The Changing Face of Nanotechnology

M.C. Roco
National Science Foundation (NSF) and
U.S. National Nanotechnology initiative (NNI)

Korea-US Nanotechnology Workshop,
April 17-18, 2008
Nanotechnology

is the control and restructuring of matter
(measure – manipulate – integrate)

at dimensions of roughly 1 to 100 nanometers
(from atomic size to about 100 molecular diameters),

where new phenomena enable new applications
(where nanoscale modules are established).
Nanoscale modules / building blocks

NATURAL THRESHOLD
from individual to collective behavior,
at the first level of organization of atoms and molecules
Five Generations of Products and Productive Processes

Timeline for beginning of industrial prototyping and nanotechnology commercialization (2000-2020; 2020-)

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

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

3\textsuperscript{rd}: Systems of nanosystems
Ex: guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary

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

5\textsuperscript{th}: Converging technologies
Ex: nano-bio-info from nanoscale, cognitive technologies; large complex systems from nanoscale

New R&D challenges

Perceived Higher Risks Areas (2000-2020; 2020-) as a function of the generation of products

1st: Passive nanostructures  
*Ex: Cosmetics (pre-market tests), Pharmaceuticals (incomplete tests for inflammatory effects, etc.), Food industry, Consumer products*

2nd: Active nanostructures  
*Ex: Nano-biotechnology, Neuro-electronic interfaces, NEMS, Precision engineering, Hybrid nanomanufacturing*

3rd: Systems of nanosystems  
*Ex: Nanorobotics, Regenerative medicine, Brain-machine interface, Eng. agriculture*

4th: Molecular nanosystems  
*Ex: Neuromorphic eng., Complex systems, Human-machine interface*

5th: Converging technologies  
*Ex: Hybrid nano-bio-info-medical-cognitive applic.*
Fifth generation - After 2020

NT convergence with bio, info and cogno, and bifurcation of nanosystem architectures

- Guided assembling
- Evolutionary
- Engineered molecular design and guided hierarchical selfassembling
- Robotics based
- Biomimetics

- ? New carrier of information instead of electron charge
- ? Manufacturing by nanomachines
- ? Extending human potential
- ? Collective cognitive capabilities
Fifth generation of nano products:
Four volumes on Convergence
2003, 2006 and 2007 Springer; 2004 NYAS

CONVERGING TECHNOLOGIES FOR IMPROVING HUMAN PERFORMANCE
June 2002

Workshop, Dec. 2001
www.nsf.gov/nano
Springer, 2003
Expanding nanotechnology domains since 2000

2000-2001: nano expanding in almost all disciplines

2002-2003: industry moves behind nano development

2003-2004: medical field sets up new goals

2004-2005: media, NGOs, public, international organizations get involved

2006-2007: new focus on common Earth resources - water, food, environment, energy, materials

2007-2008: increased relevance to economic-politic-military-sustainability
WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY (2000-2015)

Estimation made in 2000 after international study in > 20 countries

- Annual rate of increase about 25%
- $1T products by 2015
- ~ $120B products
- ~ 800K in U.S. and ~ 2M world workers in a NT area
- 80% U.S. public – know little/nothing about NT
  - 40K in U.S. and 100K world workers in a NT area
- 90% U.S. public – know little/nothing about NT
  - 4K in U.S. and 10K world workers in a NT area

Reference: Roco and Bainbridge, 2001

M.C. Roco, 4/18/2008
Changing research frontier focus

2000-2002
Nanoparticles, nanotubes, quantum dots, coatings

2003-2005
Self- and guided molecular assembling    Expands nanobio technology and medicine

2006-2008
Focus on nanodevices and components of nanosystems

> 2008  from COMPONENT to SYSTEM NANOTECHNOLOGY
Challenges for Systems Nanotechnology

• Understanding mechanisms and patterns of system behavior as a function of components, interaction forces and networks at the nanoscale. Consider systems with large number of nano-components and non-linear interactions.

• **Tools** for measuring, simulation and manufacturing of bio/engineering nanosystems.

• Development of a **new framework for risk assessment** to address emerging functions of nanosystems with potential use in consumer products, medical treatments, food industry and other areas.

Integrated circuits that are smaller and faster are possible with microfluidics systems built from or incorporating nanocomponents. *Ferreira, UIUC, 0328162.*

MC Roco, 4/18/2008
Examples new topics in 2008
Nanodevices and components of nanosystems

- A. Zettl (UCB), J. Rogers (U Illinois): nano radio = antenna, filter, amplifier
- IBM: Manipulation with atomic precision
- C. Mirkin (NU), O. Gang (BNL) Architectures for new, designed crystals
- Graphene to build electronic systems
- Informatics for nanosystem design
- Nanolayers for energy conversion
- Water filtration using nano membranes

M.C. Roco, 4/18/2008
Nano radio  (by Zettl Group, UCSB)
Designing molecules for hierarchical selfassembling

Example 4th generation (in research)

- **Biomaterials for human repair**: nerves, tissues, wounds (Sam Stupp, NU)
- **New nanomachines** based on 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)
Changing **R&D infrastructure** since 2000

Ex: US - NNI Infrastructure

Over 80 nanotechnology research centers, networks, and user facilities linked in a world-class interdisciplinary infrastructure

Over 4500 active research projects in 2007 at over 500 universities, Government labs, and other research institutions in all 50 states

Source: NNCO

M.C. Roco, 4/18/2008
NNI Networks and User Facilities

• NSF: eight networks with national goals and service
• NIH: four for medical research, cancer and metrology
• DOE: one network with five large facilities
• NASA: network of four centers on convergence
• DOD: three centers on nanoscience
• NIST: instrumentation and manufacturing user facilities
• NIOSH: particle characterization center
Nine Nanoscale Science and Engineering networks with national outreach

**TOOLS**
- Network for Computational Nanotechnology (2002-) > 50,000 users/ 2007

**TOPICAL**
- Nanotechnology Center Learning and Teaching (2004-) 1 million students/ 5yr
- Center for Nanotechnology Informal Science Education (2005-) 100 sites/ 5yr
- Network for Nanotechnology in Society (2005-) Involve 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-) 17 research & education centers
- MRSEC Network (2001-) 6 new research & education centers since 2000
A national resource for research, education and user-facility
Focus: from atoms to systems; same equations for various applications

NCN (7 nodes)

Norfolk State U.
U. Texas-El Paso
Stanford U.
U. Florida
Northwestern U.
U. Illinois-Urbana Champaign

http://www.nanoHUB.org – Open-source
> 50,000 users / 2007; NSF cost ~ $100 / user
National Nanomanufacturing Network
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*
### Changing national investment

**FY 2009 NNI Budget Request - $1,527 million**

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<th>Fiscal Year</th>
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<td>2008</td>
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<td><strong>R 2009</strong></td>
<td><strong>$1,527M</strong></td>
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EHS 2006: $38M (primary; $68M total eff.)
2007: $48M (primary; $86M total est.)
2008: $57M (primary; $102 total est.)
2009: $76M (primary - planned)

**NNI / R&D ~ 1/4 of the world R&D**

**NNI / EHS > 1/2 of the world EHS R&D**

MC Roco, 01/10/2008
FY 2009 Request: $397M ~1/4 of Federal and ~1/12 of World Investment

- Fundamental research - new priorities as compared to 5 years ago
- Establishing the infrastructure - over 4,000 active projects;
  24 large centers, 3 user facilities (NNIN, NCN, NNN), multidisc. teams
- Training and education – over 10,000 students and teachers/yr

<table>
<thead>
<tr>
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R 2009 $397M

M.C. Roco, 04/18/2008
ACTIVE Nanoscale Science & Engineering Awards
(FY 2001 - 2007)
Per Capita Amount for NEW NS&E Awards FY 2001 – 2007 by State

<table>
<thead>
<tr>
<th>State</th>
<th>NEW FY 2001-2007</th>
<th>$ Per Capita</th>
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FY01-07 PerCapita NEW Amt.

- Blue: <= 5.466
- Light Blue: 5.466 - 7.262
- Light Red: 7.262 - 8.859
- Red: 8.859 - 10.63
- Orange: 10.63 - 16.27
- Pink: 16.27 - 42.95

M.C. Roco, 4/18/2008
Institutions (28) with $5 Million or More (NSE Portion) in ACTIVE FY 2007 Awards

Institution

- Cornell University
- Northwestern University
- University of Wisconsin-Madison
- Purdue University
- University of Pennsylvania
- Colorado State University
- University of California-Berkeley
- Johns Hopkins University
- Columbia University
- Harvard University
- University of California-Los Angeles
- University of Michigan Ann Arbor
- University of Texas at Austin
- Pennsylvania State University
- Colorado State University
- University of California-Berkeley
- University of Virginia Main Campus
- Massachusetts Institute of Technology
- Stanford University
- University of Minnesota-Twin Cities
- Texas A&M University
- University of Texas at Austin
- University of California, Santa Barbara
- University of Colorado at Boulder
- Arizona State University

FY 2007 ACTIVE AwardAmt.

- $25,000,000
- $20,000,000
- $15,000,000
- $10,000,000
- $5,000,000
- $0
www.nsf.gov/nano or link www.nano.gov

NSF National Nanotechnology Initiative (NNI)

Search for NSF awards by keywords
(go to the "Full text search", and complete the box with your keywords; Examples of keywords are nano*, self-assemble* and nanoparticle)

NSF press releases on Nanotechnology Research since January 2004

NSF press releases on Nanotechnology Research from 2003 to 2001

SOLICITATIONS AND OUTCOMES IN FY 2005

NSF Announcement 05-543: Nanoscale Science and Engineering Education (NSEE)
"Preparation workshop: Public Engagement in Nanoscale Science and Engineering" (PDF, 776KB)

NSF Announcement 04-043: Nanoscale Science and Engineering (NSE)
NSEC on "Nanotechnology in Society" workshop

Joint EPA-NSF-NIOSH solicitation for research in Environmental and Human Health Effects of Manufactured Nanomaterials


**NNI Accomplishments (1)**

- **Developed foundational knowledge** for control of matter at the nanoscale: about **4,000 active projects** in > 500 universities, private sector institutions and gov. labs in all 50 states.

- “Created an **interdisciplinary nanotechnology community**”

- **R&D / Innovation Results**: With ~25% of global government investments, the U.S. accounts worldwide for
  - ~ 50% of highly cited papers,
  - ~ 60% of USPTO patents,
  - ~ 70% of startups in nanotech.
  Over 2,000 U.S. nanotech companies in 2006;
  ~ $60B products incorporating essential nano components.

- **Infrastructure**:
  over **80 new** large nanotechnology research centers, networks and user facilities; five large networks of user facilities.

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(1) NSF Committee of Visitors; (2) Journal of Nanoparticle Research, 2006; (3) NanoBusiness Alliance, 2006
**NNI Accomplishments (2)**

- **Partnerships:** with industry (Consultative Boards for Advancing Nanotechnology - CBAN), regional alliances (25), international (over 30 countries), numerous professional societies.

- **Societal implications and applications** - since 2000, about 15% of NSF / NNI budget has relevance to environmental health, and safety, and other societal and educational concerns; NNI estimates ~ $100 million in FY 2008 (primary/secondary).

- **Nanotechnology education and outreach** - impacting over **10,000 graduate students and teachers** in 2007; expanded to undergraduate and high schools, and outreach; create national networks for formal and informal education.

- **Global outreach:** The U.S. NNI has catalyzed global activities in nanotechnology and served as a stimulus for other programs.
Industry-academe-government R&D partnerships for common goals

- Increased role of industry in funding nanotechnology R&D; changes in gov. funding
- Special role of local governments for infrastructure, education and small business
- Global partnerships for nanotechnology knowledge, markets and organizations
- Cross-industry R&D consortia
NNI-Industry Consultative Boards for Advancing Nanotech

Key for development of nanotechnology, Reciprocal gains

- **NNI-Electronic Industry (SIA/SRC lead), October 2003** -
  Collaborative activities in key R&D areas
  5 working groups, Periodical joint actions and reports
  NSF-SRC agreement for joint funding; other joint funding

- **NNI-Chemical Industry (CCR lead)**
  Joint road map for nanomaterials R&D; Report in 2004
  2 working groups, including on EHS
  Use of NNI R&D results, and identify R&D opportunities

- **NNI – Organizations and business (IRI lead), 2004-**
  Joint activities in R&D technology management
  2 working groups (nanotech in industry, EHS)
  Exchange information, use NNI results, support new topics

- **NNI-Biotechnology (BIO lead), October 2004-**
  Collaborative activities in key R&D areas
  2 working groups, R&D collaboration and EHS; joint funding
Changing international context since 2000

~ 2000: Focus on discovery, ‘wait & see’ if applied

> 2005: Nano as a technological, economical and strategic advantage for nations and large businesses

Expanding open-source horizontal growth communication governance
Context – Nanotechnology in the World
National government investments 1997-2007 (estimation NSF)

![Graph showing nanotechnology investments by region and year.]

- **Seed funding (1991 - )**
- **NNI Preparation** (vision / benchmark)
- **1st Strategic Plan** (passive nanostructures)
- **2nd Strategic Plan** (active ns. & systems)

Industry R&D ($6B) has exceeded national government R&D ($4.6B) in 2006

J. Nanoparticle Research, 7(6), 2005, MC. Roco
Growing nanotechnology R&D investment - $12.6 billion in 2006

Private (Corp. + VC) Total = $6 billion

Public (National, regional, state) Total = $6.4 billion

National governments ~ $4.6 billion
Local governments and organizations ~ $1.8 billion

Source: Lux Research
Nanotechnology research publications

Top five countries in 2006: USA, China, Japan, Germany, France

using “Title-claims” search in SCI database for nanotechnology by keywords
(using intelligent search engine, update J. Nanoparticle Research, 2004, 6 (4))

![Graph showing the percentage of highly cited nanotechnology papers published in Science, Nature, and PNAS by country from 1991 to 2005. The graph illustrates a steady increase in contributions from the USA, with concurrent small increases from Japan, People's Republic of China, Germany, and France.](image-url)
NSE patents at USPTO by country group
Assignee country group analysis by year, 1976-2006 ("title-claims" search)

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<td>1862</td>
<td>1658</td>
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M.C. Roco, 4/18/2008
U.S. International partnerships for Nanotechnology

- Nanotechnology included in bilateral (e.g. U.S.- Japan, EU, India, etc.), and international organizations (e.g. OECD, APEC, etc.) S&T agreements

- Typical NSF activities
  - Bottom-up by individual partnerships in research
  - Periodical NanoForums (annual); other workshops
  - Using networks: NNIN / NCN and partner networks / facilities
  - Young scientists exchange programs

- Areas and modes of increased collaboration:
  - fundamental knowledge (precompetitive) - by twinning and networking
  - education - by visits, int. courses, books, int. accreditation, study institutes
  - broad societal implications: health, environment, energy, water filtration, ethics - exchanges
  - contribute to international S&T “grand challenges”
  - industry partnerships, precompetitive nanotechnology platforms

MC Roco, 4/18/2008
Changing public perception and governance since 2000

**Before 2000:** Is anything special at nanoscale? Is nanotechnology important? When the first products?

**2000-2003:** Are there self-duplicating nano-bots?

> **2003:** What are the risks of “long-term / catastrophic environmental and health events” of nanoparticles?

> **2005:** Nanotechnology can help sustainable management of global resources (water, energy, ..) Concern on using nanotechnology in food, others

MC. Roco, 4/18/2008
NANOTECHNOLOGY GOVERNANCE OVERVIEW

Core Governance Process
(Long-term view, transforming, horizontal/vertical, inclusive, priority on education, addressing societal dimensions, risk governance)

R&D Organizations
(Academe, industry, gov.)

Implementation Network
(Regulators, business, NGOs, media, public)

Social Climate
(Perceived authority of science, civil involvement)

National Political Context

International Interactions

NT Governance and Risk Governance

NT GOVERNANCE
- Investment policy
- Science policy
- Risk governance
- Others

Four key functions

NANOTECHNOLOGY RISK GOVERNANCE (IRGC)

M.C. Roco, 4/18/2008
A sampling of NSET Subcommittee publications for second strategic plan (2006-2010)

Societal Implications (II)
Inclusive: industry, academe, government

Participants in the National Nanotechnology Initiative

Year Agency Joined the NNI

2001: Six Agencies
- NSF
- DOE
- DOD
- NASA
- NIST
- NIH

2002: Seven New Agencies
- EPA
- DOT
- DOTr
- DOJ
- USDA
- IC
- DOS

2003-4: Four New Agencies
- DOC
- DHS
- NRC
- FDA

2005: Six New Agencies
- EPA
- DOT
- USDA
- IC
- DOS
- NRC

2006: Three New Agencies
- DOJ
- USGS
- NIST

2007: Three New Agencies
- NRC
- ITC
- CPSC

Sources: Roco, 4/18/2008
Overview of NNI EHS funding in 2006

- $68 million funding for 246 nanotechnology-related EHS research projects at seven NNI member agencies
- Consensus among NEHI Working Group that instrumentation, metrology, and analytical methods category is cross-cutting and generally a high priority

<table>
<thead>
<tr>
<th>Category</th>
<th>Funding in Millions $</th>
<th>Number of Projects</th>
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<tbody>
<tr>
<td>Instrumentation, Metrology &amp; Analytical Methods</td>
<td>26.6</td>
<td>78</td>
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<td>Nanomaterials &amp; Human Health</td>
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<td>Human &amp; Environmental Exposure Assessment</td>
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<td>Risk Management Methods</td>
<td>3.3</td>
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</table>
NSF Investment in Societal Dimensions of NT

Of FY 2008 NNI / NSF of $390 M, $63 M or 16.2% is for SI, and $29.2 M (7.5%) for nano EHS

New NSEC in 2008: Environmental Implications of Nanotechnology (NSF, EPA)
Five possibilities for global nanotechnology governance

1. *Establish models for the global self-regulating ecosystem* to enhance discovery, education, innovation, nanoinformatics and commercialization

2. *Create and leverage S&T nanotech platforms* for new products in areas of highest societal interest

3. Develop NT for *common resources and EHS requirements*

4. Support *global communication and international partnerships*, facilitated by international organizations

5. Commitment to *long-term, priority driven, global view* using scenarios and anticipatory measures


M.C. Roco, 4/18/2008