

# *Frontiers in science and engineering* **Nanotechnology at NSF**

F. Frankel - copyright

**M.C. Roco**  
National Science Foundation  
and National Nanotechnology Initiative

NSF, December 4, 2006

Benchmark

"Nanostructure S&T"

Book Springer, 1999

## **WHAT IS NANOTECHNOLOGY**

(definition based on international benchmark since 2000)

- **Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 nm range, in order to understand and create materials, devices and systems with fundamentally new properties and functions because of their small structure (see <http://nano.gov>)**
- NNI definition encourages new R&D that were not possible before:
  - **novel phenomena, properties and functions at nanoscale**, which are nonscalable outside of the nm domain
  - **the ability to measure, control, and restructure matter at the nanoscale** in order to change those properties and functions
  - **integration along length scales, systems and applications**
- Nanotechnology uniquely defined, while there are many applications

MC Roco, 12/04/06



## National Nanotechnology Initiative at NSF



Designed molecule for self-assembly (UCSB)

- ❑ Coordination with other 24 agencies in the NNI (WH priority, NSTC/NSET subcommittee, OMB cross-cut, several working groups, and joint R&D activities)
- ❑ Nanotechnology is a priority element of the American Competitiveness Initiative (ACI)
- ❑ New research priorities (change focus from passive nanostructures to active nanostructures and nanosystems)
- ❑ Supports a strong infrastructure through 24 large centers, networks and user facilities, as well as research equipment
- ❑ Interaction with industry (with electronic, chemical and other industry sectors, small business support, private sector – academic partnerships)
- ❑ International collaboration (International Dialogue, OECD, bilateral agreements, workshops, awards)

MC Roco, 12/04/06



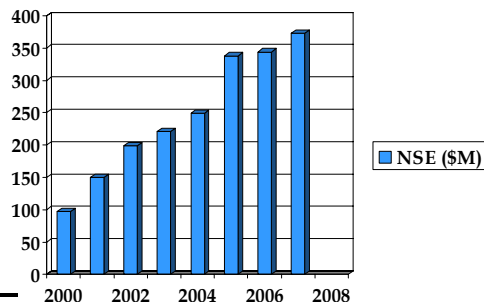
## NSF - a pioneer at the international level in Nanoscale Science and Engineering (NSE)

[www.nsf.gov/nano](http://www.nsf.gov/nano) or link from [www.nano.gov](http://www.nano.gov)

FY 2007 Request: \$373M ~1/4 of Federal and ~1/12 of World Investment

- **Fundamental research** - seven PCAs with new priorities
- **Establishing the infrastructure** - over 3,000 active projects; 24 large centers, 2 user facilities (NNIN, NCN), multidisciplinary teams
- **Training and education** - 10,000 students and teachers/yr

Fiscal Year	NSF
2000	\$97M
2001	\$150M
2002	\$199M
2003	\$221M
2004	\$254M
2005	\$338M
2006	\$344M
2007	\$373M



MC Roco, 12/04/06

## NSE: Role of Engineering

[www.nsf.gov/nano](http://www.nsf.gov/nano)

### Engineering has a leading role in NSE because:

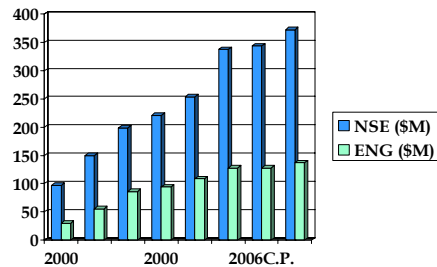
- nanotechnology deals with systems at nanoscale
- integrative, interdisciplinary
- transforming tool

Collaboration with NSF Directorates: MPS, CISE, BIO, GEO, SBE, HER

Also, NNI - 24 departments and agencies (DOE, DOD, NASA, NIH, NIST, EPA, etc.)

Changing engineering disciplines (research, education, relevance)

Fiscal Year	NSF	ENG
2000	\$97M	\$30.0M
2001	\$150M	\$55.3M
2002	\$199M	\$86.3M
2003	\$221M	\$94.4M
2004	\$254M	\$108.9M
2005	\$338M	\$127.8M
2006	\$344M	\$127.8M
R. 2007	\$373M	\$137.2M



MC Roco, 12/04/06



## NSF Program Emphasis in FY 2007

Increased investments will be dedicated to research and education on:

- **Increased focus on complex large nanosystems.** Research on nanoscale devices and system architecture, dynamic and emerging behavior, and their respective fabrication, will be emphasized
- **Increased focused on three-dimensional measurements of domains of engineering relevance with good time resolution**
- **Converging science, engineering and technology from the nanoscale, by integrating nanosystems into applications** (in manufacturing, information systems, medicine, environment, etc.)
- **Expanded joint research program addressing potential implications of nanotechnology;** partner with NIOSH, EPA and FDA, USDA and NIST
- **Earlier educational programs and teaching materials,** including for K-12, by using remote access to NSF educational networks (NU, NISE, NNIN)
- **Expand partnerships of academic researchers with industry, medical facilities and states** through two programs (GOALI, PFI), using the CBAN (Collaborative Board for Advancing Nanotechnology)

MC Roco, 12/04/06

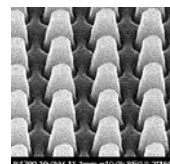


## ENG Priorities Research Areas (1)

The long-term objectives of this broad initiative focus on building a foundation of fundamental research to understand nanoscale concepts in all areas of S&E. Priority for new frontiers are:

### A. Development of nanotechnology

- Tools for measuring and restructuring with atomic precision
- Understanding and use of quantum phenomena
- Understanding and use of multi-scale selfassembling
- Nanobiotechnology – sub-cellular changes and systems approach
- Nanomanufacturing – for active nanostructures and nanosystems; use catalysts



### B. Integration of nanotechnology in application areas

- Replacing electron charge as the information carrier in electronics
- Energy conversion and water filtration/desalinization using new principles
- Nano-bio interfaces between the human body and manmade devices
- Nano-informatics for better communication and nano-system design

MC Roco, 12/04/06



## ENG Priority Research Areas (2)

### C. Societal dimensions

Environmental, health and safety (EHS) including research for the three sources (natural, incidental, manufactured) of nanomaterials

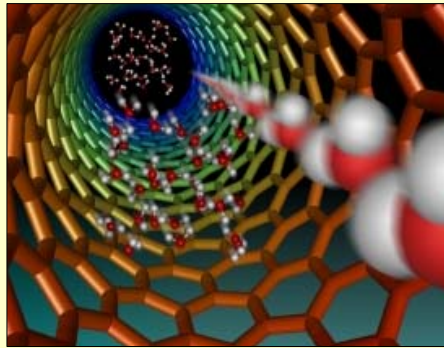
Earlier K-12 and public education

Social issues and public engagement

- **Key EHS priorities** (for knowledge creation, infrastructure, and education):
  - New instrumentation for nanoparticle characterization and nanotoxicity
  - Transport phenomena and physico- chem.- biological processes of nanoscale dispersions
  - Interaction of nanomaterials with cells and living tissues
  - Separation of nanoparticles from fluids
- **Safety of manufacturing nanoparticles** is being investigated in four Nanoscale Science and Engineering Centers (NSECs at Rice U., NE U., UPA and UWI) and one Network (NNIN)

MC Roco, 12/04/06

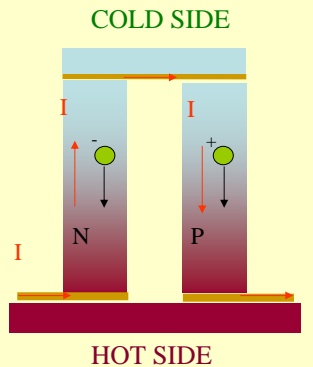
**Novel Membranes** Researchers at the University of Kentucky have fabricated membranes from billions of aligned carbon nanotubes. The surfaces of the membranes are almost friction-free. The theory has been verified in the same year by SNL



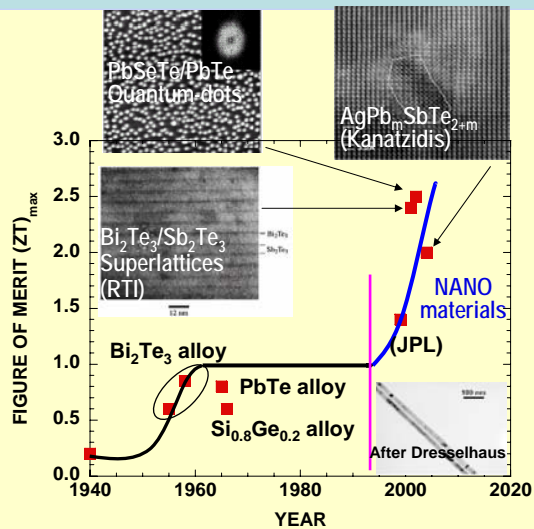
In this illustration, water is shown flowing through carbon nanotube membranes at a rate up to 100,000 times faster than models predict.

MC Roco, 12/04/06

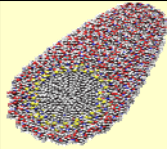
## Direct Thermo-electric Energy Conversion



Electron flux vs. phonon flux



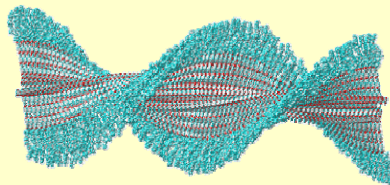
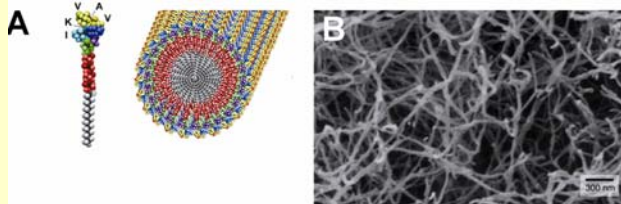
Credit: (MIT)



## Example: Designing molecules for hierarchical selfassembly

EX: SAMUEL I. STUPP, *Northwestern University*

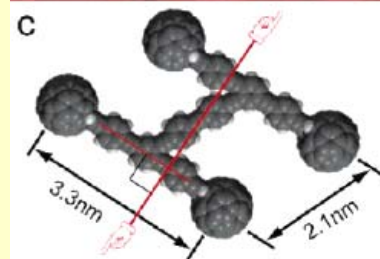
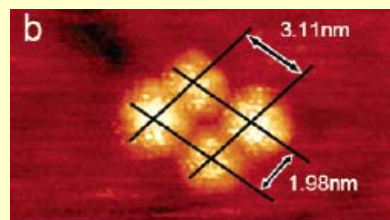
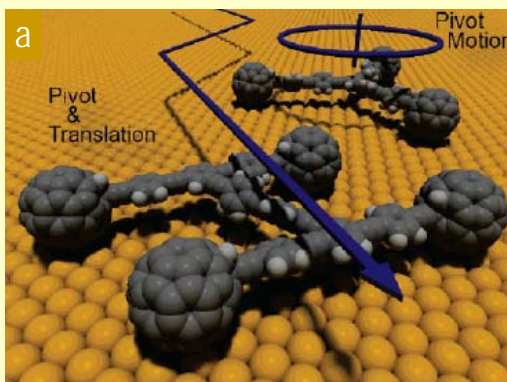
Application: biomaterials for human repair, reactive filters, others



MC Roco, 12/04/06

*Active nanostructure:*

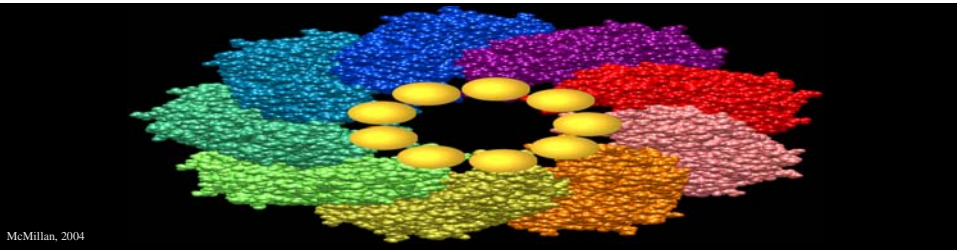
**Nano-cars driven by light-activated or thermally driven nanomotors (rolling molecules).** J. Tour group, Rice University.



Nano Letters, Vol. 5, 2005; JACS, Vol. 128, 2006

MC Roco, 12/04/06





McMillan, 2004

## Nanotechnology in the United States (some background information)

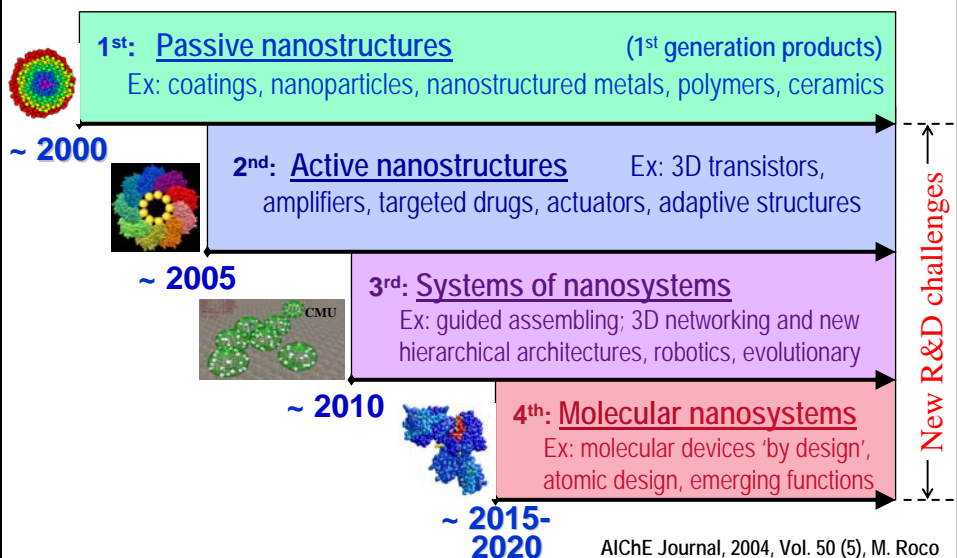
*Topics:*

*National Nanotechnology Initiative at 6 years*

*U.S. in the international context*

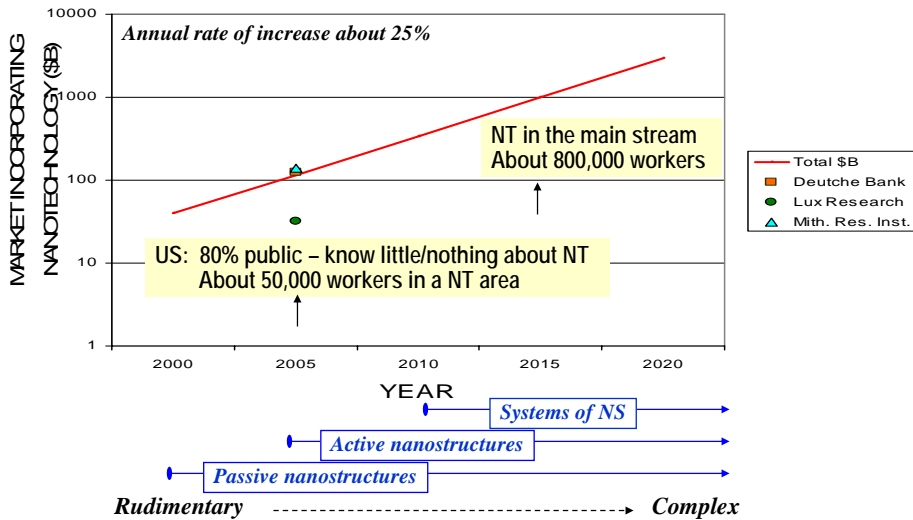
MC Roco, 12/04/06

### Timeline for beginning of industrial prototyping and nanotechnology commercialization: Four Generations



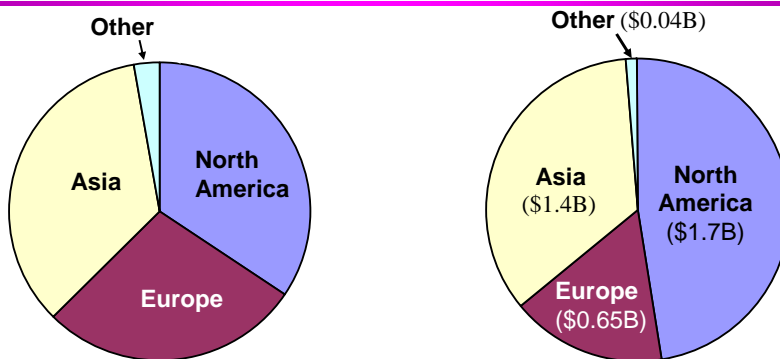


## Worldwide market incorporating nanotechnology. Estimation made in 2000 (NSF)



MC Roco, 12/04/06

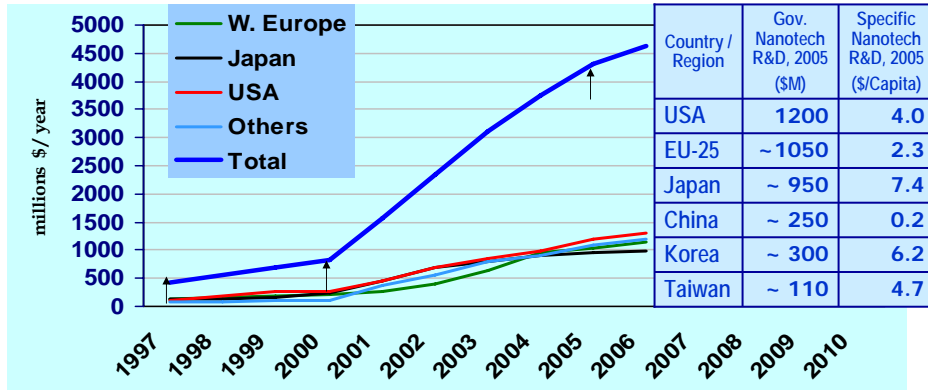
## Where do we stand? Global R&D investments in 2004 (Total = \$8.6 billion)



Source: Lux Research & NSF

## Context – Nanotechnology in the World

### National government investments 1997-2006 (est. NSF)



Seed funding  
(1991 -)

NNI Preparation  
(vision / benchmark)

1<sup>st</sup> Strategic Plan  
(passive nanostructures)

2<sup>nd</sup> Strategic Plan  
(active ns. & systems)

Industry R&D (\$5B) has exceeded national government R&D (\$4.3B) in 2005

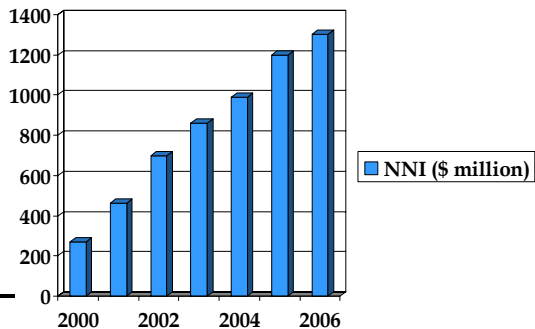
J. Nanoparticle Research, 7(6), 2005. MC, Roco

## National Nanotechnology Initiative

(NSF, DOD, DOE, NIH, NIST, EPA; total 25 agencies)

Total budget in FY 2006 = \$1.3 billion

Fiscal Year	NNI
2000	\$270M
2001	\$464M
2002	\$697M
2003	\$862M
2004	\$989M
*2005	\$1200M
*2006	\$1303M
*2007	>\$1278M



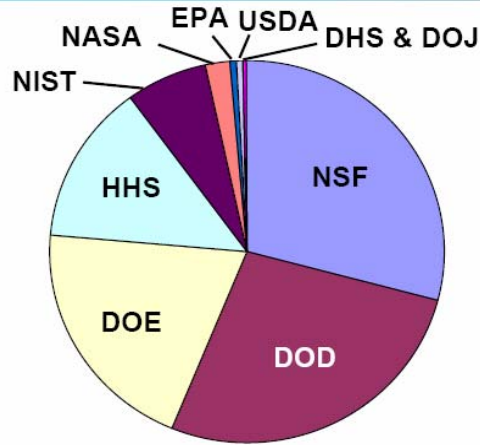
\* Includes Congressionally directed additional funding

MC Roco, 12/04/06



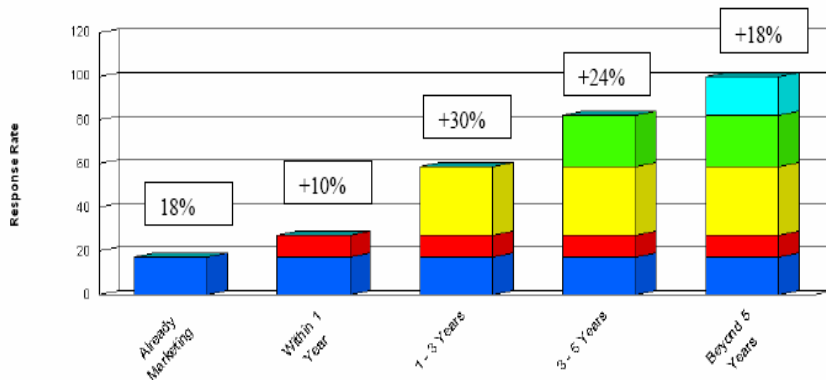
## NNI FY 2007 Budget Request

Total = \$1,277 million



MC Roco, 12/04/06

## 2005 NCMS Survey on nanotechnology in manufacturing industry (594 companies)



**Commercialization timelines indicate many new nanoproducts introductions in 2007-2011, and the high level of expectation in long-term (Jan 2006)**

MC Roco, 12/04/06



## ***NNI Accomplishments (1)***

- **Developed foundational knowledge** for control of matter at the nanoscale: over 4,000 active projects in > 500 universities, private sector institutions and gov. labs in all 50 states
- “Created an **interdisciplinary nanotechnology community**”<sup>1</sup>
- **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<sup>2</sup>, and
  - ~70% of startups<sup>3</sup> in nanotech.Over 2,000 companies with nanotechnology products in 2006 (U.S.)
- **Infrastructure**:  
59 new large nanotechnology research centers, networks in Dec 2005 and user facilities; about 16,000 users in 2 academic-based networks

(<sup>1</sup>) NSF Committee of Visitors, 2004; (<sup>2</sup>) Journal of Nanoparticle Research, 2004; (<sup>3</sup>) NanoBusiness Alliance, 2004

MC Roco, 12/04/06

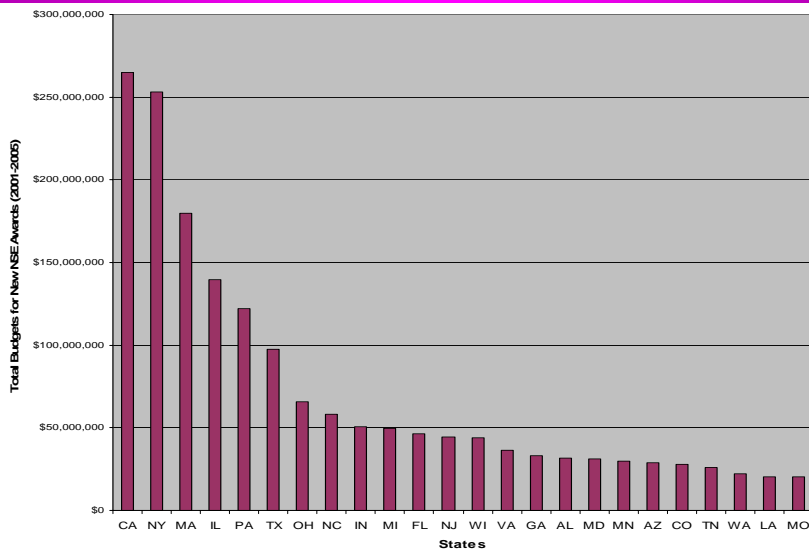


## ***NNI Accomplishments (2)***

- **Partnerships**: with industry (Consultative Boards for Advancing Nanotechnology - CBAN), regional alliances (22), international (over 25 countries), numerous professional societies
- **Societal implications and applications** -  
from the beginning, about 10% of 2004 NNI; addresses environmental and health, safety, and other societal and educational concerns; NSET SC leadership thru NEHI WG
- **Nanotechnology education and outreach** -  
impacting over 10,000 graduate students and teachers in 2004; expanded to undergraduate and high schools, and outreach; create national networks for formal and informal education
- **Leadership**:  
The U.S. NNI has catalyzed global activities in nanotechnology and served as a model for other programs.

MC Roco, 12/04/06

## Total budget for NEW NSF-NSE awards for fiscal years 2001-2005 by states

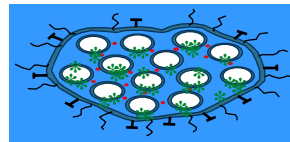


MC Roco, 12/04/06

## Directions and Impact: Synthesis and control of nanomachines

(examples 2004, [www.nseresearch.org](http://www.nseresearch.org) - over 300 projects)

- ❑ Self-assembly processing of nanoscale bio-materials and devices for micromachines components (UCSB)
- ❑ Chemistry to synthesize components of **nano machines to work on surfaces** and be activated by external electromagnetic fields (UCB)
- ❑ **Light driven molecular motors** (U. Nevada)
- ❑ **Combinatorial engineering of nanomachines**, with application to membranes and filters (U. Penn.)
- ❑ **Nanoengineering surfaces** for probing viral adhesion (UC Davis)



MC Roco, 12/04/06



## Infrastructure Outcomes of 2001-2005: NSF R&D Networks and User Facilities

<http://www.nsf.gov/crssprgm/nano/>

- **Network for Computational Nanotechnology (NCN)**  
7 universities (Purdue as the central node)  
Nanoelectronic device simulation/modeling
- **National Nanotechnology Infrastructure Network (NNIN)**  
13 universities with user facility  
Development measuring & manufacturing tools, including NEPM  
Education and societal implications
- **Oklahoma Nano Net (EPSCoR award)**

### Centers:

16 Nanoscale Science and Engineering (NSEC) - 6 (2001); 2 (2003); 6 (2004); 2 (2005)

Nanotechnology Center for Learning and Teaching (NCLT);

Nanoscale Informal S&E; Six new MRSECs on nanomaterials

MC Roco, 12/04/06



## NSF Nanoscale S&E Centers

[www.nsecnetwork.net](http://www.nsecnetwork.net)

### Nanoscale Science and Engineering Centers (NSEC)

Electron Transport in Molecular Nanostructures, [Columbia](#)  
Nanoscale Systems, [Cornell](#)  
Directed Assembly of Nanostructures, [RPI](#)  
Science for Nanoscale Systems and their Device Applications, [Harvard](#)  
Institute for Nanotechnology, [Northwestern](#)  
Biological and Environmental Nanotechnology, [Rice](#)  
Scalable and Integrated Nanomanufacturing, [UCLA](#)  
Nanoscale Chem-Electr-Mechanical Manufacturing, [U Illinois-Urbana Champ.](#)  
Integrated Nanomechanical Systems, [UC Berkeley](#)  
High Rate Nanomanufacturing, [Northeastern](#)  
Affordable Nanoengineering, [Ohio State](#)  
Molecular Function at the Nanoscale, [U Pennsylvania](#)  
Probing the Nanoscale, [Stanford](#)  
Templated Synthesis and Assembly at the Nanoscale, [U Wisconsin](#)  
Nanotechnology in Society Network, [ASU](#), [UCSB](#), [U South Carolina](#), [Harvard](#)  
Network for Hierarchical Manufacturing, [U Mass-Amherst](#)  
The Nanobiotechnology Science and Technology Center, [Cornell](#)

### Nanoscale Science and Engineering Education Centers (NSEE)

Nanotechnology Center for Learning and Teaching (NCLT), [Northwestern](#)  
Nanoscale Informal Science Education (NISE), [Boston Museum of Science](#)

MC Roco, 12/04/06



## Six Nanoscale Science and Engineering networks with national outreach

Network for Computational Nanotechnology (2002-) 12,000 users/ 2006  
National Nanotechnology Infrastructure Network (2003-) 4,000 users/ 2006

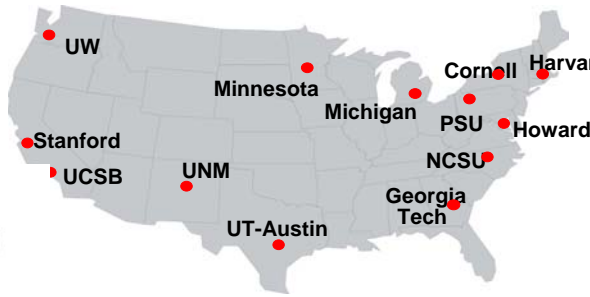
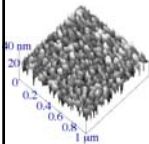
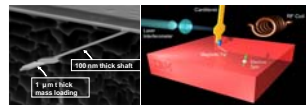
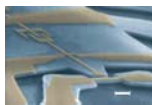
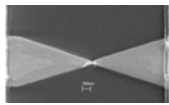
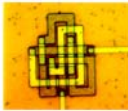


Nanotechnology Center Learning and Teaching (2004-) 1 million students/ 5yr  
Network for Nanotechnology in Society (2005-) Involve academia, public, industry  
Center for Nanotechnology Informal Science Education (2005-) 100 sites/ 5yr  
National Nanomanufacturing Network (2006-) 4 NSETs, DOD centers, and NIST

MC Roco, 12/04/06



## National Nanotechnology Infrastructure Network (NNIN)



- Cornell U (Lead)
- Stanford U
- U Michigan
- Georgia Tech
- U Washington
- Penn State U
- UC Santa Barbara
- U Minnesota
- U New Mexico
- U Texas –Austin
- Harvard U
- Howard U
- No. Carolina State U

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

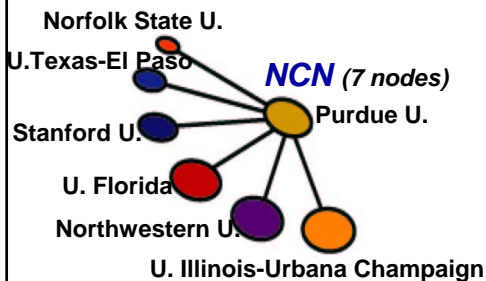
<http://www.NNIN.org>; Est. 4,000 users in 2006, NSF 3,500/ user

MC Roco, 12/04/06



## Network for Computational Nanotechnology

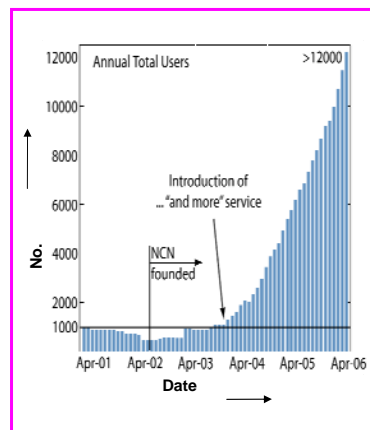
**A national resource for research, education and user-facility to accelerate the transformation of nanoscience to nanotechnology through theory, modeling, and simulation and collaboration enabled by cyberinfrastructure**



Focus: "from atoms to systems";  
"same equations for various applications"

<http://www.nanoHUB.org>

Est. 12,000 users / 2006; NSF \$350 / user



MC Roco, 12/04/06

## National Nanomanufacturing Network (NNN)

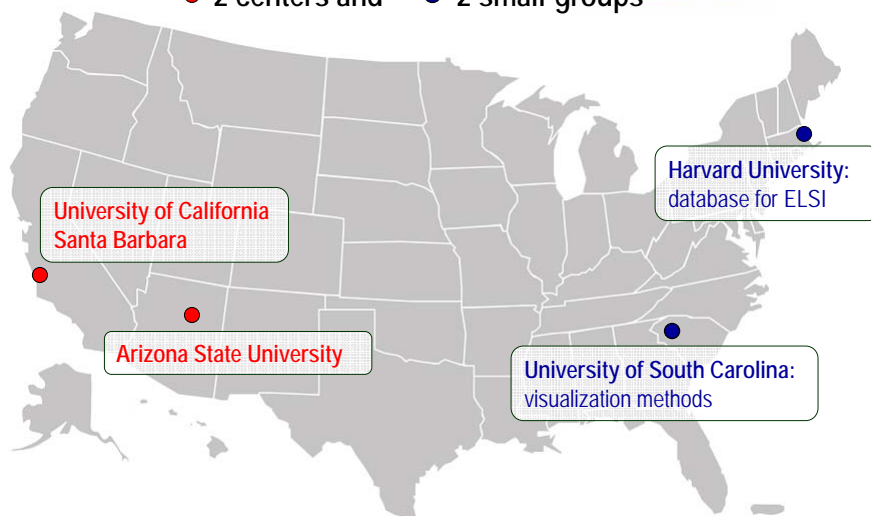
- **NSF: Four NSECs**
  - Center for Scalable and Integrated Nanomanufacturing, UCLA (2004- )
  - Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems, University of Illinois at Urbana-Champaign (2005- )
  - Center for High Rate Nanomanufacturing, Northeastern University (2005- )
  - Network for Hierarchical Manufacturing U. Mass. - Amherst (2006- ) (*Main Node of NNN*)
- **DOD**
- **NIST, Laboratory for Nanoscale Science and Technology**



## NSEC: Nanotechnology in Society

Four nodes established in September 2005:

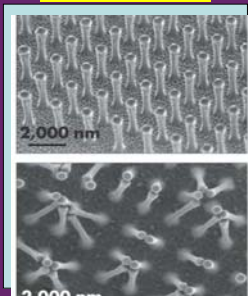
● 2 centers and ● 2 small-groups



To address Ethical, Legal and other Social Issues related to Nanotechnology

## Nanotechnology Informal Science Education Network

Center for  
NISE Research  
Exploratorium  
San Francisco



- Visualization Lab
- Resource Center
- Research and Evaluation
- Professional Development
- Public Website

Center for Public  
Engagement  
Museum of Science  
Boston



- Network Media
- Forums
- Network Administration

Center for  
Exhibits & Programs  
Science Museum of  
Minnesota



- Exhibit and Program Packages

To create 100 science museum sites in U.S. by 2010

**DOE: Construction is complete and initial operations are underway at four NSRCs**



*Center for Functional Nanomaterials  
(Brookhaven National Laboratory)*



*Molecular Foundry  
(Lawrence Berkeley National Laboratory)*



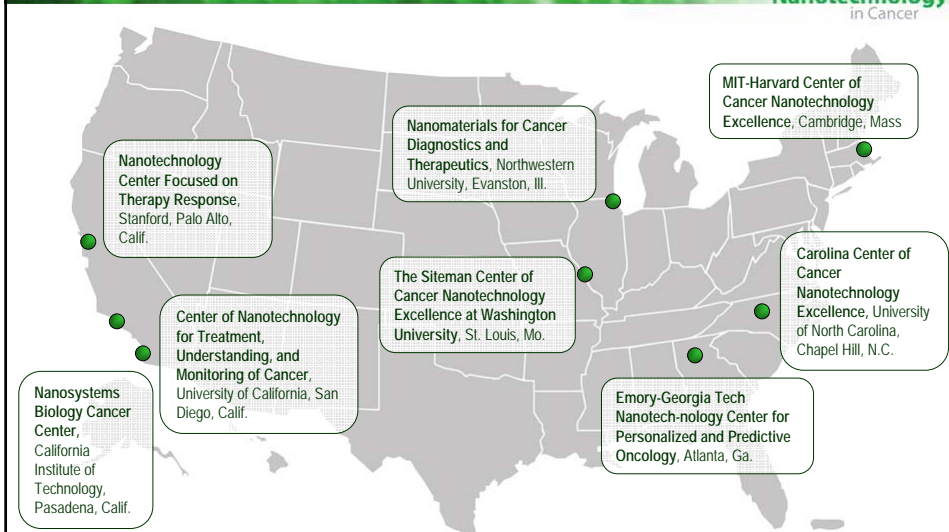
*Center for Nanophase Materials Sciences  
(Oak Ridge National Laboratory)*

*Center for Integrated Nanotechnologies  
(Sandia & Los Alamos National Labs)*



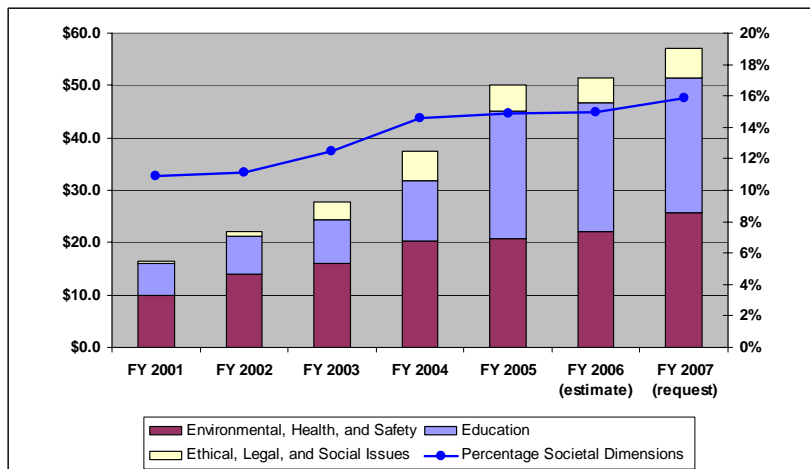
**Cancer Centers of Nanotechnology Excellence (8 established in October 2005)**

NCI Alliance for  
**Nanotechnology**  
in Cancer



MC Roco, 12/04/06

Of the total 2007 NNI/NSF Request of \$373.2 million, \$59 million - or 16 percent - is directed toward societal dimensions. This is a \$7.6 million (15 percent) increase over the FY 2006 estimated contribution of \$51.5 million.



MC Roco, 12/04/06



## Nanocomposite Solar Cells



**Goal:**

- Develop high performance, low cost lightweight flexible solar cells

**Approach:**

- Innovative solar cell design that combines precisely engineered inorganic semiconductor nanocrystals with a light-weight, flexible host-matrix

**Technical Objectives:**

- Develop optically and electronically enhanced nanocrystals
- Develop new Device Components
- Develop Advanced Device Architectures

**Commercialization Strategy:**

- Nanosys focuses on nanotechnology element in the end product
- Partner with industry leaders to jointly develop and manufacture nano-enabled component into end product.
- Our partner provides marketing resources and access to end customers

MC Roco, 12/04/06

## 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, 12/04/06