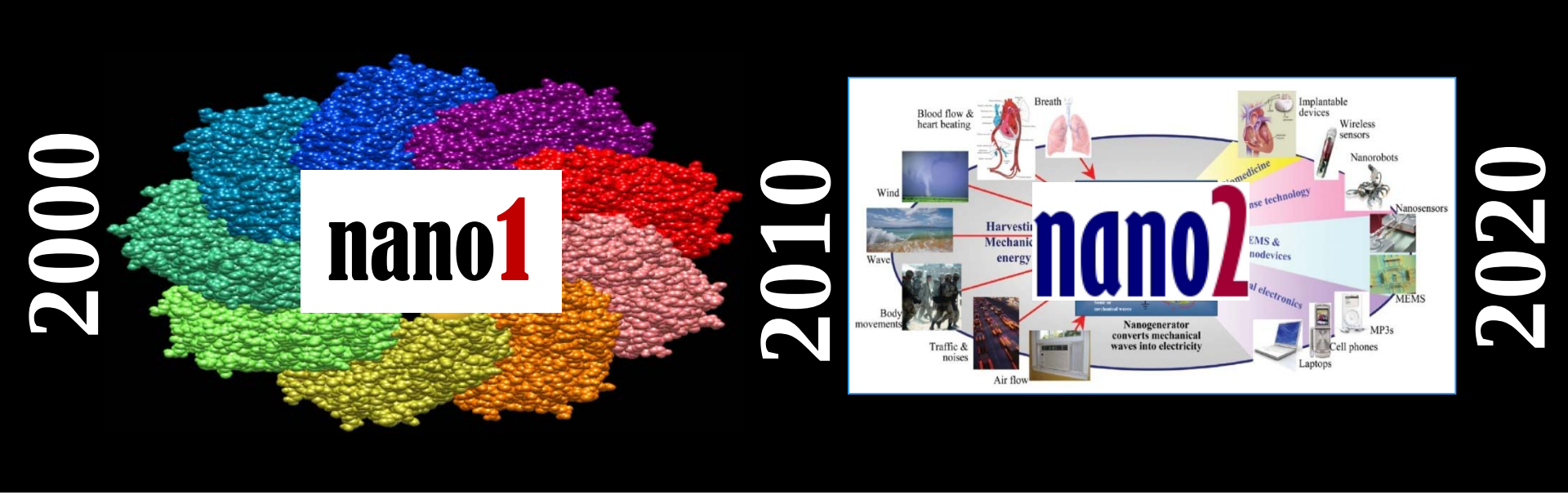


EHS research in the context of nanotechnology development

Mike Roco
National Science Foundation and National Nanotechnology Initiative

Nano OEHS, Boston, August 11, 2011

Benchmark book - experts in over 20 countries

"Nanostructure Science and Technology"

Springer, 1999

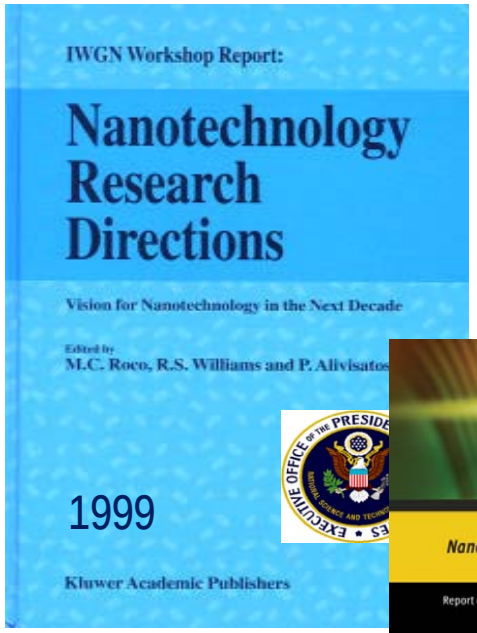
Nanotechnology

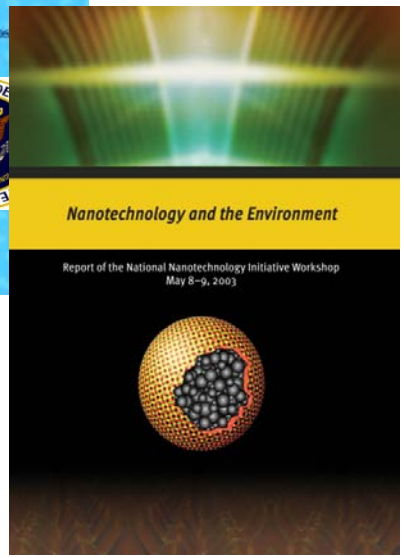
is creation of materials, devices and systems by *control and restructuring of matter* at dimensions of roughly 1 to 100 nanometers

- ⇨ at the transition from individual to collective behavior of atoms and molecules
- ⇨ where new phenomena
- ⇨ enable new applications

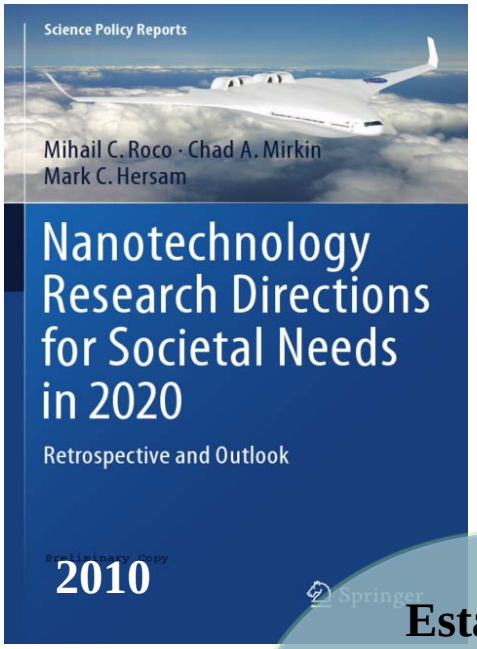
Long-term nanotechnology research directions (2000-2020)

nano1





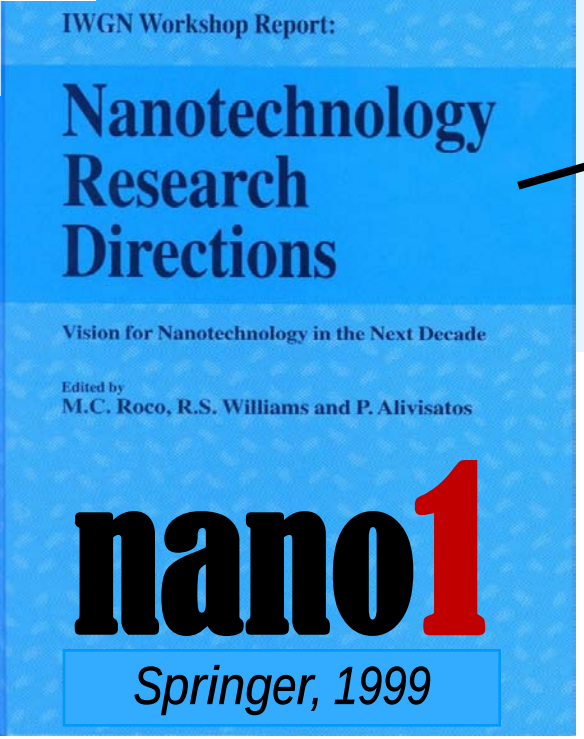
nano2



Established nanotechnology EHS community; National R&D programs. New trends and strategies

Nanotechnology and the Environment: Applications and Implications
NSF, EPA, August 2002

NSF/WTEC, www.wtec.org/nano2/ ; Springer 2010



"Vision for nanotechnology in the next decade", 2001-2010

http://www.wtec.org/loyola/nano/IWGN.Research.Directions/IWGN_rd.pdf

Systematic control of matter on the nanoscale will lead to a revolution in technology and industry

- *Change the foundations from micro to nano*
- *Create a general purpose technology (similar IT)*

More important than miniaturization itself:

Novel properties/ phenomena/ processes/ natural threshold

Unity and generality of principles

Most efficient length scale for manufacturing, biomedicine

Show transition from basic phenomena and components to system applications in 10 areas and 10 scientific targets

Nano 2020 Report

Panel of U.S. experts

Input from 250 leading nanotechnologists from 35 countries

5 brainstorming workshops

Peer review

Public comment

Open source

CREATING A NEW FIELD AND COMMUNITY IN TWO FOUNDATIONAL STEPS (2000~2020)

Mass Application of Nanotechnology after ~ 2020

New areas

MATERIALS | ELECTRONICS | HEALTH CARE | ENVIRONMENT | ENERGY | TRANSPORT | MANUFACTURING | SECURITY | INSTRUMENTS

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

Nano2 Report, 2010, p. XXXVII

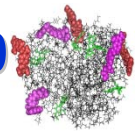
TIMELINE FOR BEGINNING OF INDUSTRIAL PROTOTYPING AND NANOTECHNOLOGY COMMERCIALISATION:
FOUR GENERATIONS OF PRODUCTS AND PRODUCTION PROCESSES

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

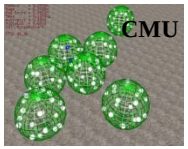


2nd: Active nanostructures

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

Frame 1

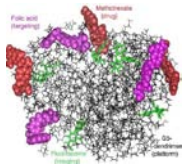
Risk Governance Frame 2

Perceived Higher Risks Areas (2000-2020; 2020-)

as a function of nanotechnology generation

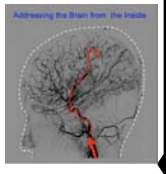
~ 2000

1st: Passive nanostructures *Ex: Cosmetics (pre-market tests), Pharmaceuticals (incomplete tests for inflammatory effects, etc.), Food industry , Consumer products*



~ 2005

2nd: Active nanostructures *Ex: Nano-biotechnology, Neuro-electronic interfaces, NEMS, Precision engineering, Hybrid nanomanufacturing*



~ 2010

3rd: Nanosystems *Ex: Nanorobotics, Regenerative medicine, Brain-machine interface, Eng. agriculture*

?

~ 2015-2020

4th: Molecular nanosystems *Ex: Neuromorphic eng., Complex systems, Human-machine interface*

~ 2020-

Converging technologies *Ex: Hybrid nano-bio-info-medical-cognitive application*

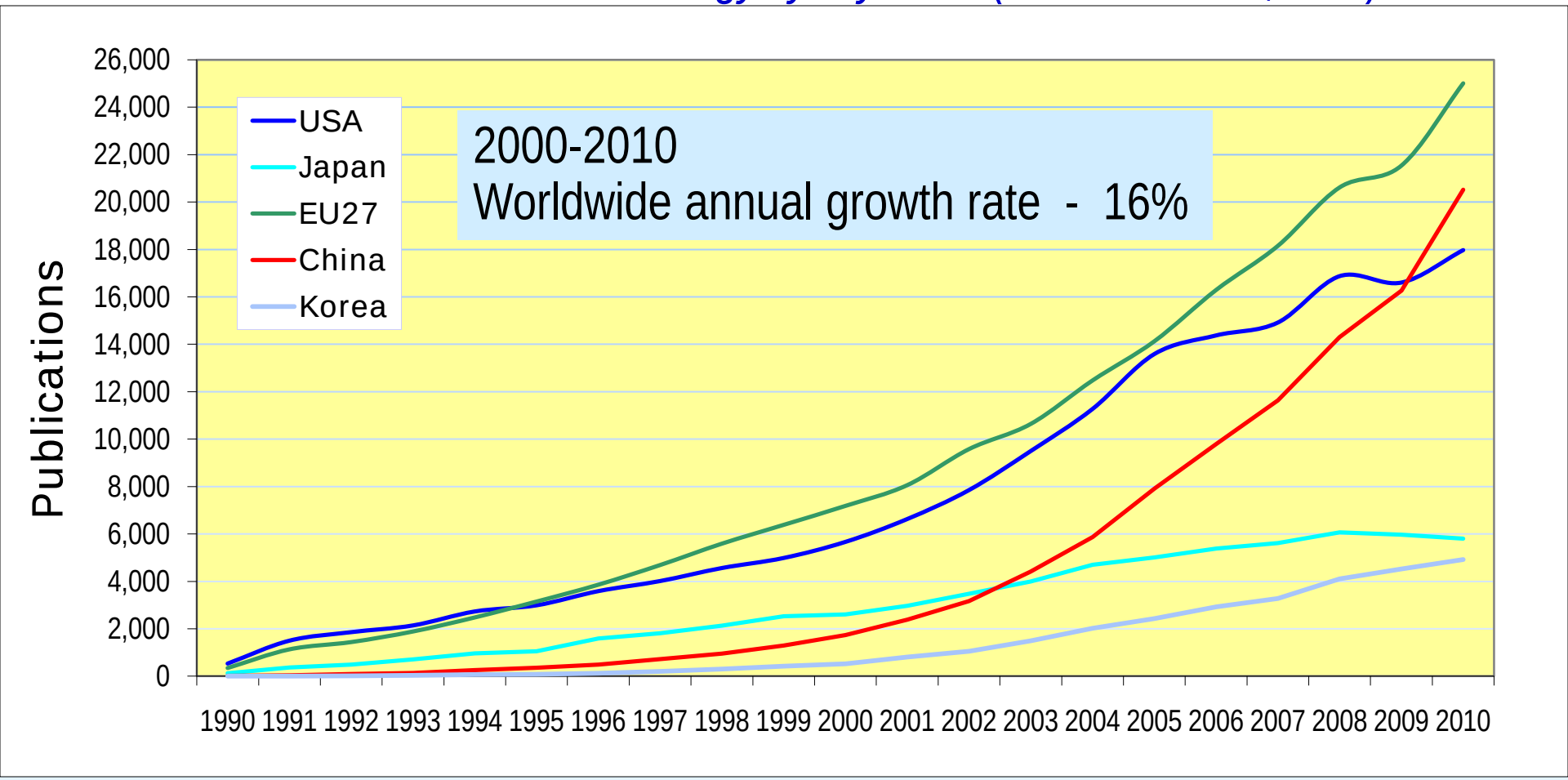
Higher uncertainty & risk

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*					

Nanotechnology publications in the Science Citation Index (SCI) 1990 - 2010

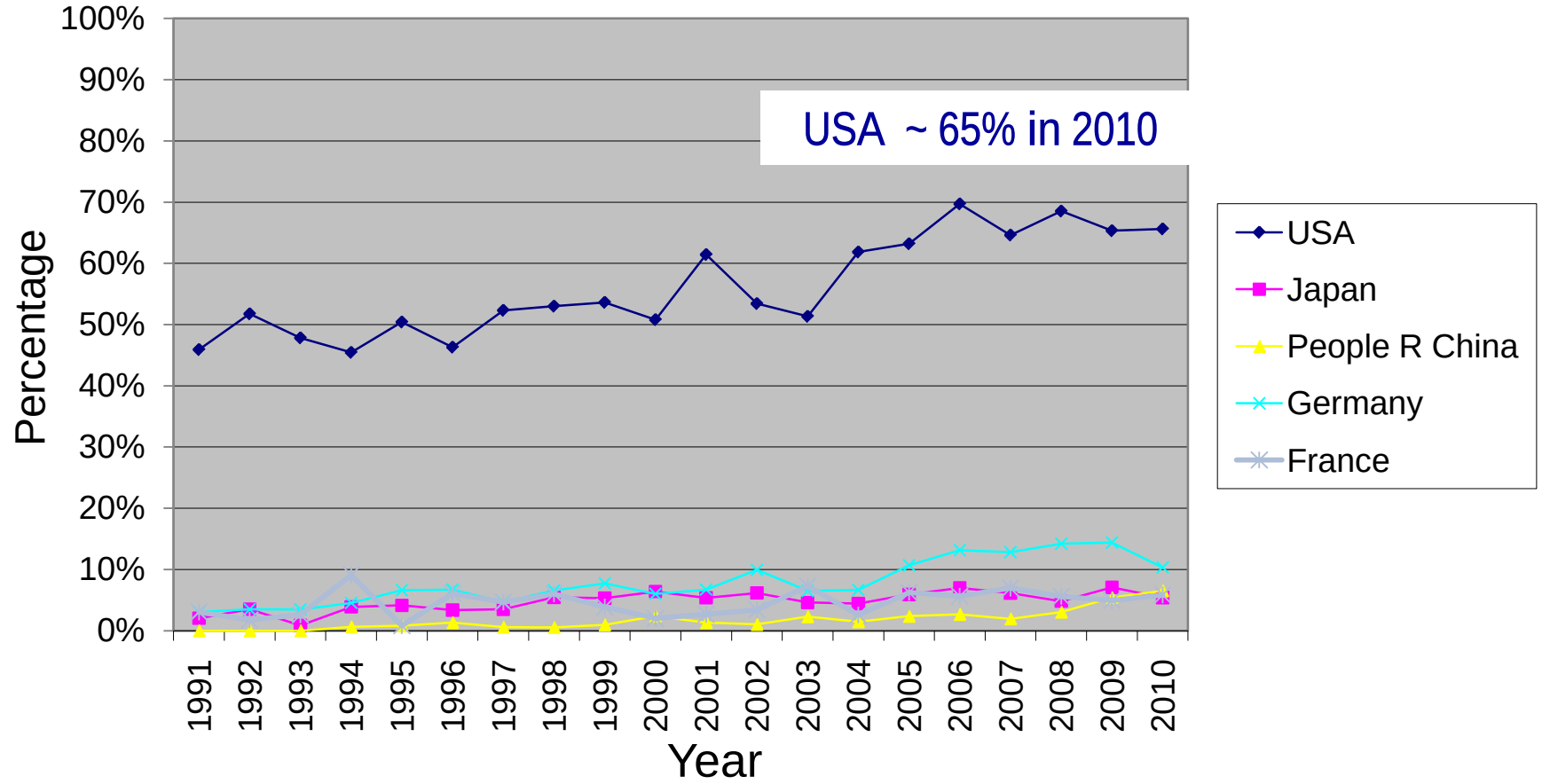
Data was generated from online search in Web of Science using "Title-abstract" search in SCI database for nanotechnology by keywords (Chen and Roco, 2011)



Rapid, uneven growth per countries

Percent contribution by country to nanotechnology publications in Science, Nature, and Proc. NAS

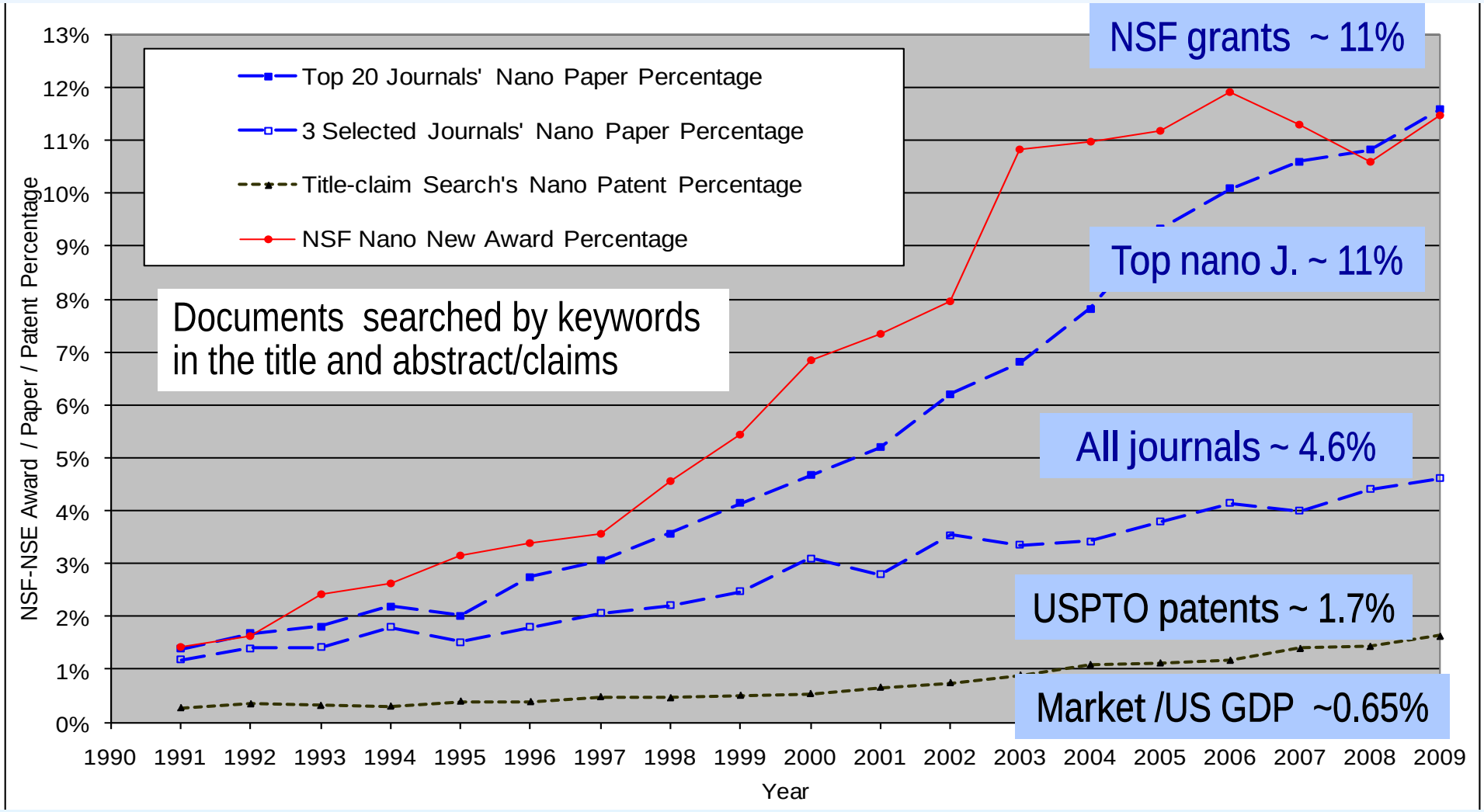
Title-abstract search (Chen and Roco, 2011)



U.S. maintain the lead in highly cited publications

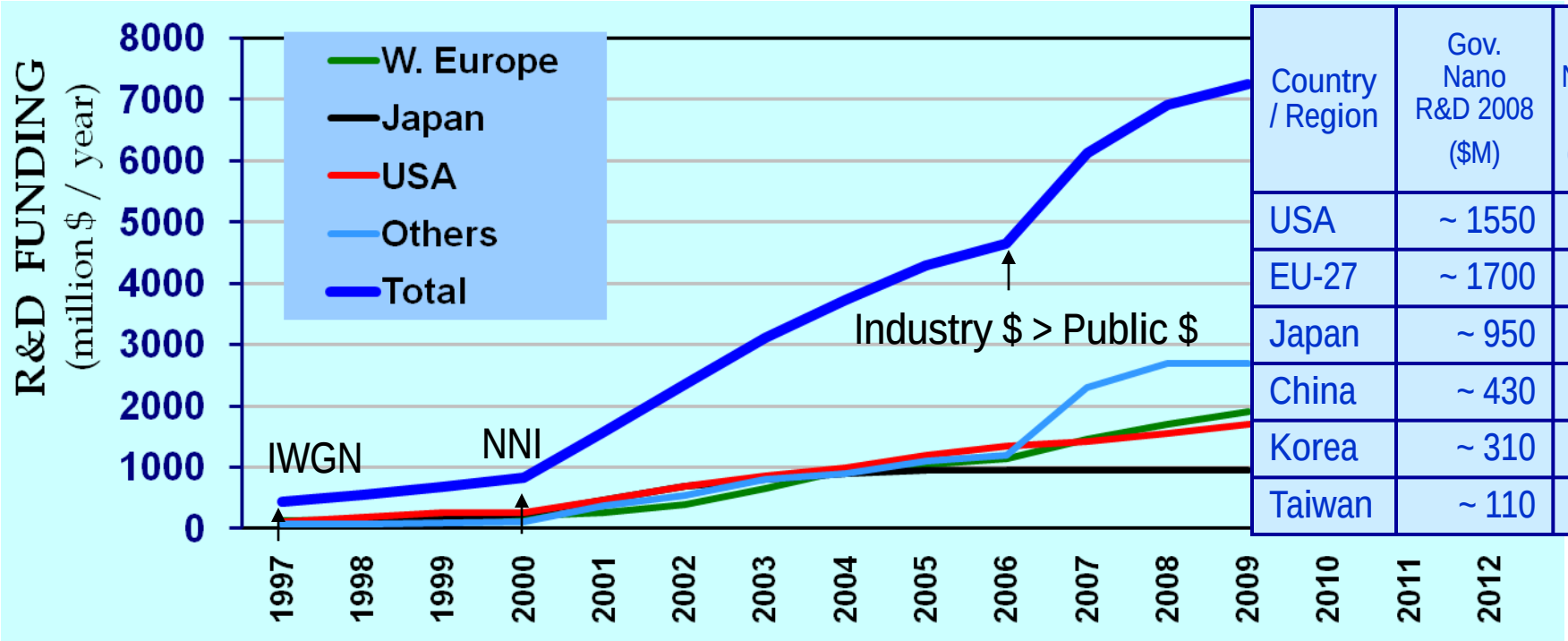
Percentage of nanotechnology content in NSF awards, ISO papers and USPTO patents (1991-2009)

(update after Encyclopedia Nanoscience, Roco, 2008)



Similar, delayed penetration curves: for R&D funding /papers /patents /products

2000-2009
Changing international context:
federal/national government R&D funding (NNI definition)



Country / Region	Gov. Nano R&D 2008 ($M)	Specific Nano R&D 2008 ($/Capita)
USA	~ 1550	~ 5.1
EU-27	~ 1700	~ 4.6
Japan	~ 950	~ 7.3
China	~ 430	~ 0.4
Korea	~ 310	~ 6.0
Taiwan	~ 110	~ 4.5

Seed funding 1991 - 1997

NNI Preparation vision/benchmark

1st Generation products passive nanostructures

2nd Generation active nanostructures

3rd Generation nanosystems

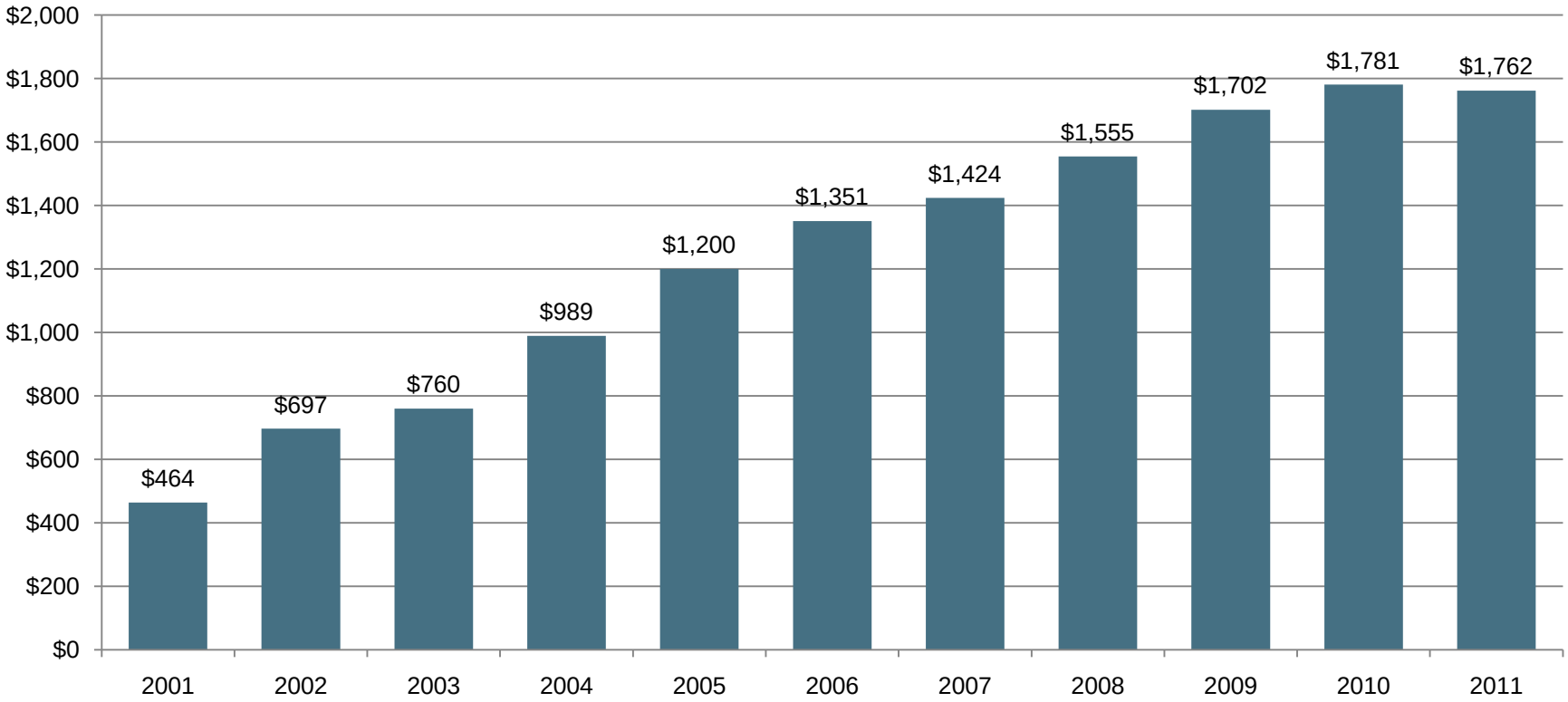
Rapid, uneven growth per countries

MC Roco, August 11 2011

2001-2010

NNI budget information

- **NNI expenditures* have grown from $464 million in FY '01 to an FY '11 request of nearly $1.8 billion.****



*** All numbers shown above are actual spending, except 2010, which is estimated spending for the current year and 2011 , which is requested amount for next year (FY '09 figure shown here does *not* include ~$500 million in additional ARRA funding).**

**** 2011 figure shown here does *not* include DOD earmarks included in previous yrs. ($117 M '09)**

2001-2010

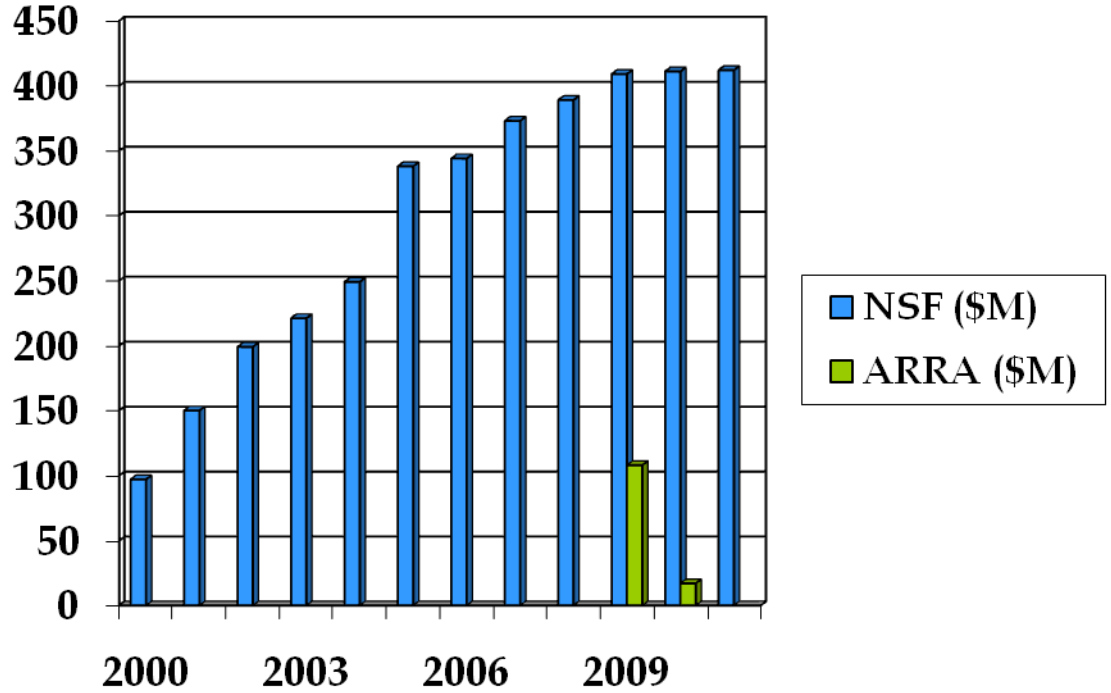
NSF – discovery, innovation and education in Nanoscale Science and Engineering (NSE)

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

FY 2011 Budget Request $412M

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

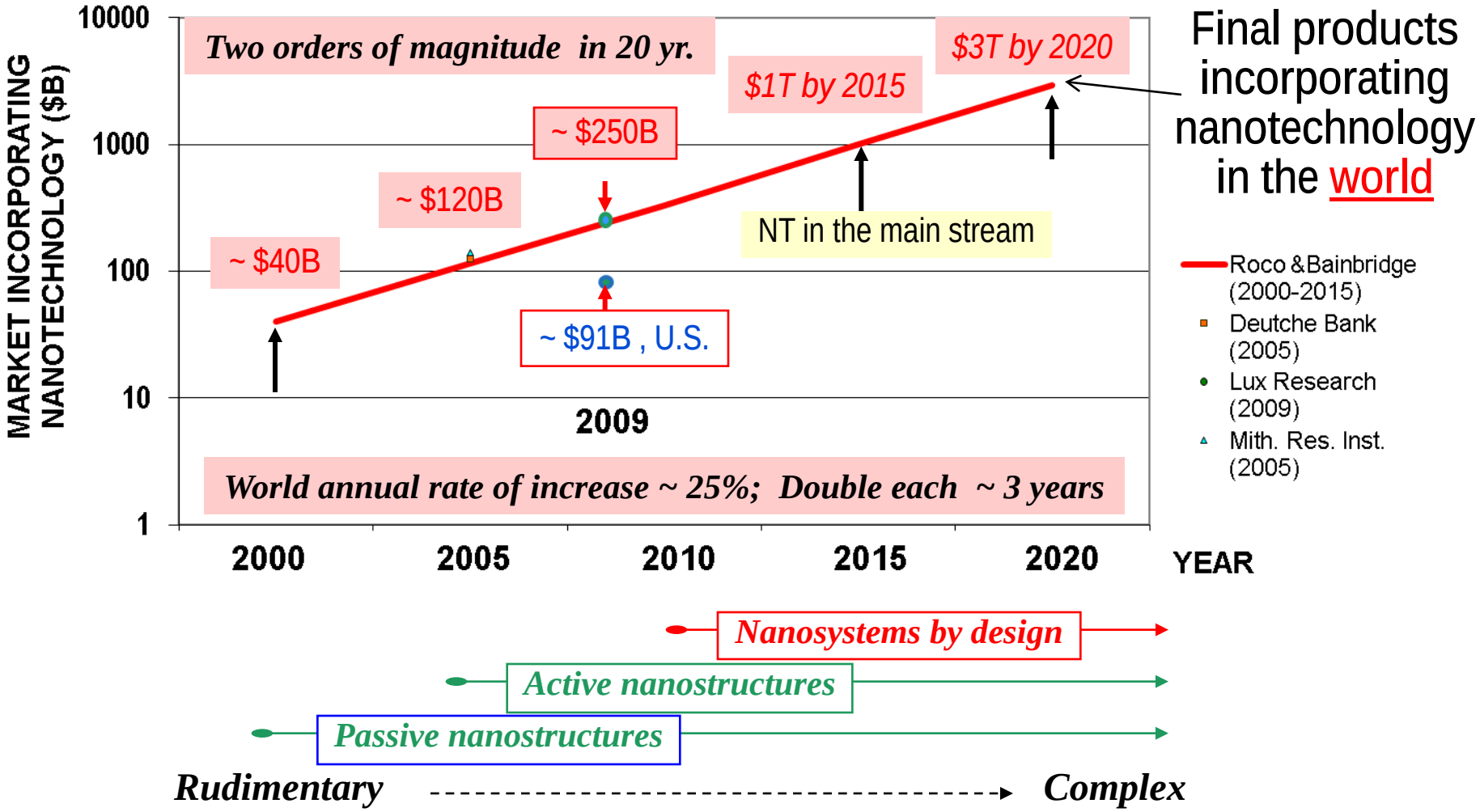
Fiscal Year	NSF
2000	$97M
2001	$150M
2002	$199M
2003	$221M
2004	$254M
2005	$338M
2006	$344M
2007	$373M
2008	$389M
2009	$409M + $108M (ARRA) = $517M
2010	$411M + $17M (ARRA) = $428M



2011: $412M, nano EHS $33M; Request FY 2012 -$456M

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

(Estimation made in 2000 after international study in > 20 countries)



Reference: Roco and Bainbridge, Springer, 2001

2000-2010 Outcomes

- 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

2001-2010

RE ~10,900 awards

by NSF's Principal Investigators

(patents 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 Berkely	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**	Universit 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

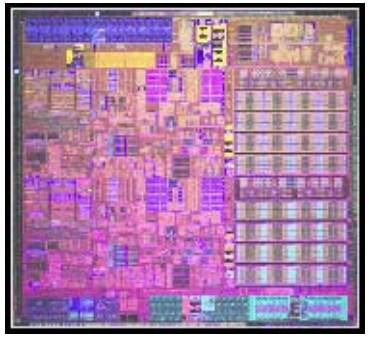
Ten highly promising products incorporating nanotechnology in 2010

- Catalysts
- Transistors and memory devices
- Structural applications (coatings, hard materials, cmp)
- Biomedical applications (detection, implants,.)
- Treating cancer and chronic diseases
- Energy storage (batteries), conversion and utilization
- Water filtration
- Video displays
- Optical lithography and other nanopatterning methods
- Environmental applications

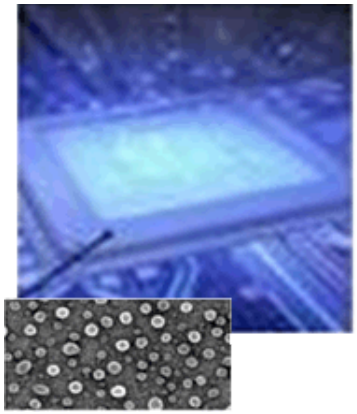
With safety concerns: cosmetics, food, disinfectants,..

2010 nanosystems: nano-radio, tissue eng., fluidics, etc

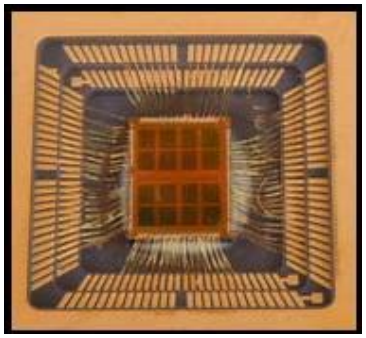
Nanoelectronic and nanomagnetic components incorporated into common computing and communication devices, in production in 2010



32 nm CMOS processor technology by Intel (2009)

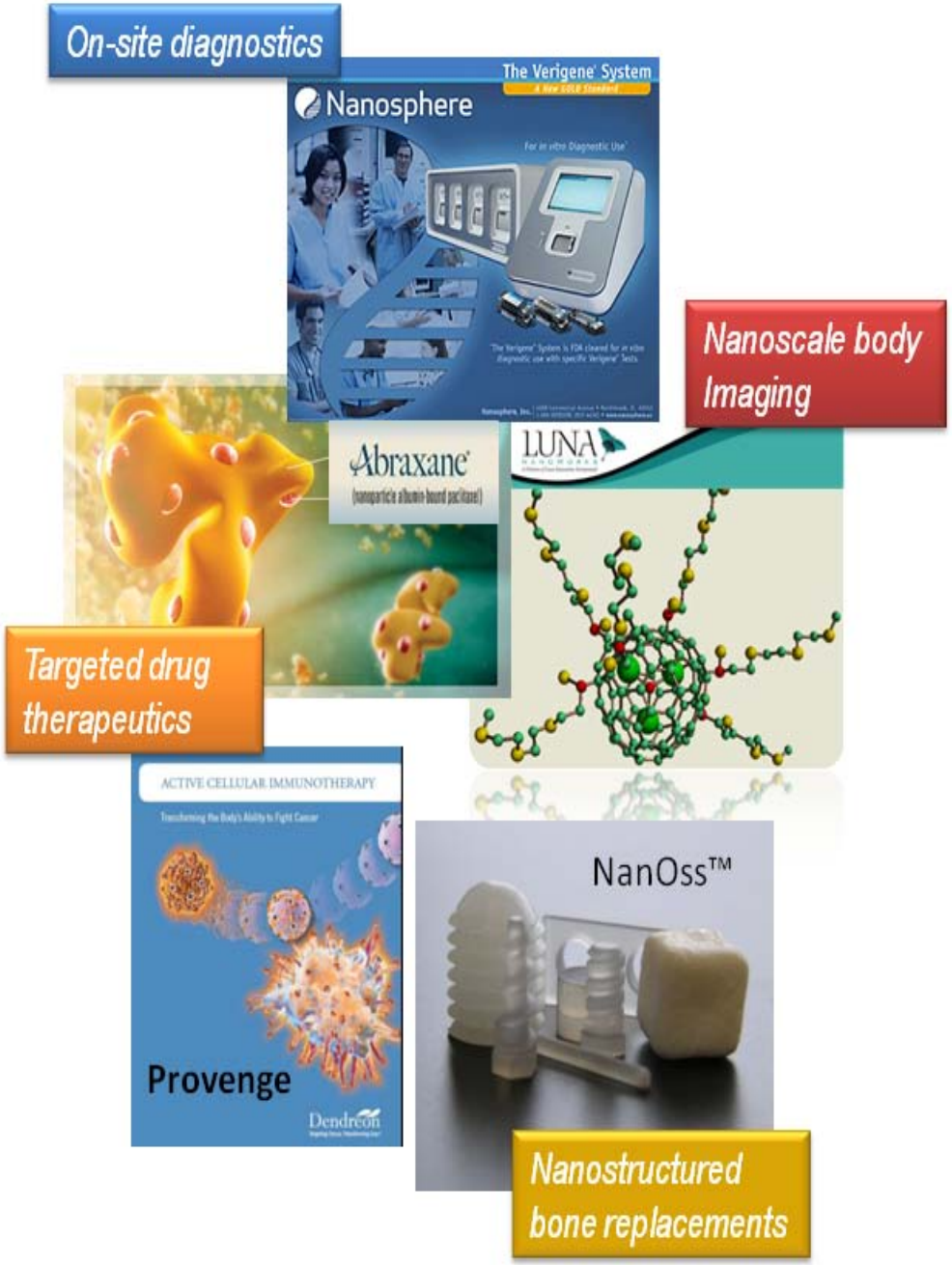


90 nm thin-film storage (TFS) flash flexmemory by Freescale (2010)



16 megabit magnetic random access memory (MRAM) by Everspin (2010)

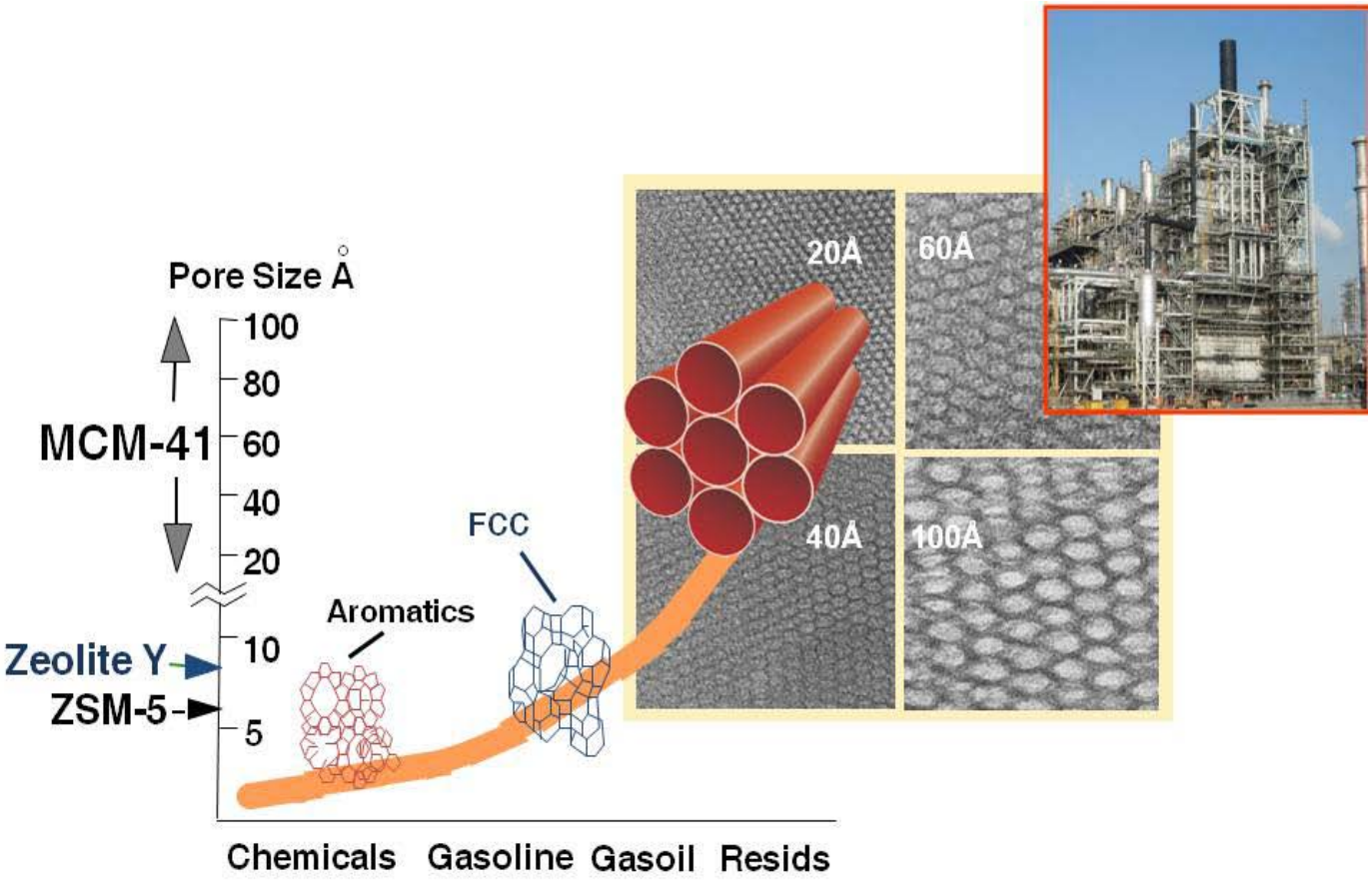
Nano2 Report, 2010, p. XII



Nano2 Report, 2010, p. XIV

Examples of nanotechnology incorporated into commercial healthcare products, in production in 2010

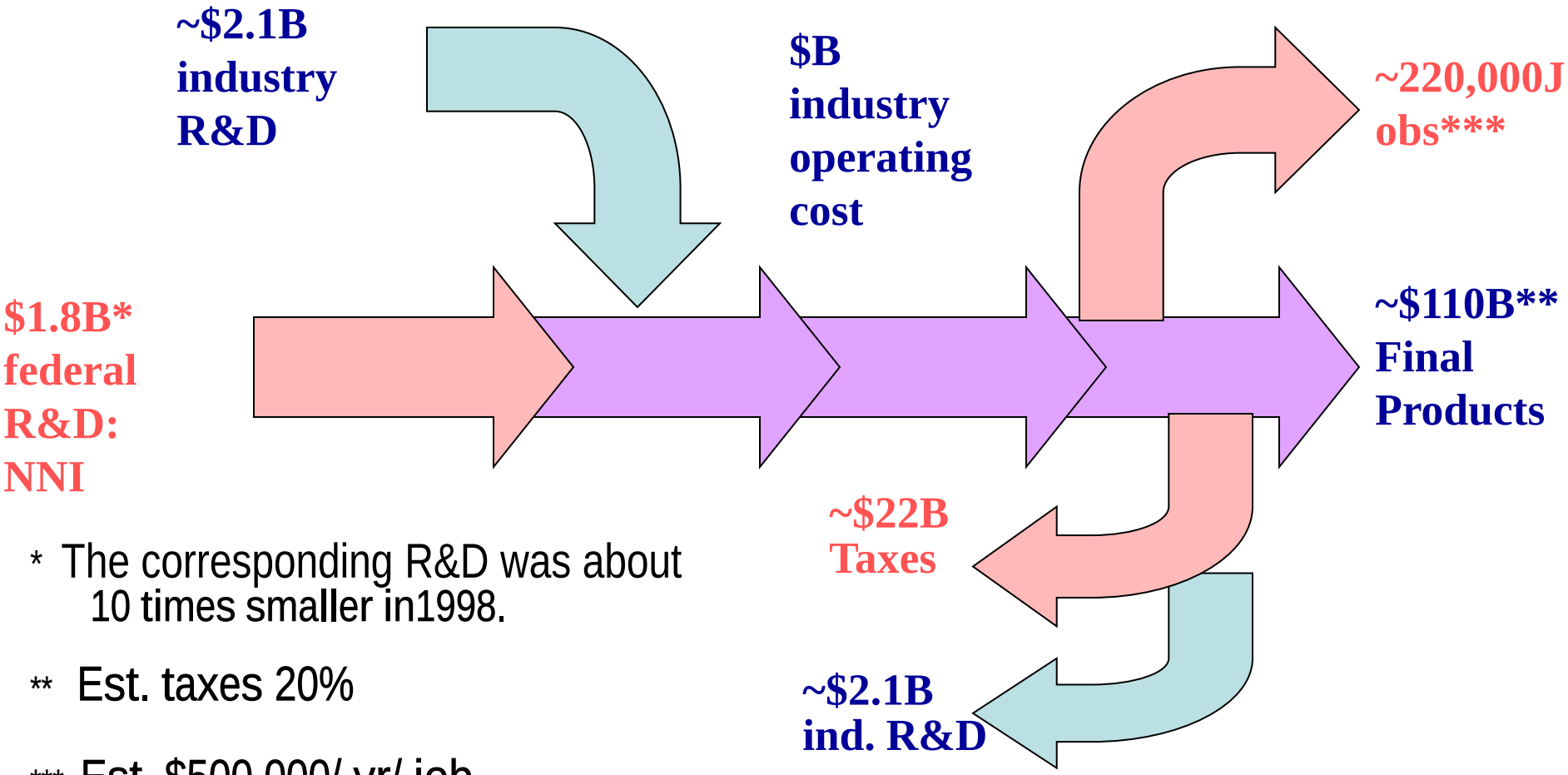
Examples of nanotechnology in commercial catalysis products for applications in oil refining, in production in 2010



Redesigned since 2000 mesoporous silica materials, like MCM-41, along with improved zeolites, are used in a variety of processes such as fluid catalytic cracking (FCC) for producing gasoline from heavy gas oils, and for producing polyesters. Nano-engineered materials now constitute 30–40% of the global catalyst market

Nano2 Report, 2010, p. XVII

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

Not fully realized objectives after ten years

- General methods for **"materials by design"** and composite materials (because the direct TMS 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

On target in 2010, even if doubted in 2000

- Steep, quasi-exponential growth of papers (16%) and patents (33%); at rates higher than the averages in all fields
- Nanotechnology stimulated interdisciplinary research and education, creating numerous multidisciplinary projects, organizations, and communities
- Increased nanotechnology R&D investment (government and private-sector) ~ 30% annual growth rate (because vertical and horizontal development); International coordination and collaboration (collective after 2004)

Better than expected after ten years

- ✓ **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

- ✓ **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 ..

- ✓ **The formation / strength of the international community**, including in nanotechnology EHS and ELSI that continue to grow

Main lessons learned after ten years

- Need continued, focused investment on **theory, direct measuring and simulation, and integration** at the nanoscale. Nanotechnology still in the formative phase
- Besides nanostructured metals, polymers and ceramics, **classical industries can provide excellent opportunities**, such as in: textiles, wood and paper (cellulose) , plastics, agricultural and food systems. Improved mechanisms for public-private partnerships to establish consortia or platforms are needed
- Need to increase **multi-stakeholder and public participation** in nanotechnology governance (policies, EHS, ELSI,..)

Planning NNI "signature initiatives" with nanomanufacturing components in FY 2012

Sustainable Nanomanufacturing

$ 84M (NSF $35.4M; DOE $35.3M; NIST $7.4M; NASA $5M; USDA/FS $0.9M)

Nanoelectronics for 2020 and Beyond

$ 98.5M (NSF $50M, DOE $33.8M; NIST $11.7M; NASA $3M)

Nanotechnology for Solar Energy

$ 125.7M (DOE $79.2M; NSF $32M; NIST $11.5M; NASA $2M; USDA/NIFA $1M)

In FY 2012 Request: a new system oriented nano centers

- Nanosystems Engineering Research Centers
  for 5 + 5 years (~ $4 M/year)
- Pre-proposal in September 2011 … awards in 2012
- Address major topics from discovery to innovation

Part of the NNI increased focus on improving the innovation ecosystem and translational research in 2011-2012

University-Industry-government partnerships (Public-private hybrids)

- Nanoelectronics Research Initiative, U.S.
- U. Albany College of Nanoscale Science and Engineering, U.S.

- Grenoble center, France
- IMEC/ Aachen/ Eindhoven triangle
- University-Industry-Government Tsukuba Nano Center
- Industrial Technology Research Institute, Taiwan

University-Industry Demonstration Partnerships (Academies, U.S.).
Ex: TurboNegotiator (www.turbo.sitesetup.net) a software tool that would facilitate the negotiation of industry-university research agreements

Nanotechnology Governance

NANOTECHNOLOGY GOVERNANCE

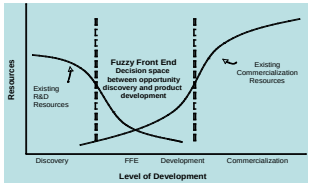
- Investment policy
- Science policy
- Risk management
- Others . . . .

Four key functions:

Visionary →

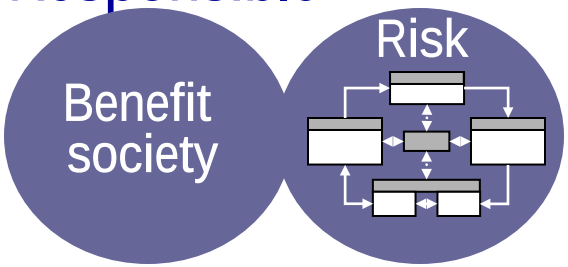
1999: Outline 2000-2020
Nano1: Vision 2000-2010
Nano2: Vision 2010-2020

Transformative



→ Invest in tools, infrastructure
Education, Innovation
Short and long term results

Responsible



→ Risk Governance (EHS, ELSI,..)

Inclusive →

Disciplines, Economy sectors,
Agencies,
International

Reference: Governance of Emerging Technologies (Roco 2008)

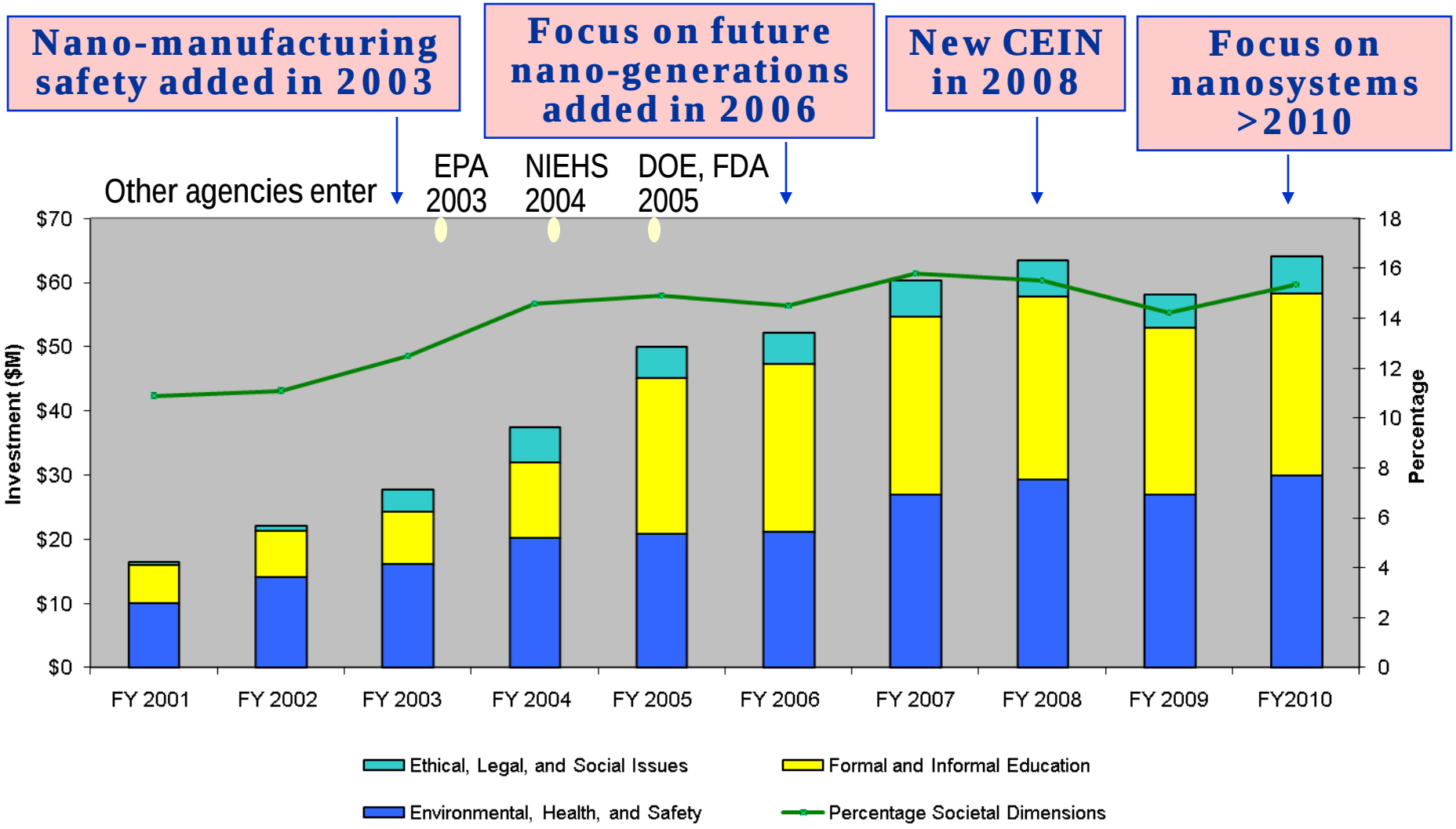
NSF Overview on nano ENV (1)

- "Upstream" research and education since 2000

  2000 – nanoparticles and other passive nanostructures
  2003 – nano-manufacturing safety; NISE, NCLT, NSEC
  2006 – added focus on the 2nd-3rd generations
  2008 – two CEIN have been established (NSF-EPA)
  2010 – to focus on nanosystems (more complex, dynamic)

- Main topics funded since 2006 in the EHS NNI cross-cut
  - instrumentation and analytical methods
  - effects on biological systems and human health
  - effects on the environment
  - exposure of nanomaterials
  - risk assessment and management methods

NSF Investment in Nanotechnology Implications for Safety and Society



NSF Overview on nano ENV (2)

- Societal Implications* (SI) in FY 2010:

  NSF $64.1 million -49% of NNI SI budget - $131.5 million

  *SI is the combined Environmental Health and Safety (EHS) and the Education & Societal Dimensions program components

- EHS: NSF dedicates about 7-8% of its NNI budget for projects with a primary focus on fundamental aspects of environmental implications and applications of nanomaterials:

  7.2 % in FY 2008

  6.6% in FY 2009

  7.1% in FY 2010

  8.2% in FY 2011

- These topics are supported through all NSF programs

NSF Overview on nano ENV (3)

- Transport and transformation of nanomaterials in all media:
  - air
  - water (freshwater and marine)
  - soil
  - biological systems
  - work place
- Consider all sources of nanomaterials
  - natural
  - incidental (byproducts)
  - engineered (manufactured)
- Exposure to food and water with incidental nanomaterials may have high risk

Nano EHS priorities at NSF in 2011

for knowledge creation, infrastructure, and education

- New measurement methods and instrumentation for characterizing nanoparticles, other nanostructured materials and nanosystems, and their potential implications, including nanotoxicity
- Physical-chemical-biological processes of nanostructures dispersed in the environment, including transport phenomena of nano aerosols/colloids
- Safety in nanoscale manufacturing of materials and systems
- Separation of nanoparticles from fluids: water, air, industrial fluids
- Development of experimental and simulation facilities; "user" facilities
- Educational programs for nano EHS
- Predictive approaches and exposure studies:

Examples solicitations: 2008 CEINs ($38.4 M for 5 years) with EPA; Nano-EHS supplements to NSECs; Interagency solicitations in 2008 and 2010 with EPA, USDA, DOE; Nano-EHS supplement to NSECs in 2009 and 2011

Core Program in Nano EHS

Environmental Health and Safety of Nanotechnology Engineering and Sustainability (ENG)

Program Director: Barbara Karn

- Understanding and mitigating how new developments in nanotechnology and biotechnology will interact with the environment
- Nanotechnology environmental, health, and safety implications and applications
- Predictive methodology for the interaction of nanoparticles with the environment and with the human body, including predictive approaches for toxicity
- Fate and transport of natural, engineered, and incidental (by-product) nanoparticles
- Risk assessment and management of the effect of nanomaterials in the environment

NSF Centers with EHS relevance – Examples:

- Center for Biological and Environmental Nanotechnology at Rice University (manufactured nanoparticles at the wet/dry interface)
- Center for High-rate Nanomanufacturing at Northeastern University (occupational safety in nanomanufacturing)
- Nano/Bio Interface Center at University of Pennsylvania (interaction of nanomaterials and cells)
- NSEC on Templated Synthesis and Assembly at the Nanoscale at University of Wisconsin, Madison (effect of nanostructured polymers on EHS)
- Center for Integrated Nanomechanical Systems at University of California, Berkeley (detecting exposure to individual and portable nanomaterials)
- Center for Affordable Nanoengineering of Polymeric Biomedical Devices at the University of Ohio (nanoscale devices for monitoring and healing)
- Center for Hierarchical Manufacturing at University of Massachusetts, Amherst (occupational safety)
- CEINT Center for Environmental Implications of NanoTechnology at Duke University
- UC-CEIN Center for Environmental Implications of Nanotechnology at University of California Los Angeles

Center for Biological and Environmental Nanotechnology

(Funding FY 2001-2010)

to discover and develop nanomaterials that enable new medical and environmental technologies

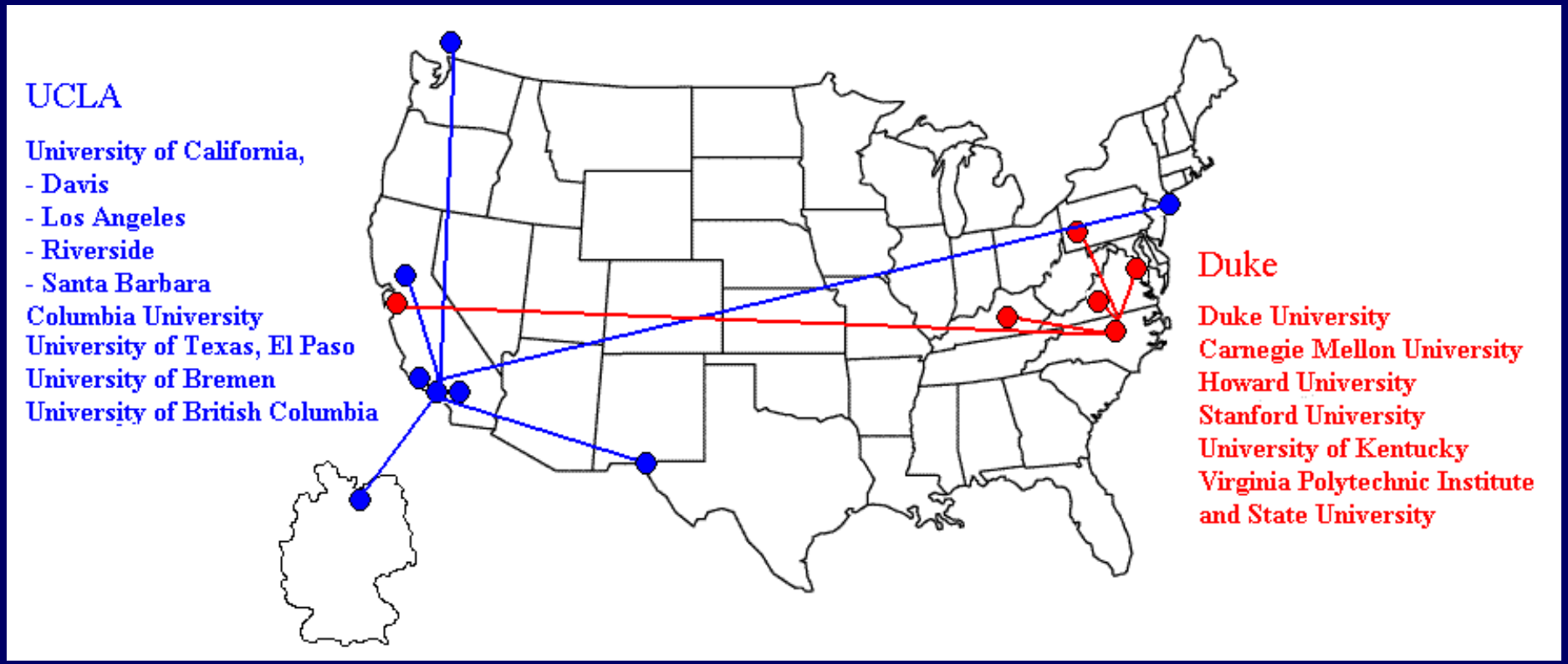
Fundamental examination of the 'wet/dry' interface between nanomaterials, complex aqueous systems, and ultimately our environment

Engineering research that focuses on multifunctional nanoparticles that solve problems in environmental and biological engineering

Vicki Colvin – Director

Centers for the Environmental Implications of Nanotechnology FY 2008

Interagency effort to expand EHS investments within NNI



http://www.cnsi.ucla.edu/ http://www.ceint.duke.edu/

The Environmental Implications of Nanotechnology

Funding FY 2008-2017

To elucidate the relationship between a vast array of nanomaterials — from natural, to manufactured, to those produced incidentally by human activities — and their potential environmental exposure, biological effects, and ecological consequences

Partners:

- Carnegie Mellon
- Howard University
- Virginia Tech
- University of Kentucky
- Stanford University

Mark Wiesner - Director

The Environmental Implications of Nanotechnology

UCCEIN Center for Environmental Implications of NanoTechnology

Funding FY 2008-2017

UCLA

University of California Los Angeles

Partners:

- UC-Santa Barbara
- UC-Riverside
- UC-Davis
- Columbia
- University of Texas- El Paso
- University British Columbia
- University of Bremen

Andre Nel - Director

To explore the impact of engineered nanomaterials on a range of cellular life forms, organisms and plants in terrestrial, fresh water and sea water environments.

National Nanomanufacturing Network origins: 4 Nanomanufacturing NSECs

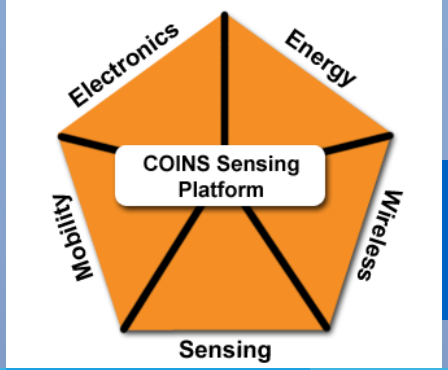
(including occupational safety R&D)

- **Center for Hierarchical Manufacturing** (CHM)
  - UMass Amherst/UPR/MHC/Binghamton including clearinghouse, informatics

- **Center for High-Rate Nanomanufacturing** (CHN)
  - Northeastern/UMass Lowell/UNH

- **Center for Scalable and Integrated Nanomanufacturing** (SINAM)
  - UC Berkeley/UCLA/UCSD/Stanford/UNC Charlotte

- **Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems** (Nano-CEMMS)
  - UIUC/CalTech/NC A&T



Center of Integrated Nanomechanical Systems

PACMON Vision

Personal and Community Environmental Monitoring (PACMON)

- Goal: better air-quality detection:
  - Should be portable, sensitive, low-cost, low-power
  - Something that people can use easily
- The COINS personal environmental monitor will have better detection sensitivity, fit on a bracelet, and run for months at a time

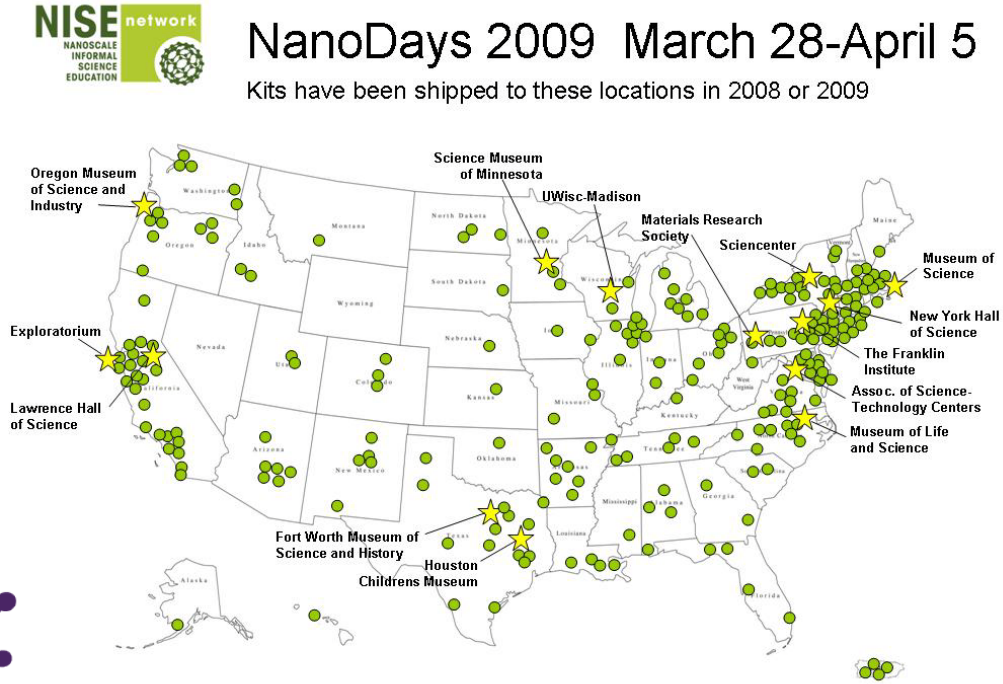
Outreach on Nanoscience

NISE network™
NANOSCALE INFORMAL SCIENCE EDUCATION

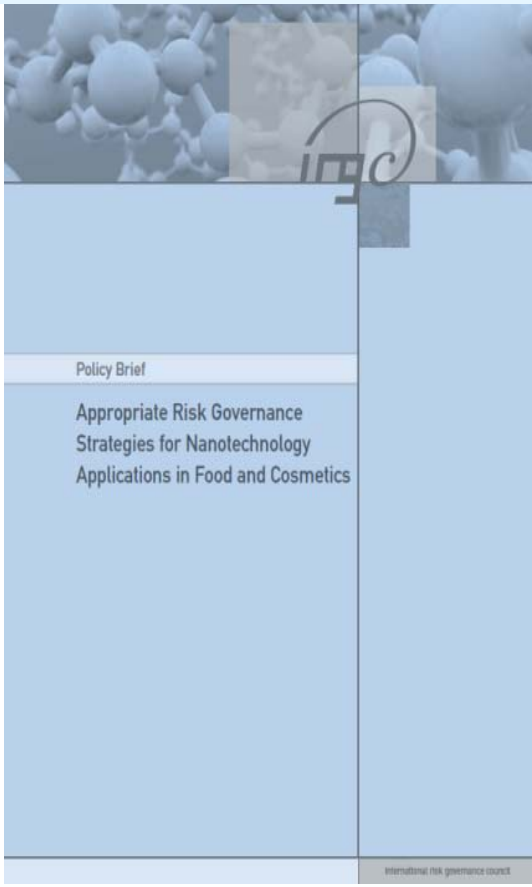
NSF Award ESI-0532536

A national community of researchers and informal science educators dedicated to fostering public awareness, engagement, and understanding of nanoscale science, engineering, and technology.

NanoDays



Advances in 2000-2010



- Significant advances in methods, concepts, tools for research on societal implications of nanotechnology (Ex: IRGC, 2005-2009)

- Strategic orientation of social science research in nanotechnology towards risk management and anticipatory governance

- Standardization and Metrology
  - International activities in ISO and other organizations
  - Innovation is moving ahead of regulation, waiting for standards, nomenclature, traceability methods

Advances in 2000-2010

Creation of new community **of multidisciplinary researchers**

EHS-related issues

international research community has formed through bottom-up processes; there is exemplary integrative work that brings together sciences and social sciences; voluntary reporting schemes have been introduced (limited impact)

Ethics and Studies of Societal Dimensions:

there is now an international community of scholars with journals ex. *NanoEthics*,
an academic society *S.NET www.theSnet.net*

Advances in 2000-2010

Regulation - two approaches are developing in parallel

- Probing extendability of regulatory schemes (“developing the science” approach)
- Exploratory (soft) regulatory and governance models that work with insufficient knowledge for risk-assessment

International collaboration

- Several different formats for international dialogue have emerged, each with strengths and limitations, such as International Dialogue on Responsible Development , OECD Working Groups, or ISO Working Groups

Twelve trends to 2020

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 capabilities, integrated
- Energy photosynthesis, storage use – solar economic by 2015
- Enabling and integrating with new areas – bio, info, cognition
- Earlier preparing nanotechnology workers – system integration
- Governance of nano for societal benefit - institutionalization

Vision for the next ten years

- Preparing for **mass application of nanotechnology by 2020**, with shift to more complex generations of nanotechnology products and increased connection to biology. Risk governance deficits in knowledge, uncertainty, institutional
- **Greater emphasis on innovation and commercialization**: incentives for greater use of public/private partnerships to foster innovation. Create new models for innovation
- **Focus on job creation**: increasing use of automation, reinvigorate mfg., strategic targeting of high value sectors
- *Nanotechnology governance will be **institutionalized*** , with increased globalization and a co-funding mechanism

Goals for 2010-2020

- Nanotechnology is emerging as a *general purpose technology*
- *The shift to new generations of nanotechnology products*,
  - uncertainty in risk management
  - taking decision with incomplete information
- Several possibilities for improving the governance of nanotechnoogy in the global self-regulating ecosystem:
  - using open-source and incentive-based models,
  - implementing long-term planning with international perspective
  - institute voluntary measures for risk management
  - adopt an anticipatory, participatory, real-time technology assessment and adaptive governance of nanotechnology

Strategies for risk governance as a function of the generation of nanoscale products : Frame 1 and Frame 2

Frame 2 long-term:
Future work on social and global dimensions; focus on nano ELSI and nano EHS

Frame 2 short-term:
Broader review, design and recommendations

Frame 1:
Focus on nano EHS and regulators

Possible System Uncertainty and **higher Ambiguity in Society**

Possible System Uncertainty

Component Complexity

Linear Systems

3rd/4th Generation
Nanosystems

2nd Generation
Active nanostructures

1st Generation
Passive nanostructures

Naturally nanostructured materials

Risk framing ***Knowledge level*** ***Generation of nanoproducts***

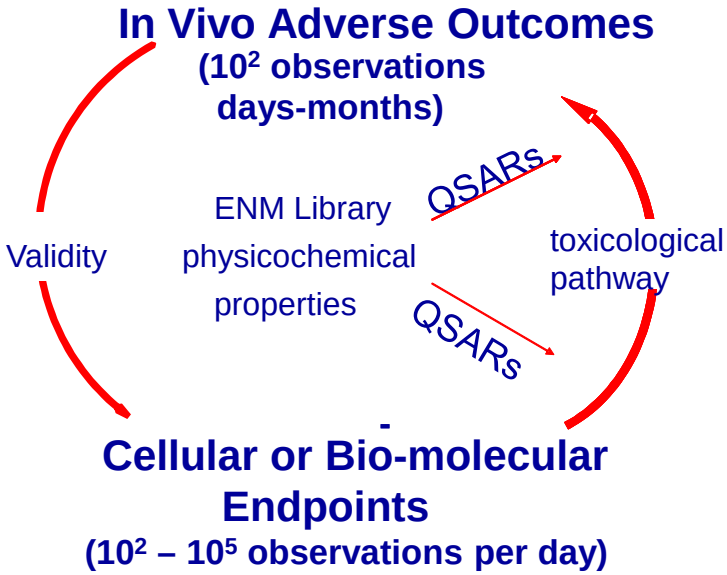
Reference: Roco and Renn (2008)

2010-2020: Increasing R&D intensity and return

- Research into the systematic control of matter at the nanoscale will accelerate in the first part of the next decade (2011-2015)
- Nanotechnology by 2020 seamlessly integrated with most technologies and applications, driven by economics and by the strong potential for achieving previously unavailable solutions
- Support for **fundamental research** and infrastructure - essential
- Support **focused R&D programs** for frontiers and bottlenecks
- **Realize nanomaterials and nanosystems by design**
- High potential of nanotechnology to support **sustainable development** in water, energy, minerals, and other resources

Vision for the next 10 years

- To establish validated and robust scientific platforms for hazard, exposure and risk assessment
- Implement a predictive scientific approach that uses testing at molecular, cellular and organism level → knowledge that is instructive of more complex organisms and humans
- Replace one-material-at-a-time screening in animals → rapid throughput bio-molecular and cellular approaches



Nano 2 Report, Chapter 3, A. Nel

Vision for the next 10 years

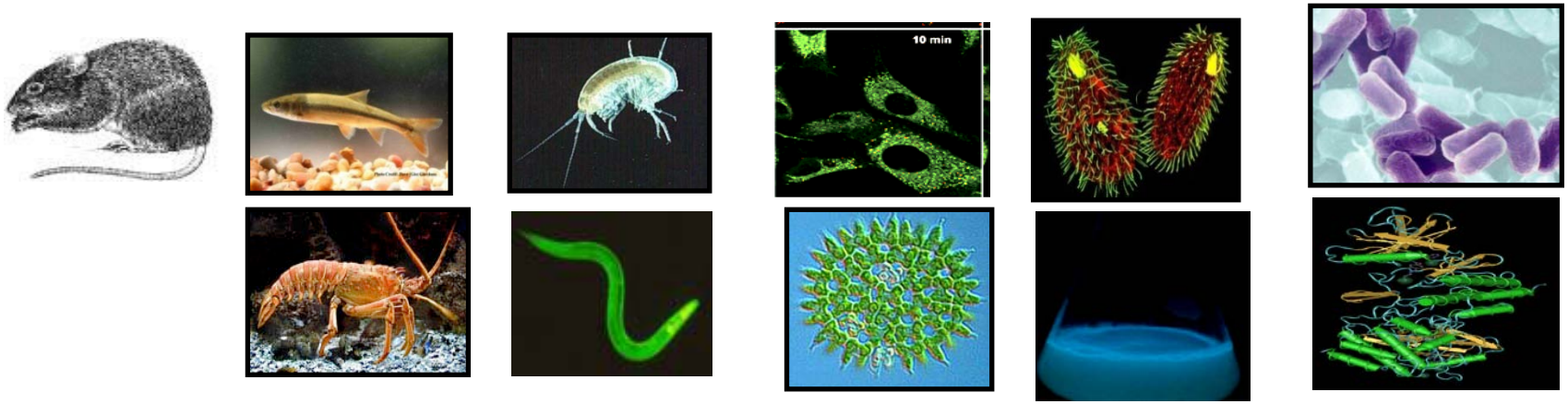
- Build a nano EHS enterprise with the capacity to keep pace with the rate of growth of nanotechnology
- Develop computational methods, nano-informatics, modeling and decision-making tools to speed up nano EHS knowledge generation
- Develop safe-by-design approaches as an integral part of product development
- Industry participation in data and knowledge gathering to facilitate safe implementation of nanotechnology and active participation in nano EHS decision-making

Expected major nano EHS advances in the next 10 years

- Develop validated screening methods, harmonized protocols and risk reduction strategies

  (requires correct balance between in vitro/in vivo, appropriate dosimetry metrics, improved technology to track fate/transport & exposure)

- Develop predictive toxicological approaches that utilize the correct balance between in vitro and in vivo testing



100's/year **1000's/year** **10,000's/day** **100,000's/day**

Nano 2 Report, Chapter 3, A. Nel

2010-2020: OTHER PRIORITIES

- Advance **partnerships** between industry, academia, NGOs, multiple agencies, and international organizations
- Support precompetitive R&D and system application **platforms**
- Promote **global coordination**; Create an international co-funding mechanism for databases, nomenclature, standards, and patents
- Support horizontal, vertical, and system **integration in nanotechnology education; and personalized learning**
- Use **nanoinformatics** and computational science prediction tools
- **New strategies** for mass dissemination, public participation
- **Institutionalize**—create standing organizations and programs to fund and guide nanotechnology

It will be imperative over the next decade to focus on four distinct aspects of nanotechnology development

- How nanoscale science and engineering can improve understanding of nature, generate breakthrough discoveries and innovation, and build materials and systems by nanoscale design – "knowledge progress"
- How nanotechnology can generate economic and medical value —"material progress"
- How nanotechnology can address sustainable development, safety, and international collaboration —"global progress"
- How nanotechnology governance can enhance quality-of-life and social equity —"moral progress"

Several background references

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