Nanotechnology Research Directions for Societal Needs in 2020

Mike Roco
NSF and NNI

WWCS
December 1, 2010
Context: Emergence of new technologies
Nanotechnology is a prime example

Knowledge generation has quasi-exponential growth
There is an accelerating & non-uniform process of discoveries and innovations leading to emerging technologies

Societal needs of radically new technologies
Demographics (more crowded, aging, non-uniform) & development with limited natural resources (sustainability constrain)

Emerging technologies governance
- Integration of new tools and separated disciplines,
- General purpose integrators: nanotechnology, IT, and complex systems
Examples of emerging technologies and corresponding U.S. long-term S&T projects

Justified mainly by societal/application factors

• 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)
• IT Research (top-down born & managed; application driven)

Justified mainly by science and technology potential, competitive

• National Nanotechnology Initiative (bottom-up science opportunity born, for 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.

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

- the ability to control and restructure matter at nanoscale
- collective effects \(\rightarrow\) new phenomena \(\rightarrow\) novel applications
- integration along length scales, systems and applications
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
Nanotechnology Research Directions for Societal Needs in 2020

Goals

– Global progress made in nanotechnology 2000 - 2010

– Vision and research directions by 2020?

– How to re-define nanotechnology as a S&E megatrend in the next decade (2010-2020) with new goals

– How to institutionalize advances in nanotechnology R&D
Approach

- **Leading expert panel** (US); questionnaires; five brainstorming workshops in Chicago (US), Hamburg (EU and US), Tokyo (Japan, Korea, Taiwan and US), Singapore (Singapore, Australia, China, India, Saudi Arabia) and Arlington (all); input from over 35 countries; peer / industry / public review

- **Inclusive study** with input from and evaluations for industry, academe, government and public

- **Open source approach**: on [http://www.wtecf.org/nano2](http://www.wtecf.org/nano2) and Springer book publication (2010)
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Main topics of the study

- Fundamental scientific and engineering Issues for nanotechnology
- Investigative tools: Theory, modeling, and simulation
  Measure, instrumentation and metrology
- Synthesis, processing and manufacturing
- Nanotechnology environmental, health and safety (EHS) issues
- Sustainability: Environment, Water, Food and Climate
  Energy conversion, storage and conservation
- Applications: Nanobiosystems, medical and health
  Nanoelectronics and nanomagnetics
  Photonics and plasmonics
  Nanostructured catalysts and other chemicals
  High performance materials, systems, emerging areas
- Governance: Preparation of people and physical infrastructure
  Innovative and responsible governance

MC Roco, Dec 1 2010
Mass Application of Nanotechnology after ~ 2020

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

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

~ 2020

New disciplines
New industries
Societal impact

Nano2 Report, 2010, p. XXXVII
Market of final products incorporating nanotechnology

Nano1: R&D focus on fundamental discoveries and empirical processing (2000-2010)
Nano2: focus on applications-driven fundamental and system research (2010-2020)
2000-2008
Estimates show an average growth rate of key nanotechnology indicators of 23 - 35%.

<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>2000 (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>2008 (actual)</td>
<td>~ 400,000 /150,000/</td>
<td>65,000 /15,000/</td>
<td>12,776 /3,729/</td>
<td>~ $200 B /$80 B/</td>
<td>~ $14 B /$3.7 B/</td>
<td>~ $1.4 B /$1.17 B/</td>
</tr>
<tr>
<td>2000 - 2008 average growth</td>
<td>~ 25%</td>
<td>~ 23%</td>
<td>~ 35%</td>
<td>~ 25%</td>
<td>~ 35%</td>
<td>~ 30%</td>
</tr>
<tr>
<td>2015 (estimation in 2000)</td>
<td>~ 2,000,000 /800,000/</td>
<td></td>
<td></td>
<td>~ $1,000B /$400B/</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020 (extrapolation)</td>
<td>~ 6,000,000 /2,000,000/</td>
<td></td>
<td></td>
<td>~ $3,000B /$1,000B/</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Evolving Topics

Nano2 Report, 2010, p. XXXIII
### 2000-2009

**Changing international context:** federal/national government R&D funding (NNI definition)

#### Graph
- **R&D FUNDING (million $/year)**
- **Country/Region**
  - **USA** ~1550 ~5.1
  - **EU-27** ~1700 ~4.6
  - **Japan** ~950 ~7.3
  - **China** ~430 ~0.4
  - **Korea** ~310 ~6.0
  - **Taiwan** ~110 ~4.5

#### Notes
- Rapid, uneven growth per countries
- **Seed funding** 1991-1997
- **NNI Preparation** vision/benchmark
- **1st Generation products** passive nanostructures
- **2nd Generation** active nanostructures
- **3rd Generation** nanosystems

**Image Text:**
- **Context**
- **National government investments 1997-2007 (estimation NSF)**
- **1st Generation** passive nanostructures
- **2nd Generation** active nanostructures
- **3rd Generation** nanosystems
- **Industry $ > Public $**
- **Rapid, uneven growth per countries**
Japan

The United States

China

South Korea

Strengths per country

Nano2, T. Kawai (Japan), 2010
WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY
(Estimation made in 2000 after international study in > 20 countries)

- Passive nanostructures
- Active nanostructures
- Nanosystems by design
- Rudimentary → Complex

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

- ~ $40B (2000)
- ~ $120B (2005)
- ~ $250B (2010)
- NT in the main stream

- $1T by 2015
- ~ $91B, U.S.
- ~ $40B

- $3T by 2020

From: Nano2 Report, 2010, p. XXXV
Ranking the nations on nanotechnology

by David Hwang, Lux Research, August 2010
2000-2010 Outcomes

- 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.

- New S&E fields have emerged such as: spintronics, plasmonics, metamaterials, carbon nanoelectronics, molecules by design, nanobiomedicine, 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.
2000-2010: 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
- **Simulation** from basic principles has expanded to **assemblies of atoms 100 times larger** than in 2000
- **Measure**: 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
2000-2010: Examples of innovations

• An illustration is the discovery of spin torque transfer (the ability to switch the magnetization of nanomagnet using a spin polarized current), which has significant implications for memory, logic, sensors, and nano-oscillators. A new class of devices has been enabled.

• Scanning probe tools for printing one molecule or nanostructure high on surfaces over large areas with sub-50 nm resolution have become reality in research and commercial settings. This has set the stage for developing true “desktop fab” capabilities that allow researchers and companies to rapidly prototype and evaluate nanostructured materials or devices at point of use.
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)

From: Nano2 Report, 2010, p. XII
2000-2010: Safe Development

There is greater recognition of the essential areas of nanotechnology-related EHS and ELSI issues

- Building physico-chemical-biological understanding
- Regulatory challenges for specific nanomaterials
- Experiment governance methods under conditions of uncertainty and knowledge gaps
  - risk assessment frameworks
  - life cycle analysis based on expert judgment
  - use of voluntary codes, and
  - incorporation of safety considerations into the design and production stages of new nano-enabled products
• 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 improved hydrogen storage and CO$_2$ 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.
Sustainable nanotechnology solutions for clean environment; energy, water, food, mineral resources supplies; green manufacturing, habitat, transportation, climate change, biodiversity

Current critical planetary boundaries are biodiversity, nitrogen cycle, climate change (Rockström et al. 2009)
2000-2010: Towards nanotechnology applications

• Current applications are based upon relatively simple “passive” (steady function) nanostructures used as components to improve products (e.g., nanoparticle-reinforced polymers). However, since 2005, more sophisticated products with “active” nanostructures and devices have been introduced (e.g., point-of-care molecular diagnostic tools and life-saving targeted drug therapeutics).

• Entirely new classes of materials have been discovered and developed: from one-dimensional nanowires and quantum dots of various compositions to polyvalent noble metal nanostructures, graphene, metamaterials, nanowire superlattices, and many other nanocomposites. A periodic table of nanostructures is emerging.
Nanoscale medicine has made significant breakthroughs in the laboratory, advanced rapidly in clinical trials, and made inroads in biocompatible materials, diagnostics, and treatments.

Ex: Abraxane is commercialized for treating different forms of cancer. The first point-of-care nano-enabled medical diagnostic tools such as the Verigene System are now being used to rapidly diagnose disease. Over 50 cancer-targeting drugs based on nanotechnology are in clinical trial in the U.S. alone. Nanotechnology solutions are enabling companies such as Pacific Biosciences and Illumina to offer products that are on track to meet the $1000 genome challenge.
Examples of nanotechnology incorporated into commercial healthcare products, in production in 2010
• **Patterning on surfaces:** a versatile library has been invented of surface patterning methods including directed selfassembling, optical and “dip-pen” nanolithography, nanoimprint lithography, and roll-to-roll processes for manufacturing graphene and other nanosheets.
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.
Examples of Penetration of Nanotechnology in Several Industrial Sectors

The market percentage and its absolute value affected by nanotechnology are shown for 2010

<table>
<thead>
<tr>
<th>U.S.</th>
<th>2000</th>
<th>2010</th>
<th>Est. in 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semiconductor industry</td>
<td>0 (with features &lt; 100 nm)</td>
<td>60% (~$90B)</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>0 (new nanoscale behavior)</td>
<td>30% (~$45B)</td>
<td>100%</td>
</tr>
<tr>
<td>New nanostructured catalysts</td>
<td>0</td>
<td>~ 35% (~35B impact)</td>
<td>~ 50%</td>
</tr>
<tr>
<td>Pharmaceutics (therapeutics and diagnostics)</td>
<td>0</td>
<td>~ 15% (~$70B)</td>
<td>~ 50%</td>
</tr>
<tr>
<td>Wood</td>
<td>0</td>
<td>0</td>
<td>~ 20%</td>
</tr>
</tbody>
</table>
Ten highly promising products incorporating nanotechnology in 2010

- 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

With safety concerns: cosmetics, food, disinfectants,..

2010 nanosystems: nano-radio, tissue eng., fluidics, etc

- ~$1.9B industry R&D
- $1.7B* federal R&D: NNI
- $B industry operating cost
- ~$18B Taxes
- ~$1.9B ind. R&D
- ~$91B** Final Products
- ~180,000 Jobs***

* The corresponding R&D was about 10 times smaller in 1999
** Estimated taxes = 20%
*** Estimated $500,000/yr/job

MC Roco, Dec 1 2010
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

Nano2 Report, 2010, p. 360
Key NNI education networks in 2010

- Oregon Museum of Science and Industry
- Science Museum of Minnesota
- Dakota County Technical College
- U Wisconsin-Madison
- U Michigan
- Northwestern Univ
- U Illinois Chicago Argonne Nati Labs
- U Illinois Urbana-Champaign
- Purdue Univ
- Fisk Univ
- Alabama A&M Univ
- Morehouse College
- Children's Museum of Houston
- U Texas El Paso
- Sciencenter
- New York Hall of Science
- The Franklin Institute
- Hampton Univ
- UC Santa Barbara
- Lawrence Hall of Science
- Exploratorium
- The Maricopa Community Colleges
- NACK CENTER (college centers)
- National Centers for Learning and Teaching in Nanoscale Science and Engineering (core partners)
- NISE network (regional hubs/museums)
- nanoHUB (host node)
- CNS (The Centers for Nanotechnology in Society)

Nano2 Report, 2010, p. XVIII
Corporate entry into nanotechnology by city in 2008
(establishments with nano publications or patents for cities with 10 or more establishments)
US: 5,440 co. with papers/patents/products (31% of the world; 44% of nano patents)

Nano2 Report, 2010, p. 411, Courtesy A. Shapira
Transformative governance
Ex.: Corporate Entry in leading countries (has products, articles and/or patents), 1990-2009

Courtesy Phil Shapira, Jan Youtie and Luciano Kay

Nano2 Report, 2010, p. 411
Nanotechnology governance has evolved considerably:

- The viability and societal importance of nanotechnology has been confirmed, while extreme predictions have receded.
- An international community has been established.
- Greater recognition to nanotechnology EHS and ELSI after 2004.
- Nanotechnology has become a model for governance issues (transformative/responsible/inclusive/visionary) of other emerging technologies. Increasing role of innovation.
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: energy received momentum only after 5 years, nanotechnology for water filtration and desalination only limited; delay on nanotechnology for climate research (because of insufficient support from beneficiary stakeholders?)

• Public awareness remains low, at about 30%. Challenge for public participation
On target in 2010, even if doubted in 2000

• The growth rates of papers and inventions (23-35%) is quasi exponential at rates higher than the average in all fields (about 5-10%)

• Nanotechnology stimulated interdisciplinary research and education, creating a multidisciplinary projects, organizations, and communities

• Estimation that nanotechnology R&D investment in US will grow by about 30% annual growth rate (government and private sector, vertical and horizontal development) in 2000-2008; International coordination and collaboration
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

- Discoveries in several S&E fields
  plasmonics, metamaterials, spintronics, graphene, cancer detection and treatment, drug delivery, synthetic biology, neuromorphic engineering, quantum information system

- The formation / strength of the international community, including in nanotechnology EHS and ELSI; governance studies
Main lessons learned after ten years

- Need continued, focused investment on theory, direct measuring and simulation at the nanoscale. Nanotechnology still in the formative phase.

- Besides nanostructured metals, polymers and ceramics, classical industries can provide excellent opportunities, such as in: textiles, wood and paper, plastics, agricultural and food systems. Improved mechanisms for public-private partnerships to establish consortia or platforms are needed.

- Need to increase multi-stakeholder and public participation in nanotechnology governance.
Nanotechnology in 2010 - 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
Twelve trends to 2020

www.wtec.org/nano2/

- 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, Dec 1 2010
1. Theory, modeling and simulation - faster, more useful in design

Ex: Growth of computing power on classical molecular dynamics (CMD), 2000-2010

Left axis: CMD computational complexity

Right axis: For monatomic fluid, # of atoms that can be simulated for 10 ns in one day

To improvement factor of simulated nano-structure size ~ 1000 times in next decade

Nano2 Report, 2010, p.5
2. “Direct” measurements and metrology

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

Semiconductor Moore's law (black):

- 2 orders of magnitude in last decade

X-ray source brilliance (red):

- Estimated 3.6 orders of magnitude
- To increase ~ 5,000 times in next decade

Ex.:
- Targeted drugs and chemicals
- NEMS
- Self-healing materials
- Remote actuated (e.g., magnetic, electrical, light and wireless tagged nanotech)
- Environmentally responsive
- Energy storage devices
- Semiconductors, molecular electronics

Active nanostructures: doubling from 3,000 to over 6,000 publications in one year

4. Ex: Self-powered nanosystems

Multifunctional, self-powered nanosystems (using fluid motion, temperature gradient, mechanical energy..) in wireless devices, biomedical systems...

UC CEIN predictive model for hazard ranking and risk profiling

UC CEIN Predictive Multi-disciplinary Science Model

- ENM libraries
- Nanoparticle structural & physicochemical information
- Cell, embryo, biomolecules
- In vivo toxicity
- Predictive toxicology
- Fate & transport
- Data integration
- Pattern Recognition (heatmaps, self-organizing etc)
- Machine Learning
- Computer decision making
- Hazard ranking
- Risk profiling
- Exposure modeling
- Property-activity relationships

Multimedia Analysis
Expanded CNT sheet production with broad impact

- Shielding
- Lightweight Shielded Wires Cables
- Heaters
- Deicers
- Thermal Spreaders
- Anode/Cathode
- Thermoelectrics
- EMI /EMP Shields Ground Plane
- Armor
- Composites

Commercial and Defense Impact
Multi-Industry Use

- Satellites
- Aircraft
- Data Centers
- High Performance Batteries
- Waste Heat Power
- Thermovoltaics
- Consumer Electronics
- First Responders
- Wind Energy Systems
- Ground Transportation

Nano2 Report, 2010, p. XLVI. Courtesy R. Ridgley
Nanotechnology for Aerospace

Future aircraft designs include nanocomposite materials for ultra-lightweight multifunctional airframes; “morphing” airframe and propulsion structures in wing-body that can change their shape; resistance to ice accretion; with carbon nanotube wires; 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.

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>
</thead>
<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>

Investment Tax Credit (ITC) Changes after 2016

Cost of Energy in Cents/kWh (2009$)


Courtesy DOE, 2010
2010-2020: Key areas of emphasis

• Integration of knowledge at the nanoscale and of nanocomponents in nanosystems, aiming toward creating fundamentally new products

• Better experimental and simulation control of molecular self-assembly, quantum behavior, creation of new molecules, and interaction of nanostructures with external fields to create products

• Understanding of biological processes and of nano-bio interfaces with abiotic materials, and their biomedical applications

• Nanotechnology solutions for sustainable development

• Governance to increase innovation and public-private partnerships; oversight of nanotechnology EHS, ELSI, multi stakeholder, public and international participation. Sustained support for education, workforce preparation, and infrastructure all remain pressing needs
2010-2020: Increasing R&D intensity and return

- Research into the systematic control of matter at the nanoscale will accelerate in the first part of the next decade (2011-2015)
- Nanotechnology by 2020 seamlessly integrated with most technologies and applications, driven by economics and by the strong potential for achieving previously unavailable solutions
- Support for fundamental research and infrastructure - essential
- Support focused R&D programs for frontiers and bottlenecks
- Realize nanomaterials and nanosystems by design
- High potential of nanotechnology to support sustainable development in water, energy, minerals, and other resources
A shift to new nano enabled commercial products after 2010
Survey of 270 manufacturing companies

Emerging nanotechnology products will introduce modifications to today’s products

The overall growth of nano-enabled products to 2015 will consist largely of emerging applications in materials and manufacturing as well as electronics. Healthcare and life sciences will grow as these fields overcome safety, testing, and consumer acceptance barriers not faced by other applications.
2010-2020: OTHER PRIORITIES

• Advance **partnerships** between industry, academia, NGOs, multiple agencies, and international organizations

• Support precompetitive R&D and system application **platforms**

• Promote **global coordination**; Create an international co-funding mechanism for databases, nomenclature, standards, and patents

• Support horizontal, vertical, and system **integration in nanotechnology education**; and personalized learning

• Use **nanoinformatics** and computational science prediction tools

• **New strategies** for mass dissemination, public participation

• **Institutionalize**—create standing organizations and programs to fund and guide nanotechnology
2010-2020: FURTHER PRIORITIES

- Nanotechnology EHS - to be addressed as an integral part of the general physico-chemical-biological research
  - also for the new generation of active nanostructures and systems
  - include exposure and toxicity to multiple nanostructured compounds

- Besides new emerging areas, traditional industries may provide opportunities for application of nanotechnology mineral processing, plastics, wood and paper, textiles, agriculture, and food systems

- In the next decade, nanotechnology R&D is likely to shift its focus to socio-economic needs-driven governance, with significant consequences for science, investment, and regulatory policies
It will be imperative over the next decade to focus on four distinct aspects of nanotechnology development:

- How nanoscale science and engineering can improve understanding of nature, generate breakthrough discoveries and innovation, and build materials and systems by nanoscale design — “knowledge progress”
- How nanotechnology can generate economic and medical value — “material progress”
- How nanotechnology can address sustainable development, safety, and international collaboration — “global progress”
- How nanotechnology governance can enhance quality-of-life and social equity — “moral progress”

MC Roco, Dec 1 2010