Nanotechnology Development from Fundamental Discovery to Socio-economic Projects: 2000 - 2020

Mike Roco
National Science Foundation and National Nanotechnology Initiative

Georgia Tech, March 3, 2012
Topics

• Nanotechnology timeline: 2000-2020
• Main outcomes at 10 years
• 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
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, competitive

• 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

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
NNI timeline (2000-2020)

- Interagency group (11/1996); Preparatory reports (1997-1999) 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)
Long-term nanotechnology research directions (2000-2020)

Nano1 (2000-2010)

NSF/WTEC, www.wtec.org/nano2/ ; Springer 2010
Creating a new field and community in 2 foundational steps (2000~2020) with 4 generations of nanotechnology products

**Foundational interdisciplinary research at nanoscale**
- **~ 2001**
  - Indirect measurements, Empirical correlations; Single principles, phenomena, tools; Create nanocomponents by empirical design
- **~ 2010**
- **~ 2020**
  - Direct measurements; Science-based design and processes; Collective effects; Create nanosystems by technology integration

**NS&E integration for general purpose technology**
- **~ 2011**
- **~ 2020**
  - New disciplines
  - New industries
  - Societal impact

**Mass Application of Nanotechnology after ~ 2020**

**New areas**
- Materials
- Electronics
- Health Care
- Environment
- Energy
- Transport
- Manufacturing
- Security
- Instruments

**Key milestones**
- **Foundational interdisciplinary research at nanoscale**
  - **~ 2001**
    - Indirect measurements, Empirical correlations; Single principles, phenomena, tools; Create nanocomponents by empirical design
  - **~ 2010**
  - **~ 2020**
    - Direct measurements; Science-based design and processes; Collective effects; Create nanosystems by technology integration

**NS&E integration for general purpose technology**
- **~ 2011**
  - New disciplines
  - New industries
  - Societal impact
- **~ 2020**

**Mass Application of Nanotechnology after ~ 2020**

**New disciplines**
- Infrastructure
- Workforce
- Partnerships

**MC Roco, March 3 2012**
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 $

--- | --- | ---
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

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

MC Roco, March 3 2012
All numbers shown above are actual spending, except 2011, which is estimated spending under the continuing resolution (CR), and 2012, which is requested amount for next year (FY 2009 figure shown here does not include ~$500 million in ARRA funding).

** 2011 estimate and 2012 request do not include DOD earmarks as in previous years.
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
# Number of ACTIVE NS&E Awards by State for FY 2011

**Total Number of FY 2011 ACTIVE NS&E Awards = 5,064**

<table>
<thead>
<tr>
<th>State</th>
<th>Awards FY 2011</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td>550</td>
<td>1</td>
</tr>
<tr>
<td>NY</td>
<td>399</td>
<td>2</td>
</tr>
<tr>
<td>TX</td>
<td>367</td>
<td>3</td>
</tr>
<tr>
<td>MA</td>
<td>285</td>
<td>4</td>
</tr>
<tr>
<td>PA</td>
<td>359</td>
<td>5</td>
</tr>
<tr>
<td>IL</td>
<td>246</td>
<td>6</td>
</tr>
</tbody>
</table>

**No. ACTIVE Awards FY 2011**
- <= 21
- 21 - 39
- 39 - 62
- 62 - 107
- 107 - 175
- 175 - 550

MC Roco, March 3 2012
Per capita Nano$ for NEW Awards by State  
FY 2000 - 2011

Overall National per capita Average Amount = $22.32

<table>
<thead>
<tr>
<th>State</th>
<th>$ / capita per 11 yrs</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA</td>
<td>90.4</td>
<td>1</td>
</tr>
<tr>
<td>DC</td>
<td>81.4</td>
<td>2</td>
</tr>
<tr>
<td>RI</td>
<td>62.5</td>
<td>3</td>
</tr>
<tr>
<td>NY</td>
<td>43.8</td>
<td>4</td>
</tr>
<tr>
<td>DE</td>
<td>41.1</td>
<td>5</td>
</tr>
<tr>
<td>PA</td>
<td>38.6</td>
<td>7</td>
</tr>
</tbody>
</table>

PerCap NEW Nano Amt FY00-11
- Blue: $ ≤ 11.75
- Light Blue: 11.75 - 14.06
- Medium Blue: 14.06 - 17.26
- Dark Blue: 17.26 - 21.21
- Red: 21.21 - 33.45
- Dark Red: 33.45 - 90.42

MC Roco, March 3 2012
60-70 universities have comparable levels of NSE funding

Top 15 institutions receiving NSE awards after the new amount awarded for FY 2011
2000-2010

Estimates show an average 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>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>2010 (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>2000 - 2010 average growth</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>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>

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, March 3 2012

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

U.S. maintain the lead in highly cited publications

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

U.S. maintain the lead weaker in 2011
Effects of USPTO rules and economy
### Interval 2001-2010

~10,900 NSF awards

**Patents by NSF’s Principal Investigators**

(patents searched by “title-claims” keywords at USPTO; examples)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Name NSF P.I.</th>
<th>Institution</th>
<th># USPTO Patents (keyword search)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chad A. Mirkin</td>
<td>Northwestern University</td>
<td>74</td>
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<tr>
<td>2</td>
<td>Richard E. Smalley</td>
<td>Rice University</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>Bin Yu</td>
<td>University of Albany</td>
<td>55</td>
</tr>
<tr>
<td>4</td>
<td>Stephen R. Quake</td>
<td>Stanford University</td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>Mark E. Thompson</td>
<td>University of Southern California</td>
<td>43</td>
</tr>
<tr>
<td>6</td>
<td>Mounig G. Bawendi</td>
<td>Massachusetts Institute of Technology</td>
<td>42</td>
</tr>
<tr>
<td>7</td>
<td>Andrew G. Rinzler</td>
<td>University of Florida</td>
<td>40</td>
</tr>
<tr>
<td>8</td>
<td>Ping Liu</td>
<td>University of Texas at Arlington</td>
<td>37</td>
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<tr>
<td>9</td>
<td>Joseph M. Jacobson</td>
<td>Massachusetts Institute of Technology</td>
<td>36</td>
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<tr>
<td>10</td>
<td>George M. Whitesides</td>
<td>Harvard University</td>
<td>33</td>
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<tr>
<td>11</td>
<td>Axel Scherer</td>
<td>California Institute of Technology</td>
<td>31</td>
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<tr>
<td>12</td>
<td>Thomas J. Pinnavaia</td>
<td>Michigan State University</td>
<td>26</td>
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<tr>
<td>13</td>
<td>Tobin J. Marks</td>
<td>Northwestern University</td>
<td>23</td>
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<tr>
<td>14</td>
<td>Charles M. Lieber</td>
<td>Harvard University</td>
<td>23</td>
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<td>15</td>
<td>Nathan S. Lewis</td>
<td>California Institute of Technology</td>
<td>22</td>
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<tr>
<td>16</td>
<td>Hongjie Dai</td>
<td>Stanford University</td>
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<tr>
<td>17</td>
<td>Kerry J. Vahala</td>
<td>California Institute of Technology</td>
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<tr>
<td>18</td>
<td>Thomas W. Kenny</td>
<td>Stanford University</td>
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<td>19</td>
<td>Michael N. Kozicki</td>
<td>Arizona State University</td>
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<td>20</td>
<td>Tsu-Jae King</td>
<td>University of California at Berkeley</td>
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<td>21</td>
<td>Robert Langer</td>
<td>Massachusetts Institute of Technology</td>
<td>18</td>
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<td>22</td>
<td>Michael L. Simpson</td>
<td>University of Tennessee</td>
<td>18</td>
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<tr>
<td>23</td>
<td>Michael L. Roukes</td>
<td>California Institute of Technology</td>
<td>17</td>
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<tr>
<td>24</td>
<td>Jackie Y. Ying</td>
<td>Massachusetts Institute of Technology</td>
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<td>25</td>
<td>Ting Guo</td>
<td>University of California at Davis</td>
<td>16</td>
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<tr>
<td>26</td>
<td>Stephen C. Minne</td>
<td>Stanford University</td>
<td>15</td>
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<tr>
<td>27</td>
<td>Nicholas L. Abbott</td>
<td>University of Wisconsin-Madison</td>
<td>15</td>
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<tr>
<td>28</td>
<td>Eric V. Anslyn</td>
<td>University of Texas at Austin</td>
<td>14</td>
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<tr>
<td>29</td>
<td>R. Stanley Williams</td>
<td>HP</td>
<td>14</td>
</tr>
<tr>
<td>30</td>
<td>Kenneth J. Klabunde</td>
<td>Kansas State University</td>
<td>14</td>
</tr>
<tr>
<td>31</td>
<td>Samuel I. Stupp</td>
<td>Northwestern University</td>
<td>14</td>
</tr>
</tbody>
</table>

MC Roco, March 3 2012
Nanotechnology citations in 10 specialized journals using the Science Citation Index (SCI) for 1990 - 2011

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

Rapid, uneven changes in the last ten years
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 Market /US GDP ~0.8%
2011 USPTO patents ~1.9%
2011 All journals ~5%
2011 NSF grants ~11%
2011 Top nano J. ~13%

Similar, delayed penetration curves: for R&D funding /papers /patents /products /ELSI
WORLDWIDE MARKET INCORPORATING NANOTECHNOLOGY
(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

- $120B
- $250B
- $3T by 2020
- $1T by 2015
- ~ $91B, U.S.
- NT in the main stream

Reference: Roco and Bainbridge, Springer, 2001
Developed foundational knowledge for control of matter at the nanoscale: about 7,500 NNI (5,000 NSF) active projects in > 500 universities, private sector institutions and government labs in all 50 states.

“Created an interdisciplinary nanotechnology community”

R&D / Innovation Results: With ~22% of global government investments, the U.S. accounts worldwide for:

- ~60% of USPTO patents, and
- ~70% of startups in nanotech.

~ Over 2,500 U.S. nanotech companies with products in 2010; $110B (~38% of the world) products incorporating nano parts.

Infrastructure:

~ 100 new large NT research centers, networks and user facilities;

~ 10,000 students and teachers educated and trained each year

~ 280 new NSE curricula in all accredited ENG universities.

MC Roco, March 3 2012
• **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, plasmonics, 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.

MC Roco, March 3 2012
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)
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.
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.

MC Roco, March 3 2012
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)
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 least 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, S. Loth, S. Baumann, C.P. Lutz¹, D. M. Eigler¹, A.J. Heinrich¹ Science Jan 2012)
Example: Designing new molecules with engineered structures and functionalities

Example for hierarchical self-assembling - 4th NT generation (in research)

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)
Example: Emergence of Plasmonics after 2004

Plasmonics: Merging photonics, electronics and materials at nanoscale dimensions
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
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

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.
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/
(D) 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

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

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)
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.

Nano2 Report, 2010, p. XVII
Example: Expanded CNT sheet production platform

- Shielding
- Lightweight Shielded Wires Cables
- Heaters
- Deicers
- Thermal Spreaders
- Anode/Cathode
- Thermoelectrics
- EMI /EMP Shields
- Pre-Preg
- 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
Nanoelectronics Research Initiative
Funded Universities (SIA, NSF, NIST)

- UC Los Angeles
- UC Berkeley
- UC Irvine
- UC Riverside
- UC Santa Barbara
- U. Nebraska-Lincoln
- U. Wisconsin-Madison
- Notre Dame
- Penn State
- Purdue
- UT-Dallas
- SUNY-Albany
- MIT
- Columbia U. Virginia
- U. Maryland
- SUNY-Albany
- Harvard
- NCSU
- Virginia Nanoelectronics Center (ViNC)

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 CO₂ 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
Ten Nanoscale Science and Engineering networks with national outreach

**Nationwide Impact**

**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
- Nanotech Applications and Career Knowledge (2008-) nanotechnology educ.
- 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
Key NSF university-based User Facilities

NNIN  www.nnin.org/  (to be re--competed in 2014)

NCN  www.ncn.purdue.edu/  (to be re-competed in 2012)
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
NSF-funded PI (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.

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

** Est. taxes 20%

*** Est. $500,000/ yr/ job
A shift to new nano enabled commercial products after 2010

Survey of 270 manufacturing companies

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
The long-term objective is systematic understanding, control and restructuring of matter at the nanoscale for societal benefit (Annual NSF Request, NSE Group)

Key scientific challenges

- Theory at the nanoscale
  Ex: transition from quantum to classical physics, collective behavior; simultaneous nanoscale phenomena

- Designing new molecules with engineered functions

- New architectures for assemblies of nanocomponents

- The emergent behavior of nanosystems
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
2. “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):
- Estimated 3.6 orders of magnitude
- To increase ~ 5,000 times in next decade

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

Nano2 Report, 2010, p. 41
Platforms for systems nanotechnology

- Create controllable systems built from nano components: unifying principles that enable control of emergent behavior in complex nanosystems
- Wide application: revolutionary new products, petascale computing, organ regeneration, sensors for health monitoring
- Enable other goals for: nanomanufacturing, efficient use of energy; sensor capabilities
- Development of a new framework for risk assessment

Ex UIUC: Microfluidics systems incorporating nanocomponents

Ex UCB: Nano radio = antenna, filter, amplifier

MC Roco, March 3 2012
Exemple: Self-powered nanosystems

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

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.

Sustainable Nanomanufacturing
Nanoelectronics for 2020 and Beyond
Nanotechnology for Solar Energy
*Nanotechnology-enabled Sensors to Assess Health and the Environment*
Nanotechnology Knowledge Infrastructure
(Nanotechnology to Regenerate Human Body)
2010-2020: Key areas of emphasis

• Integration of knowledge at the nanoscale and of nanocomponents in nanosystems and 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 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