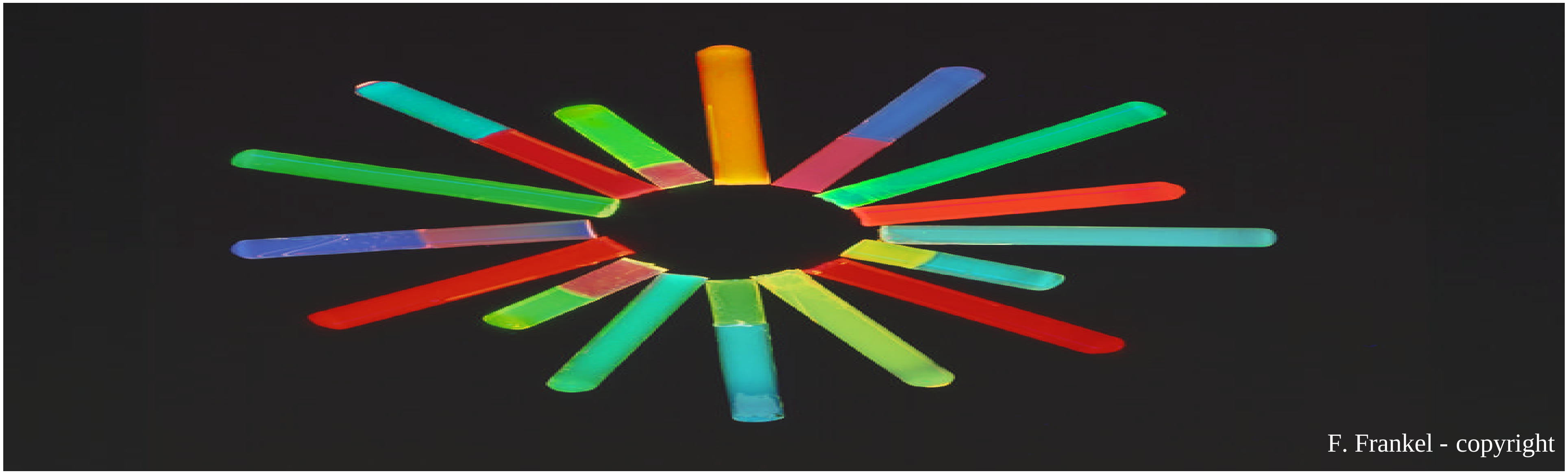


The Future of

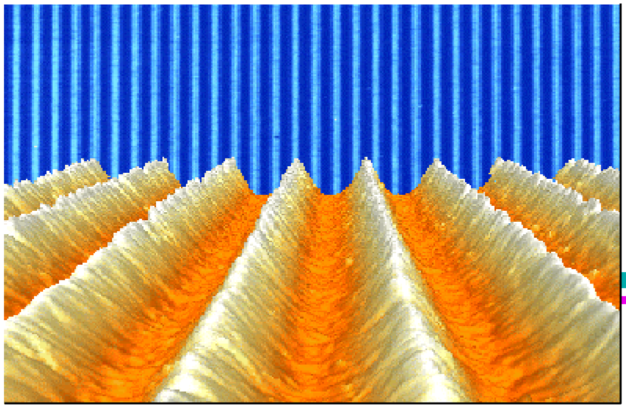
NATIONAL NANOTECHNOLOGY INITIATIVE

Dr. M.C. Roco

Chair, Subcommittee on Nanoscience, Engineering and Technology (NSET),
National Science and Technology Council (NSTC), http://nano.gov

Senior Advisor for Nanotechnology, National Science Foundation

November 5, 2002



Nanotechnology

- Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 nm range, in order to create materials, device sand systems with fundamentally new properties and functions because of their small structure (see website http://nano.gov)

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

Why moving into nanoworld ?
A. Intellectual drive:

- **Miniaturization is of interest**
  - Less space, faster, less material, less energy

More important:

- **Novel properties/ phenomena/ processes**
  - New structures and functions; Engineering beyond nature
- **Unity and generality**
  - At the building blocks of all natural/artificial things; Systems!
- **Most efficient length scale for manufacturing**
  - Less energy than for subatomic or macroscopic
- **Transcendent effects: at the confluence of steams**
  - S&T; Living/non-living ; Interdisciplinarity; Relevance areas

It requires a grand coalition, cooperative national program

B. Promise of nanotechnology
(examples of societal implications)

- **Knowledge base**: better comprehension of nature, life
- **A new world of products: ~ $1 trillion / year in 2010-2015**
  - **Materials** beyond chemistry: **$340B/y** in 10 years for materials and processing
  - **Electronics in 10-15 years**: **$300B/y** for semiconductor industry, > integrated circuits
  - **Pharmaceuticals in 10-15 years**: about half of production will depend on nanotechnology, affecting about **$180 B/y**
  - **Chemical plants in 10-15 years**: nanostructured catalysts in petroleum and chemical processing, about **$100B/y**
  - **Aerospace** (about **$70B/y in 10 years)**
  - **Tools** (measurement, simulations) ~ **$22 B/y** in 10y

Would require worldwide ~ 2 million nanotech workers

- **Improved healthcare**: extend life-span, its quality, human physical capabilities (~ **$31B** in tools for healthcare in 10 years)
- **Sustainability**: agriculture, water, energy (**~$45B/y** in 10 years), materials, environment; ex: lighting energy reduction ~ 10% or **$100B/y**

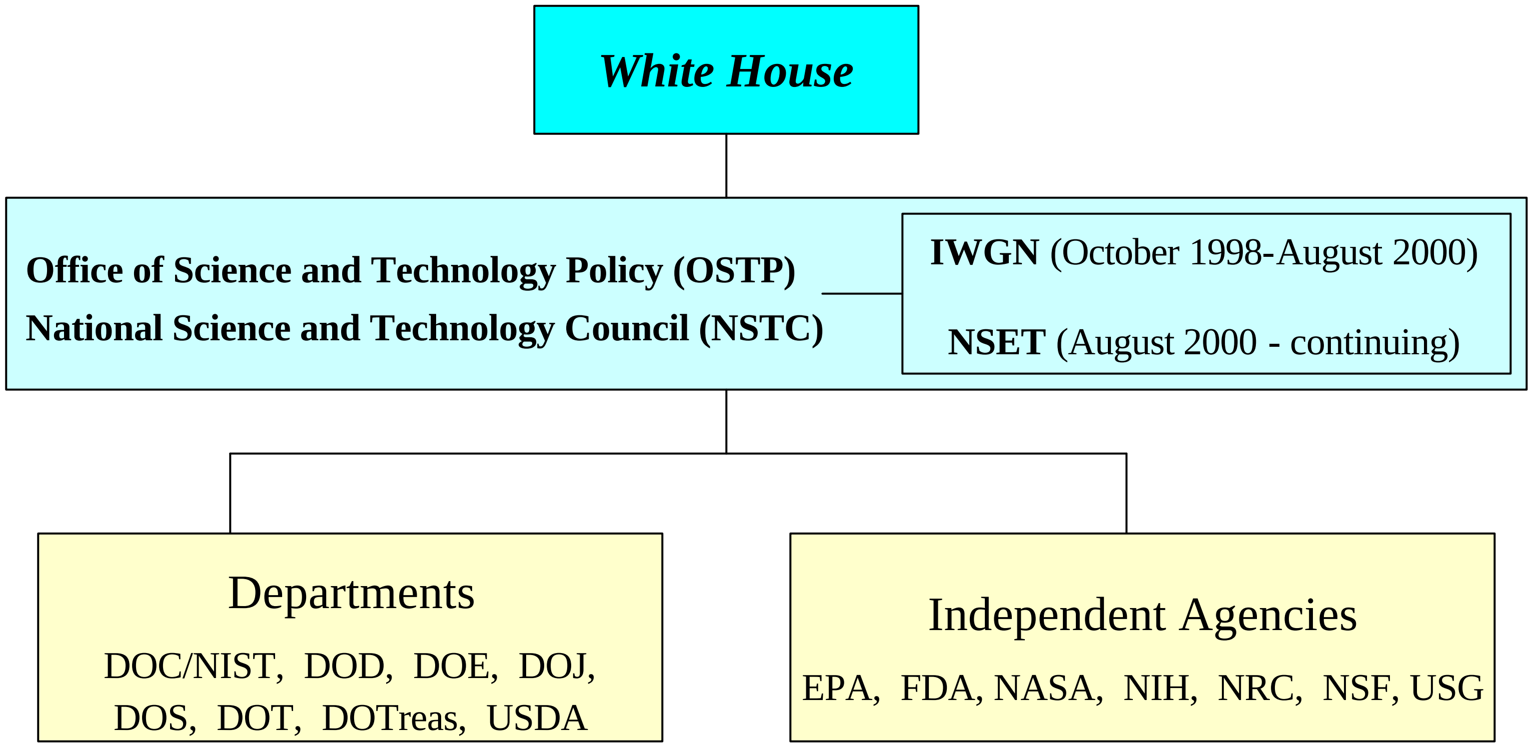
Timeline for beginning of industrial prototyping and commercialization

Accidental nanotechnology: since **1000s yr** (carbon black)

Isolated applications (catalysts, composites, others) since **1990**

- **First Generation: passive nanostructures**
  in coatings, nanoparticles, bulk materials (nanostructured metals, polymers, ceramics):
  ~ 2001 –
- **Second Generation: active nanostructures**
  such as transistors, amplifiers, actuators, adaptive structures:
  ~ 2005 –
- **Third Generation: 3D nanosystems**
  with heterogeneous nanocomponents and various assembling techniques
  ~ 2010 –
- **Fourth Generation: molecular nanosystems**
  with heterogeneous molecules, based on biomimetics and new design
  ~ 2020 (?) -

Organizations that have prepared and contribute to the National Nanotechnology Initiative



Estimation:	Federal Government R&D funding	NNI ($604M in 02)
	Industry (private sectors)	~ NNI funding
	State and local (universities, foundations)	~ 1/2 NNI funding

Elements of NNI Initiative FY 2001-2003
(see nano.gov)

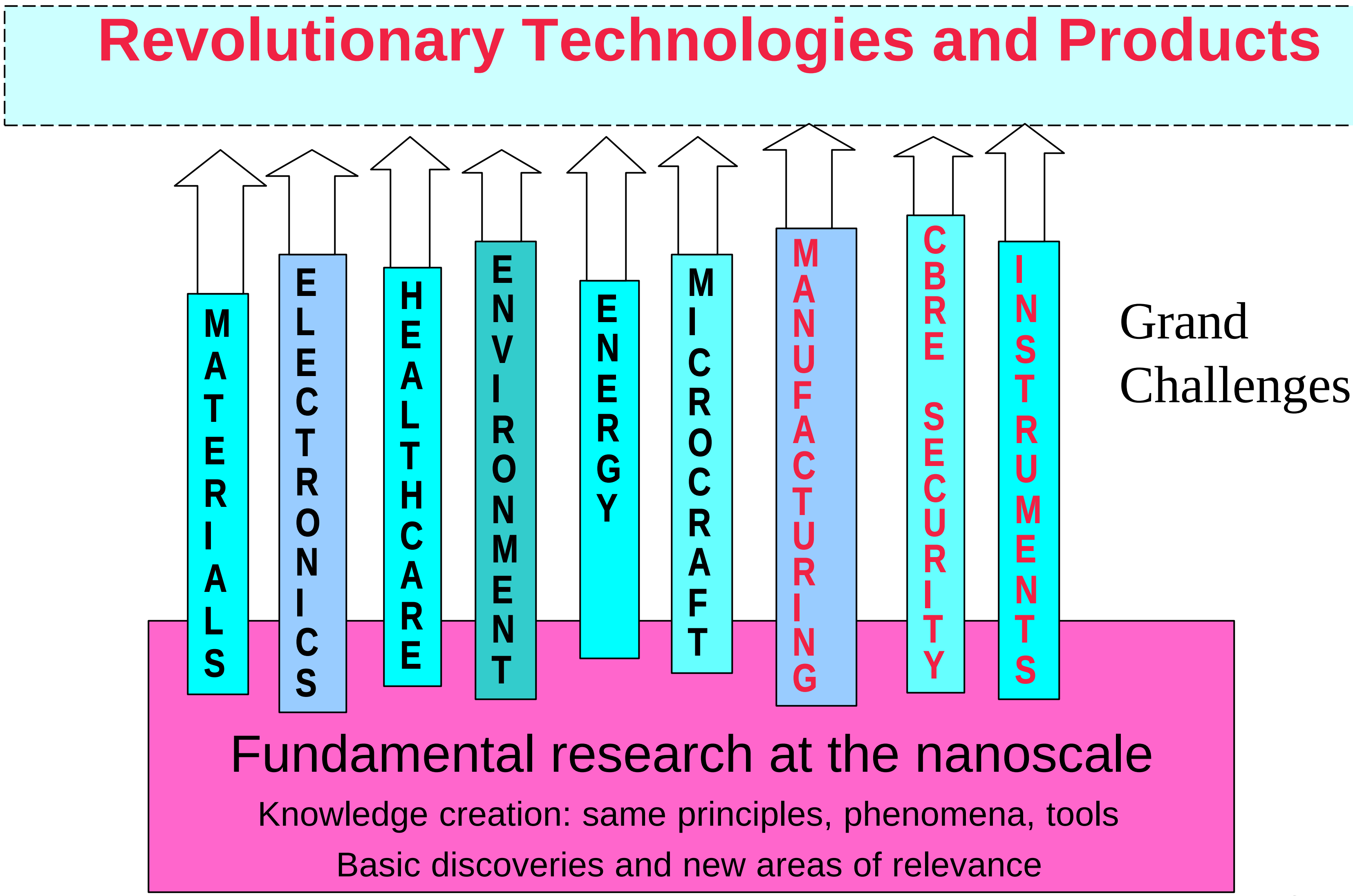
- **Fundamental Research -**
  Provides sustained support to individual investigators and small groups doing fundamental, innovative research
- **Grand Challenges**
  for research on major, long-term objectives
- **Centers and Networks of Excellence**
  for interdisciplinary research, networking, industry partnerships
- **Research Infrastructure**
  metrology, instrumentation, modeling/simulation, user facilities
- **Societal Implications and Workforce Education and Training**
  for a new generation of skilled workers; the impact of nanotechnology on society (legal, ethical, social, economic)

NNI: Key Investment Strategies

- ***Focus on fundamental research*** **(‘horizontal’)**
  + transition to technological innovation (“vertical’)
- ***Policy of inclusion and partnerships***
- ***Long-term vision***
- ***Prepare the nanotechnology workforce***
- ***Address broad humanity goals***
- ***Transforming strategy; bio-inspired approach***

NNI as part of U.S. Federal R&D ~ 0.6%
U.S. as part of world nanotech investment ~ 30%

Interdisciplinary, multidomain "horizontal" knowledge creation versus "vertical" transition from basic concepts to Grand Challenges



Nanotechnology R&D Funding by Agency

Fiscal year (all in million $)	*2000*	*2001* Appropr/eff./		*2002* Appropr.	*2003* Request
National Science Foundation	97	150	/150/	199	221
Department of Defense	70	110	/125/	180	201
Department of Energy	58	93	/88/	91.1	139.3
National Institutes of Health	32	39	/39.6/	40.8	43.2
NASA	5	20	/22/	46	51
NIST	8	10	/33.4/	37.6	43.8
Environmental Protection Agency	-		/5.8/	5	5
Depart. of Transportation/FAA	-			2	2
Department of Agriculture	-		/1.5/	1.5	2.5
Department of Justice	-		/1.4/	1.4	1.4
TOTAL	270.0	422.0	/464.7/	604.4	~ 710.2

Other NNI participants are: DOC, DOS, DOTreas, NOAA, NRC, USG

Fundamental nanoscale science and engineering
Principal Areas of Investigation (Fiscal year 2002)

- **Biosystems at the Nanoscale** ~ 14%
  - biostructures, mimicry, bio-chips
- **Nanostructure 'by Design', Novel Phenomena** 45%
  - physical, biological, electronic, optical, magnetic
- **Device and System Architecture** 20%
  - interconnect, system integration, pathways
- **Environmental Processes** 6 %
  - filtering, absorption, low energy, low waste
- **Multiscale and Multiphenomena Modeling** 9 %
- **Manufacturing at the nanoscale** 6%
- **Education and Social Implications** (distributed)

Grand Challenges (NNI, FY 2002)

✍ Nanostructured materials "by design"	~ 22%
✍ Nanoelectronics, optoelectronics and magnetics	**39%**
✍ Advanced healthcare, therapeutics, diagnostics	8%
✍ Environmental improvement	4%
✍ Efficient energy conversion and storage	5%
✍ Microcraft space exploration and industrialization	3%
✍ CBRE Protection and Detection (revised in 2002)	7%
✍ Instrumentation and metrology	6%
✍ Manufacturing processes	5%

(details in the NNI Implementation Plan, http://nano.gov)

Nanotechnology in the world

Comparison for industrialized countries 1997-2002

Estimated government sponsored R&D in $ millions/year

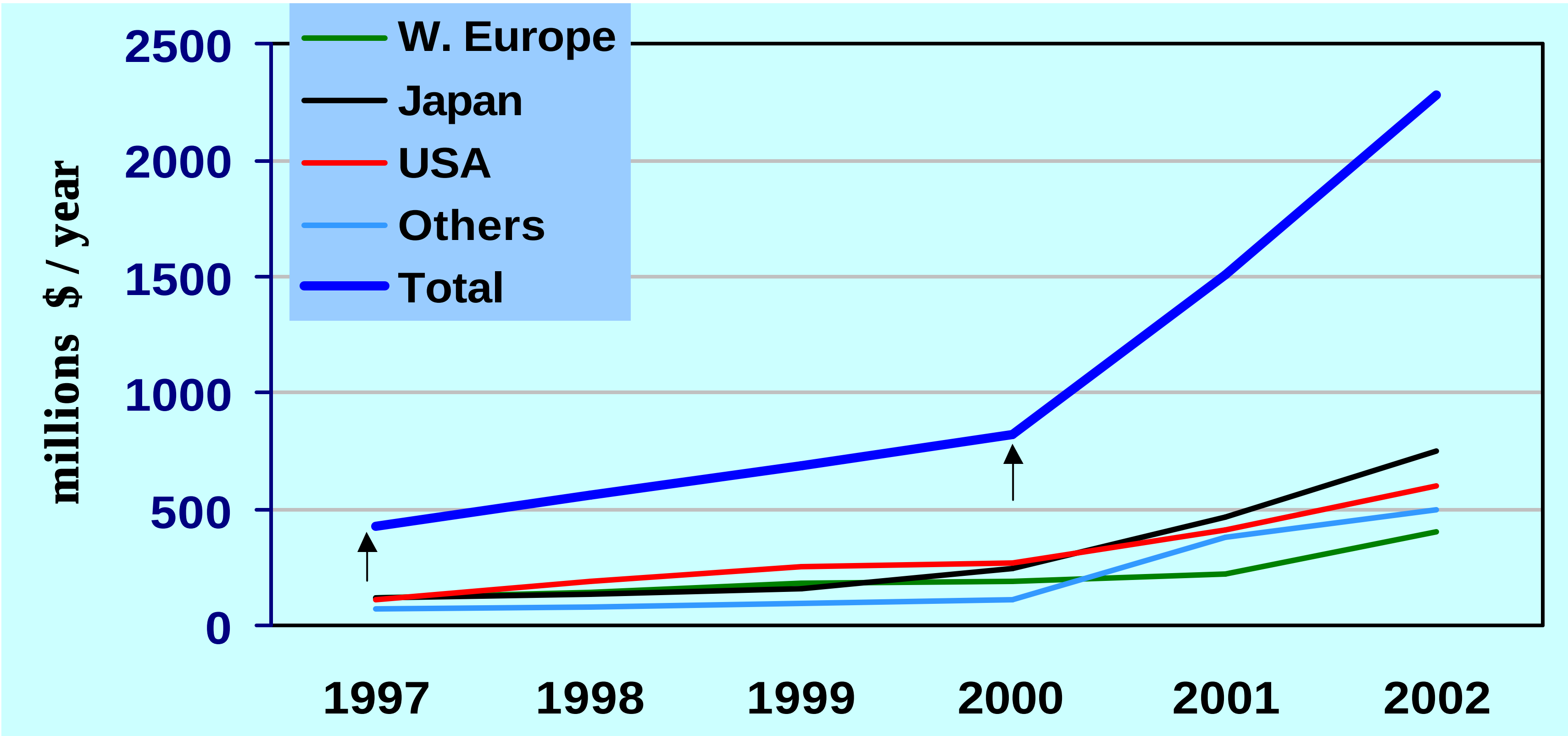
Fiscal Year	1997	2000	2001	2002
W. Europe	126	200	~ 225 /270/*	~ 400
Japan	120	245	~ 465	~ 650
USA	116	270	422 /465/*	604
Others	70	110	~ 380	~ 520
Total	***432*** 100%	***825*** 190%	***1,492*** *350%*	***2,174*** 503%

Others: Australia, Canada, China, E. Europe, FSU, Israel, Korea, Singapore, Taiwan

(*) Actual budget

Senate Briefing, May 24, 2001 (M.C. Roco), updated on April 30, 2002

Context – Nanotechnology in the World
Government investments 1977-2002



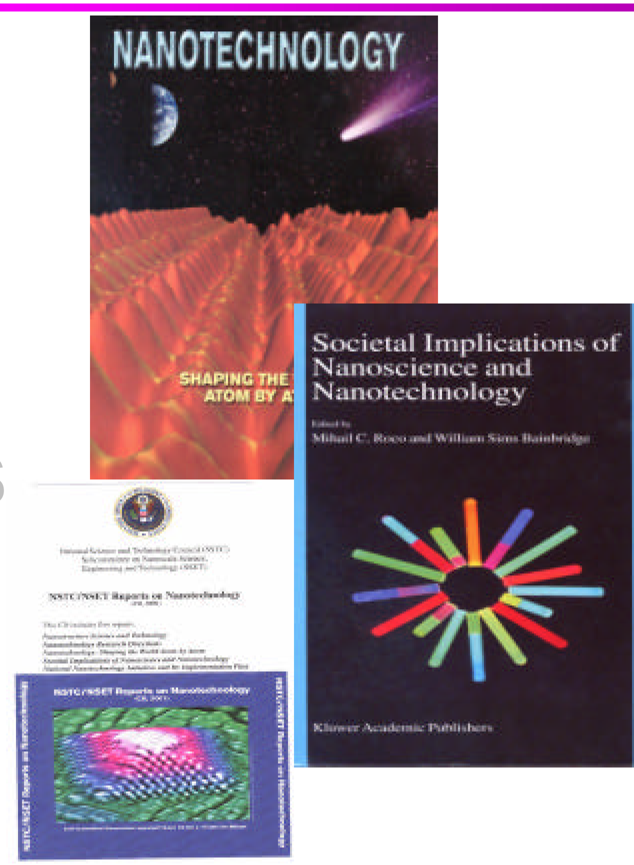
Note:

- U.S. begins FY in October, six month before EU & Japan in March/April
- U.S. does not have a commanding lead as it was for other S&T megatrends (such as BIO, IT, space exploration, nuclear)

Defining the vision

National Nanotechnology Initiative

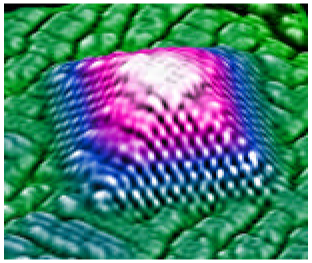
Reports



6/02 "Review of NNI" by NRC for WH/OSTP

6/02 FY 2003 NNI and Its Implementation Plan, NSTC/NSET

7/02 Converging Technologies (NBIC) for Improving Human Performance



Examine expanding the frontiers in **Grand Challenges**

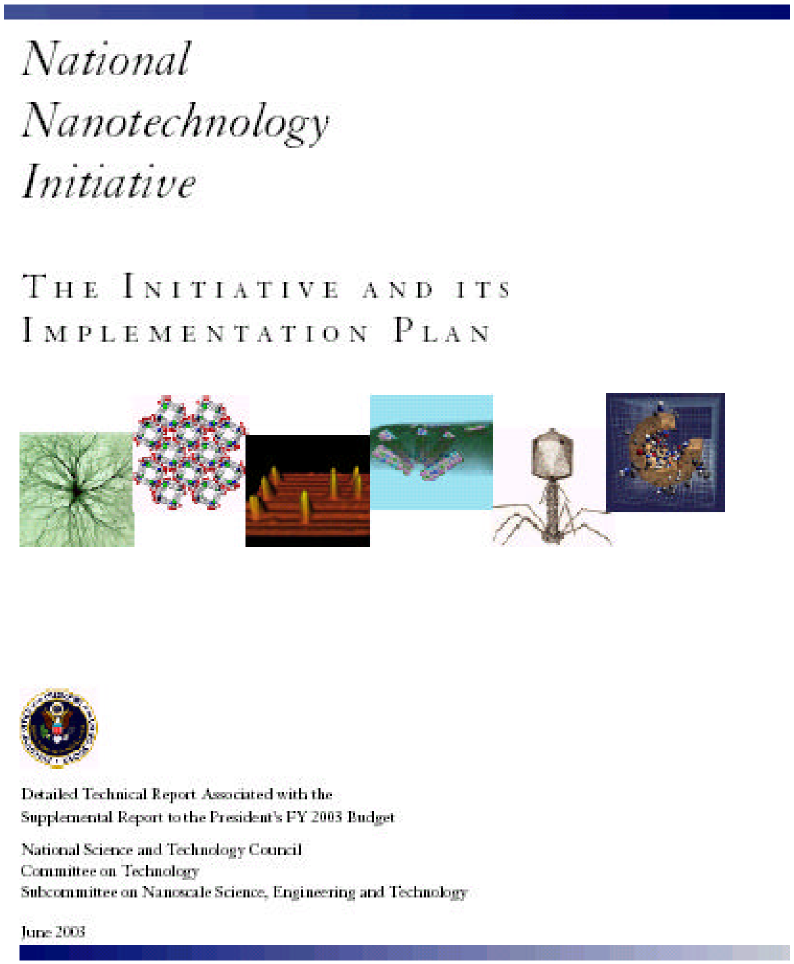
Workshops for receiving input from the community (examples):

- Nanostructured materials "by design" - Workshops on 10/02, 04/03
- Nanoelectronics, optoelectronics and magnetics - Workshops 09/02, 11/02
- Advanced healthcare, therapeutics, diagnostics - Workshops 06/00, 11/02
- Environmental improvement- Workshops 06/02, 08/02, 03/03
- Efficient energy conversion and storage - Workshops 10/02; 01/03
- Microcraft space exploration and industrialization - Workshop Spring 03
- CBRE protection and detection (revised in 2002) - Workshop 05/02
- Manufacturing processes - Workshops 01/02; 05/02

"Nanotechnology Research Directions (II)" - January 2004

Revisit the NNI long-term vision formulated in January 1999

NSTC: NNI in fiscal year 2003



National Nanotechnology Initiative

THE INITIATIVE AND ITS IMPLEMENTATION PLAN

Detailed Technical Report Associated with the Supplemental Report to the President's FY 2003 Budget

National Science and Technology Council
Committee on Technology
Subcommittee on Nanoscale Science, Engineering and Technology

June 2002

- Outcomes in FY 2001
- Plan of activities in FY 2002
- Priorities and implementation plan in FY 2003
- The role of each agency
- NNI budgets in FY 2001, 2002 and 2003

(June 2002)

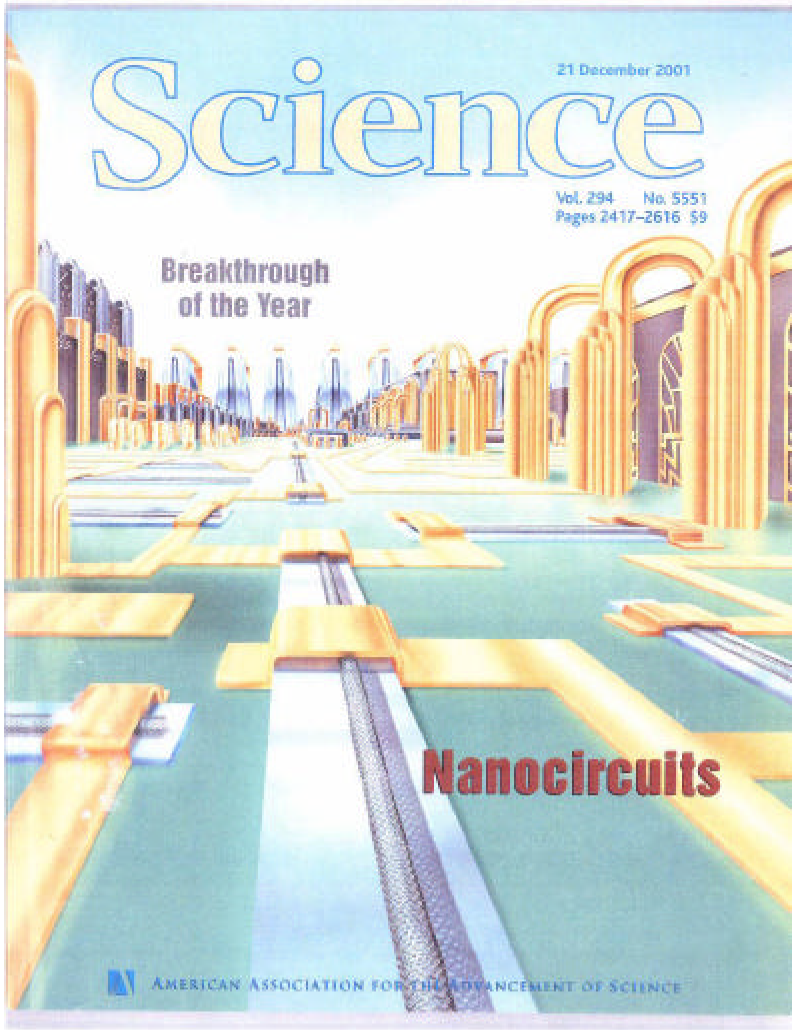
Scientific Breakthroughs
in the first year (NNI, 2001)

- **Developments faster than expected**

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

- **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 . . . .

FY 2001 Outcomes: Example



- Create transistors with amplification and memory devices at the nanoscale
- Create systems/circuits that can be addressed at the nanoscale
- The time scale for commercial application has been reduced: less than 2 years for memory devices, 5-6 years for logical devices

Partial refocus in 2002:

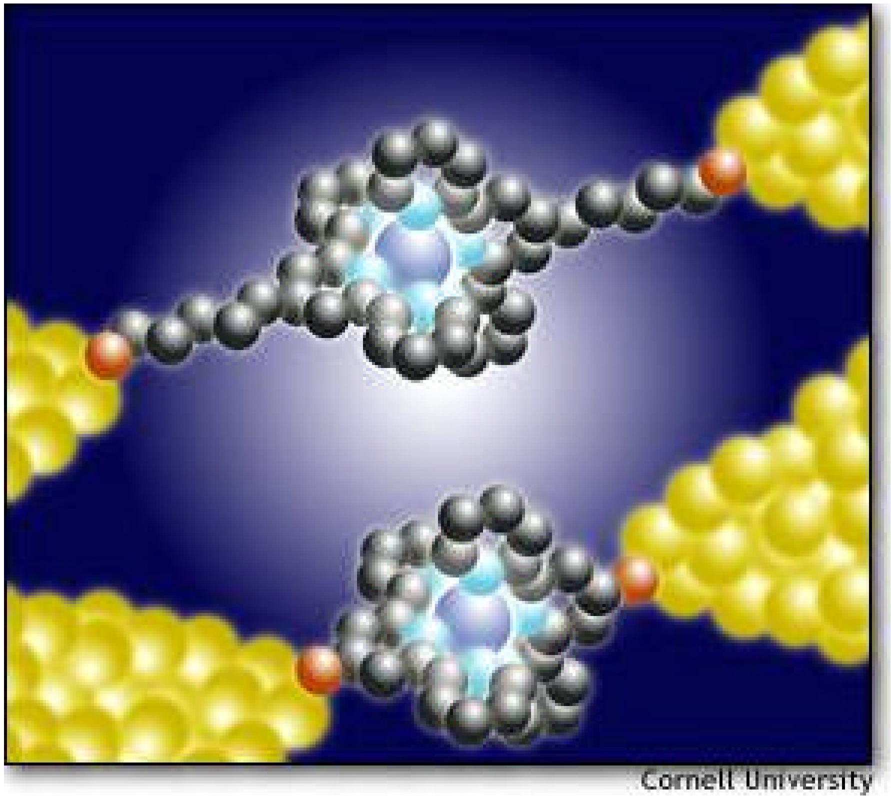
From synthesis to use of nanostructures

Examples of new functions

(A) Single Electron Molecular Transistor

F. Di Salvo and D. Ralph, Cornell University, 2002

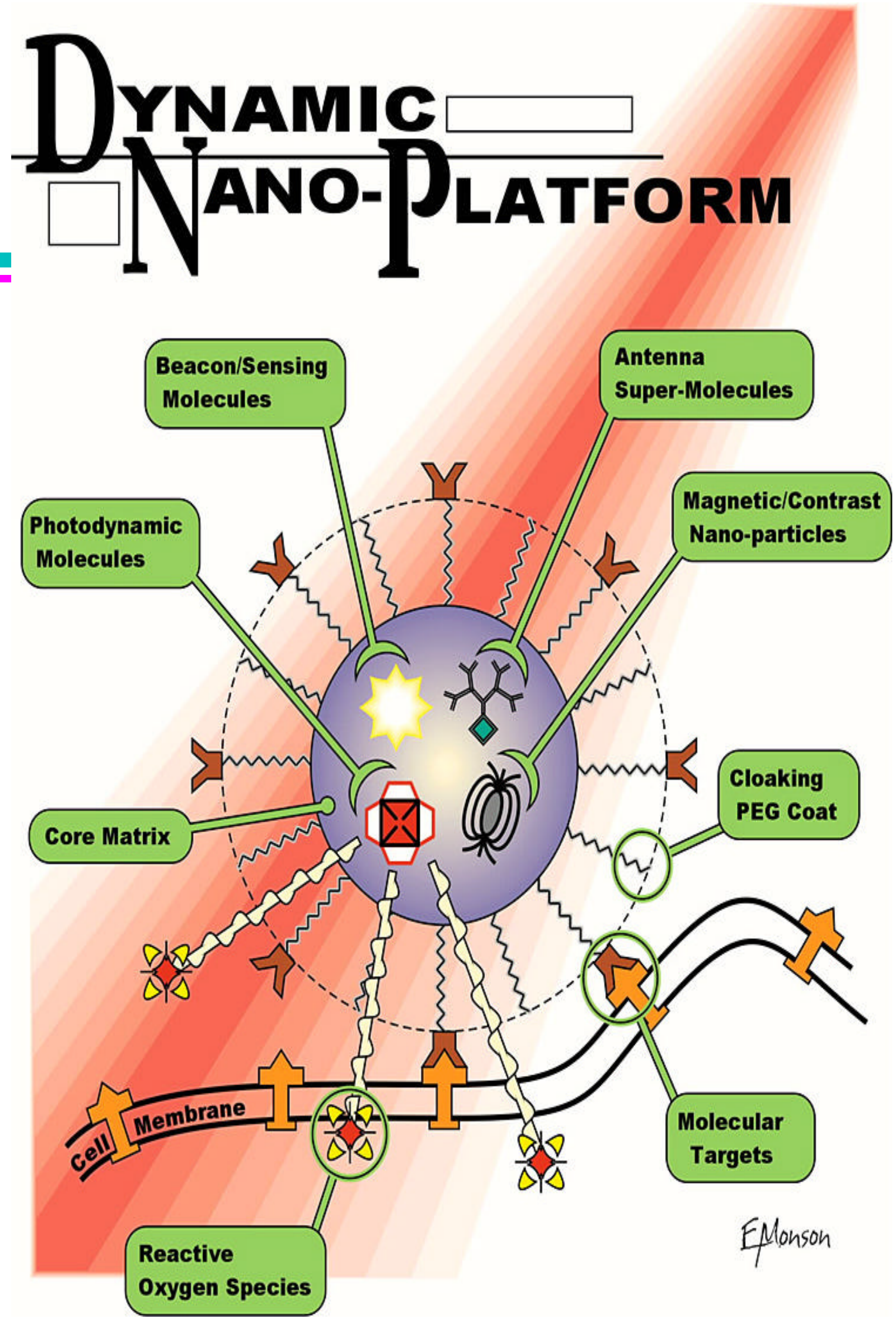
- The two molecules contain a central cobalt atom and differ in their length -- the shorter of about 2 nm one exhibits less resistance. At low temperature, the longer molecule functions as a single electron transistor, and the shorter molecule exhibits both transistor action and the Kondo effect.
- The electrical characteristis of the transistor can be varied systematically by making chemical changes to the molecule.



(B) Optical Nanosensors for Chemical Analysis inside Living Cells

M.A. Philbert et al. ,
University of Michigan, 2002

- 20 nm radius Optochemical Biosensors (1 ppb of cell vol.)
- Non-Invasive Chem Lab inside Live Cell
- Cell Viability 97%
- Response Time < 1 ms.
- H^+, Ca^{2+}, K^+, Na^+, Mg^{2+}, Zn^{2+}, Cl^-, NO_2^-, O_2, NO, Glucose…
- Detection of ROS Production
- MR imaging



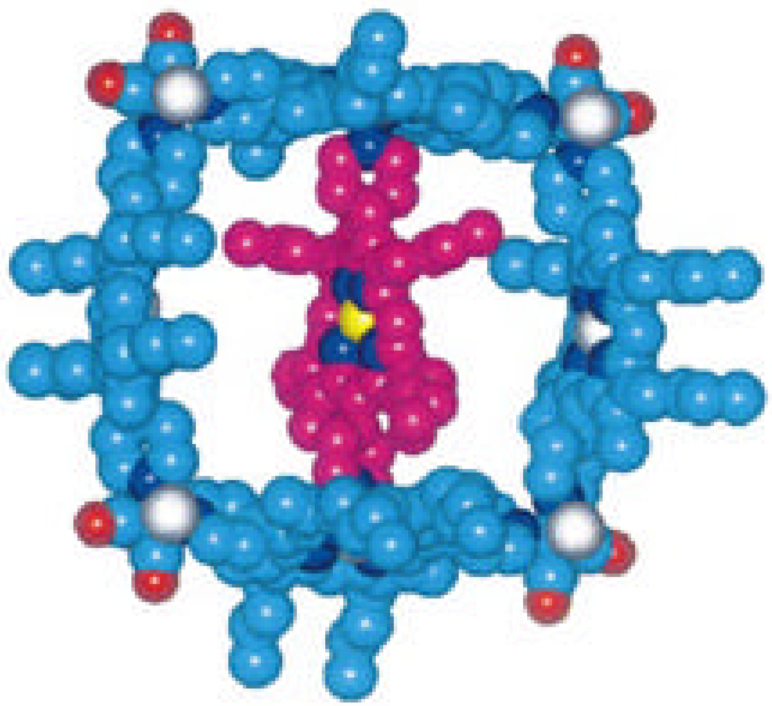
(C) **Selective Membranes**

J. Hupp, S.-B. Nguyen and R. Snurr, Northwestern University, 2002

- Membranes that allow the passage of some substances while blocking others. A network of these supramolecules can act as a molecular filter and catalyst

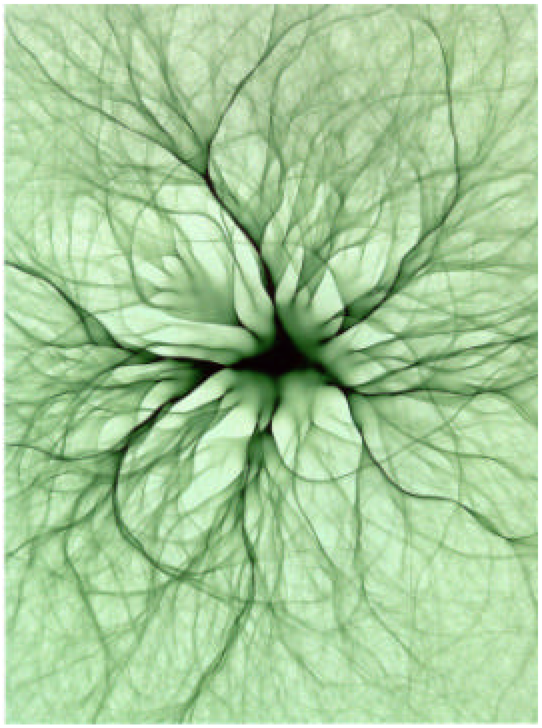
- The thin-film material with nanometer-sized cavities can be manipulated to allow the passage of certain molecules but not others depending on size, shape and other properties

- Chemically transforming molecules can be placed within these cavities

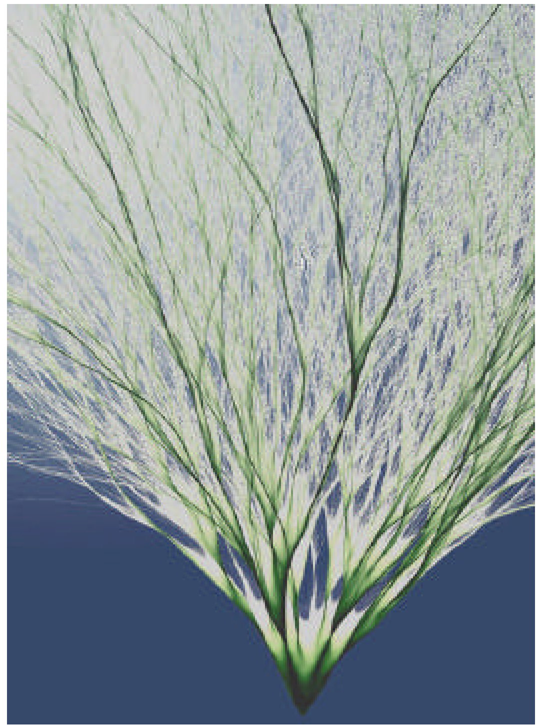


Patterns of flow of electrons in nanostructures

M. Heller et al., Harvard U., 2002



From a quantum hole

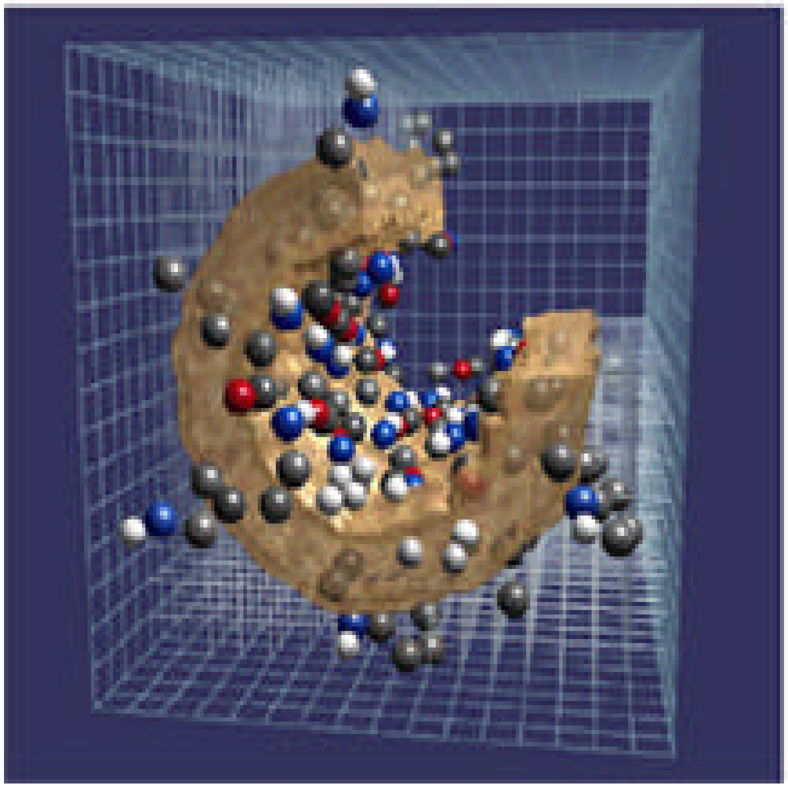


Between narrow channels

Within a nanotube

Modeling and simulation in biological ion channel

K. Hess, U. of Illinois, Urbana



Predictions help medical solutions

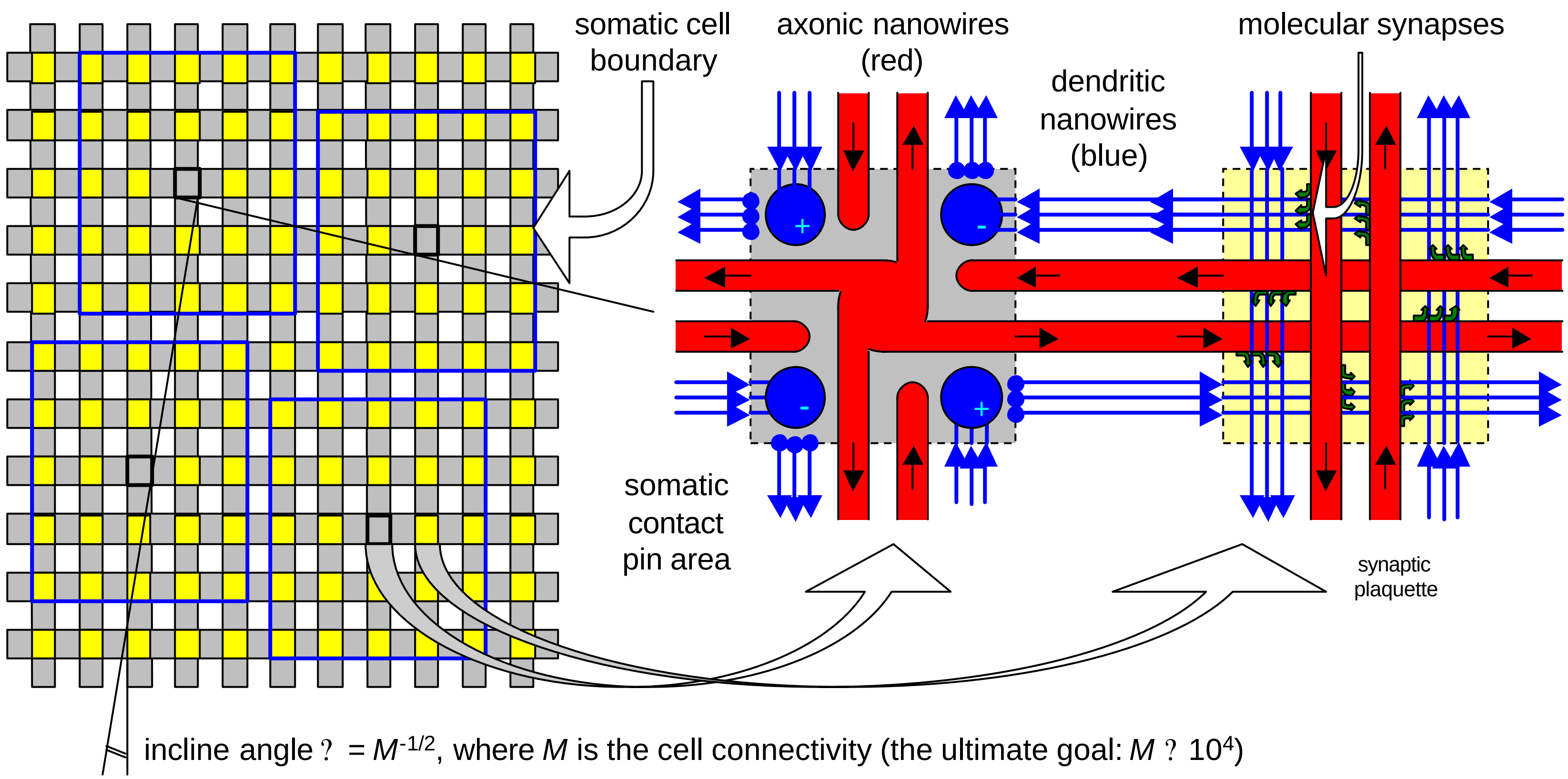
Nanoengineering

Issues

- Three dimensional material/device/system spatial/temporal architecture
- Directed assembling/patterning/templating
  for heterogeneous nanosystems
- Hybrid and bio nanosystems for medicine and manufacturing
- Energy conversion and transfer
- Multiphenomena, multiprocesses, multiscale design
- Large scale atomistic modeling and simulation
- Integration of nanoscale into larger scales:
  use of intermediary standard components
- Thermal and chemical stability
- Operational and environmental safety
- Reliability and reproductivity at the nanoscale

Several NNI centers are focused on nanoengineering.
Ex: Cornell, NWU, Sandia, ORNL

EX: Nanoscale Single-Electron Switching Arrays for Self-Evolving Neuromorphic Networks



This architecture allows to combine high density CMOS-based somatic cells (up to 10^8 per cm^2) with extremely high density of single-electron latching switches working as synapses (up to 10^{12} per cm^2) necessary for our “final” goal: placing a hardware analog of a mammal cerebral cortex on a 10?10 cm^2 silicon area.

K. Likharev, SUNY Stony Brook

Education and Training

- **Integrated Research and Education - Make Every Lab a Place of Learning: looking for systemic changes**

  ~ 6,000 students/2002, technicians, teachers, and faculty

- **Curriculum development**

  new courses, course modules, summer courses, 7 IGERT

- **All NSF centers have education and outreach programs**

  from K-12 up ; includes science museums

- **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

Examples : IGERT projects

Focus on interdisciplinary fellowships, research and education
Each IGERT (Integrative Graduate Education, Research and Training) provide support for > 12 interdisciplinary graduate fellowships / site.

- **NEAT (Nanophases in the Environment, Agriculture and Technology)**
  University of California -Davis (A. Novrotski)
- **Nanostructural Materials and Devices**
  City University of New York (D.L. Akins)
- **Nanobiotechnology**
  University of Washington (A. Vogel)
- **Nanoparticle Science and Engineering**
  University of Minnesota (U. Kortshagen)
- **11 sites in FY 2002 (4 since 2001, and 4 since 2002)**

Examples: Curriculum development including NSF support

- **Nano-course** (for undergraduate, summer course), Cornell Nanofabrication Facility
- **Nanoscale processes**, University of Wisconsin, Madison
- **Nanostructured materials**, Renssellaer Polytechnic Institute
- **Colloid chemical approach to construction of nanoparticles and nanostructured materials** Clarkson University
- **Nanoparticles processes** , Yale University
- **Nanorobotics**, South California University
- **Nanoscale manufacturing**, Penn State, technical education

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.

About 40 awards in FY 2003

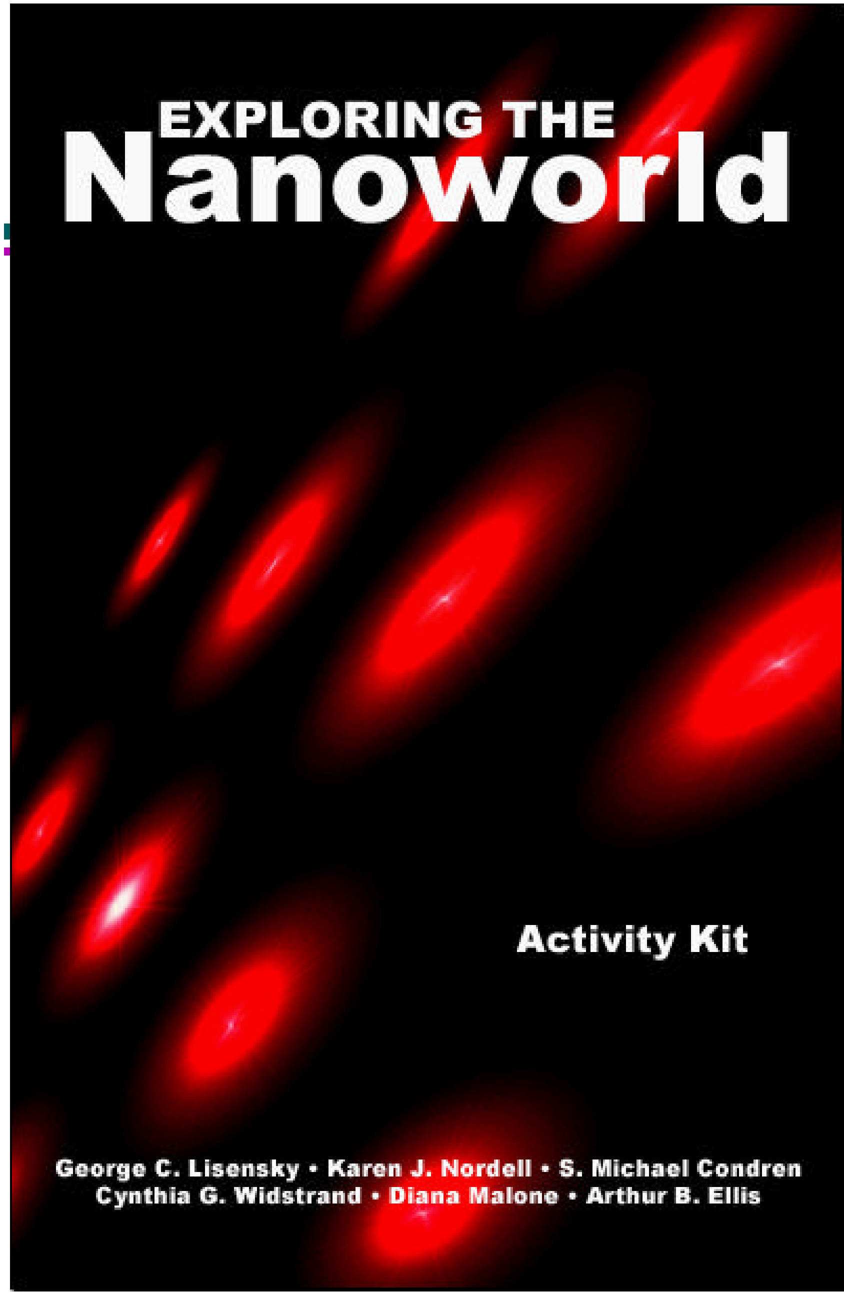
Reviewed by the NSF workshop on September 11-12, 2002 at NSF (www.nanofab.psu.edu/education/nsf-nue-program.htm)

K-12 NANOTECHNOLOGY Education Modules

Illustrations

- University of Wisconsin - Art Ellis: Nanoworld for kids
- 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)

NSF plans to have 10 K-12 education modules in 2003



http://www.mrsec.wisc.edu/nano

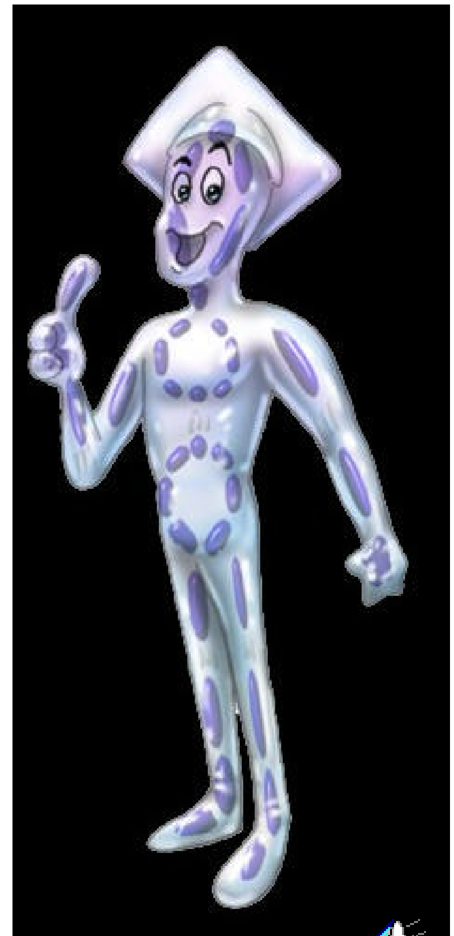
J. Tour, Rice University: “NanoKids”

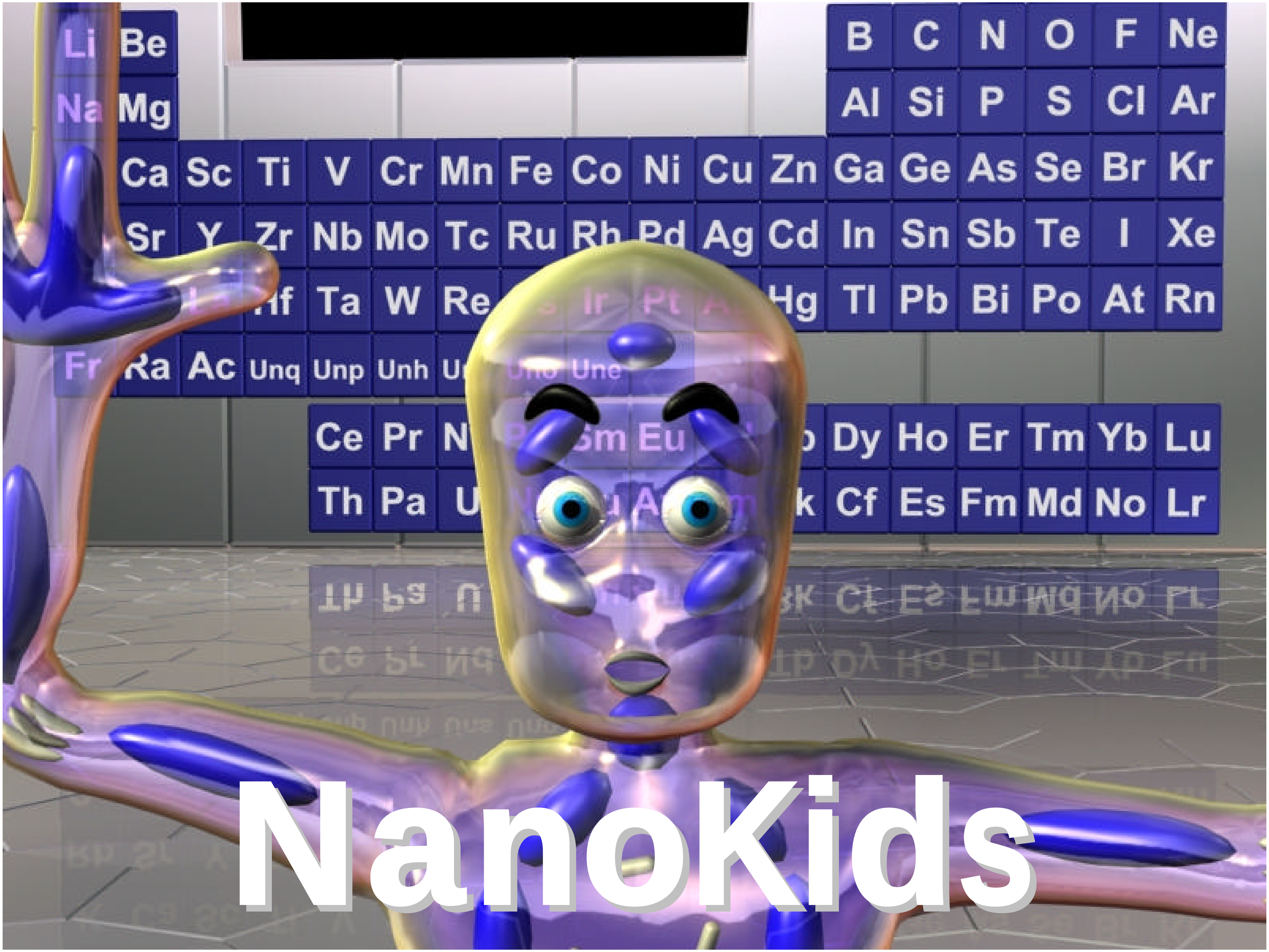
J. Tour, Rice University


e-
F
Bond With Me
The NanoKids
[bond+with+me]
said the fluorine

Student-Explorer NanoScholar

- Draws the student into the adventure
- Increases emotional involvement in the NanoWorld.
- Suggests models of learning and scientific discovery.



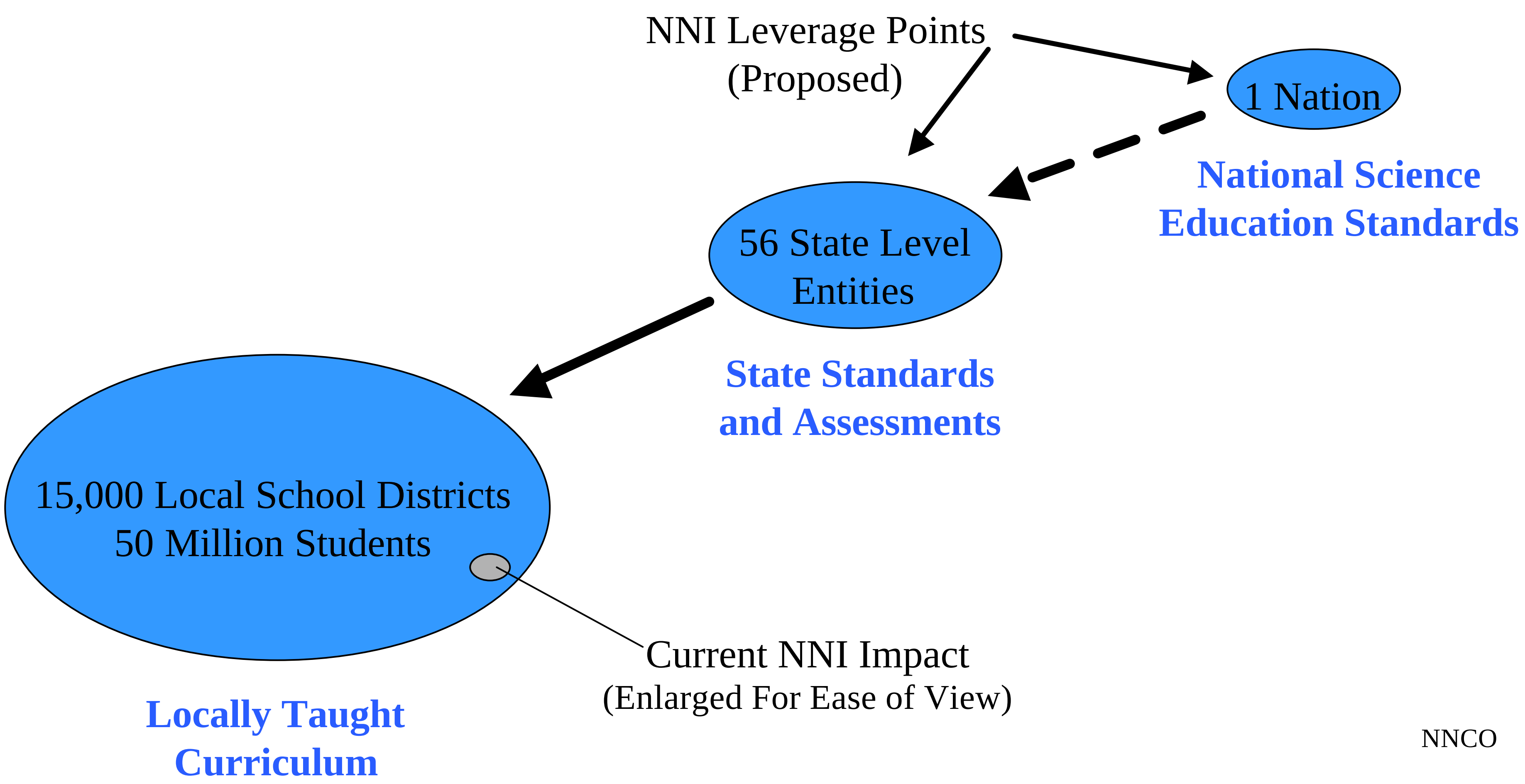


Li Be
Na Mg
B C N O F Ne
Al Si P S Cl Ar
Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Sr Y Zr Nb Mo Tc Ru Ag Cd In Sn Sb Te I Xe
Ta W Re Hg Tl Pb Bi Po At Rn
Fr Ra Ac Unq Unp Unh
Ce Pr Dy Ho Er Tm Yb Lu
Th Pa U Cf Es Fm Md No Lr
NanoKids

What to do in the future?

- **Coherent, longitudinal program** with proper bridges between K-12, UG, G, postdoctoral, and continuing education
- **Target systemic changes** for broader impact
- **Partnering** for cross-disciplinarity, cross-relevance, and sharing resources (such as facilities and expertise)
- **Enabling the teachers**
  - Training activities periodical available (ex: RET)
  - Create educational materials (modules, hand-on-kits, course notes)
  - Access to experimental facilities

State K-12 Curriculum Standards and NNI



Nanoscale Science and Engineering Program (pending, FY 2003)

- **FY 2003 NSE request** - **$221 M (~1400 projects), of which**
  > $72 M for proposal solicitation
  > $12 M for National Nanotechnology Infrastructure Network

- **Seven themes.** Several New areas of Emphasis :
  - Research to enable the nanoscale as the most efficient manufacturing domain
  - Innovative nanotechnology solutions to biological-chemical-radiological-explosive detection and protection
  - Development of instrumentation and standards
  - Exploratory on nanobio, energy, converging technologies, others

- **Four modes of support in FY 2003 solicitation**
  - Interdisciplinary Research Teams
  - Nanoscale Exploratory Research
  - Nanoscale Science and Engineering Centers
  - Nanotechnology Undergraduate Education

Transition of Fundamental Discoveries into Innovative Technology

✍ Actions

- Grand challenges for long term technology base
- Infrastructure for instrumentation, tools, physical laboratory
- Prepare the workforce at all levels
- Various mechanisms for interaction with industry

✍ Metrics

- Industry/state investments matching NNI R&D
- Number of partnerships between private sector and states, and NNI research and education providers
- Scientific, technological, and commercial outcomes with joint support
- NNI outreach activities: workshops, continuing education, etc.

Main mechanisms of interaction with industry (NSET)

– Fund partnerships with industrial partner - all agencies

– Provide the NNI results to industry – create data base

– Provide user facilities: NSF, DOE, NASA

– Assistance for instrumentation, standards, tools for manufacturing: NIST

– Direct technology transfer and funding industrial projects SBIR/STTR all agencies , DARPA/DOD, DOE, NASA, NIST, NIH

– Partnerships with industrial groups - ex. SIA, CCR, IRI

Information data base of nanotechnology companies, and commercial success stories (NNCO, http://nano.gov)

Outreach: series of workshops, involve new industries, networking

Nanotechnology in SBIR/STTR

http://www.eng.nsf.gov/sbir

Participating Agencies

DOD, HHS, NASA, DOE, NSF, USDA, DOC, EPA, DOT, DoED

NSF

- FY 1998 “Nanotechnology” appeared in the STTR Program Solicitation
- FY 1999 to the present “Nanotechnology” a permanent subtopic
- Funded awards to date:

  240 awards (phases I and II)

  $10 M / year

SBIR/STTR

examples with support from NSF

Chemical Industry

- S. Stevenson – *The Development of Fullerene Materials*
- S. Jaffe – *Nano Composites for Gas Seperation*
- D. Shulz – *The CeraMem Nanotechnology*

Electronics Industry

- R. Bhargava – *Quantum Confined Atom Based Particle Nanotechnology*
- R. Burger – *Integrated Magnetoelectronics*
- J.J. Marek – Molecular Electronics

Materials Industry

- L. Farrar – *Nanocomposites and Nanomaterials*
- C.P. Singh – *Microemulsions in the Nano-Biotech Industries*
- J.D. Wright – *Fullerenes for Electronics*

Nanoparticle Manufacturing

- T.S. Sudarshan – *Nanopowder Manufacturing*
- T. Wong – *Nanometer-scale Metal Alloy Powders in Superconducting Materials*
- B. Eranezhuth – *Consolidation of Nanocrystalline Materials*

Regional alliances

- **Nanotechnology Alliance in Southern California** www.larta.org/Nano
- **Nanotechnology Franklin Institute, Pennsylvania** www.sep.benfranklin.org/resources/nanotech.html
- **Texas Nanotechnology Initiative** www.texasnano.org
- **Virginia Nanotechnology Initiative** www.INanoVA.org
- **Denver Nano Hub** www.nanobusiness.org/denver.html
- **Silicon Valley, San Diego and Michigan Nano Hubs** May 2002
- **Massachusetts Nanotech Initiative (MNI)** Jan. 2003
- **Connecticut Nanotechnology Initiative (CNI)** Feb. 2003

NSET/NNCO sponsors series of regional research providers / industry / business meetings for networking, www.nano.gov

Others in partnerships in sight:
regional activities; NanoBusiness Alliance www.nanobusiness.org

State participation

Illustrations from 15 states

CA	California NanoSystem Instititute	$100M/ 4yrs
NY	Center of Excellence in Nanoelectronics; Albany Center	$50M, $212M/ 5yrs
PA	Nanotechnology Center	$37M
IL	Nanoscience Center	$34M
IN	Nanotechnology Center	$5M
TX	Nanotechnology Center	$0.5M over 2 yrs
SC	NanoCenter	$1M
NM	Consortium University of NM and National labs	
NJ	Support at NJIT and future nanophotonics consortium	
FL	Center at the University of South Florida	
GA	Center at Georgia Tech	
OK	Nano-Net (~$3M/yr for 5 years)	

- Pending: Ohio (support Center), Tennessee ($24M), Louisiana

Professional societies

- "AIAA - Nanotech 2002" www.aiaa.org
- ACS - Nano Letters
- AIChE - Topical Conf.on Nanoscale Science and Engineering
- ASME - Nanotechnology Institute www.asme.org/nano
- AVS - Nano-meterscale S&T Division kesey.ucsd.edu/avs-nstd
- ICEE – Engineering Education fie.engrng.pitt.edu/icee
- IEEE - Nanotechnology Virtual Community, ewh.ieee.org/tc/nanotech
- MRS- Nanotechnology Initiative, www.mrs.org/pa/nanotech
- "SPIE- Materials and Nanotechnology" www.spie.org/Conferences

Convergent technologies (NBIC)

The synergistic combination of four major "NBIC" (nano-bio-info-cogno) provinces of science and technology, each of which is currently progressing at a rapid rate:

- nanoscience and nanotechnology
- biotechnology and biomedicine, including genetic engineering
- information technology, including advanced computing and communications
- cognitive science, including cognitive neuroscience

NSF-DOC Report, June 2002
(http://www.nsf.gov/nano)

NNI key issues to be addressed in 2002 and beyond

Need for coherent 5-10 year programs:

draft Bill in preparation in Congress

“21st Century Nanotechnology R&D Act”

5-year “National Nanotechnology Program”

Horizontal versus vertical S&T development:

0.5% (on basics) versus 5% (plus precompetitive R&D) of national R&D budget

Exploratory research in nanobio-medicine, molecular nanosystems, energy, agriculture and food, improving human performance, others

Maintaining focus on:

Manufacturing, Infrastructure and Education
Partnership with industry
Societal issues
International collaboration and competition