p. 360
2000-2010: Ten highly promising products incorporating nanotechnology

- Catalysts
- Transistors and memory devices
- Structural applications (coatings, hard materials, CMP)
- Biomedical applications (detection, implants,..)
- Treating cancer and chronic diseases
- Energy storage (batteries), conversion and utilization
- Water filtration
- Video displays
- Optical lithography and other nanopatterning methods
- Environmental applications

Leading to new industries, some with safety concerns: cosmetics, food, disinfectants,..

After 2010 nanosystems: nano-radio, tissue eng., fluidics, etc
Nanoelectronic and nanomagnetic components incorporated into common computing and communication devices, in production in 2010

- 32 nm CMOS processor technology by Intel (2009)
- 90 nm thin-film storage (TFS) flash flexmemory by Freescale (2010)
- 16 megabit magnetic random access memory (MRAM) by Everspin (2010)

Nano2 Report, 2010, p. XII
Examples of nanotechnology incorporated into commercial healthcare products, in production in 2010

Nano2 Report, 2010, p. XIV
Examples of nanotechnology in commercial catalysis products for applications in oil refining, in production in 2010

Redesigned since 2000, mesoporous silica materials, like MCM-41, along with improved zeolites, are used in a variety of processes such as fluid catalytic cracking (FCC) for producing gasoline from heavy gas oils, and for producing polyesters. Nano-engineered materials now constitute 30–40% of the global catalyst market.
Example of production platform: Expanded CNT sheet

Nano2 Report, 2010, p. XLVI. Courtesy R. Ridgley
Example of research platform: Nanoelectronics Research Initiative (SIA, NSF, NIST)

Partnerships NSF, NIST, SIA, SRC with over 30 Universities in 16 States
Nanotechnology has provided solutions for about half of the new projects on energy conversion, energy storage, and carbon encapsulation in the last decade.

Entirely new families have been discovered of nanostructured and porous materials with very high surface areas, including metal organic frameworks, covalent organic frameworks, and zeolite imidazolate frameworks, for H storage and CO\textsubscript{2} separations.

A broad range of polymeric and inorganic nanofibers for environmental separations (membrane for water and air filtration) and catalytic treatment have been synthesized.

Testing the promise of nanomanufacturing for sustainability.

Evaluating renewable materials and green fuels.
Goal: U.S. grid parity by 2015 for photovoltaic technologies

Levelized cost of energy (LCOE)

Residential PV

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2015 (est.)</th>
<th>2030 (est.)</th>
</tr>
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<tbody>
<tr>
<td>PV LCOE without ITC *</td>
<td>21 - 34</td>
<td>10 - 16</td>
<td>6 - 10</td>
</tr>
<tr>
<td>PV LCOE with 30% ITC *</td>
<td>16 - 25</td>
<td>7 - 12</td>
<td>N/A</td>
</tr>
<tr>
<td>Residential Electricity Rates ‡</td>
<td>8 - 14</td>
<td>8 - 15</td>
<td>9 - 19</td>
</tr>
</tbody>
</table>

Based on DOE, 2010

Investment Tax Credit (ITC) Changes after 2016

MC Roco, April 26 2012
NSF-funded PIs (1991-2010) have a higher number of citations (166 in average) than researchers in other groups: IBM, UC, US (32 in average), Entire world Set (26 in average), Japan, European, Others
NSF-funded PI-Inventors (1991-2010) have more citations (**31 in average**) than inventors in the TOP10, UC, IBM, US (**9 in average**), Entire World Set (7 in average), Japan, Others, and European group.
A shift to new nano enabled commercial products after 2010

Survey of 270 manufacturing companies

Commercialized Product By 2009 to Market (2010)

<table>
<thead>
<tr>
<th>Time to Market</th>
<th>Response Rate</th>
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<tbody>
<tr>
<td>&lt; 1 year</td>
<td>25%</td>
</tr>
<tr>
<td>1 - 3 years</td>
<td>38%</td>
</tr>
<tr>
<td>3 - 5 years</td>
<td>70%</td>
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<tr>
<td>&gt; 5 years</td>
<td>85%</td>
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</tbody>
</table>

Survey of 270 manufacturing companies

Nano2 Report, 2010, p. XXXIX

Courtesy National Center for Manufacturing Sciences (NCMS, 2010)

* The corresponding R&D was about 10 times smaller in 1998.

** Est. taxes 20%

*** Est. $500,000/yr/job
Expert review (international WTEC study): Not fully realized objectives after ten years

- General methods for “materials by design” and composite materials (because the direct TMS and measuring techniques methods were not ready)

- **Sustainable development projects** - only energy projects received significant attention in the last 5 years; Nanotechnology for water filtration and desalination only limited; Delay on nanotechnology for climate research (because of insufficient support from beneficiary stakeholders?)

- Widespread public awareness of nanotechnology – awareness low ~30% in U.S.; Challenge for public participation
Better than expected after ten years

✓ Major industry involvement after 2002-2003
  Ex: >5,400 companies with papers/patents or products (US, 2008); NBA in 2002; Keeping the Moore law continue 10 years after serious doubt raised din 2000

✓ Unanticipated discoveries and advances in several S&E fields: plasmonics, metamaterials, spintronics, graphene, cancer detection and treatment, drug delivery, synthetic biology, neuromorphic engineering, quantum information ..

✓ The formation / strength of the international community, including in nanotechnology EHS and ELSI that continue to grow
Nanotechnology in 2011, still in an earlier formative phase of development

- **Characterization** of nanomodules is using micro parameters and not internal structure

- **Measurements and simulations** of a domain of biological or engineering relevance cannot be done with atomic precision and time resolution of chemical reactions

- **Manufacturing Processes** – empirical, synthesis by trial and error, some control only for one chemical component and in steady state

- **Nanotechnology products** are using only rudimentary nanostructures (dispersions in catalysts, layers in electronics) incorporated in existing products or systems

- **Knowledge for risk governance** – in formation
The long-term objective is systematic understanding, control and restructuring of matter at the nanoscale for societal benefit

**A. Scientific challenges**

- Theory at the nanoscale
  Ex: transition from quantum to classical physics, collective behavior; simultaneous nanoscale phenomena
- Non-equilibrium processes
- Designing new molecules with engineered functions
- New architectures for assemblies of nanocomponents
- The emergent behavior of nanosystems
B. Development of nanotechnology

- **Tools** for measuring and restructuring with atomic precision and time resolution of chemical reactions

- Understanding and use of **quantum phenomena**

- Understanding and use of **multi-scale selfassembling**

- **Nanobiotechnology** – **sub-cellular** and systems approach

- **Nanomanufacturing** hybrid, on site

- **Systems nanotechnology**
C. Integration of nanotechnology in application areas

- Nanomanufacturing for sustainable environment
- Replacing electron charge as the information carrier in electronics (Ex: NRI)
- Energy conversion, water filtration / desalinization
- Nano-bio interfaces between the human body and manmade devices
- Nano-informatics for communication, nanosystem design
- Converging science, engineering and technology
D. Societal dimensions of nanotechnology

- Understanding and sustainable ENV, including research for natural / incidental / manufactured nanomaterials
- Earlier formal and informal education
- Social issues and public engagement
Twelve trends to 2020

- Theory, modeling & simulation: x1000 faster, essential design
- “Direct” measurements – x6000 brighter, accelerate R&D & use
- A shift from “passive” to “active” nanostructures/nanosystems
- Nanosystems, some self powered, self repairing, dynamic
- Penetration of nanotechnology in industry - toward mass use; catalysts, electronics; innovation– platforms, consortia
- Nano-EHS – more predictive, integrated with nanobio & env.
- Personalized nanomedicine - from monitoring to treatment
- Photonics, electronics, magnetics – new capabilities, integrated
- Energy photosynthesis, storage use – solar economic by 2015
- Enabling and integrating with new areas – bio, info, cognition
- Earlier preparing nanotechnology workers – system integration
- Governance of nano for societal benefit - institutionalization

MC Roco, April 26 2012
"Direct" measurements and metrology

**EX:** Exponential law for X-ray Sources: Coherence for 3D dynamic (~ femtosecond) imaging of structures with atomic precision

- **X-ray source brilliance** (red line):
  - Increase of ~ 3.6 orders of magnitude in last decade
  - To increase ~ 5,000 times by 2020

- **Semiconductor Moore's law** (black line):
  - Increase of ~ 2 orders of magnitude in last decade

Nano2 Report, 2010, p. 41
Future aircraft designs include (a) nanocomposite materials for ultra-lightweight multifunctional airframes; (b) “morphing” airframe and propulsion structures in wing-body that can change their shape; (c) resistance to ice accretion; (d) with carbon nanotube wires; (e) networks of nanotechnology based sensors for reduced emissions and noise and improved safety.

Design by NASA and MIT for a 354 passenger commercial aircraft that would be available for commercial use in 2030-2035 and would enable a reduction in aircraft fuel consumption by 54% over a Boeing 777 baseline aircraft.
Sustainable Nanomanufacturing
Nanoelectronics for 2020 and Beyond
Nanotechnology for Solar Energy
Nanotechnology Knowledge Infrastructure
Nanotechnology-enabled Sensors to Assess Health and the Environment
(Nanotechnology to Regenerate Human Body)
2010-2020: Key areas of S&T emphasis

- Integration of nanocomponents at the nanoscale in nanosystems of larger scales, for fundamentally new products
- Better experimental and simulation control of self-assembly, quantum behavior, creation of new molecules, transport processes, interaction of nanostructures with external fields
- Understanding of biological processes and of nano-bio interfaces with abiotic materials, and their biomedical applications
- Nanotechnology solutions for sustainable development
- Governance for responsible innovation and public-private partnerships; oversight of nanotechnology EHS, ELSI, multi stakeholder, public and international participation. Sustained support for education, workforce preparation, and infrastructure.
The next ten years

- Preparing for **mass application of nanotechnology by 2020**, with shift to more complex generations of nanotechnology products and increased connection to biology. Address risks (EHS, long-term DNA, nanobiology) and public participation.

- **Greater emphasis on innovation and commercialization**, with incentives for greater use of public/private partnerships.

- **Focus on return to society and serving human dimensions** (health, cognition, human-machine interface, productivity high-added value nanomanufacturing, sustainability).

- **Nanotechnology governance will be institutionalized**, with increased globalization and a co-funding mechanism.
Several background references

"Nanotechnology Research Directions“, Springer 2000

"Societal Implications of Nanoscience and Nanotechnology“, Springer (2001); updated in 2 volumes in 2007


"Mapping Nanotechnology Innovations and Knowledge" Springer 2009

“Nanotechnology Research Directions for Societal Needs in 2020” Springer (Roco, Mirkin and Hersam 2011)

“Nanotechnology: From Discovery to Innovation and Socioeconomic Projects” AIChE/CEP Roco, May 2011)