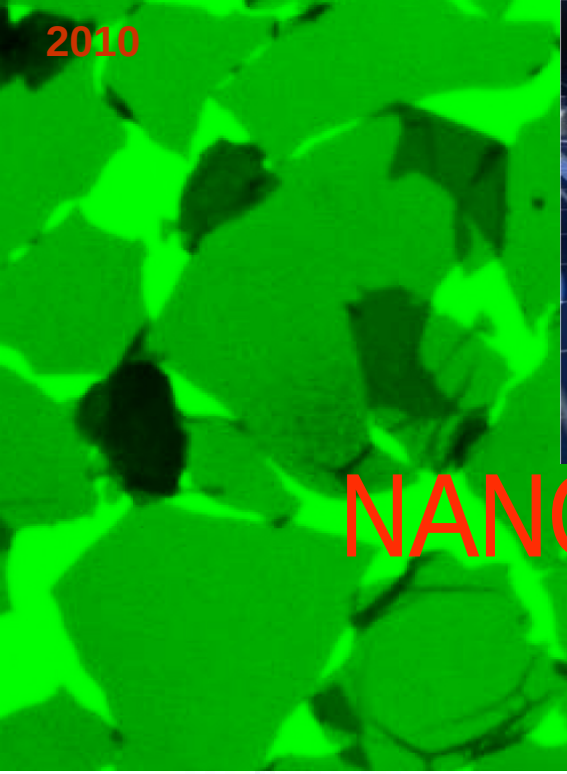
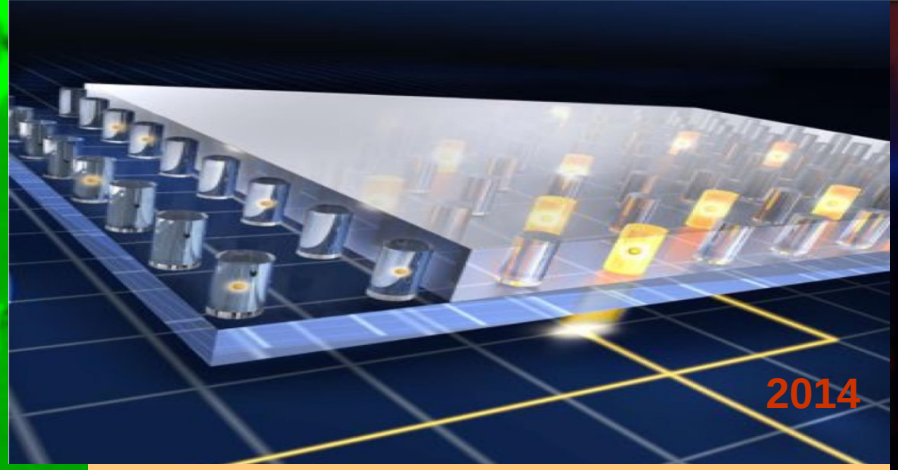
Nanoscale Science and Engineering at NSF

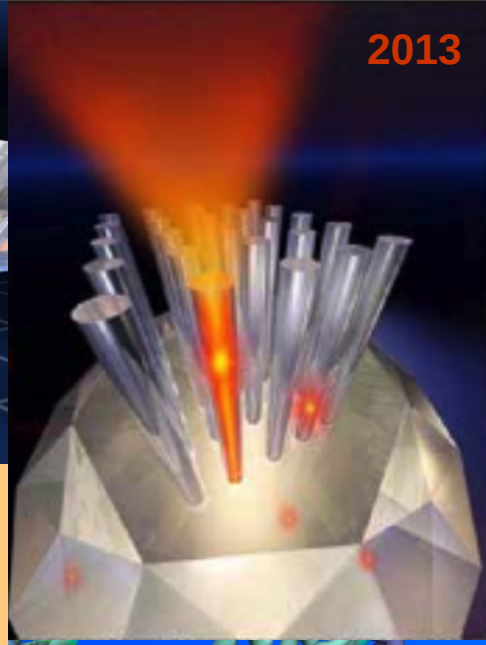
Mike Roco

NSF and NNI

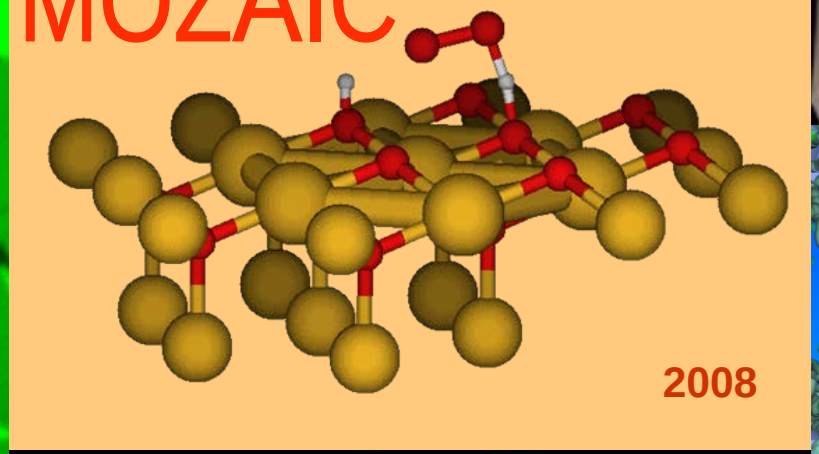
2014 NSF Nanoscale Science and Engineering Grantees Conference
Arlington, December 9-10

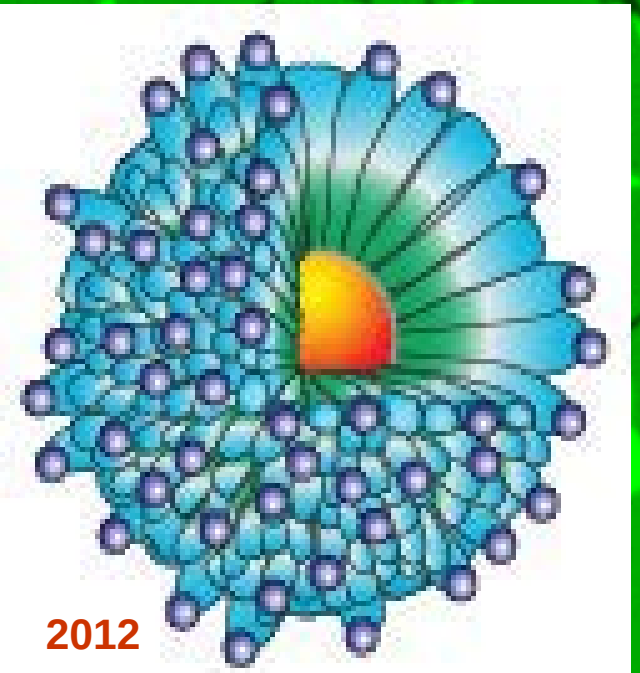


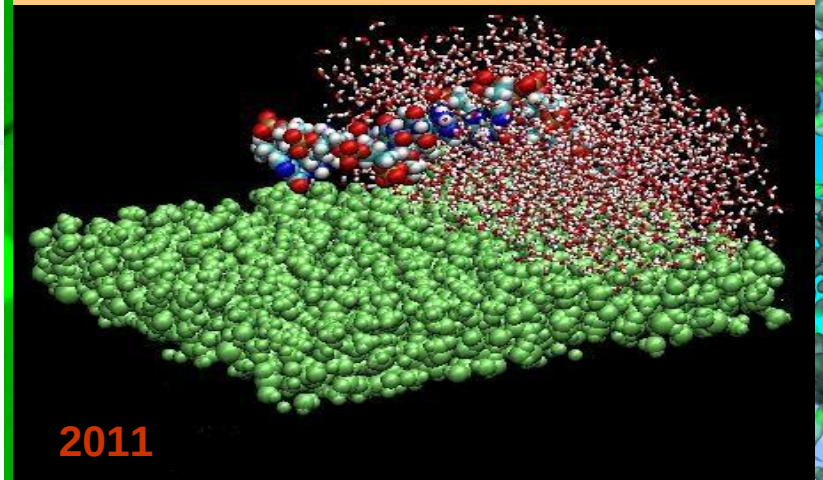


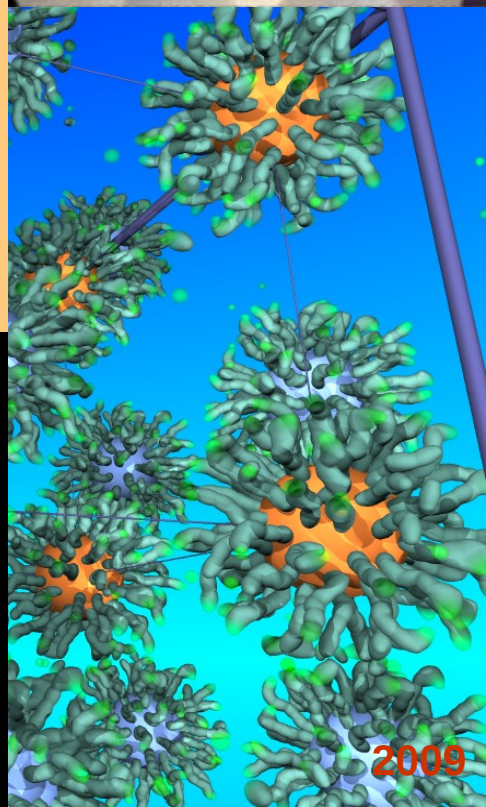


NANO MOZAIC







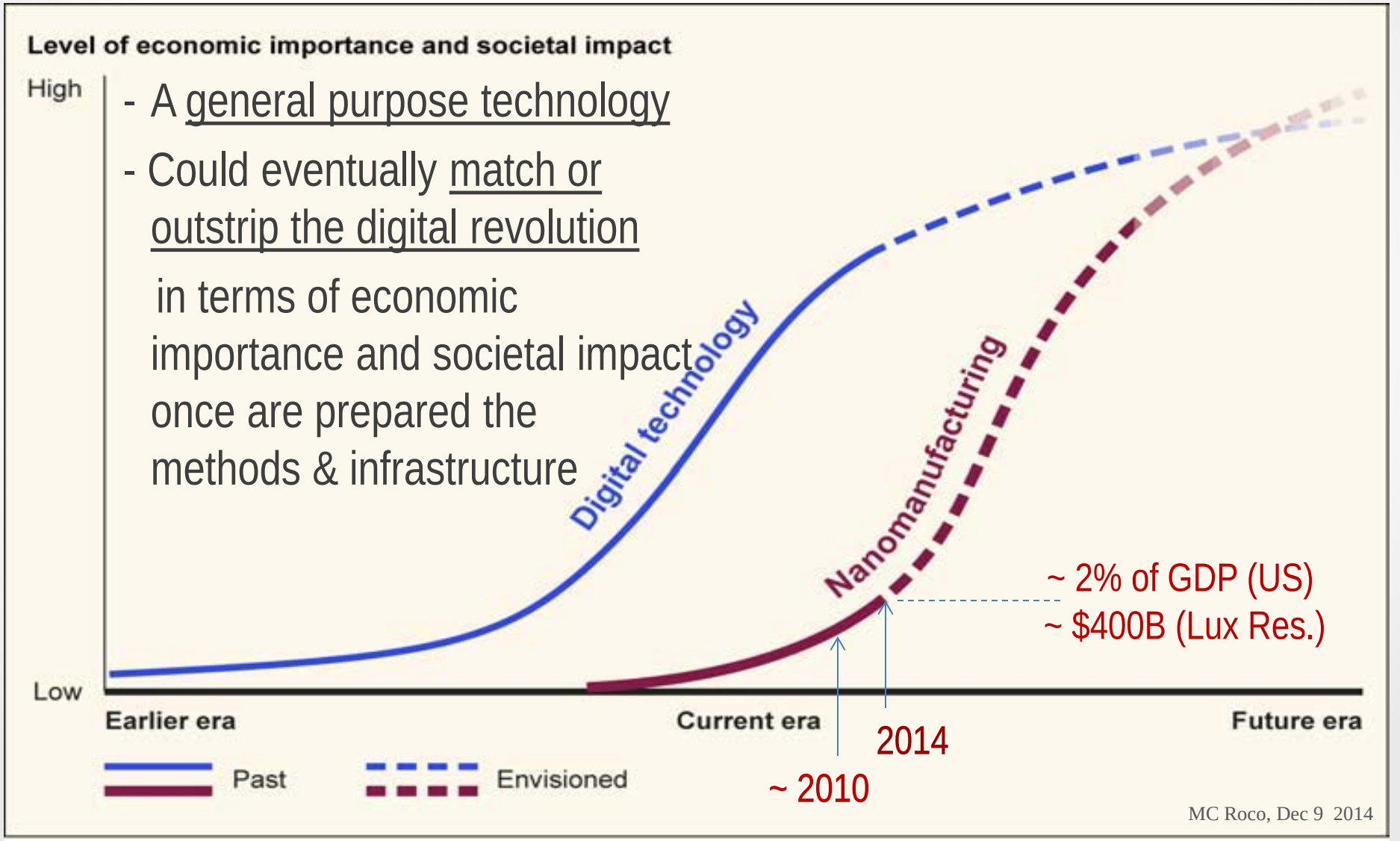


Topics

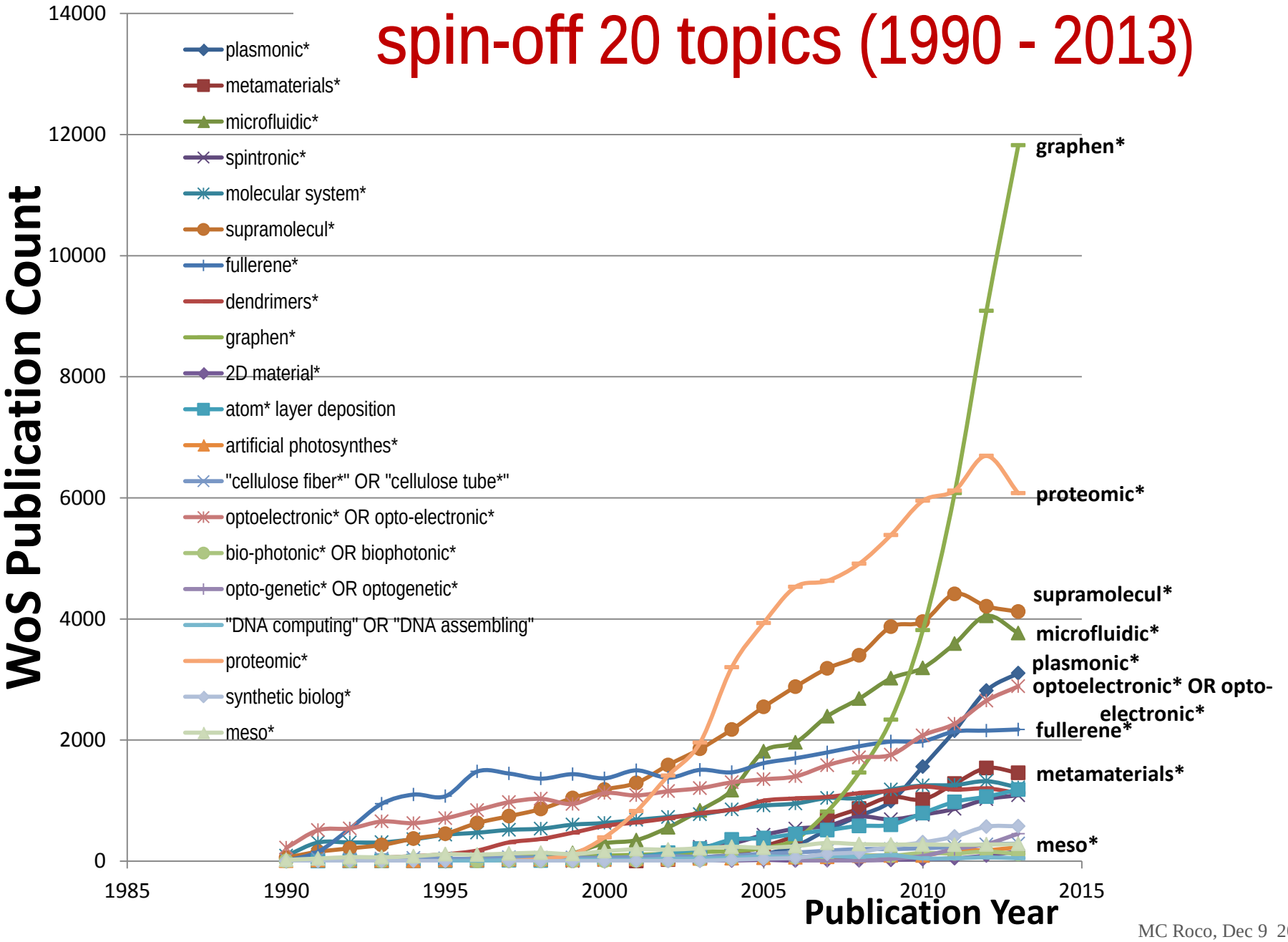
- 2000-2030 view of nanotechnology development in three stages: "S-curve"
- Nanoscale science and engineering activities at NSF
- On priorities, outcomes and challenges

Conceptualization of "Nanomanufacturing" and "Digital Technology" megatrends: *S-curves*

(GAO-14-181SP Forum on Nanomanufacturing, Report to Congress, 2014)



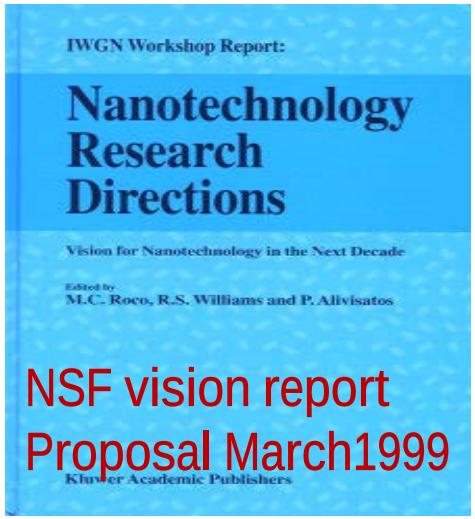
WoS publications on nano-extended spin-off 20 topics (1990 - 2013)



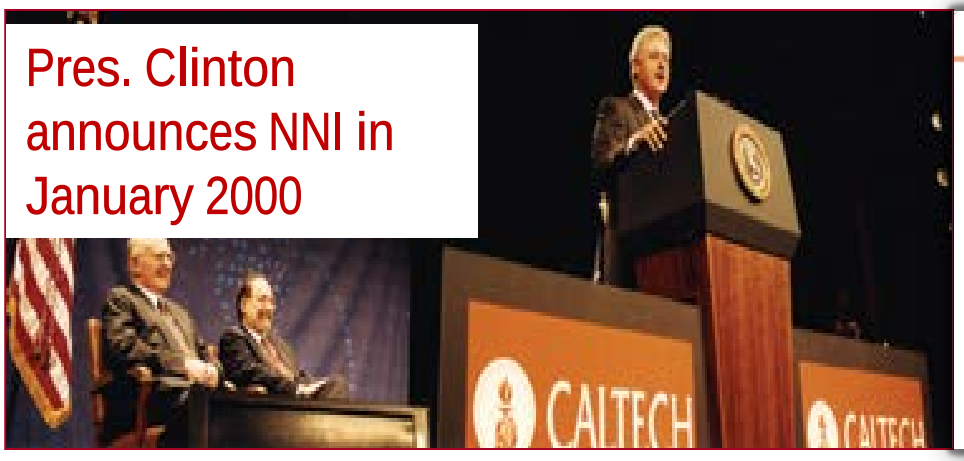
MC Roco, Dec 9 2014

2014 nanotechnology is still a S&E field in formation

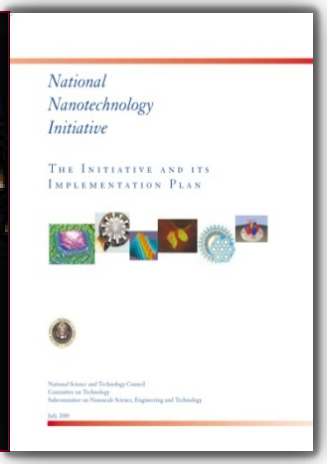
NNI in three administrations: Clinton, Bush and Obama



NSF vision report
Proposal March1999



Pres. Clinton announces NNI in January 2000

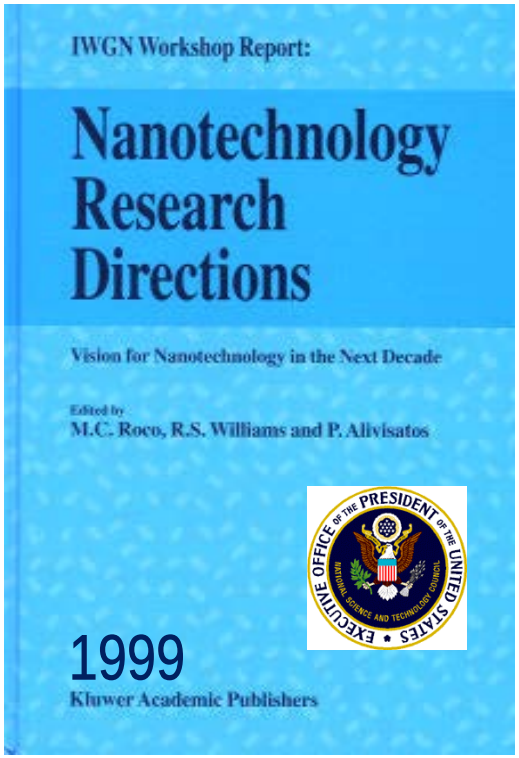


Pres. Bush Signing 21st Century Nanotechnology R&D Act – December 2003

WH approves 10 yr view by PCAST 2012

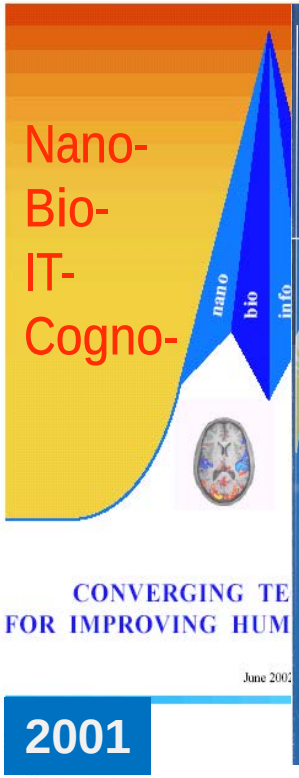
Nanotechnology: from scientific curiosity to immersion in socioeconomic projects

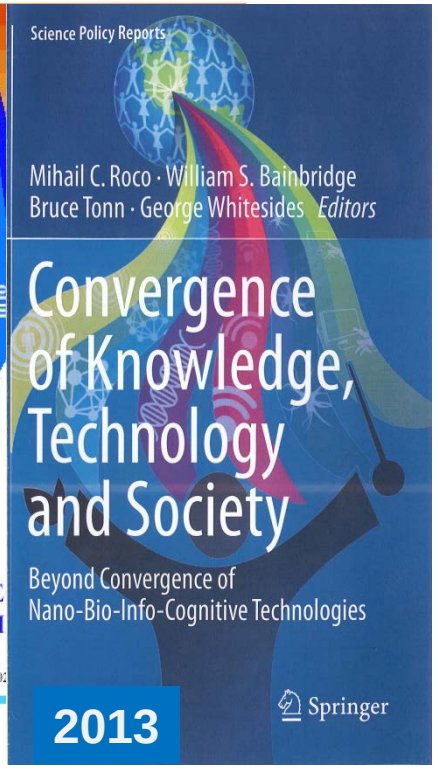
nano1 (2001-2010)



nano2 (2011-2020)

NBIC1 & 2 (2011-2030)

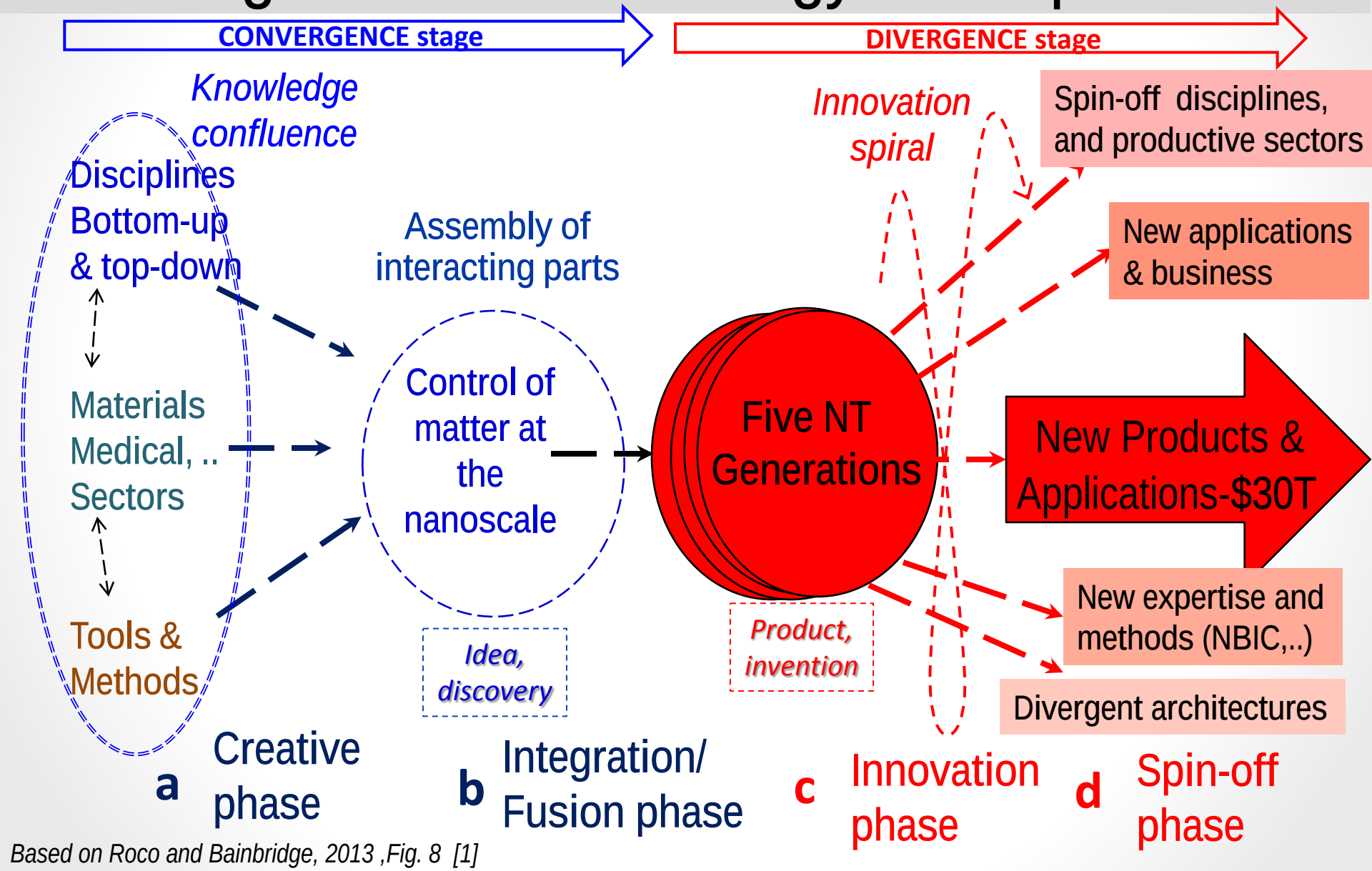




30 year vision to establish nanotechnology: changing focus and priorities; used by > 80 countries

Reports available on: www.wtec.org/nano2/ and www.wtec.org/NBIC2-report/ (Refs. 2-5)

2000-2030 Convergence-Divergence Cycle for global nanotechnology development



Based on Roco and Bainbridge, 2013 ,Fig. 8 [1]

OVERVIEW: *CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES (2000 – 2030)*

(Refs. 2-5)

FIVE GENERATIONS NANOPRODUCTS

2030

DIVERGENCE

CONVERGENCE

2000

New convergence platforms & economy immersion

~ 2021 ← **nano3 technology divergence** → **~ 2030**

Create spin-off nano-platforms
in industry, medicine and services;

NS&E integration for general purpose technology

~ 2011 ← **nano2 system integration** → **~ 2020**

Create nanosystems by science-based
design/processes/technology integration

Foundational interdisciplinary research at nanoscale

~ 2001 ← **nano1 component basics** → **~ 2010**

Create passive and active nanocomponents
by semi-empirical design

5. NBIC Technologies Platforms

4. Molecular Nanosystems

3. Nanosystems

2. Active Nanostructures

1. Passive Nanostructures

2010-2013 (data from Lux Research world industry survey, Jan 2014)

Global and US revenues from Nano-enabled products

(All budgets in *$ billion*)	2001-2010 (NANO2 report)	2011 (Lux Res)	2012	2013	2010-2013
Total world revenues	*339*	*514*	*731*	*1,014*	*+ 676*
US revenues	109.8	170.0	235.6	318.1	+ 208
World annual increase	annually ~ 25%	52%	42%	39%	44%
US annual increase	annually ~ 24%	55%	39%	35%	43%
US / World	in 2010: 32.4% average: ~ 35%	33%	32%	31%	32%

MC Roco, Dec 9 2014

Total nano product revenues annual growth > 40% in 2010-2013. "S – curve"

Perception

"Nanotechnology" is not:

- Not "a buzz word" – corresponds to the transition in nature and technology from individual atomic properties to their collective effects enabling diversity on the Earth
- Not "a polluant technology" – aims at non-covalent assembling, low (p,T) & pollution, "how molecules like"
- Not "a mature field" – going beyond the 1st generation of passive nanoparticles toward complex nanosystems
- Not "limited to unsolicited research" - it needs new tools, infrastructure, unifying concepts in education, focus R&D efforts on emerging and bottleneck research


DOE
HHS/NIH
OSTP
OMB
NSF
DOD
DOC/NIST
HHS/FDA
NASA
USDA/NIFA
USDA/ARS
HHS/CDC/
NIOSH
National Nanotechnology Initiative, 2000
(Vision: control of matter at nanoscale will bring a revolution in technology; see www.nano.gov)
USDA/FS
DOS
EPA
DOTr
NRC
PCAST Report on NNI, 2014:
Recommends New Grand Challenges,
expand infrastructure and education
DOT
DOC/
USPTO
IC/DNI
DOI/
USGS
DOJ
DOL
DOC/EDA
DOC/BIS
DHS
CPSC
ITC
DOEd

2001-2014

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

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

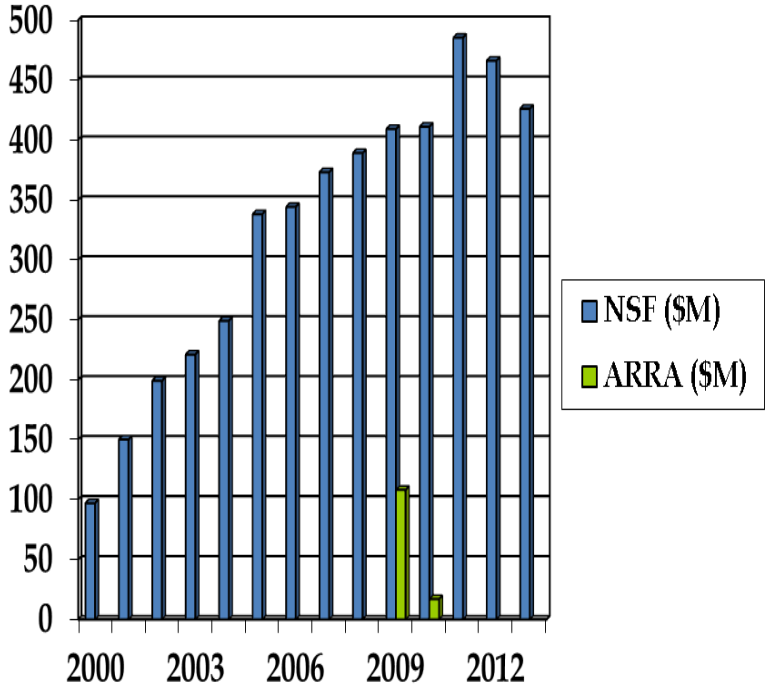
FY 2015 Budget Request - $412 million

FYs 2000-2014: NSF average investment is $31.5 per capita (US)

– Fundamental research
  ~ 5,000 active projects in all NSF directorates

– Establishing the infrastructure
  26 large centers, 2 general user facilities, teams

– Training and education
  > 10,000 students and teachers/y; ~ $30M/y



Several NSF announcements in FY 2015

www.nsf.gov

- National Nanotechnology Coordinated Infrastructure, NNCP
- Scalable nanomanufacturing, SNM
- Two-Dimensional Atomic-layer Research and Engineering, 2-DARE/EFRI
- International nano-EHS collaboration: Communities of Research (http://us-eu.org/); Safe Implementation of Innovative Nanoscience and Nanotechnology, SIINN
- Nanotechnology Undergraduate Education, NUE
- Translational: GOALI; I/UCRP; PFI; Nano-ERC; I-Corps

I (innovation)-Corps

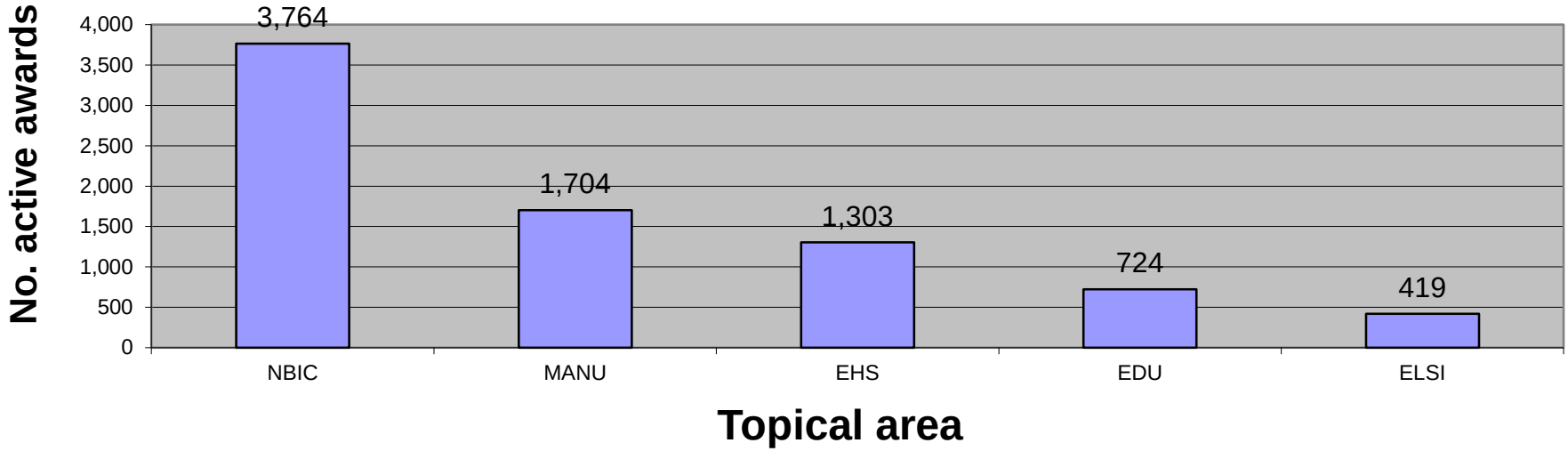
Leveraging NSF investments in fundamental research by supporting education and networking to transcending the "valley of death" after research

(http://www.nsf.gov/pubs/2012/nsf12586/nsf12586.htm)

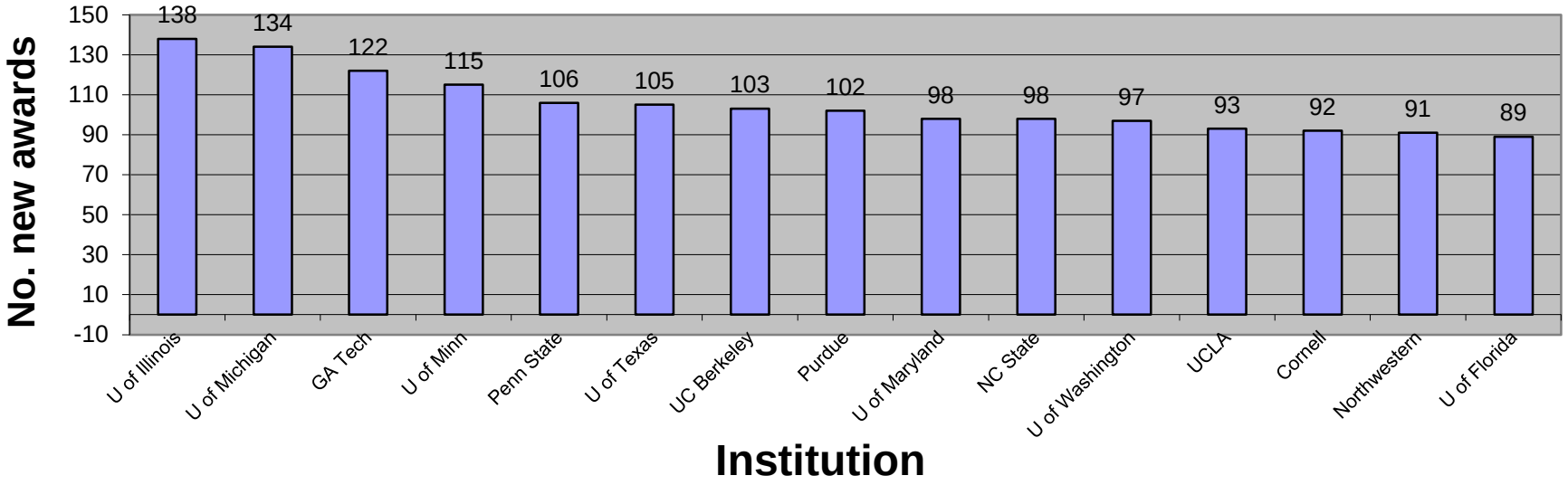
NSE examples in 2014

- High Quality Boron Nitride Nanotubes *(PI: Yoke Khin Yap, MTU) : Insulating heat sink materials for high-performance electronic devices and engines.*
- Photocatalysts for Water Remediation *(PI: Pelagia Gouma, SUNY): Ceramic nanocatalysts based on the CuO/WO3 system that are using the visible part of the solar energy to break down hydrocarbons in water*
- Targeted Drug Delivery *(PI: Rebecca Bader, Syracuse): Site-specific delivery of drugs by using polysialic acid (PSA)-based nanocarriers as platforms.*

Number FY 2014 NSE awards in several topical areas



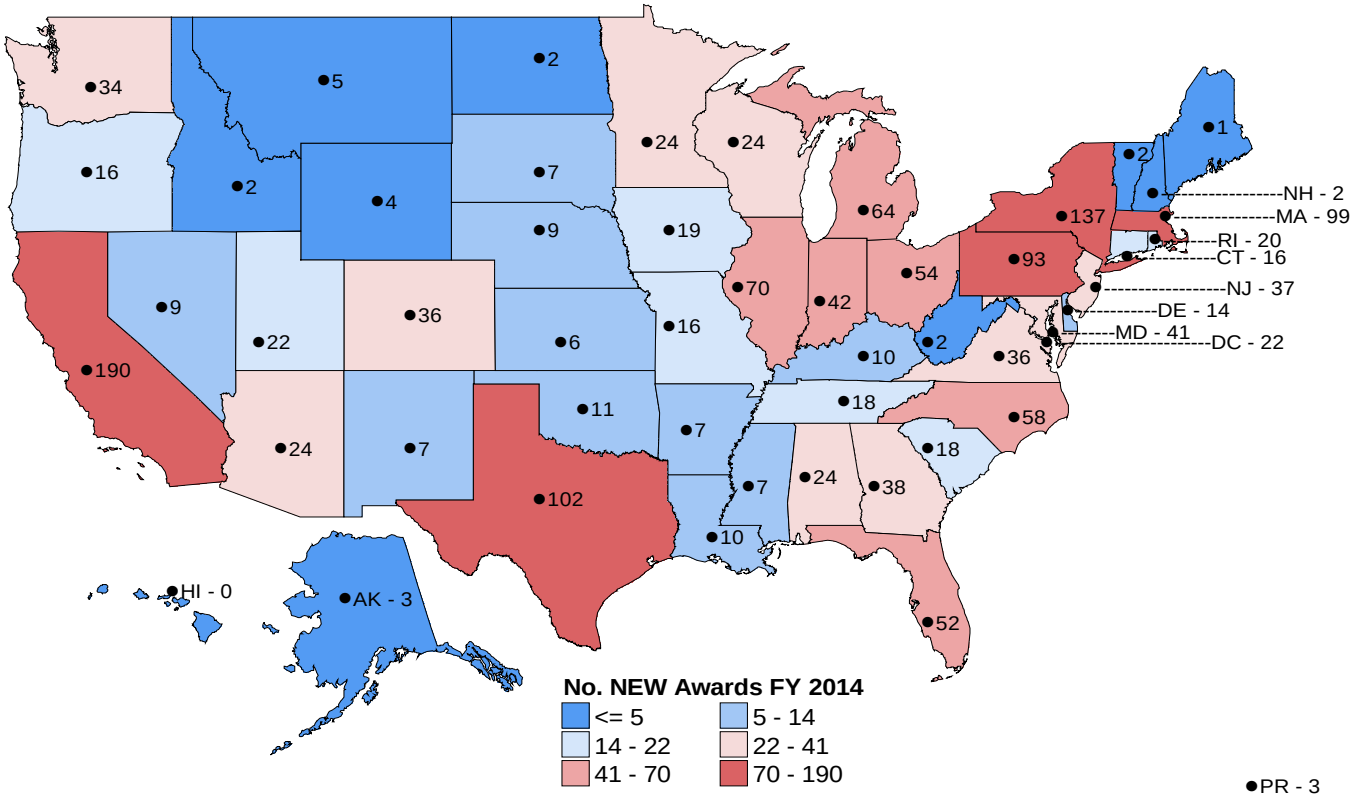
Top15 institutions with active FY 2014 NSE awards



NSF's NSE number of new awards per state

FY 2014: U.S. total new awards = 1,569

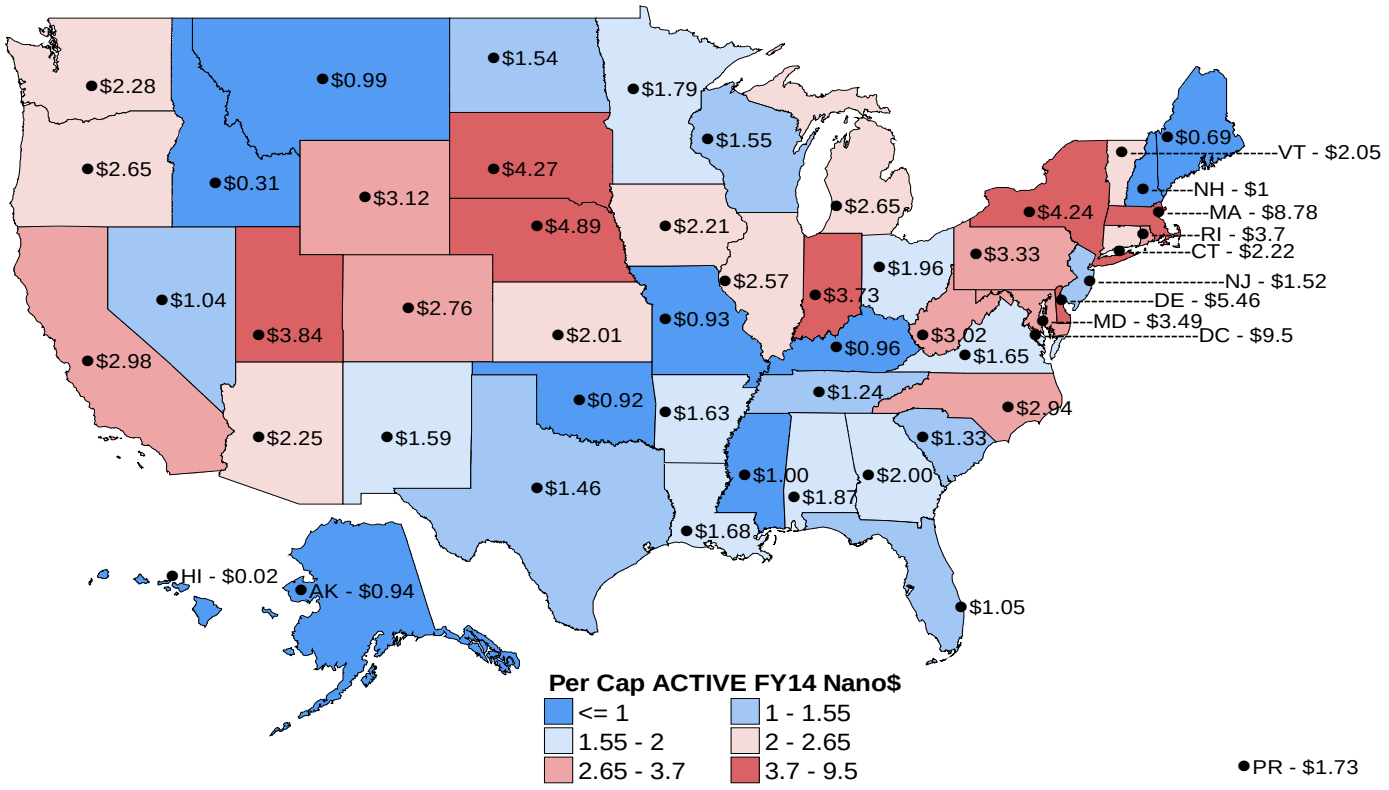
(total active awards = 7,438)



AK 3; AL 24; AR 7; AZ 24; CA 190; CO 36; CT 16; DC 22; DE 14; FL 52; GA 38; HI 0; IA 19; ID 2; IL 70; IN 42; KS 6; KY 10; LA 10; MA 99; MD 41; ME 1; MI 64; MN 24; MO 16; MS 7; MT 5; NC 58; ND 2; NE 9; NH 2; NJ 37; NM 7; NV 9; NY 137; OH 54; OK 11; OR 16; PA 93; PR 3; RI 20; SC 18; SD 7; TN 18; TX 102; UT 22; VA 36; VT 2; WA 34; WI 24; WV 2; WY 4

NSF's NSE amount new awards per capita, by state

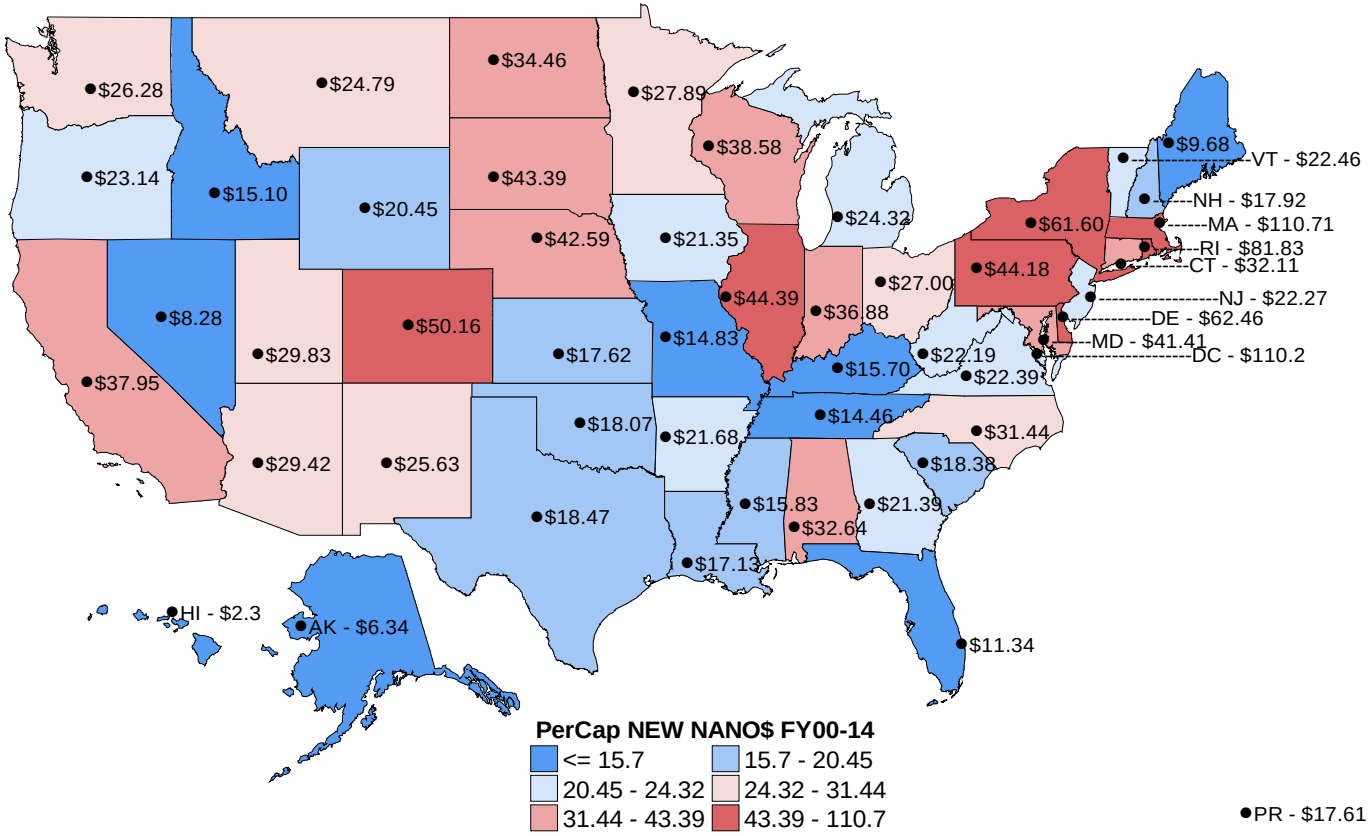
FY 2014: U.S. average amount = $2.42 / capita



AK 0.94; AL 1.87; AR 1.63; AZ 2.25; CA 2.98; CO 2.76; CT 2.22; DC 9.5; DE 5.46; FL 1.05; GA 2; HI 0.02; IA 2.21; ID 0.31; IL 2.57; IN 3.73; KS 2.01; KY 0.96; LA 1.68; MA 8.78; MD 3.49; ME 0.69; MI 2.65; MN 1.79; MO 0.93; MS 1; MT 0.99; NC 2.94; ND 1.54; NE 4.89; NH 1; NJ 1.52; NM 1.59; NV 1.04; NY 4.24; OH 1.96; OK 0.92; OR 2.65; PA 3.33; PR 1.73; RI 3.7; SC 1.33; SD 4.27; TN 1.24; TX 1.46; UT 3.84; VA 1.65; VT 2.05; WA 2.28; WI 1.55; WV 3.02; WY 3.12

NSF's NSE amount new awards per capita, by state

FYs 2000-2014: U.S. average amount = $31.5 / capita



AK 6.34; AL 32.64; AR 21.68; AZ 29.42; CA 37.95; CO 50.16; CT 32.11; DC 110.2; DE 62.46; FL 11.34; GA 21.39; HI 2.3; IA 21.35; ID 15.1; IL 44.39; IN 36.88; KS 17.62; KY 15.7; LA 17.13; MA 110.71; MD 41.41; ME 9.68; MI 24.32; MN 27.89; MO 14.83; MS 15.83; MT 24.79; NC 31.44; ND 34.46; NE 42.59; NH 17.92; NJ 22.27; NM 25.63; NV 8.28; NY 61.6; OH 27; OK 18.07; OR 23.14; PA 44.18; PR 17.61; RI 81.83; SC 18.38; SD 43.39; TN 14.46; TX 18.47; UT 29.83; VA 22.39; VT 22.46; WA 26.28; WI 38.58; WV 22.19; WY 20.45

Research Directions for Nanotechnology

- *at four time scales* -

- 30-year perspective (2000-2030) of establishing nanotechnology in 3 stages: *component basics, system integration, technology divergence*

- 10-year research vision: by 2010, by 2020, by 3030 with input from the national & international communities. (Ref: Nano1, Nano 2020, NBIC)

- 3-5 year S&T targets (Refs: 3-year 2011 & 2014 NNI Strategic Plans; five Nanotechnology Signature Initiatives , www.nano.gov)

- Annual fiscal year priority research areas: methods, emerging research, responsible nanotechnology, education & physical infrastructure for annual investments. (Ref: NNI & NSF annual budgets & WGs, ex: nseresearch.org; nsf.gov/nano)

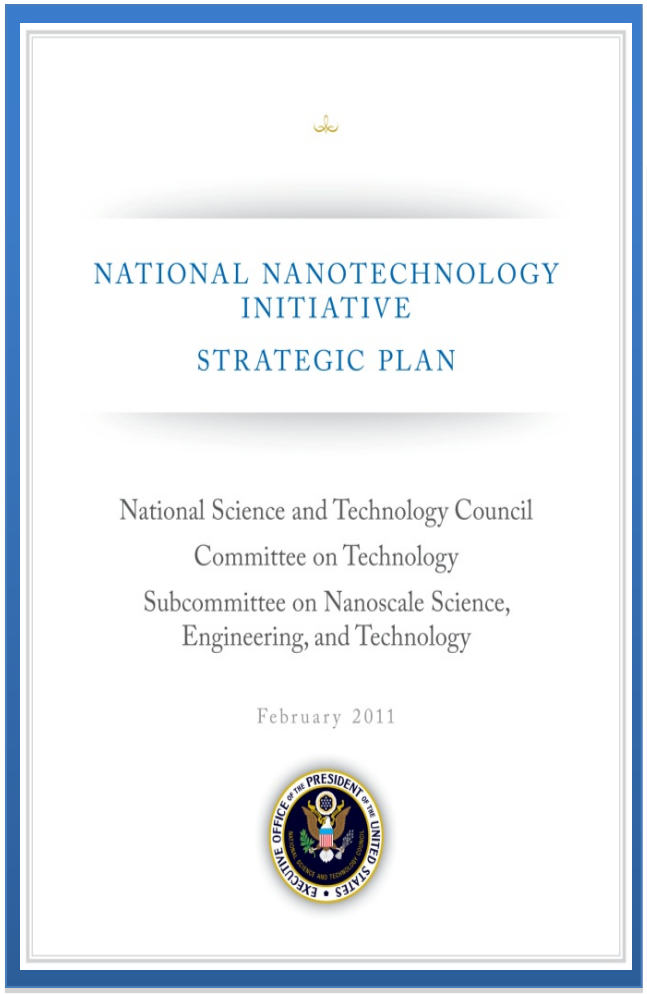
Twelve global trends to 2020

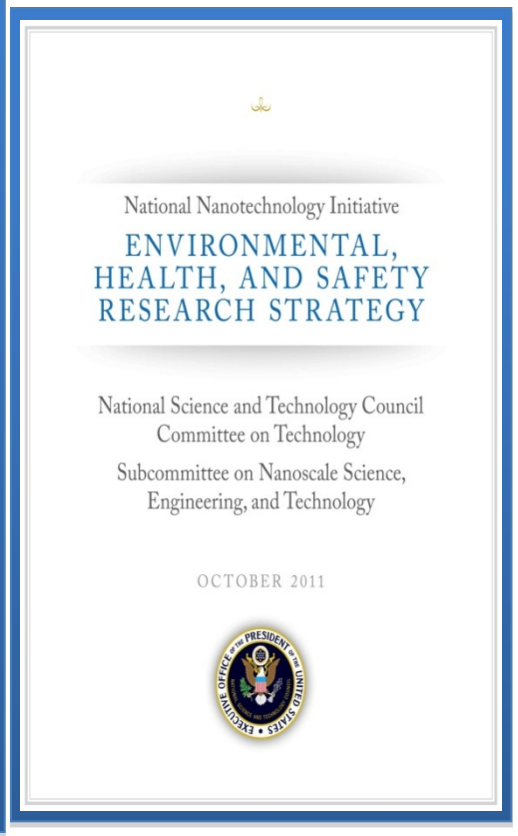
10 year perspective, www.wtec.org/nano2/

- Theory, modeling & simulation: **x1000 faster**, essential design
- "Direct" measurements – **x6000 brighter**, accelerate R&D&use
- A shift from "passive" to **"active"** nanostructures/nanosystems
- **Nanosystems**, some self powered, self repairing, dynamic
- **Penetration** of nanotechnology in industry - toward mass use; catalysts, electronics; innovation– platforms, consortia
- **Nano-EHS** – more predictive, integrated with nanobio & env.
- **Personalized nanomedicine** - from monitoring to treatment
- Photonics, electronics, magnetics – new **integrated** capabilities
- **Energy** photosynthesis, storage use – solar economic
- Enabling and **integrating with new areas** – bio, info, cognition
- **Earlier** preparing nanotechnology workers – system integration
- Governance of nano for societal benefit - **institutionalization**

NNI periodical documents

Developing the Strategic (each 3 years) and Budget Plans (annual)





Strategic plans:

2000, 2005, 2008, 2011, 2014

Annual NNI Presidential Budget Supplements;

Additions in 2011:

- Measureable objectives for each NNI goal
- Nanotechnology Signature Initiatives

Topical reports,

such as NNI EHS Strategy (2011), sensors, informatics, four workshop reports, and follow up documents

Nanotechnology Signature Initiatives

National Nanotechnology Initiative (NNI), 2011-2014 (www.nano.gov)

Sustainable Nanomanufacturing

Nanoelectronics for 2020 and Beyond

Nanotechnology for Solar Energy

Nanotechnology for Sensors and Sensors for Nanotechnology

Nanotechnology Knowledge Infrastructure

New topics under consideration for 2015:

nanomodular systems, water filtration, nanocellulose, nanophotonics, nano for infrastructure, nano-city…

FY 2015 NS&E Priorities Research Areas

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

Scientific challenges

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

FY 2015 NS&E Priorities Research Areas (2)

B. Investigative and Transformative Methods

- 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 scalable, modular, hybrid, on site
- Systems nanotechnology

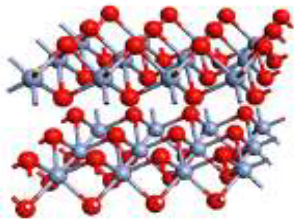
Modular Nanosystems

Example: using 2D electronic materials

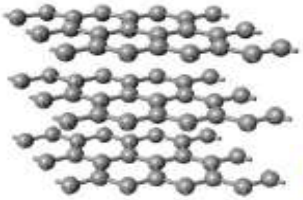
- A Broad Range of Choices:
  - From Insulator to Superconductor
  - Provide Possibility for 2D Circuits

Graphene Family (C, Si, BN)
MX_2 (TMD) Family (>88 members)

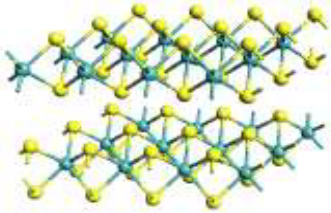
Half-metal (E_g: **0-1 eV**)
Example: **CrO_2, CrS_2**



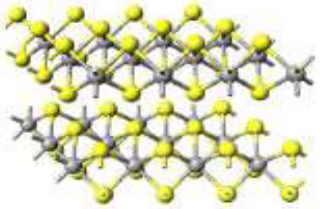
Semi-metal (E_g: **0 eV**)
Interconnect, Gate, RF, etc.
Example: **Graphene**

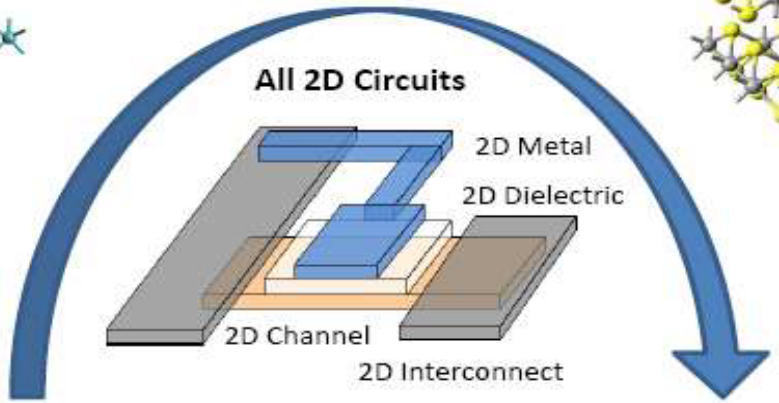


Semiconductor (E_g: **1-2 eV**)
Channel Material
Example: **MoS_2, WSe_2**

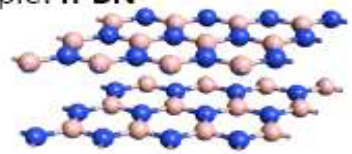


Metal
Interconnect, Gate , etc.
Example: **VO_2, VS_2**

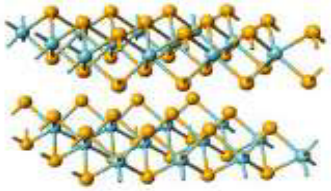




Insulator (E_g: **~5 eV**)
Dielectric
Example: **h-BN**



Superconductor
Example: **$NbSe_2$**

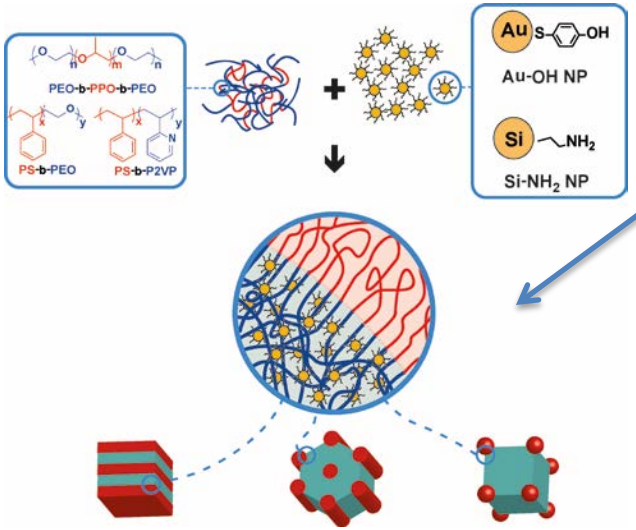


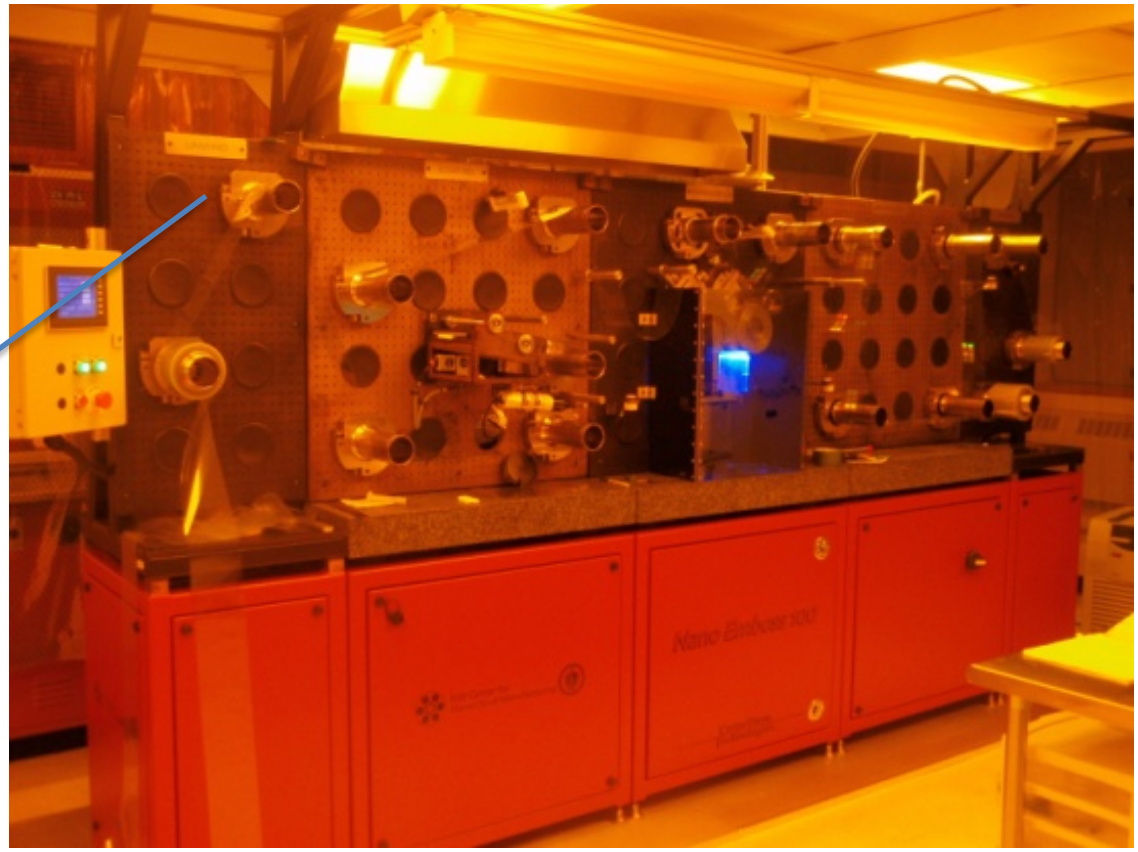
Courtesy Kaustav Banerji (UCSB)

FY 2015 NS&E Priorities Research Areas (3)

C. Integration of nanotechnology with other areas

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





Additive selfassembling on roll-to-roll process

(U. Mass. – Amherst, J. Watkins)

Additive-driven self assembly yields well ordered periodic assemblies of nanoparticle polymer hybrids (left) while R2R nanoimprint lithography produces sub-100 nm device patterns 70 nm grating pattern shown (right).

FY 2015 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 physic- 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
- Long-term and convergence approach (government – wide)

Convergence of Knowledge, Technology, and Society:

Beyond Convergence of Nano-Bio-Info-Cognitive Techologies

www.wtec.org/NBIC2-Report

Five convergence principles for progress applied in five human activity platforms.

Several trends and challenges

- Integration of knowledge at the nanoscale and of nanocomponents in nanosystems. Ex: Nanomodular systems; Nanoengineering; NBIC systems with emerging nano-bio behavior (hybrid, robot, synthetic)
- Experimental and simulation control of molecular self-assembly, quantum behavior, synthesis new molecules, direct measurements, and interaction of biological processes
- Molecular medicine for individualized healthcare. Ex: preventive, subcellular detection of cancer such as bio-photonics and –genetics
- Nanotechnology for increased productivity and sustainability. Ex: Reducing energy dissipation in nanoelectronics by >100; Water resources; Wood, agriculture and food systems
- Institutionalize nanotechnology: create standing organizations and programs for sustained support of future nanotechnology efforts

FY 2014 NSF's NSE Grantees Conference

- Contents: Keynotes, posters and panels to facilitate exchanges, partnerships, networking, mutual evaluation and research planning – *on selected topics in 2014*
- Focus: progress in four fundamental areas; 8 NSECs graduation; increased complexity, system approach, convergence with bio/info/cogno;
  identify new research and education trends
- Meetings between researchers and program officers

Related publications

(4 reports with R&D recommendations for 2020)

1. *"The new world of discovery, invention, and innovation: convergence of knowledge, technology and society"* (JNR 2013a)
2. *NANO1: "Nanotechnology research directions: Vision for the next decade"* (Springer, 316p, 2000)
3. *NANO2: "Nanotechnology research directions for societal needs in 2020"* (Springer, 690p, 2011a)
4. *NBIC1: "Converging technologies for improving human performance: nano-bio-info-cognition"* (Springer, 468p, 2003)
5. *NBIC2: "Convergence of knowledge, technology and society: Beyond NBIC"* (Springer, 604p, 2013b)
6. *"Nanotechnology: from discovery to innovation and socioeconomic projects: 2000-2020"* (CEP, 2011b)
7. *"Mapping nanotechnology innovation and knowledge: global and longitudinal patent and literature"* (Springer, 330p, 2009)
8. *"Global nanotechnology development from 1991 to 2012"* (JNR 2013c)
9. "Long View of Nanotechnology Development: the NNI at 10 Years"(JNR, 2011d)