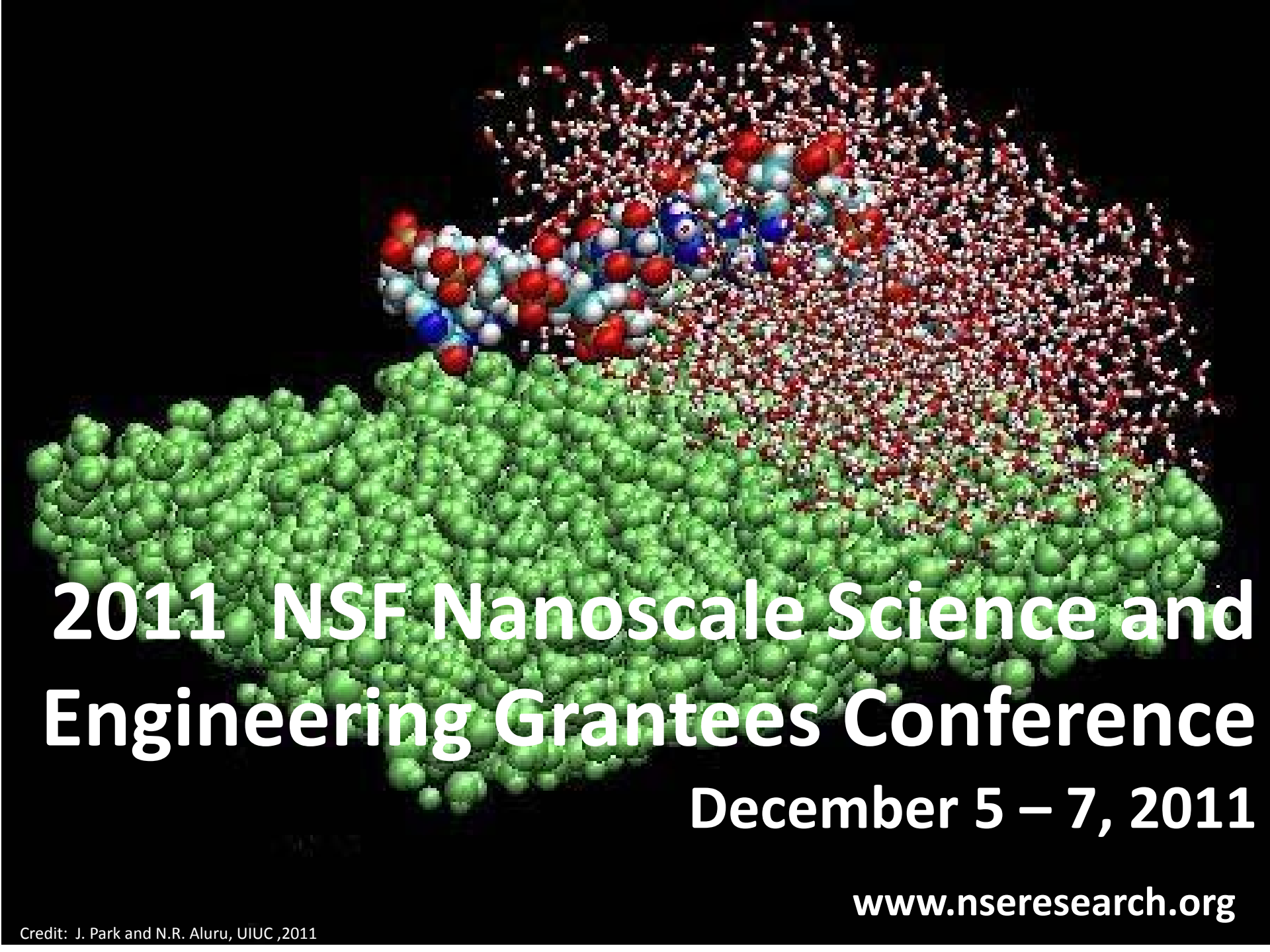


2011 NSF Nanoscale Science and Engineering Grantees Conference

December 5 – 7, 2011

www.nseresearch.org

Credit: J. Park and N.R. Aluru, UIUC ,2011

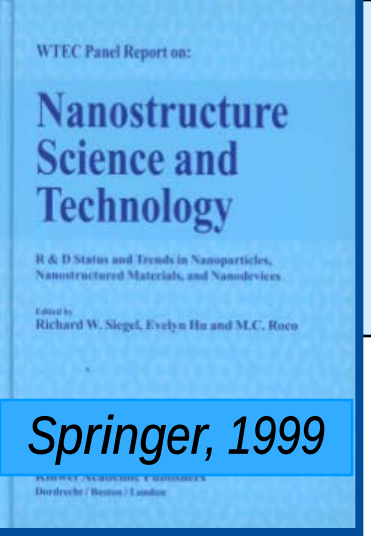
Nanoscale Science and Engineering at NSF

Mike Roco

National Science Foundation (www.nsf.gov/nano)

and National Nanotechnology Initiative (www.nano.gov)

NSF's Nanoscale Science and Engineering Grantees Conference
Arlington, December 5, 2011



Benchmark with experts in over 20 countries in 1997-1999

"Nanostructure Science and Technology"

NNI preparatory Report, Springer, 1999

Nanotechnology Definition for the R&D program

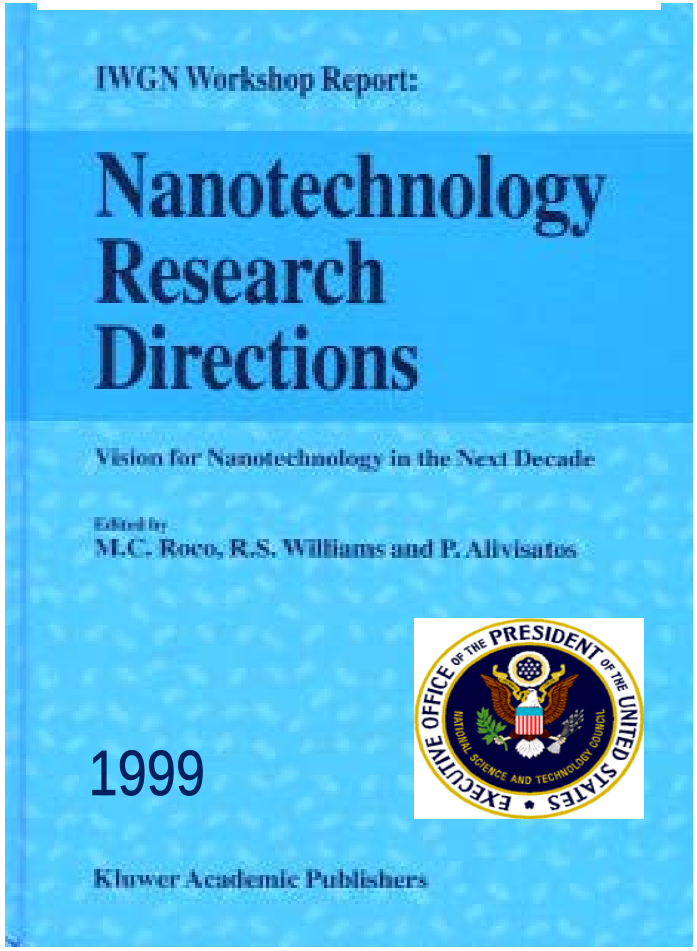
Working at the atomic, molecular and supramolecular levels, in the length scale of ~ 1 nm (a small molecule) to ~ 100 nm range, in order to understand, create and use materials, devices and systems with specific, fundamentally new properties and functions because of their small structure (natural threshold)

NNI definition encourages new R&D that were not possible before:

- *the ability to control and restructure matter at nanoscale*
- *collective effects → new phenomena → novel applications*
- *integration along length scales, systems and applications*

Long-term view for nanotechnology research directions (2000-2020)

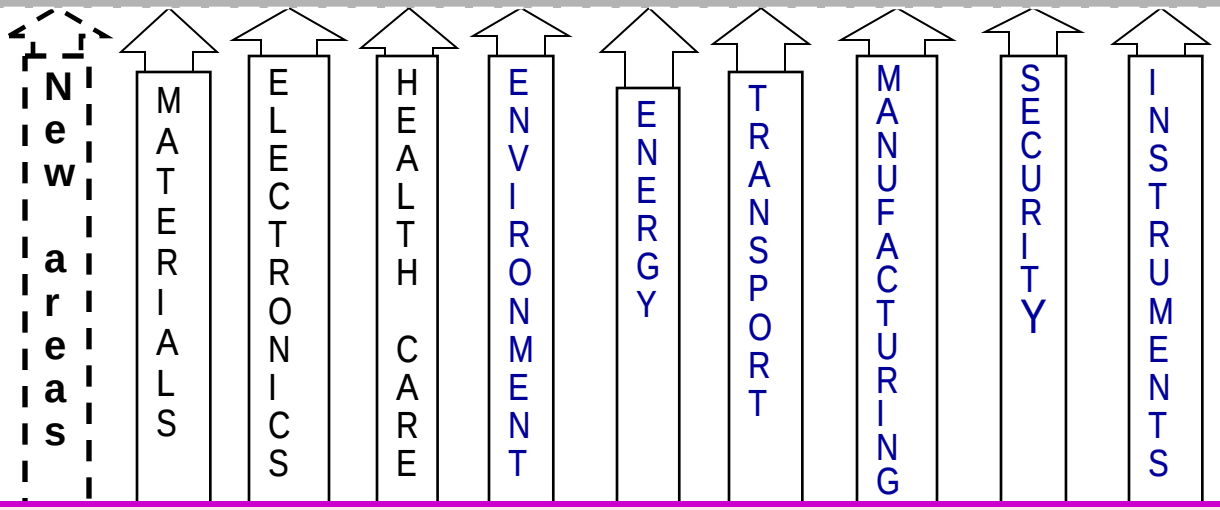
nano1 (2000-2010)



nano2 (2010-2020)

NSF/WTEC, www.wtec.org/nano2/ ; time scales in planning: from 20 yr to 1 m

Mass Application of Nanotechnology after ~ 2020



CREATING A NEW FIELD AND COMMUNITY IN 2 FOUNDATIONAL STEPS (2000~2020) with 4 generations of nanotechnology products

2020

NS&E integration for general purpose technology

~ 2011 ← **nano2** → **~ 2020**

Direct measurements; Science-based design and processes; Collective effects; Create nanosystems by technology integration

New disciplines

New industries

Societal impact

Foundational interdisciplinary research at nanoscale

~ 2001 ← **nano1** → **~ 2010**

Indirect measurements, Empirical correlations; Single principles, phenomena, tools; Create nanocomponents by empirical design

Infrastructure

Workforce

Partnerships

2000

MC Roco, Dec 5 2011

2000-2010
Estimates show an average growth rate of key nanotechnology indicators of 16% - 33%

World (US)	People -primary workforce	SCI papers	Patents applicat-ions	Final Products Market	R&D Funding public + private	Venture Capital
2000 *(actual)*	~ 60,000 (25,000)	18,085 (5,342)	1,197 (405)	~ $30 B ($13 B)	~ $1.2 B ($0.37 B)	~ $0.21 B ($0.17 B)
2010 *(actual)*	~ 600,000 (220,000)	78,842 (17,978)	~ 20,000 (5,000)	~ $300 B ($110 B)	~ $18 B ($4.1 B)	~ $1.3 B ($1.0 B)
2000 - 2010 average growth	~ 25% (~23%)	~ 16% (~13%)	~ 33% (~28%)	~ 25% (~24%)	~ 31% (~27%)	~ 30% (~35%)
2015 *(estimation in 2000)*	~ 2,000,000 (800,000)			~ $1,000B ($400B)		
2020 *(extrapolation)*	~ 6,000,000 (2,000,000)			~ $3,000B ($1,000B)		
Evolving Topics	*Research frontiers change from passive nanostructures in 2000-2005, to active nanostructures after 2006, and to nanosystems after 2010*					

2001-2012

NNI expenditures have grown > 4 times

from $464 million in FY 2001 to $2.1B in FY 2012 request

NNI budget: $2,100M (2012 Request) / $464M (2001 Actual) ~ 4.5 times

NNI at NSF: $456M (2012 Request) / $97M (2001 Actual) ~ 4.7 times

Fundamental S&E remains the main focus, with increased attention to innovation, manufacturing, societal implications

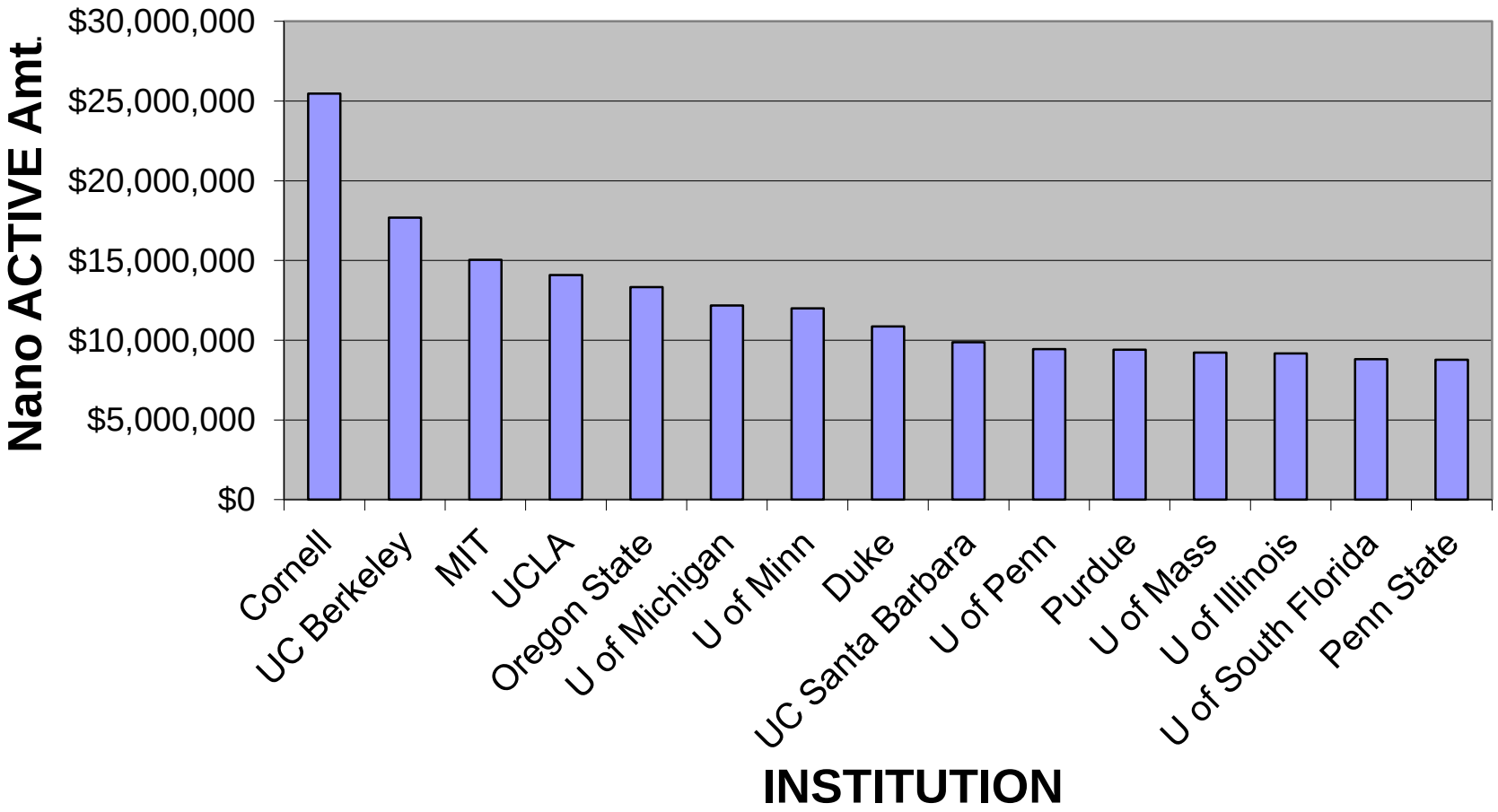
Nanomanufacturing in 2012 Request: all NNI 5.8%; NSF 12.6%,

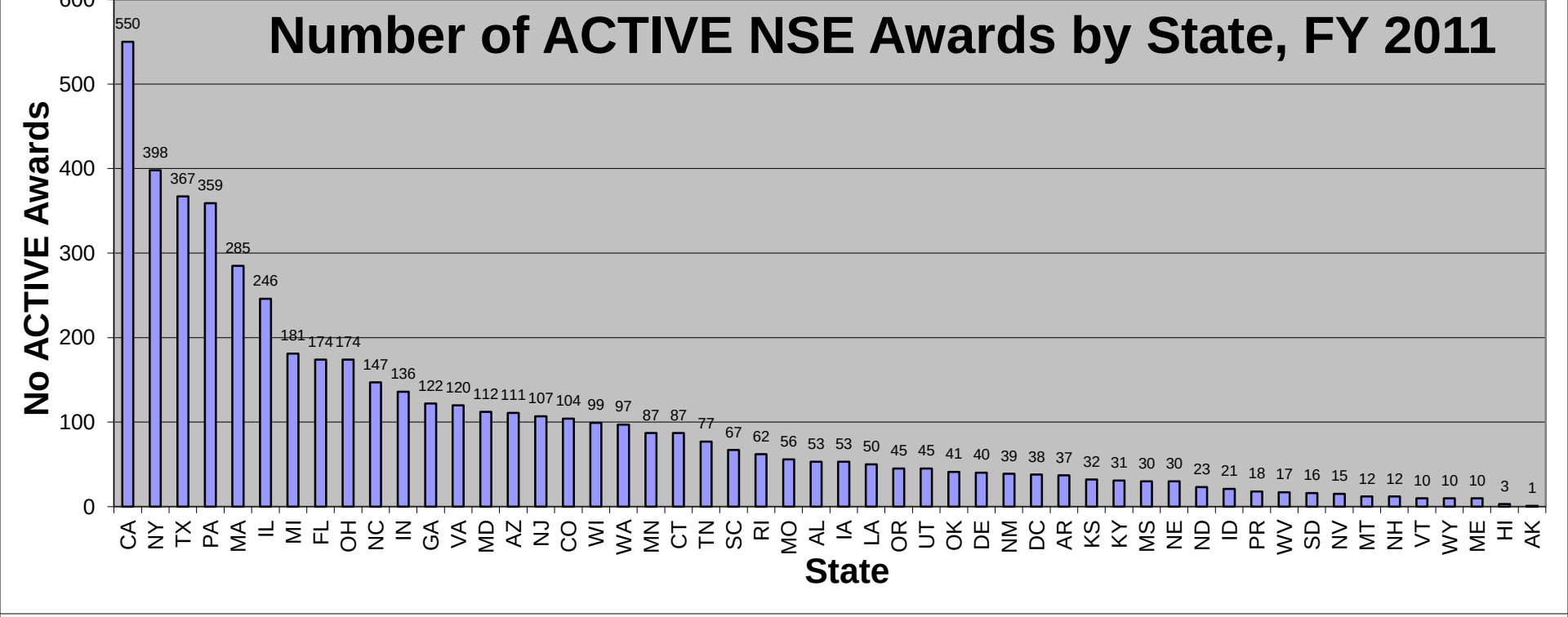
Nano EHS NNI has increased from 4% in 2011 to 7% in 2012 Request
NSF has ~ 7 % in the last five years

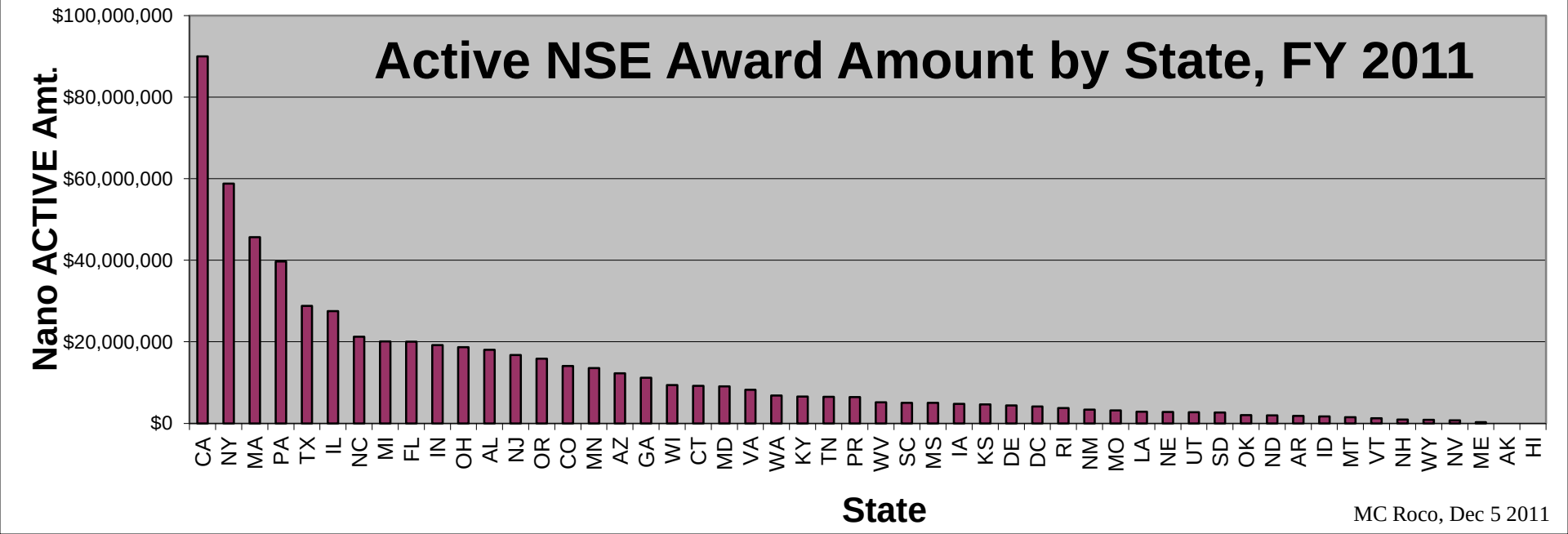
Nano penetration is time-staggered, in 2010: ~11% in NSF awards, ~5% in all papers, ~1.7% in USPTO patents, ~ 0.7% in Nano market/US GDP

60-70 universities have comparable levels of NSE funding

Top 15 institutions receiving NSE awards after the amount awarded for FY 2011



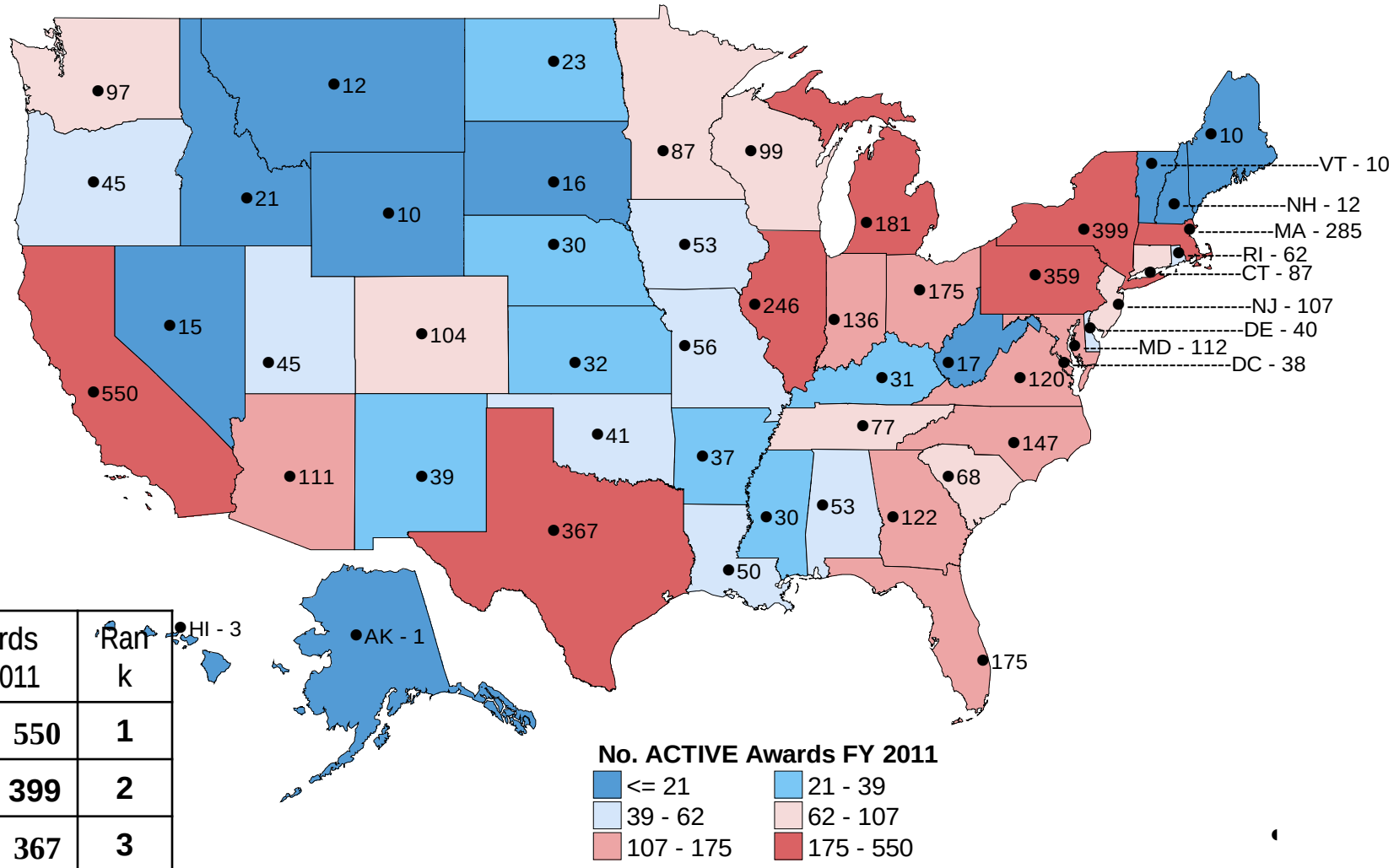




MC Roco, Dec 5 2011

Number of ACTIVE NS&E Awards by State for FY 2011

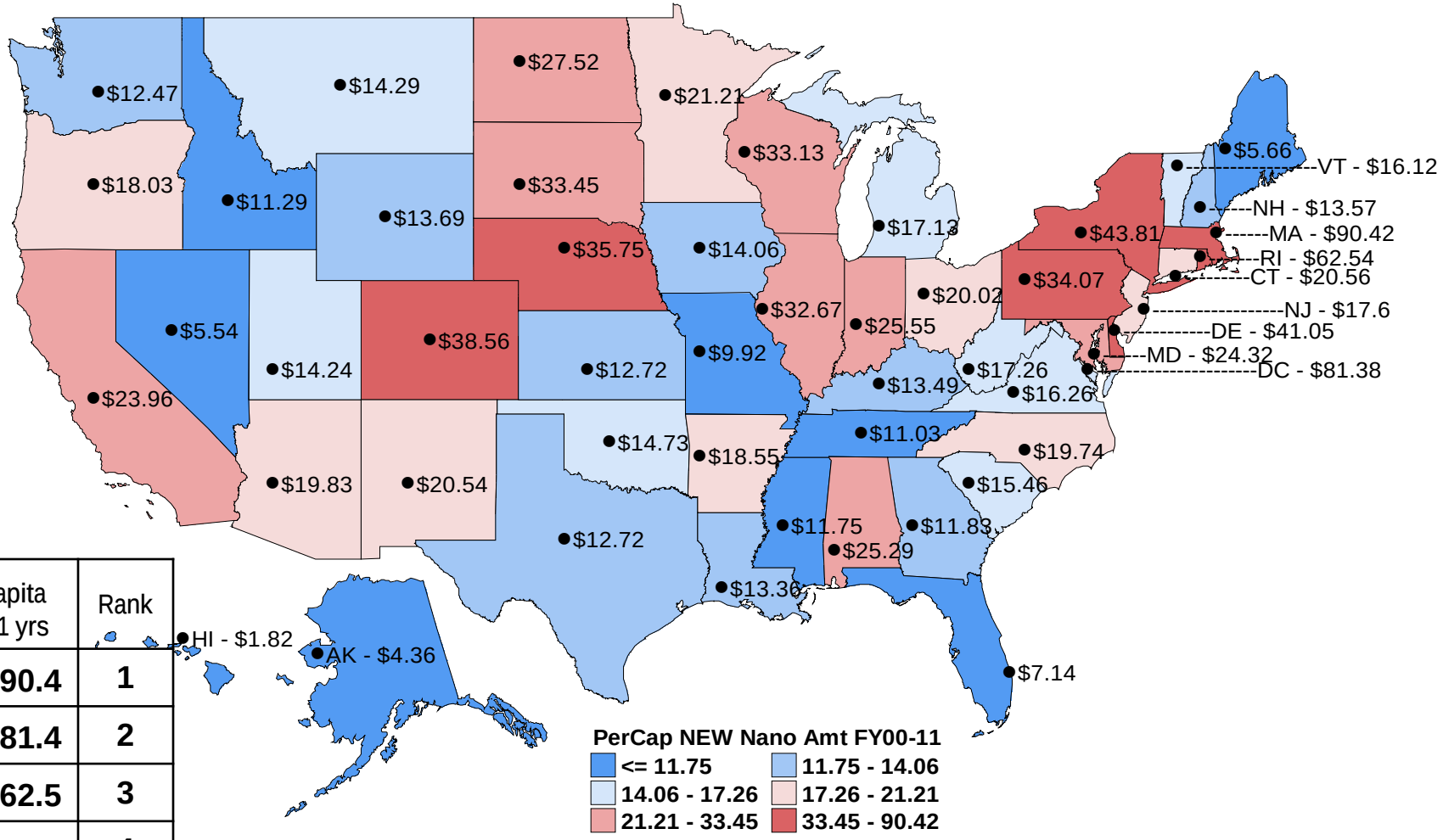
Total Number of FY 2011 ACTIVE NS&E Awards = 5,064



State	Awards FY 2011	Rank
CA	550	1
NY	399	2
TX	367	3
MA	285	4
PA	359	5
IL	246	6

MC Roco, Dec 5 2011

Per capita Nano$ for NEW Awards by State
FY 2000 - 2011
Overall National *per capita* Average Amount = $22.32



State	$ / capita per 11 yrs	Rank
MA	**90.4**	**1**
DC	**81.4**	**2**
RI	**62.5**	**3**
NY	**43.8**	**4**
DE	**41.1**	**5**
CO	**38.6**	**6**

MC Roco, Dec 5 2011

2001-2011 Significant outcomes after ten years

- Remarkable scientific discoveries than span better understanding of the smallest living structures, uncovering the behaviors and functions of matter at the nanoscale, and creating a library of 1D - 4D nanostructured building blocks for devices and systems
- New S&E fields have emerged such as: *spintronics, plasmonics, metamaterials, carbon nanoelectronics, molecules by design, nanobiomedicine, branches of nanomanufacturing, and nanosystems*
- Technological breakthroughs in advanced materials, biomedicine, catalysis, electronics, and pharmaceuticals; expansion into energy resources and water filtration, agriculture and forestry; and integration of nanotechnology with other emerging areas such as quantum information systems, neuromorphic engineering, and synthetic and system nanobiology

2001-2011 *Objectives not fully realized after ten years*

- General methods for **"materials by design"** and composite materials (because the direct simulation and measuring techniques methods were not ready)
- **Sustainable development projects** - only energy projects received significant attention in the last 5 years; Nanotechnology for water filtration and desalination only limited; Delay on nanotechnology for climate research (because of insufficient support from beneficiary stakeholders?)
- **Widespread public awareness of nanotechnology** – awareness low ~30% in U.S.; Challenge for public participation

2001-2011

Better than expected after ten years

- ✓ Unanticipated discoveries and advances in several S&E fields: plasmonics, metamaterials, spintronics, graphene, cancer detection and treatment, drug delivery, synthetic biology, neuromorphic engineering, quantum information ..
- ✓ Major industry involvement after 2002-2003
  Ex: >5,400 companies with papers/patents or products (US, 2008); NBA in 2002; Keeping the Moore law continue 10 years after serious doubt raised din 2000
- ✓ The formation / strength of the international community, including in nanotechnology EHS and ELSI that continue to grow

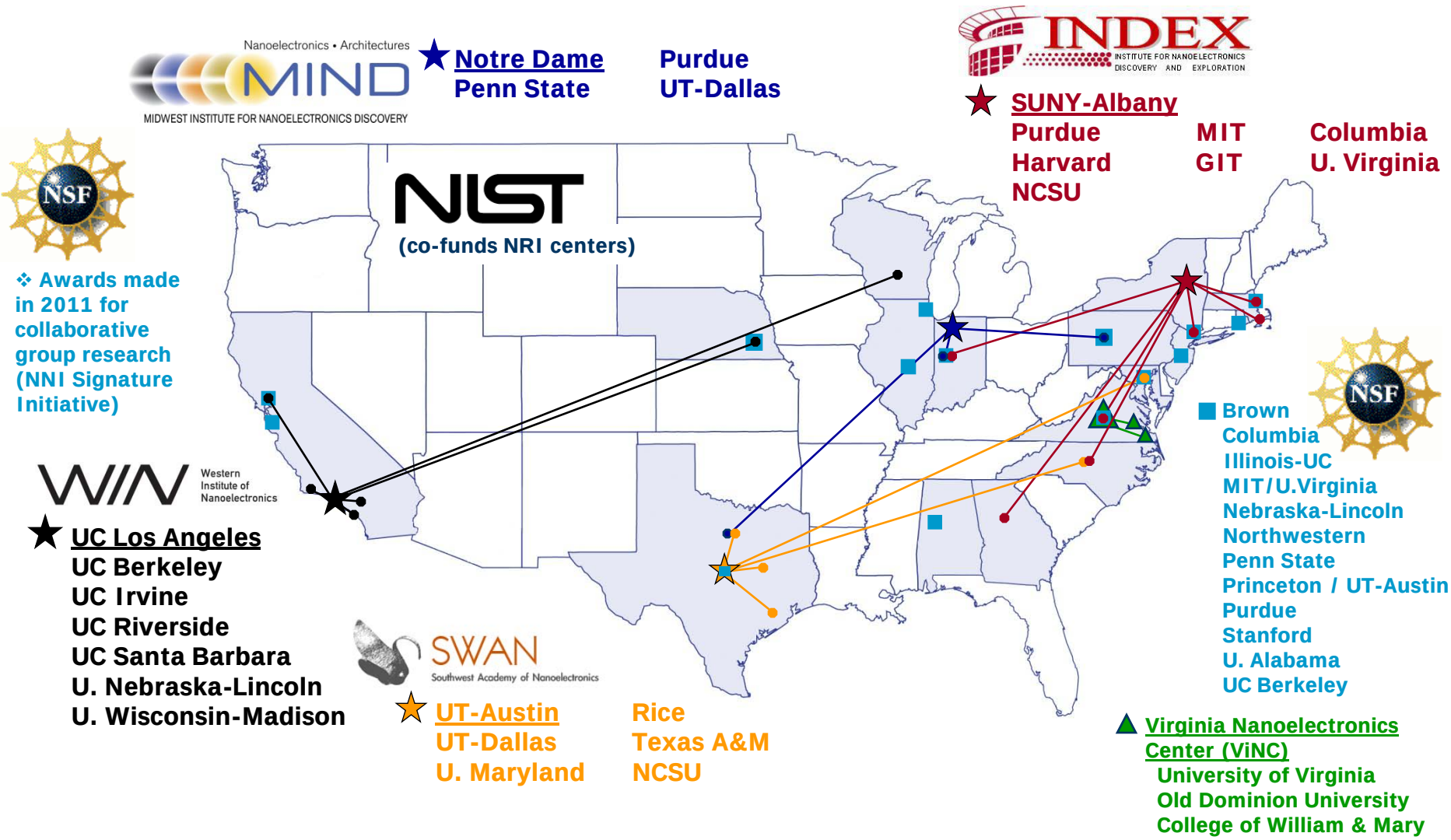
2001-2010

~10,900 awards by NSF's Principal Investigators

The patents were searched by "title-claims" keywords at USPTO; examples

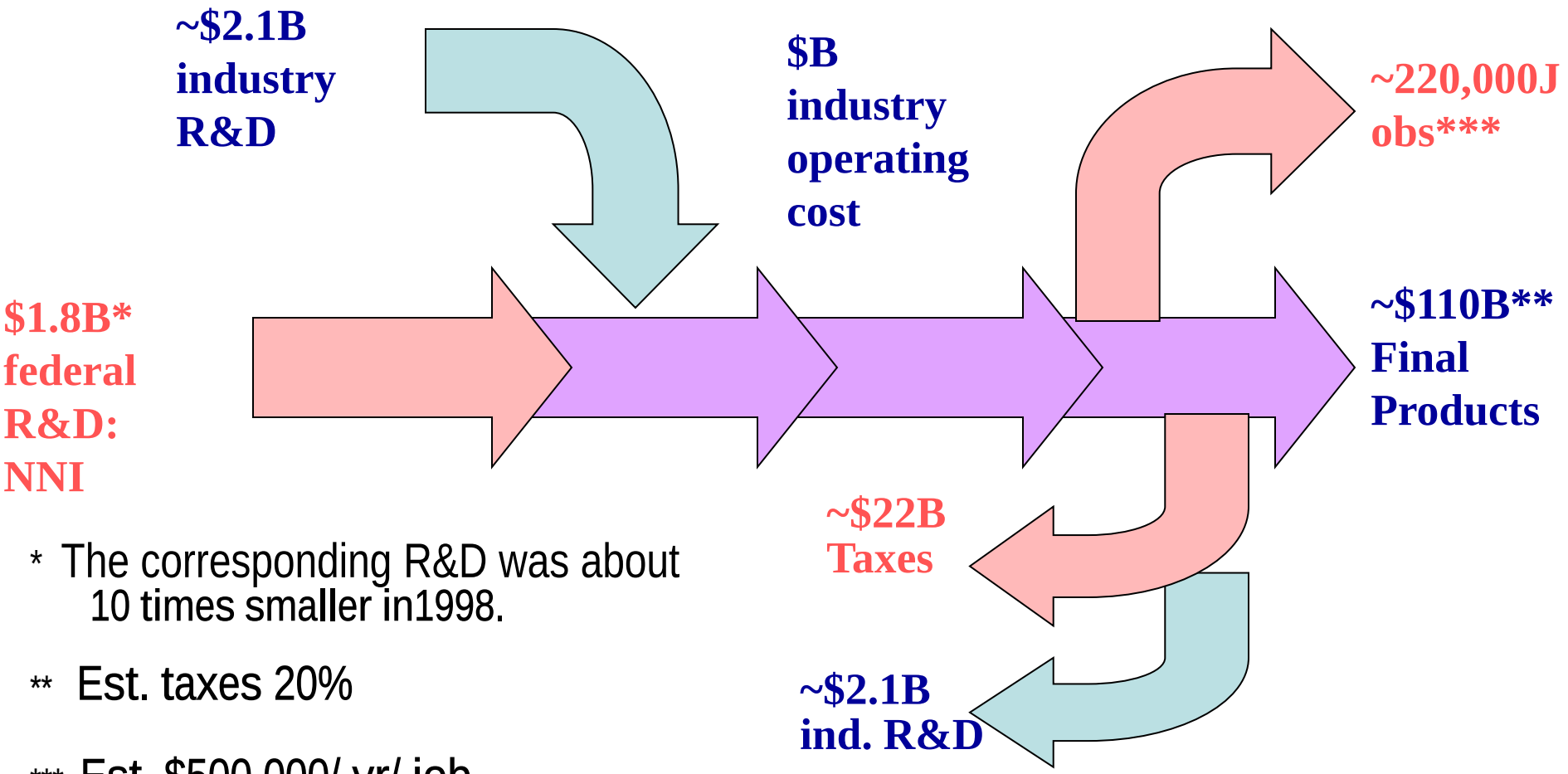
Interval	2001-2010	NSF supported investigators with most patents - NNI at 10 years -	
Rank	**Name NSF P.I.**	**Institution**	**# USPTO Patents (keyword search)**
1	**Chad A. Mirkin**	Northwestern University	74
2	**Richard E. Smalley**	Rice University	70
3	**Bin Yu**	University of Albany	55
4	**Stephen R. Quake**	Stanford University	48
5	**Mark E. Thompson**	University of Southern California	43
6	**Moungi G. Bawendi**	Massachusetts Institute of Technology	42
7	**Andrew G. Rinzler**	University of Florida	40
8	**Ping Liu**	University of Texas at Arlington	37
9	**Joseph M. Jacobson**	Massachusetts Institute of Technology	36
10	**George M. Whitesides**	Harvard University	33
11	**Axel Scherer**	California Institute of Technology	31
12	**Thomas J. Pinnavaia**	Michigan State University	26
13	**Tobin J. Marks**	Northwestern University	23
14	**Charles M. Lieber**	Harvard University	23
15	**Nathan S. Lewis**	California Institute of Technology	22
16	**Hongjie Dai**	Stanford University	22
17	**Kerry J. Vahala**	California Institute of Technology	20
18	**Thomas W. Kenny**	Stanford University	20
19	**Michael N. Kozicki**	Arizona State University	19
20	**Tsu-Jae King**	University of California at Berkeley	19
21	**Robert Langer**	Massachusetts Institute of Technology	18
22	**Michael L. Simpson**	University of Tennessee	18
23	**Michael L. Roukes**	California Institute of Technology	17
24	**Jackie Y. Ying**	Massachusetts Institute of Technology	17
25	**Ting Guo**	University of California at Davis	16
26	**Stephen C. Minne**	Stanford University	15
27	**Nicholas L. Abbott**	University of Wisconsin-Madison	15
28	**Eric V. Anslyn**	University of Texas at Austin	14
29	**R. Stanley Williams**	HP	14
30	**Kenneth J. Klabunde**	Kansas State University	14
31	**Samuel I. Stupp**	Northwestern University	14

Nanoelectronics Research Initiative Funded Universities (SIA, NSF, NIST)



Partnerships NSF, NIST, SIA, SRC with over 30 Universities in 16 States

Estimation of Annual Implications of U.S. Federal Investment in Nanotechnology R&D (2010)



* The corresponding R&D was about 10 times smaller in1998.

** Est. taxes 20%

*** Est. $500,000/ yr/ job

NNI "signature initiatives" at NSF

2011-2012

Sustainable Nanomanufacturing (NSF 10614)

FY 2011: Program solicitation $11.3M + core programs
FY 2012: Request $57.2M

Nanoelectronics for 2020 and Beyond (NSF 10618)

FY 2011: Program solicitation with SRC $20M + Core
FY 2012: Request $50M

Nanotechnology for Solar Energy

FY 2011: Program solicitations, one with DOE + Core
FY 2012: Request $32M

Examples of other activities

2011-2012

Nanosystems Engineering Research Centers

For 5 + 5 years ($3-4 M/year per center)

Environmental, Health and Safety (EHS)

FY 2011 CP: $33.0M, including supplements to centers

FY 2012 Request: $34.01M (7.5% of NSF NNI)

Programs for interaction with industry

GOALI, PFI, ARI, SBIR/STTR, Collaboration NRI …

International study: Transforming Tools of Emerging & Converging Technologies (NBIC2)

NNI is funded across NSF: Samples of core (unsolicited proposals) with a focus on NSE

- "Metals and Metallic Nanostructures", MPS/DMR
- "Macromolecular, Supramolecular and Nanochemistry ", MPS/CHE
- "Nanomanufacturing" ENG/CMMI
- "Environmental Chemical Sciences" MPS/CHE
- "Environmental Health and Safety of Nanotechnology", ENG/CBET
- "Electronics, Photonics, and Magnetic Devices", ENG/ECCS
- "Computing and Communication Foundations", CISE

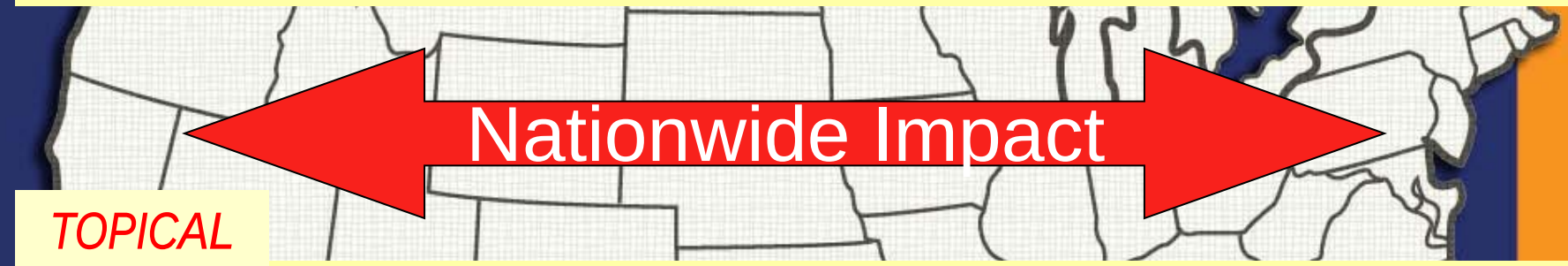
A new funding opportunity: "Career-Life Balance Initiative " (www.nsf.gov/career-life-balance)

Ten Nanoscale Science and Engineering networks with national outreach

TOOLS

Network for Computational Nanotechnology (2002-) > *180,000 users/ 2011*

National Nanotechnology Infrastructure Network (2003-) *~ 7,000 users/ 2011*



TOPICAL

Nanotechnology Center Learning and Teaching (2004-2011)

Nanoscale Informal Science Education Network (2005-) *>200 sites/ 5yr*

Network for Nanotechnology in Society (2005-) *Involves academia,public,industry*

Nanotech Applications and Career Knowledge (2008-) *– nanotechnology educ.*

National Nanomanufacturing Network (2006-) 4 NSETs , DOD centers, and NIST

Environmental Implications of Nanotechnology (2008-) with EPA

GENERAL RESEARCH AND EDUCATION

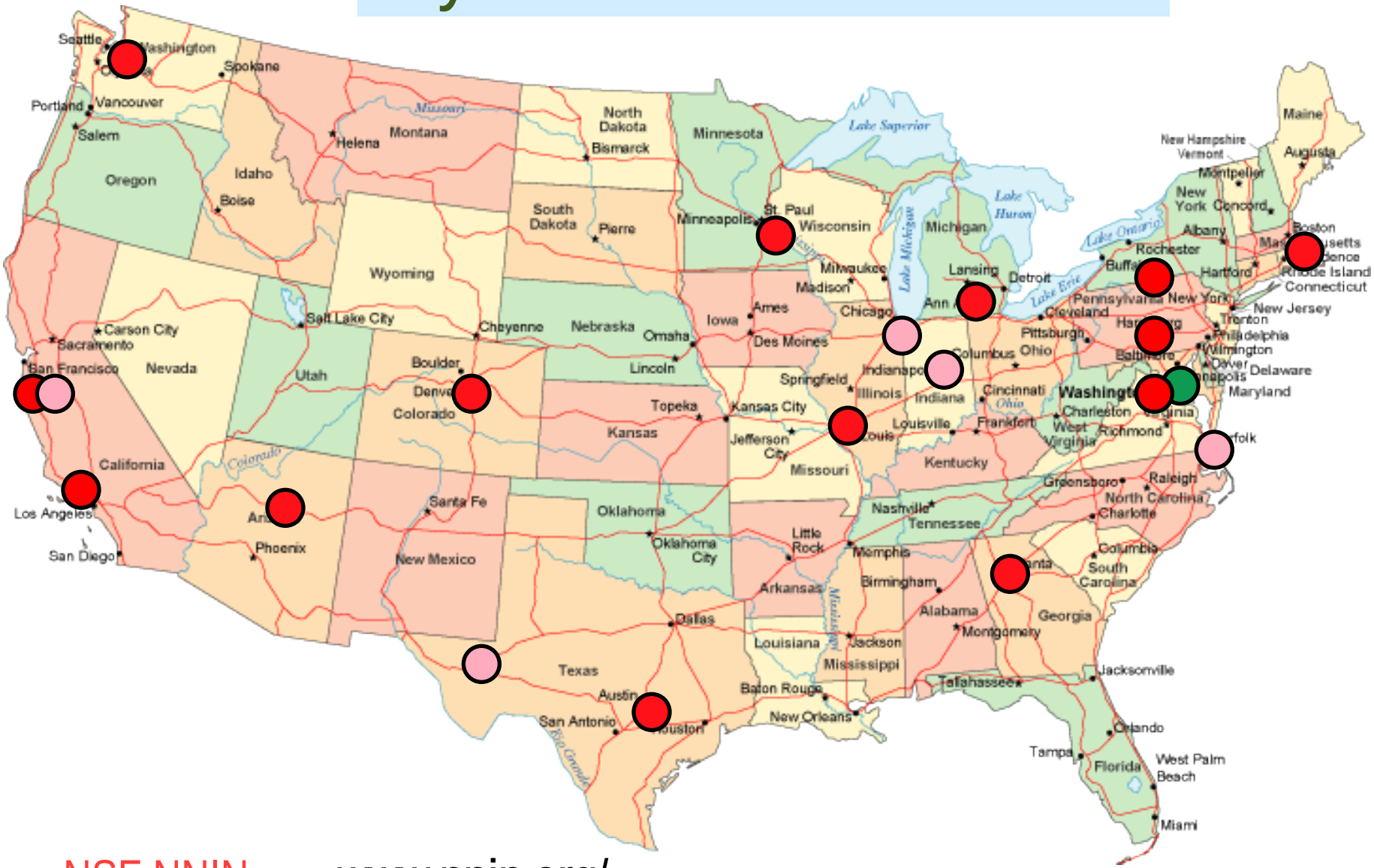
NSEC Network (2001-) *19 research and education centers*

MRSEC Network (2001-) about 2/3 cover NSE

MC Roco,
Dec 5, 2011

U.S. Infrastructure

Key NSF R&D User Facilities

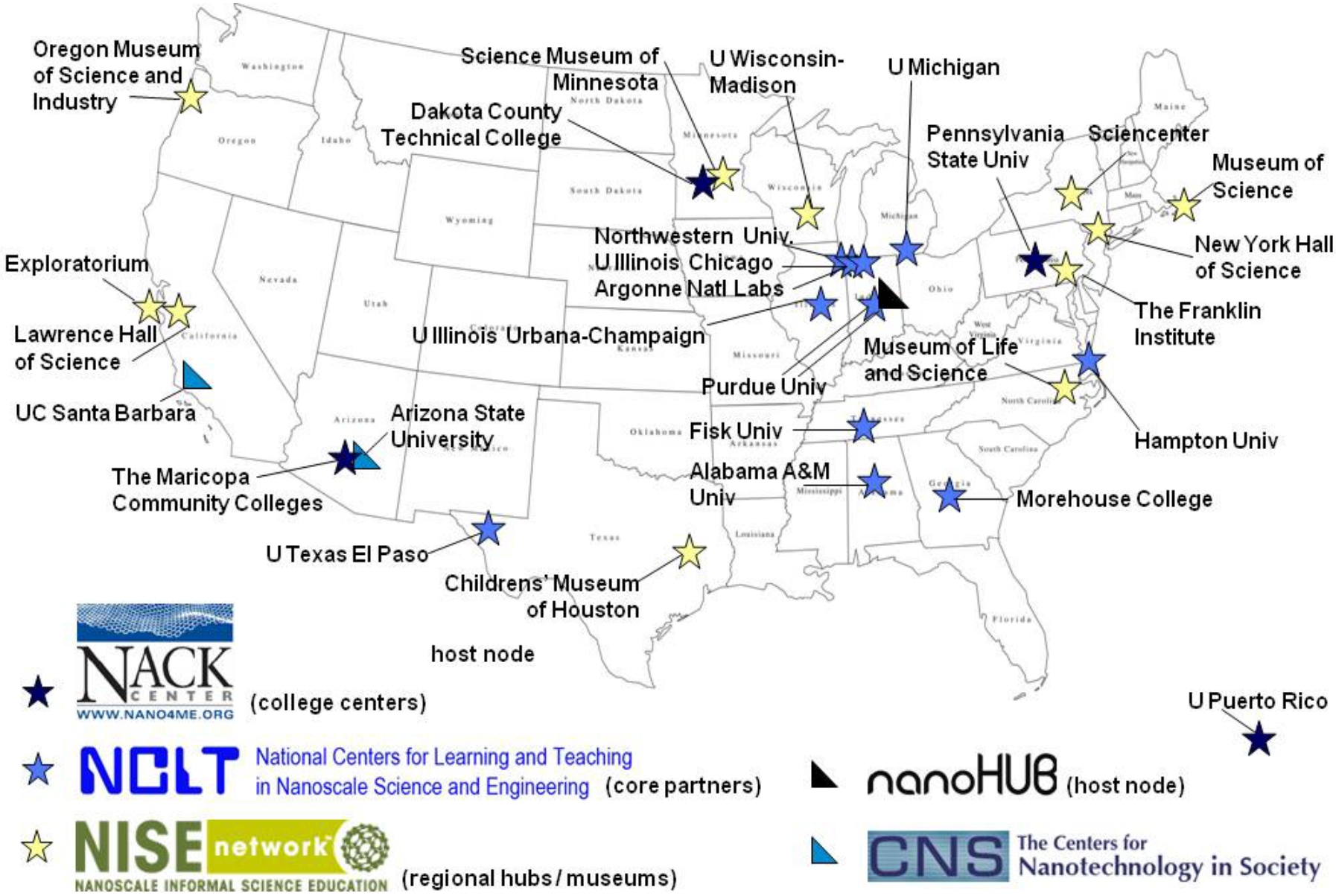


NSF NNIN www.nnin.org/

NSF NCN www.ncn.purdue.edu/

MC Roco, Dec 5 2011

Key NNI education networks in 2010



"Nanotechnology Research Directions for ..2020" , 2010, p. XVIII

FY 2011 NS&E Priorities Research Areas (1)

The long-term objective is systematic understanding, control and restructuring of matter at the nanoscale for societal benefit

A. Scientific challenges

- New theories at nanoscale
  Ex: transition from quantum to classical physics, collective behavior, for simultaneous phenomena
- Non-equilibrium processes
- Designing new molecules with engineered functions
- New architectures for assemblies of nanocomponents
- The emergent behavior of nanosystems

FY 2011 NS&E Priorities Research Areas (2)

B. Development of nanotechnology

- Tools for measuring and restructuring
  with atomic precision
  and time resolution of chemical reactions
- Understanding and use of quantum phenomena
- Understanding and use of multi-scale selfassembling
- Nanobiotechnology – sub-cellular and systems approach
- Nanomanufacturing hybrid, on site
- Systems nanotechnology

FY 2011 NS&E Priorities Research Areas (3)

C. Integration of nanotechnology in application areas

- Nanomanufacturing for sustainable environment
- Replacing electron charge as the information carrier in electronics (Ex: NRI)
- Energy conversion, water filtration / desalinization
- Nano-bio interfaces between the human body and manmade devices
- Nano-informatics for communication, nanosystem design
- Converging science, engineering and technology

From FY 2011 NSF priority research areas (4)

D. Societal dimensions of nanotechnology

- Understanding and sustainable ENV, including research for natural / incidental / manufactured nanomaterials

  Key nano- EHS priorities at NSF
  - New instrumentation for nanoparticle characterization and nanotoxicity
  - Transport phenomena and physico- chem.- biological processes
  - Nano-bio interface: ecological and human health implications
  - Predictive models for nanomaterials interaction with cells/living tissues
  - Separation of nanoparticles from fluids
  - Safety of manufacturing nanoparticles

- Earlier formal and informal education

- Social issues and public engagement

Main Evaluations of NNI with NSF input

Congress; WH/ OSTP and OMB - annually

PCAST - 1999, 2005, 2008, 2010

Academies, NRC: 2002, 2005, 2008, (2011)

GAO - 2007, 2009, 2010, 2011

NSF - Annually (GPRA, annual plan, cross-agency, for centers)

- NSF COVs; SRI (2005-2006), NSECs (2010), NSEE, ..
- International evaluation and vision for ten years ahead, WTEC (1999-2000) and WTEC (2010)
- Topical NSE meetings sponsored by NNI, NSF

International organizations: OECD, UNESCO, ISO, APEC, …

2011-2015: Key areas of emphasis

www.wtec.org/nano2/

- Integration of knowledge at the nanoscale and assembling nanocomponents into nanosystems by design
- Better experimental and simulation control of processes such as: molecular self-assembly, quantum behavior, creation of new molecules, and interaction of nanostructures with external fields
- Understanding of biological processes and of nano-bio interfaces with abiotic materials, and their biomedical applications
- Nanotechnology solutions for sustainable development
- Governance to increase innovation and public-private partnerships; education and infrastructure; oversight of nanotechnology, public and international participation.

FY 2011 NSF's Grantees Meeting

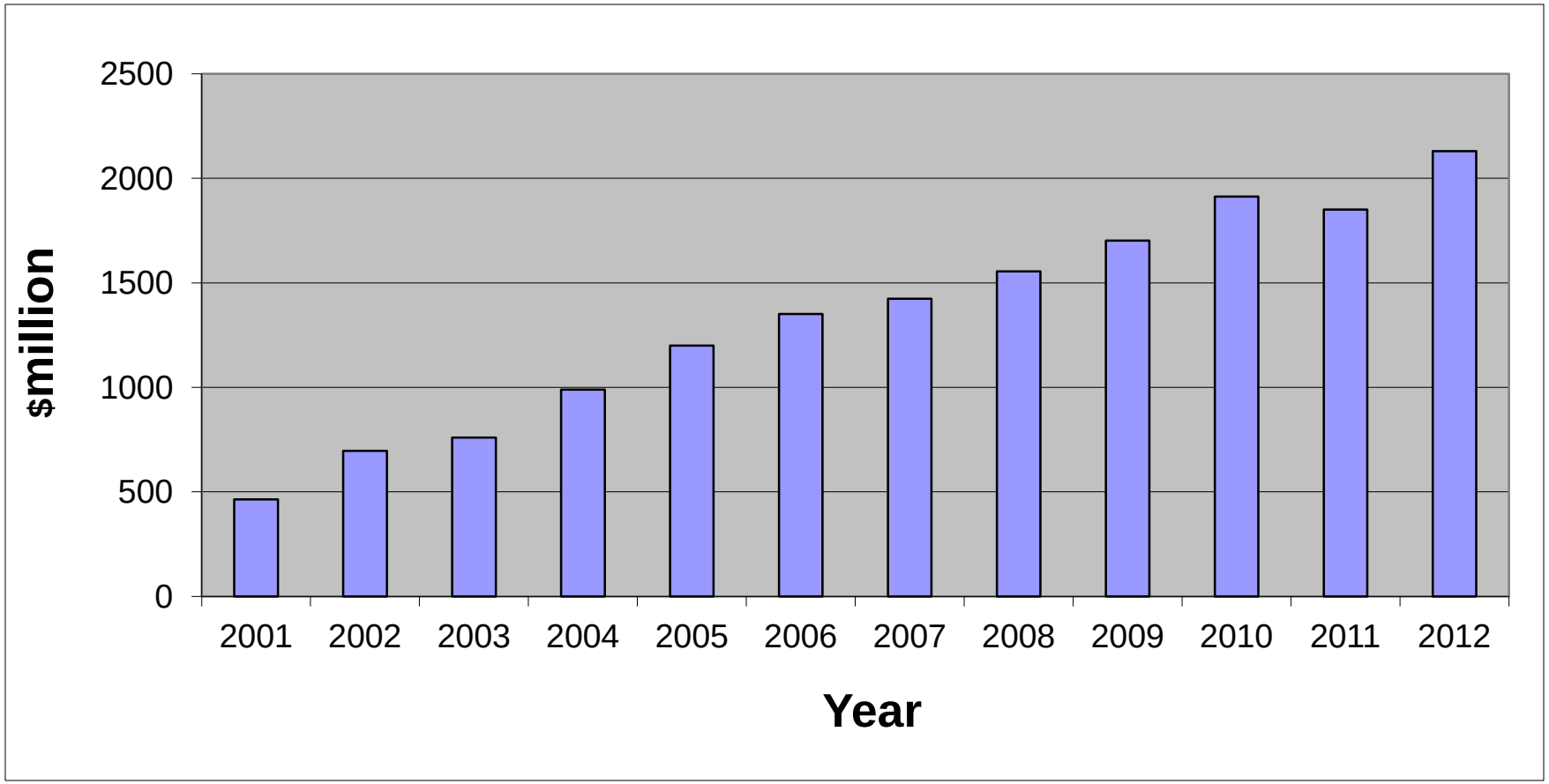
- Reviews of selected NSE awards
  Keynotes, posters and panels to facilitate exchanges, partnerships, and research planning
- Contributions from FDA, DOE/NREL, industry, others
- Strengthen NSE trans-disciplinary community
  Prepare for increased complexity in research, knowledge integration and innovation
- Meetings between researchers/educators with P.D.s

Reserves

2001-2012

NNI expenditures* have grown > 4 times

from $464 million in FY 2001 to $2.1B** 2012 request



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

** 2012 figure shown here does *not* include DOD $75 M included in 2010)

2001-2012

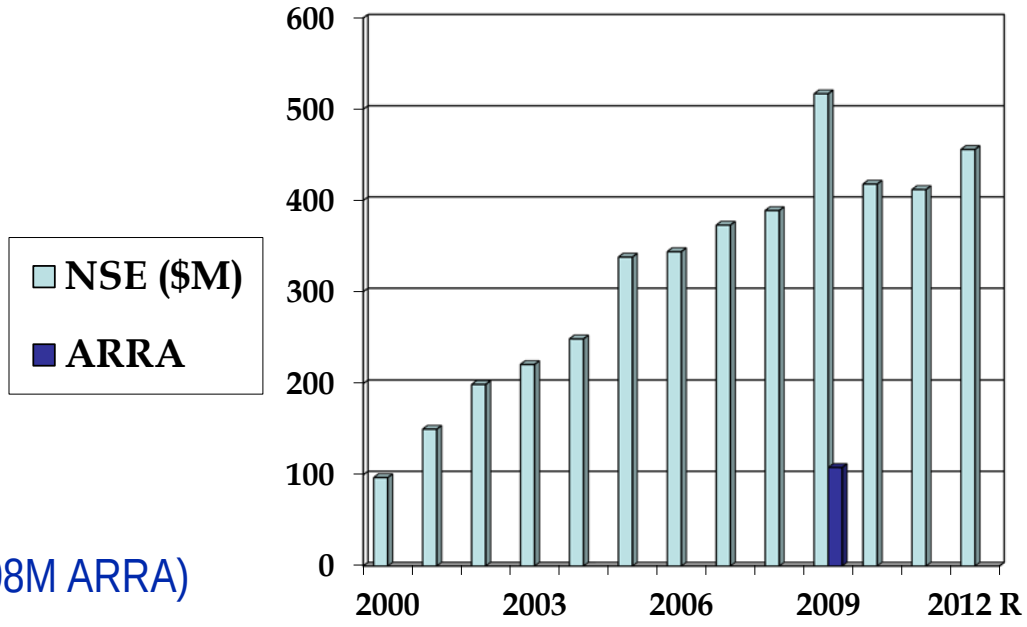
NSF – discovery, innovation and education in Nanoscale Science and Engineering (NSE)

www.nsf.gov/nano , www.nano.gov

FY 2012 Budget Request $455.9M

- Fundamental research ~ 5,000 active projects in all 50 states
- Establishing the infrastructure - 26 large centers, 2 user facilities, teams
- Training and education >10,000 students and teachers/y; ~ $30M/y

Fiscal Year	NSF	MANU	
2000	$97M		
2001	$150M		
2002	$199M		
2003	$221M		
2004	$254M		
2005	$338M		
2006	$344M		
2007	$373M		
2008	$389M	$20.7M	
2009	$397M	$21.9M	(+$108M ARRA)
2010	$428.7M	$21.4M	
CP 2011	$412.1M	$22.4M	
Request 2012	$455.9M	$57.2M	



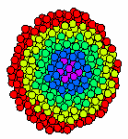
TIMELINE FOR BEGINNING OF INDUSTRIAL PROTOTYPING AND NANOTECHNOLOGY COMMERCIALISATION:
FOUR GENERATIONS OF PRODUCTS AND PRODUCTION PROCESSES

Complexity and integration

Higher uncertainty & risk

Frame 1

Risk Governance Frame 2

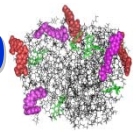


1st: Passive nanostructures (1st generation products)

a. *Dispersed and contact nanostructures* Ex: aerosols, colloids

b. *Products incorporating nanostructures* Ex: coatings; nanoparticle reinforced composites; nanostructured metals, polymers, ceramics

~ 2000

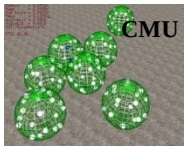


2nd: Active nanostructures

a. *Bio-active, health effects* Ex: targeted drugs,biodevices

b. *Physico-chemical active* Ex: 3D transistors, amplifiers, actuators, adaptive structures

~ 2005



3rd: Systems of nanosystems

Ex: guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary

~ 2010

4th: Molecular nanosystems

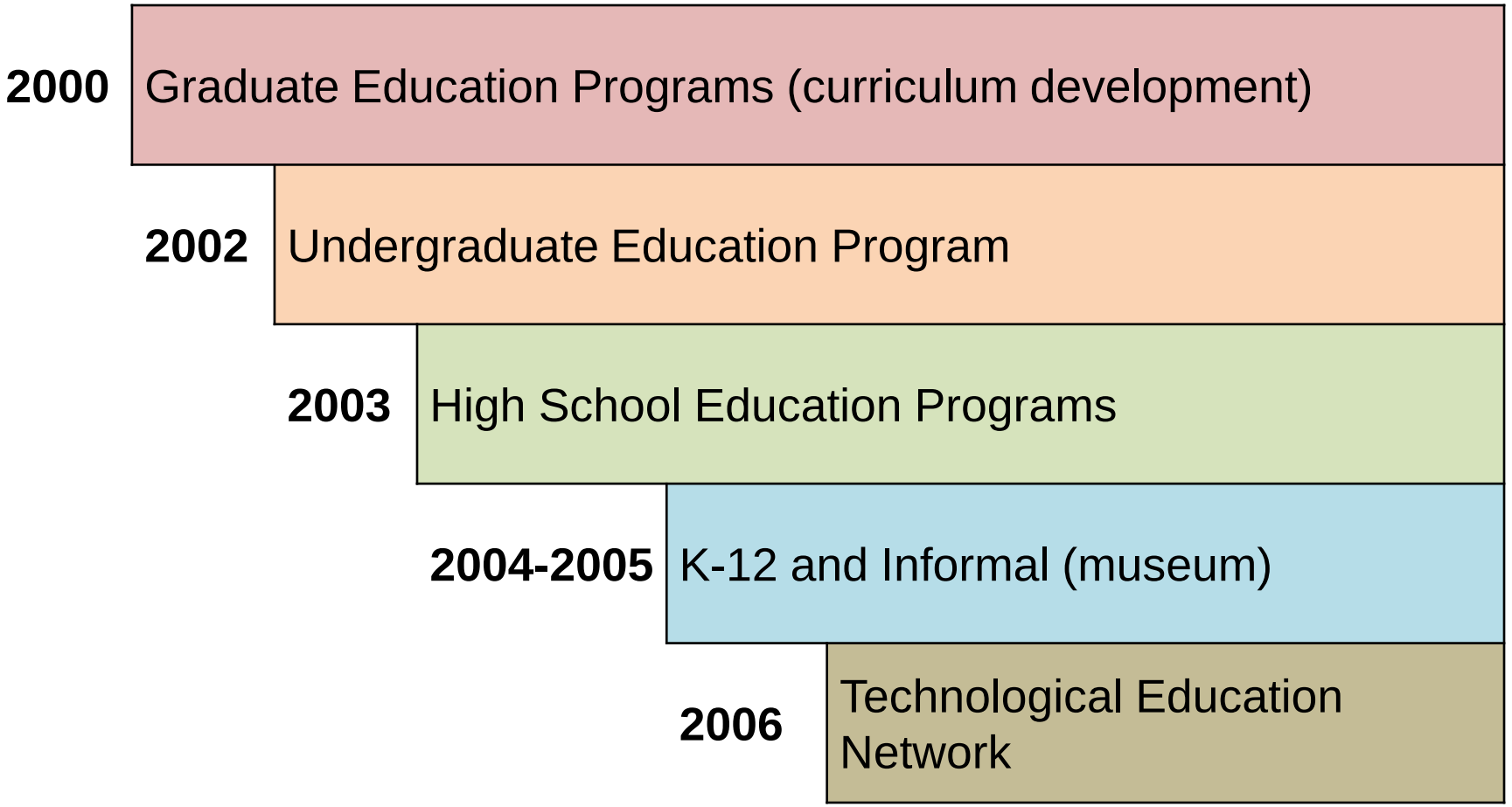
Ex: molecular devices 'by design', atomic design, emerging functions

~ 2015-2020

Converging technologies

MC Roco, Dec 5 2011

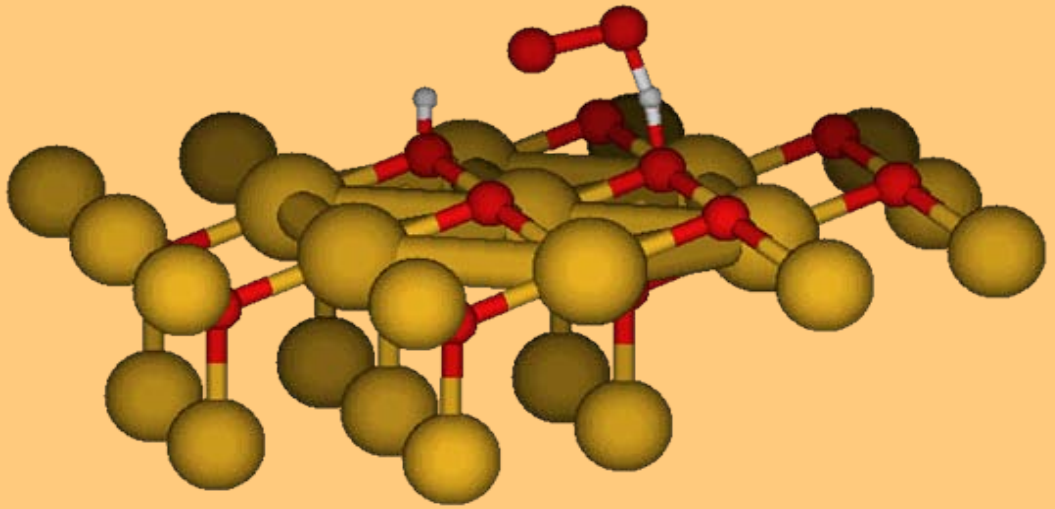
NSF investment in nanoscale science and engineering education, moving over time to broader and earlier education and training



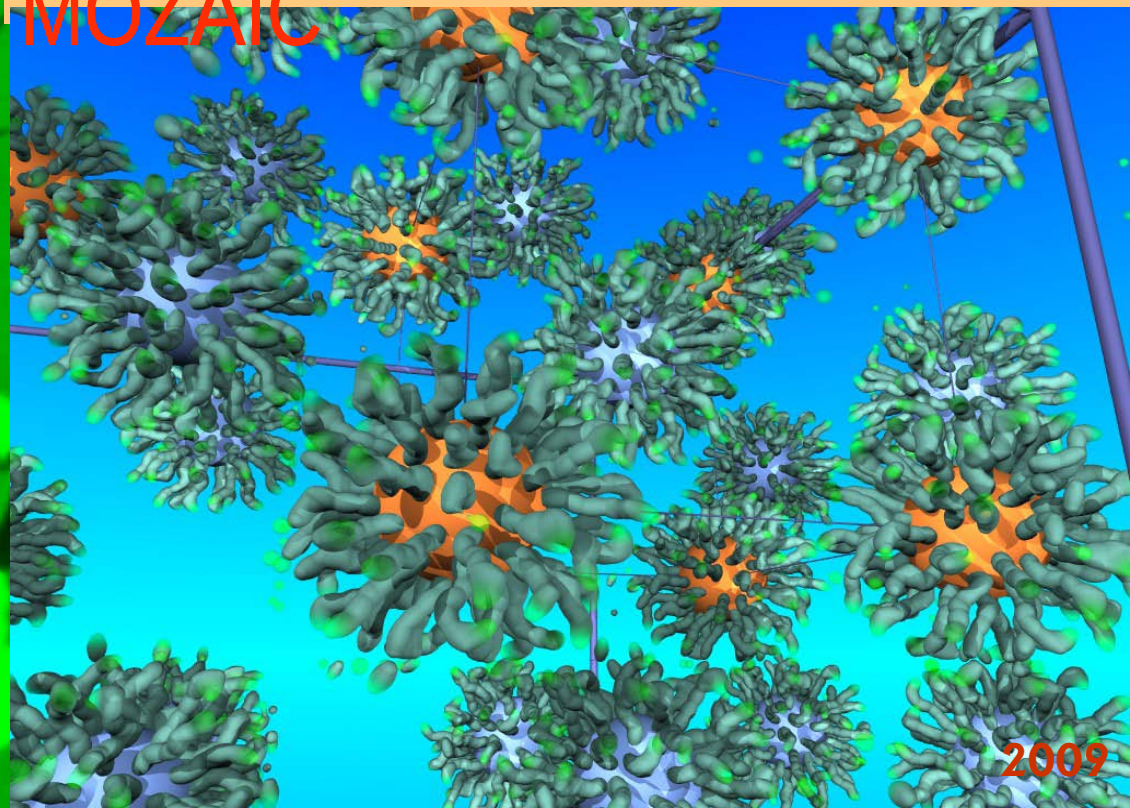
"Nanotechnology Research Directions for ..2020" , 2010, p. 360

2010

2008



NANO MOZAIC



2009