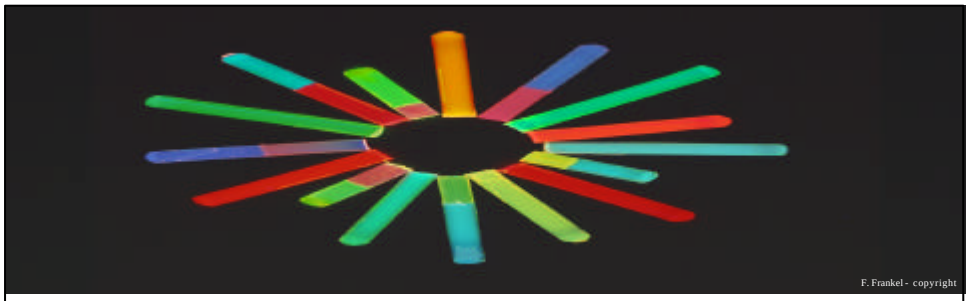


The Future of the National Nanotechnology Initiative

Dr. M.C. Roco

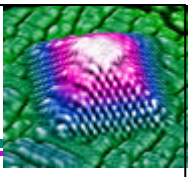
Chair, Subcommittee on Nanoscience, Engineering and Technology (NSET), National Science and Technology Council (NSTC)

Senior Advisor for Nanotechnology, National Science Foundation

Seoul, Korea, October 14, 2003

Nanotechnology

Definition on http://nano.gov/omb_nifty50.htm



- 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
- **NNI definition encourages new contributions that were not possible before.**
  - novel phenomena, properties and functions at nanoscale, which are nonscalable outside of the nm domain
  - the ability to control / manipulate matter at the nanoscale in order to change those properties and functions
  - integration along length scales, and fields of application

Broad societal implications

(examples of societal implications;
worldwide estimations made in 2000, NSF)

- **Knowledge base**: better comprehension of nature, life
- **New technologies and products: ~ $1 trillion/year by 2015**
  (With input from industry US, Japan, Europe 1997-2000, access to leading experts)

  Materials beyond chemistry: $340B/y
  Pharmaceuticals: $180 B/y
  Aerospace about $70B/y
  Electronics: over $300B/y
  Chemicals (catalysts): $100B/y
  Tools ~ $22 B/y

  Est. in 2000 (NSF) : about $40B for catalysts, GMR, materials, etc.; + 25%/yr
  Est. in 2002 (DB) : about $116B for materials, pharmaceuticals and chemicals

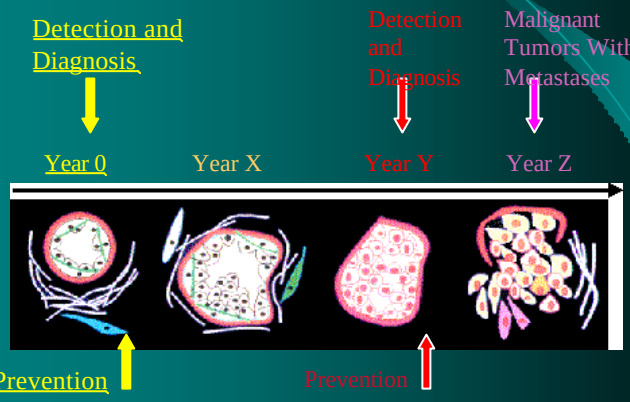
  Would require worldwide ~ 2 million nanotech workers
- **Improved healthcare**: extend life-span, its quality, physical capabilities
- **Sustainability**: agriculture, food, water, energy, materials, environment; ex: lighting energy reduction ~ 10% or **$100B/y**

MC. Roco, 9/26/03

Challenge: To Eliminate Suffering and Death Due to Cancer – 2015

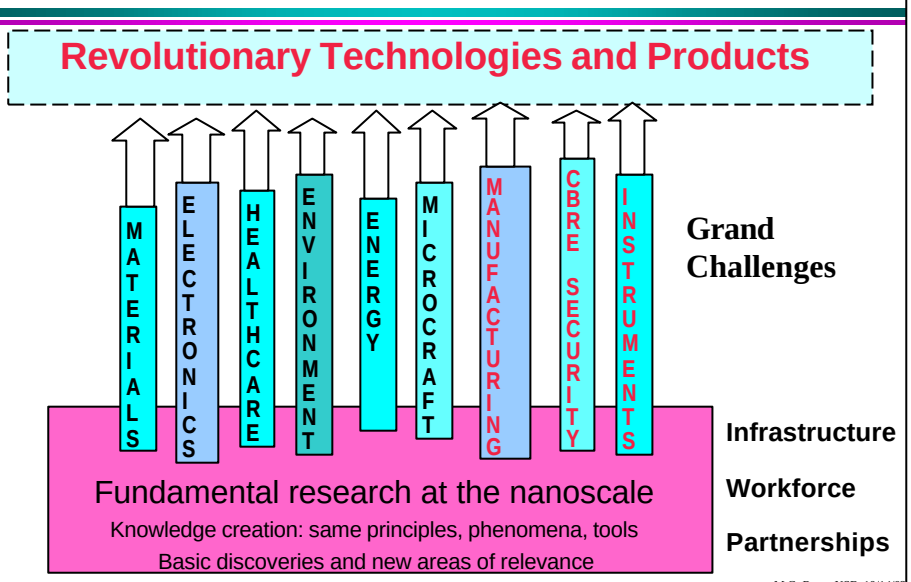
"A Vision Not a Dream!" by using nanotechnology, A v. *Eschenbach, NCI*

Where We Want To Be ◄ **Where We Are**



Cancer results from accumulation of multiple genetic changes in a cells.
Nanotechnology will allow earlier detection and prevention (Year 0)

Interdisciplinary "horizontal" knowledge creation vs. "vertical" transition from basic concepts to Grand Challenges



M.C. Roco, NSF, 10/14/03

Scientific Breakthroughs

in the first two years (NNI, 2001-2002)

- **Developments faster than expected**

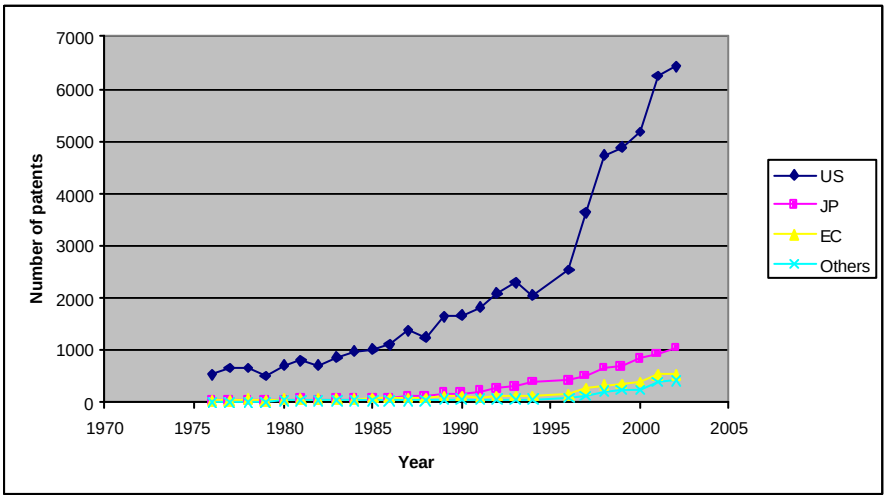
  Reducing the time of reaching commercial prototypes by at least of factor of two for several key applications

- **10 key advancements**
  - Engineer materials with atomic precision using biosystems as agents
  - Create circuits with the logic element a molecule wide
  - Assemble DNA, nanocrystals to build molecular devices and systems
  - Detect anthrax, other contaminants with unprecedented speed
  - Single molecule behavior and interaction
  - Artificial genetic system
  - Conducting polymers
  - New concepts for large scale production of nanotubes, their use
  - Drug delivery systems
  - Detection of cancer

MC. Roco, 10/14/03

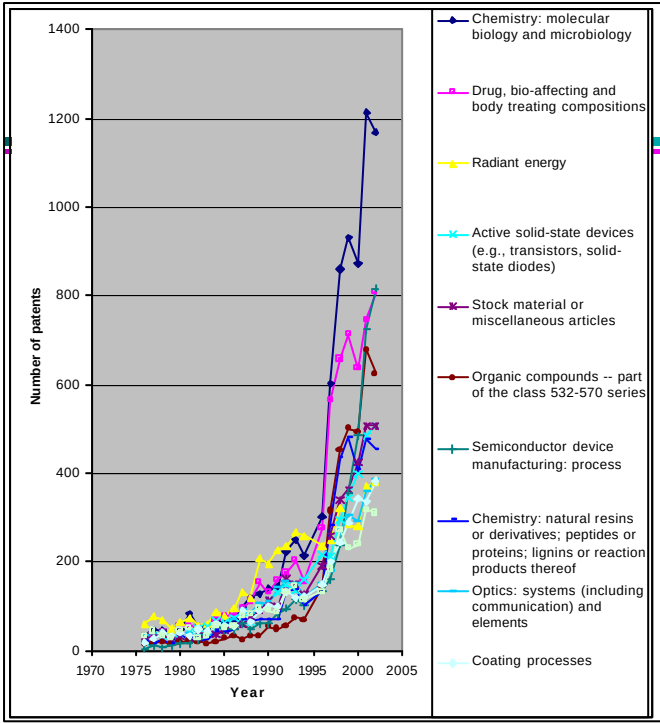
Nanotechnology patents per region (NSF, 2003)

Searched by keywords at USPTO : nano*, atomic force microscop*, atomistic/molecular simulation, biomotor, molecular device, molecular electronics, molecular modeling, molecular motor, molecular sensor, quantum computing, quantum dot*, quantum effect*, scanning tunneling microscop*, selfassembl*



www.nsf.gov/nano (from J. of Nanoparticle Research, 2003)

MC. Roco, 6/19/03



Technology field analysis by year

www.nsf.gov/nano (Longitudinal Nanotechnology Patent Analysis, from J. of Nanoparticle Research, 2003)

MC. Roco, 6/19/03

Integrating science and technology from the nanoscale

- **Broad and timely opportunity**
  - **Understanding unity in nature, and technology integration from the nanoscale**
  - **Powerful transforming tools (NBIC: nano-bio-info-cogno) developing at confluence of disciplines**
  - **Improvement of individual and group human performance becomes possible**
  - **Need for anticipation ('learning before doing') and deliberate choices**
- **NBIC - agents of accelerated, synergistic change**

(December 2001)

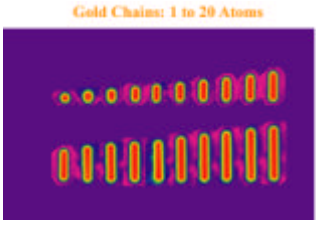
Online www.nsf.gov/nano,
also Kluwer Academic Publ

MC. Roco, 10/14/03

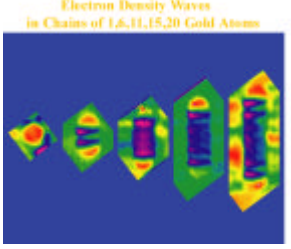
Specify the state of a molecule

EX: Atom-by-Atom Construction of Nanostructures, W. Ho et al.

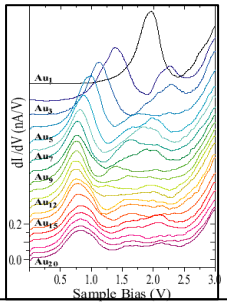
A



B



C

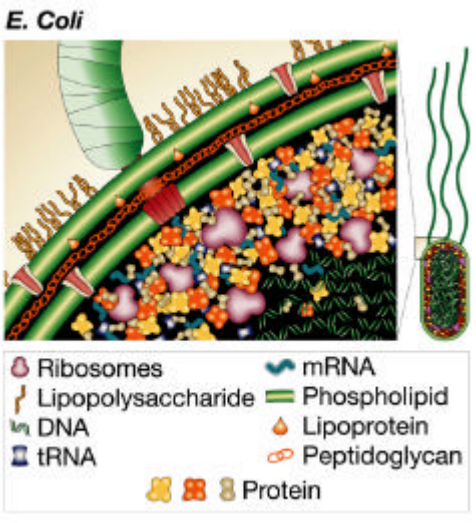


A: STM images of 1 to 20-atom Au chains constructed atom-by-atom by atomic manipulation on NiAl(110) at 12 K.

B: Electron density waves of 5 different Au chains on NiAl(110) exhibiting standing waves of 1-D particle in a box.

C: Electron density of states measured in the middle of the 1-20 atom Au chains, revealing the development of 1-D band structure from a single atomic level.

Specify the state of a cell



Measure and simulate the populations of all the proteins present

3 dimensional
Highly parallel
…

Functional Nano-Scale Bio-Materials by Controlled Self-Assembly

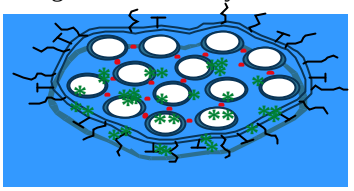
EX: Matthew Tirrell, UCSB, NSF-0103516

- Self-assembly processing of nanoscale bio-materials and devices (Creating bio-mimetic nested structures, micromachines components)

Triple Helix

- Molecules (e.g., a Triple Helix) have been designed to incorporate into bilayer walls of structures to control their interactions both with each other and with their surroundings.

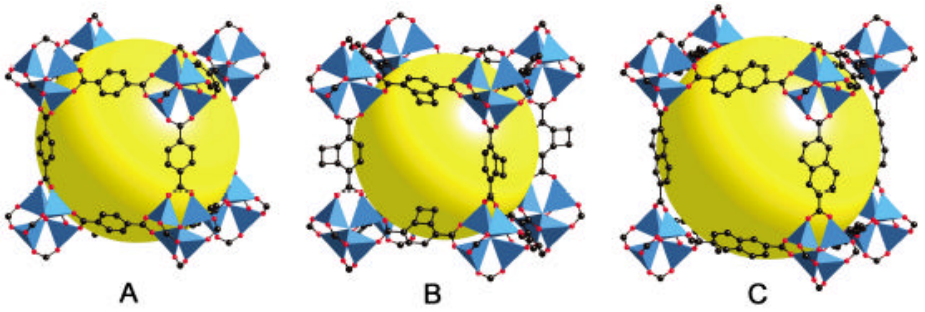
- Controllable secondary structures such as rods, tubules, vesicles, and micelles will lead to structures for functions that may not be naturally occurring or that mimic or supply interesting functionality.



Vesosomes: Vesicle-Encapsulated Vesicles

Molecular Fuel Tanks

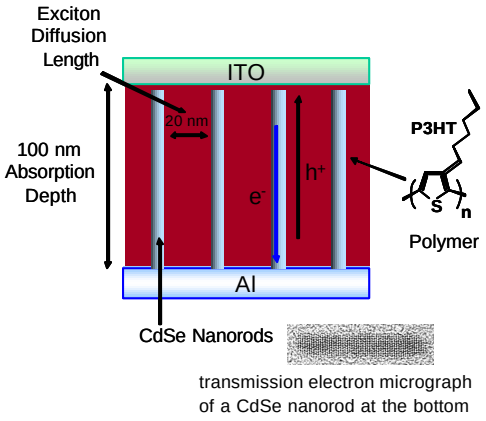
O.M. Yaghi, U. Michigan, #0242630



0.5 % **1.0 %** **2.0 %**

Uptake (wt%) of hydrogen storage in Metal-Organic Frameworks at RT and 10 bar

Energy: Schematic design of the nanorod-polymer solar cell

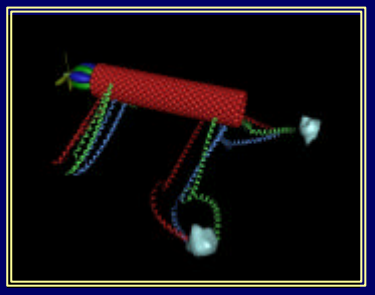


(courtesy P. Alivisatos, Univ. California, Berkeley; and Nanosys, Inc.).

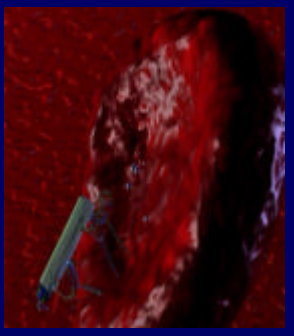
Nano-Bio-Locomotion Systems

EX: C. Mavroidis, Rutgers University (NSF NIRT 0303950)

Vision: To Develop Protein and DNA Based Nano "Robots"



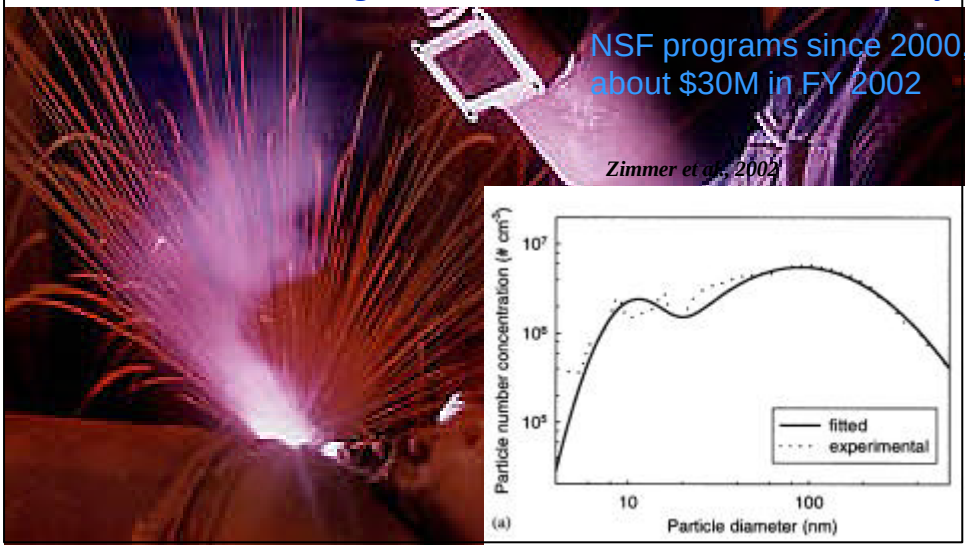
An example of a bio-nano-robotic system: carbon nano-tubes form the main body; peptide limbs can be used for locomotion and object manipulation; a biomolecular motor can propel the device.



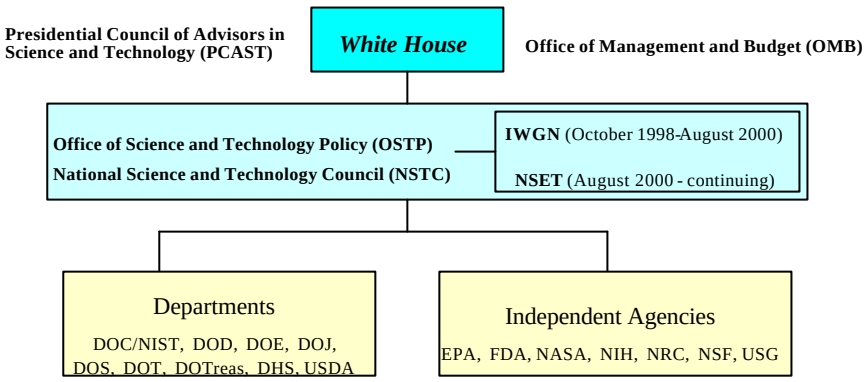
Possible scenario for a biomedical application. A "nano-robot" flowing inside a blood vessel, finds an infected cell, attaches on it and projects a drug to repair or destroy it.

Environmental issues related to nanotechnology include:

- **Sustainable development, life-cycle of products, measurement and mitigation, clean-up techniques, global effects**
- **Combustion, welding, water/air filtration, cell behavior, toxicity**



Organizations that have prepared and contribute to the National Nanotechnology Initiative (NNI)



Estimation: Federal Government R&D funding — NNI (~$700M in 02)
Industry (private sectors) — ~ NNI funding
20 state and local (universities, foundations) — ~ 1/2 NNI funding

M.C. Roco, NSF, 5/29/03

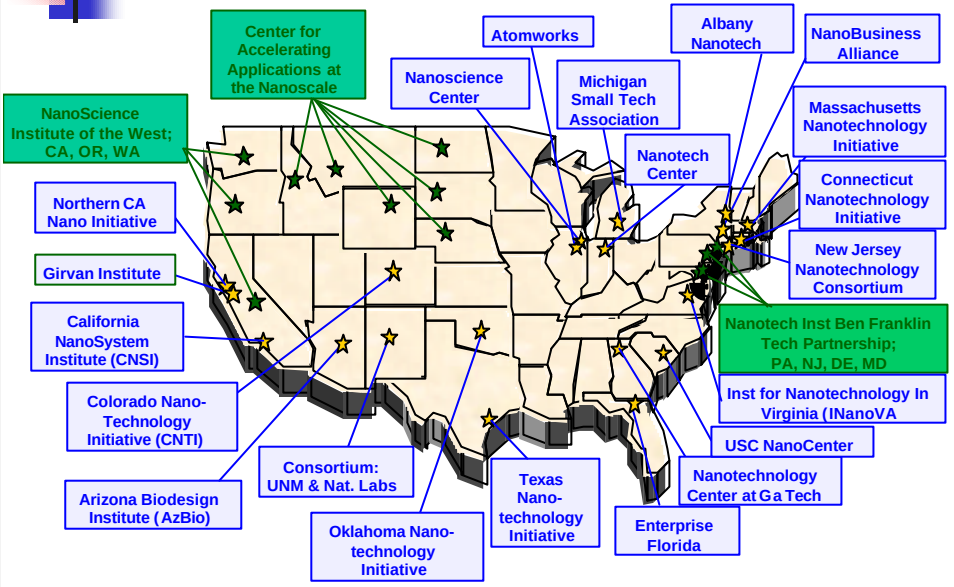
NNI: R&D Funding by Agency

Fiscal year (all in million $)	*2000*	*2001* Enacted/actual	*2002* Enacted/actual	*2003*	*2004* Request
National Science Foundation	97	150 /150	199 /204	221	249
Department of Defense	70	110 /125	180 /224	243	222
Department of Energy	58	93 /88	91.1 /89	133	197
National Institutes of Health	32	39 /39.6	40.8 /59	65	70
NASA	5	20 /22/	35 /35	33	31
NIST	8	10 /33.4	37.6 /77	66	62
Environmental Protection Agency	-	/5.8	5 /6	5	5
Homeland Security (TSA)	-		2 /2	2	2
Department of Agriculture	-	/1.5	1.5 /0	1	10
Department of Justice	-	/1.4	1.4 /1	1.4	1.4
TOTAL	270.0	422.0 /464.7	~ 600 /697	~ 770	~ 849

Other NNI (NSET) participants are:
OSTP, NSTC, OMB, DOC, DOS, DOT, DOTreas, FDA, NRC, DHS, IC

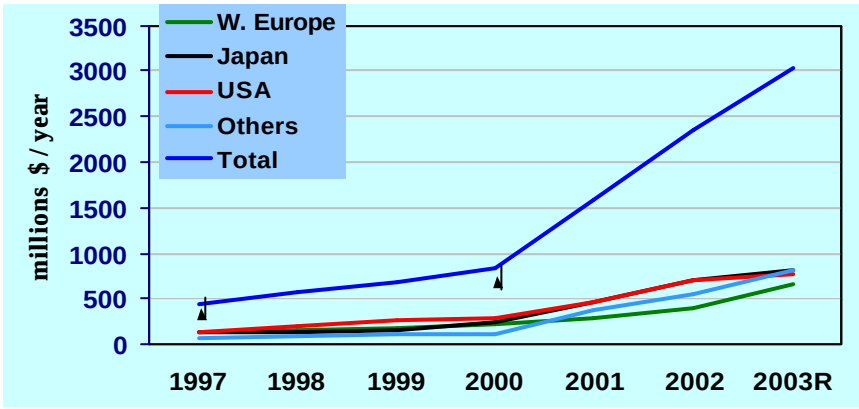
M.C. Roco, NSF, 9/10/03

Sampling of Current Regional, State, & Local Initiatives in Nanotechnology



Context – Nanotechnology in the World

Government investments 1977-2003 (estimation NSF)



Note:

- U.S. begins FY in October, six months in advance of EU & Japan (in March/April)

MC. Roco, 10/14/03

Comprehensive programs on nanoscience and nanotechnology (over $100M/yr)

	Preparation of NNI *Broad definition, 10 year vision,*			**U.S. NNI (announced January 2000)**			
		. *worldwide study, investment plan*			**Japan (announced April 2001)**		
					South Korea (announced Nov. 2001)		
						EC - 6th Frame (March 2002)	
						Germany (May 2002)	
						Taiwan (Sept. 2002)	
1996	**1987**	**1988**	**1999**	**2000**	**2001**	**2002**	**2003**

MC. Roco, 10/14/03

Defining the vision

National Nanotechnology Initiative

1999: 10-year vision

Government plan

Reports

Worldwide benchmark

Brochure for public

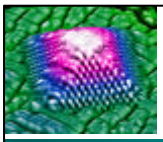
Societal implications

June 2002: "Review of NNI" by U.S. Academies for WH/OSTP

April 2003: "FY 2004 NNI and Its Implementation Plan", NSET

In preparation: Updated 10 year vision

MC. Roco, 10/14/03



Planning for the future: expanding the frontiers of nanotechnology

Workshops for receiving input from the community (examples):

- Nanostructured materials "by design" - Workshops on 10/02, 06/03
- Catalysts that function at the nanoscale - 06/03
- Nanoelectronics, optoelectronics and magnetics - 11/02, 2/03
- CBRE protection and detection - 05/02
- Advanced healthcare, therapeutics, diagnostics - 06/00
- Nano-biology and medicine - 10/03
- Environmental improvement - 06/02, 08/02, 07/03, 09/03
- Efficient energy conversion and storage - 10/02, 02/03
- Microcraft space exploration and industrialization - Spring 04
- Manufacturing processes - 01/02, 05/02; Instrumentation – 01/04
- Agriculture and food systems - 11/02; Converging Technologies – 09/03
- Societal implications (II) - 12/03; Education (NSEE) – 09/03

"Nanotechnology Research Directions (II)" - Spring 2004

Revisit the NNI long-term vision formulated in January 1999

M.C. Roco, 10/09/03

R&D focus in 2003

- **Growing area towards technological innovation**
  - **Materials, including bulk, coating, dispersed systems**
  - **Chemicals, including catalysts**
  - **Pharmaceuticals**
  - **Electronics**
- **Emerging areas**
  - **Nanomedicine**
  - **Energy conversion and storage**
  - **Agriculture and food systems**
  - **Molecular architectures**
  - **Realistic multiphenomena/multiscale simulations**
  - **Environmental implications**
  - **Converging technologies from the nanoscale**

MC. Roco, 10/12/03

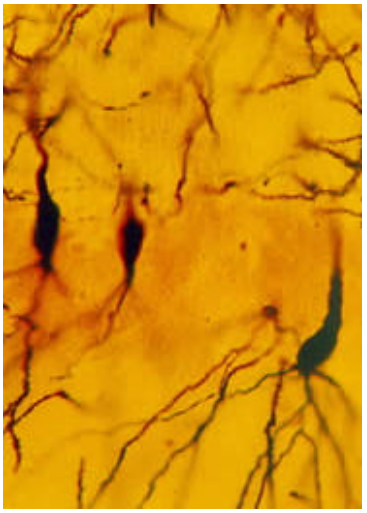
Improving human performance: by technology integration from the nanoscale

- **Expanding human cognition and communication**
- **Improving human health and physical capabilities**
- **Enhancing societal outcomes, incl. new products**
- **National security**
- **Unifying science and education**
- **Reshaping organization and business**

Other societal outcomes, implications

Successive breakthroughs

Lasers operate inside single cells



Nanosurgery vaporizes cellular components leaving rest intact

- **Cut a nerve connection without killing it**

Harvard U. (Nature, October 2003)

Examples of networks

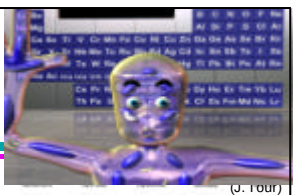
New since 2001

- **Network for Computational Nanotechnology** (NCN)
  7 universities (Purdue as the central node)
- **National Nanotechnology Infrastructure Network**
  User facility
  Development measuring & manufacturing tools
  Education and societal implications
- **Oklahoma Nano Net (EPSCoR award)**
- **DOE network for large scale facilities**

22 new centers and networks supported by NNI since 2001:
10 NSF, 3 DOD, 5 DOE, 4 NASA (at universities); continuing MRSECs

M.C. Roco, NSF, 10/14/03

Education and Training


(J. Tour)

- **Integrated Research and Education - Make Every Lab a Place of Learning: looking for systemic changes**
  ~ 7,000 students/year, technicians, teachers, and faculty
- **Curriculum development**
  New courses and modes of support from elementary schools to continuing education (Undergraduate education ~ 33 awards in FY 2003; Expand to K -12 education in 2004)
- **All NSF centers have education and outreach programs**
  Including science museums Boston, Chicago, Milwaukee
- **International education opportunities:**
  Young researchers to Japan and Europe; REU sites; attend courses abroad; PASI - Latin America, NSF-E.C.; bi-lateral workshops and exchanges

MC. Roco, 10/12/03

Nanotechnology Undergraduate Education (NUE)

New component of the 2003 NSF Nanoscale Science and Engineering (NSF 02-148) program is focused on:

- Introductory undergraduate courses presented through the development of text, software, laboratory and demonstration experiments, and web-based resources;
- Development and dissemination of new teaching modules for nanoscale science and engineering that can be used in existing undergraduate courses, particularly during first and second year studies.

33 awards in FY 2003 (www.nsf.gov/nano)

Reviewed by the NSF workshop on September 11-12, 2002 at NSF (www.nanofab.psu.edu/education/nsf-nue-program.htm)

M.C. Roco, 10/09/03

Nanoscale Science and Engineering Education program (NSF 03-044, new in FY 2004)

NSEE to produce systemic changes in nanoscale science and engineering education. $12M in FY 2004. Components:

- **Centers for Learning and Teaching (NCLT):** Create educational leadership for nanotechnology education (doctoral programs representing collaborations of researchers in nanoscale science and engineering, education, and cognitive and behavioral sciences)
- **Informal Science Education (NISE):** Foster public awareness and understanding of nanoscale science and engineering through development of media projects (film, radio, television) and exhibits.
- **Instructional Materials Development (NIMD):** Support development of prototype instructional materials that promote student learning and interest in nanoscale science, engineering, and technology concepts for grades 7 -12.
- **Nanotechnology Undergraduate Education (NUE):** Introduce nanoscale science and technology through a variety of interdisciplinary approaches into undergraduate education, particularly in the first two collegiate years.

M.C. Roco, 10/09/03

K-12 NANOTECHNOLOGY
Illustrations of Education Modules

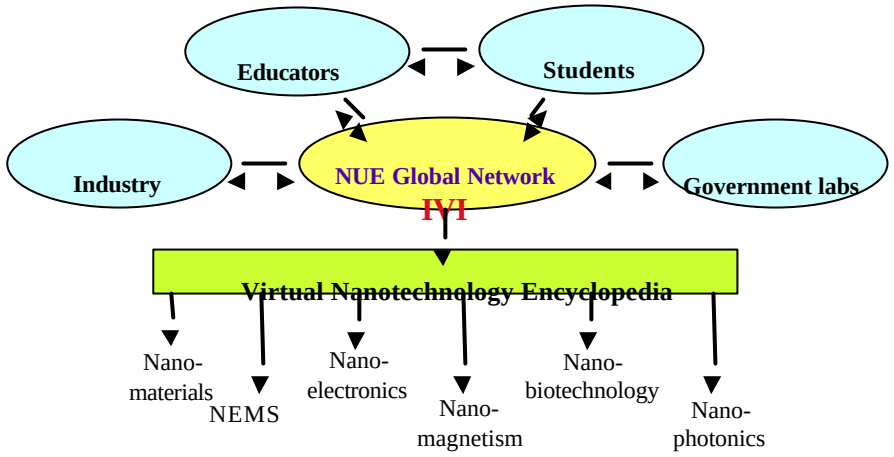
- University of Wisconsin - Art Ellis: Nanoworld for kids
- Northwestern University – Bob Chang: Virtual NT Encyclopedia
- Rice University – James Tour: NanoKids
- Cornell University: for nanobiotechnology, and nanoelectronics
- Northwestern University, Chicago: for materials, public museum
  - Harvard University: for nanosystems, public museum
- UNC Nanomanipulator by high school students
- Purdue NanoHub (www.nanohub.purdue.edu)
- RPI "Molecularium" and "Nanoscope" for K-12 students

NSF plans to have 10 K-12 education modules in 2004

M.C. Roco, NSF, 11/05/02

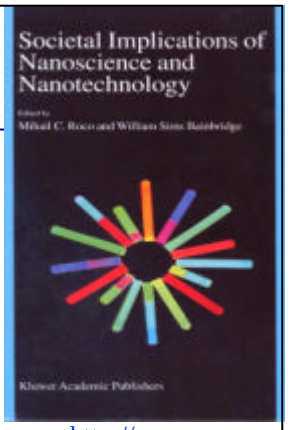
Nanotechnology Undergraduate Education Global Network

International Virtual Institute (IVI, Northwestern University)



M.C. Roco, NSF, 01/07/03

Societal Implications: Follow-up of the September 2000 report



http://nano.gov

- **Make support for social, ethical, and economic research studies a priority:**
  (a) New theme in the NSF program solicitations;
  (b) Centers with societal implications programs;
  Initiative on the impact of technology, NBIC, HSD
- **NNCO – communicate with the public and address unexpected consequences**
- **Basic reference for the interaction with the public**
- **Taking faster advantage of the benefits**
- **Converging technologies from the nanoscale**
- **International workshop with EC (2001); links to Asia**

MC. Roco, 10/14/03

International perspective: U.S. – Korea collaboration

- **Nanotechnology in current U.S.-Korea S&T agreement**
- **Activities**
  - **Bottom-up by individual partnerships in research**
  - **Korea-US NanoForum (annual); other workshops**
  - **NNUN/NNIN and Korean fabrication facilities**
- **Suggested areas and modes of increased collaboration:**
  - **fundamental knowledge** - *by twinning and networking*
  - **education** - *by visits, int. courses, books, int. accreditation*
  - **broad societal implications: health, environment, energy, water filtration, ethics** - exchanges
  - **contribute to international "grand challenges"**

MC. Roco, 10/14/03

International Grand Challenges
(suggestions)

- **Focus on single molecules and single cell**
- **Nanoscale instrumentation and metrology**
- **Theory, modeling and simulation at nanoscale**
- **Tools for manufacturing at the nanoscale**
- **Improving human performance and education**
- **Enhancing societal implications, env & health**

References : MC Roco, "**International Strategy for Nanotechnology R&D**", J. Nanoparticle Res., 2001; and "**Coherence and Divergence of Megatrends in Science and Engineering**", J. Nanoparticle Res., 2002