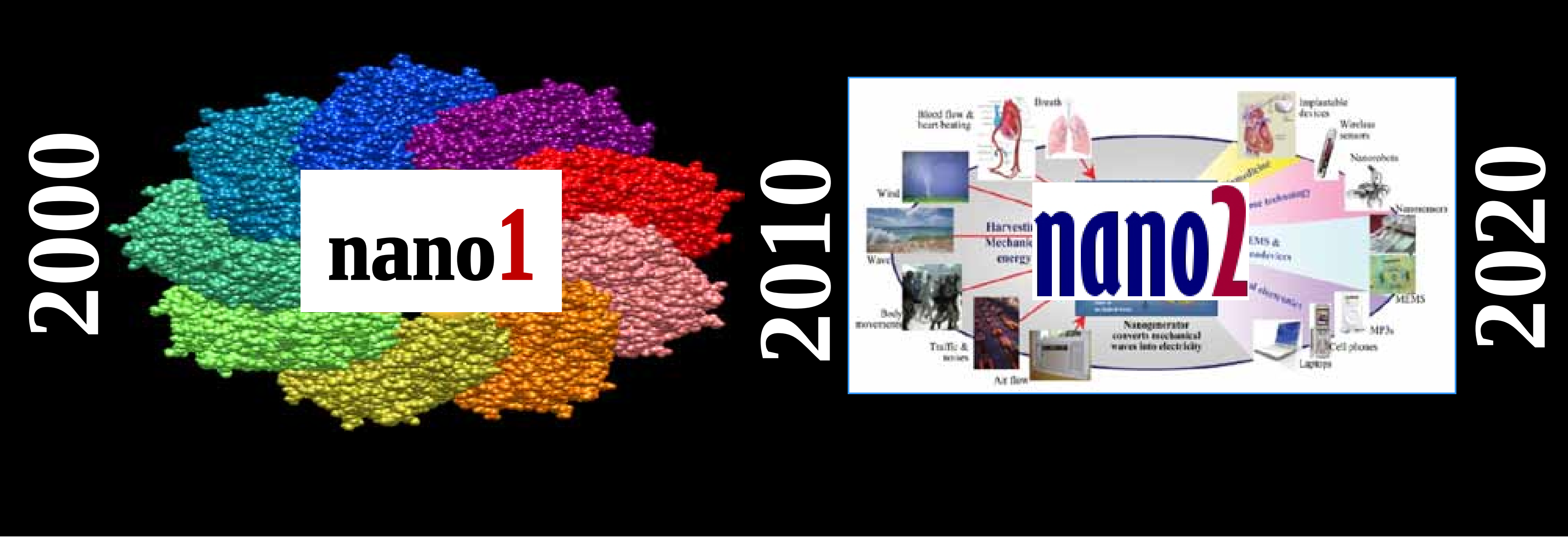


Several trends in *Nanomanufacturing*

Mike Roco
National Science Foundation and National Nanotechnology Initiative

Boston, September 5, 2012

Topics

- Nanotechnology development context
- Opportunities in nanomanufacturing
- Converging technology implications

Related publications

"Nanotechnology: From Discovery to Innovation and Socioeconomic Projects" 2010-2020 (2011)

"The Long View of Nanotechnology development: the NNI at 10 Years" (2011)

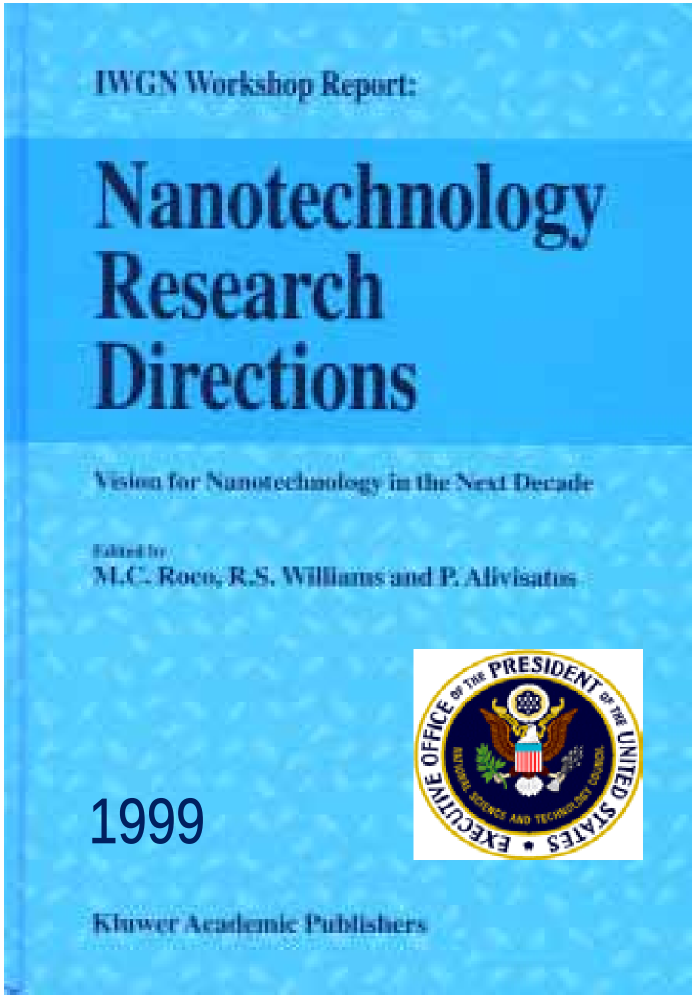
"Nanotechnology Research Directions for Societal Needs in 2020" (2011)

"Mapping Nanotechnology Innovation and Knowledge: Global and Longitudinal Patent and Literature Analysis" (2009)

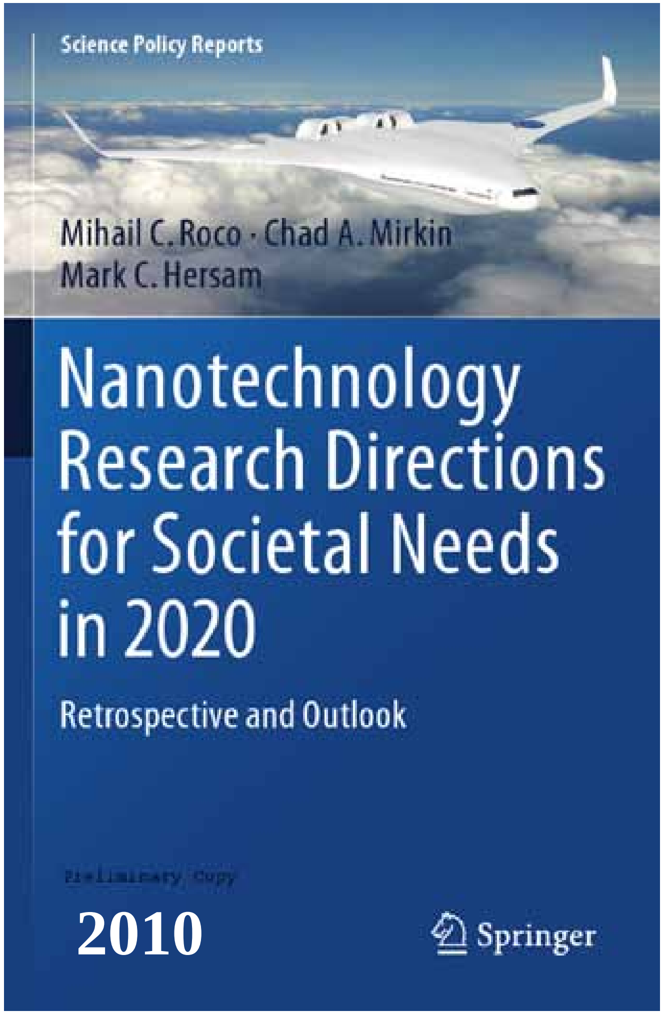
10-year vision documents, 3-year strategic plans, 1-year plans and topical workshops: www.nsf.gov/nano; www.nano.gov

Long-term nanotechnology research directions (2000-2020)

Nano1 (2000-2010)



nano2 (2010-2020)



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

Nanoproducts and Nanomanufacturing

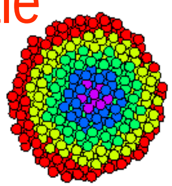
- Fragmentation
- Patterning
- Restructuring of bulk
- Lithography, ..

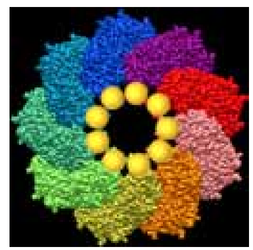
- Interfaces, field & boundary control
- Positioning assembly
- Integration, ..

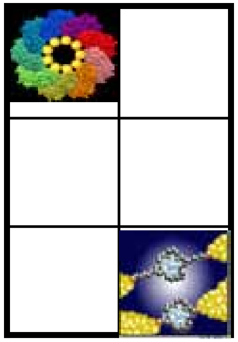
- System engineering
- Device architecture
- Integration, ..

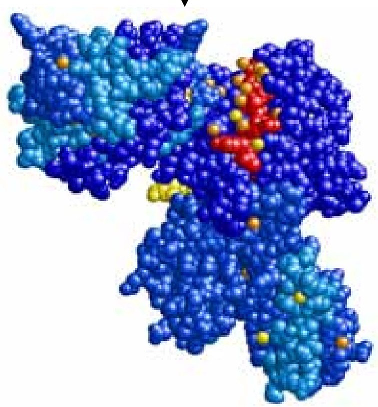
- Nanosystem biology
- Emerging systems
- Hierarchical integration..

From Nanoscale Modules

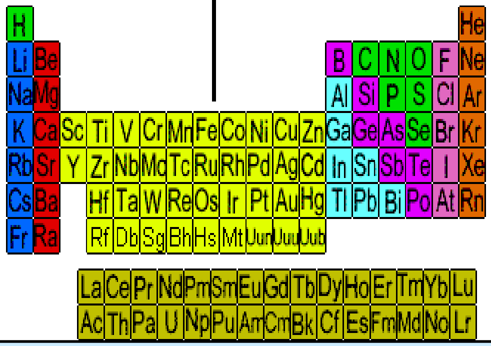








Assembling



- Directed selfassembling,
- Templating,
- New molecules

- Multiscale selfassembling,
- In situ processing, ..

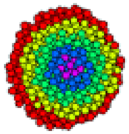
- Eng. molecules as devices,
- Quantum control,
- Synthetic biology..

PASSIVE NANOSTRUCTURES - ACTIVE NANOSTR. - SYSTEMS OF NANOSYSTEMS - MOLECULAR NANOSYSTEMS

MC Roco, Sept 5 2012

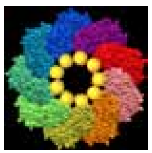
Introduction of New Generations of Products and Productive Processes (2000-2020)

Timeline for beginning of industrial prototyping and nanotechnology commercialization



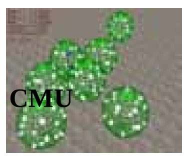
2000

1st: Passive nanostructures (1st generation products)
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics



~ 2005

2nd: Active nanostructures Ex: 3D transistors, amplifiers, targeted drugs, actuators, adaptive structures



~ 2010

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

~ 2015-2020

4th: Molecular nanosystems
Ex: molecular devices 'by design', atomic design, emerging functions

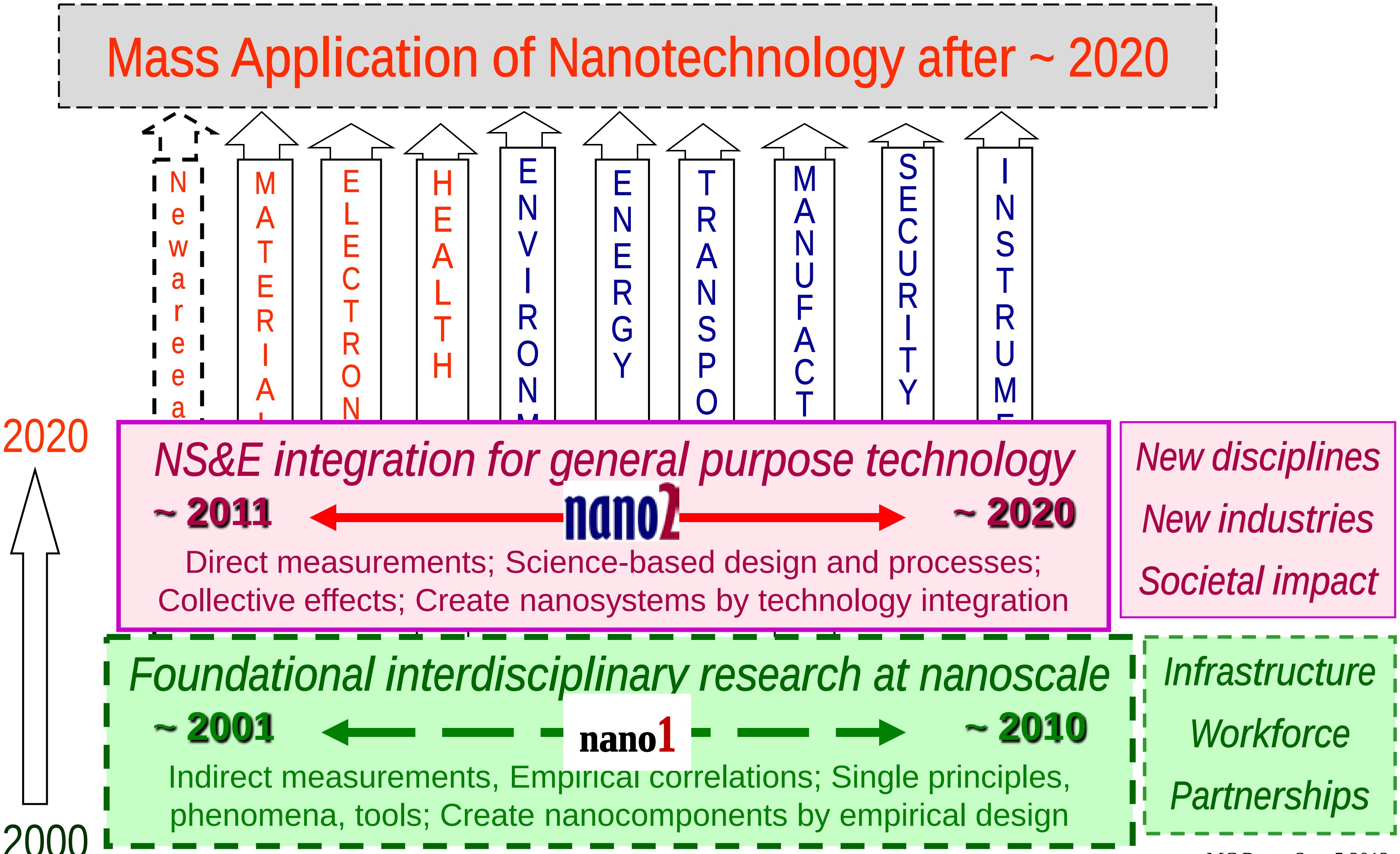
Converging technologies
Ex: nano-bio-info from nanoscale, cognitive technologies; large complex systems from nanoscale

Higher uncertainty & risk

Increase Complexity & Integration

Reference: AIChE Journal, Vol. 50 (5), 2004

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



MC Roco, Sept 5 2012

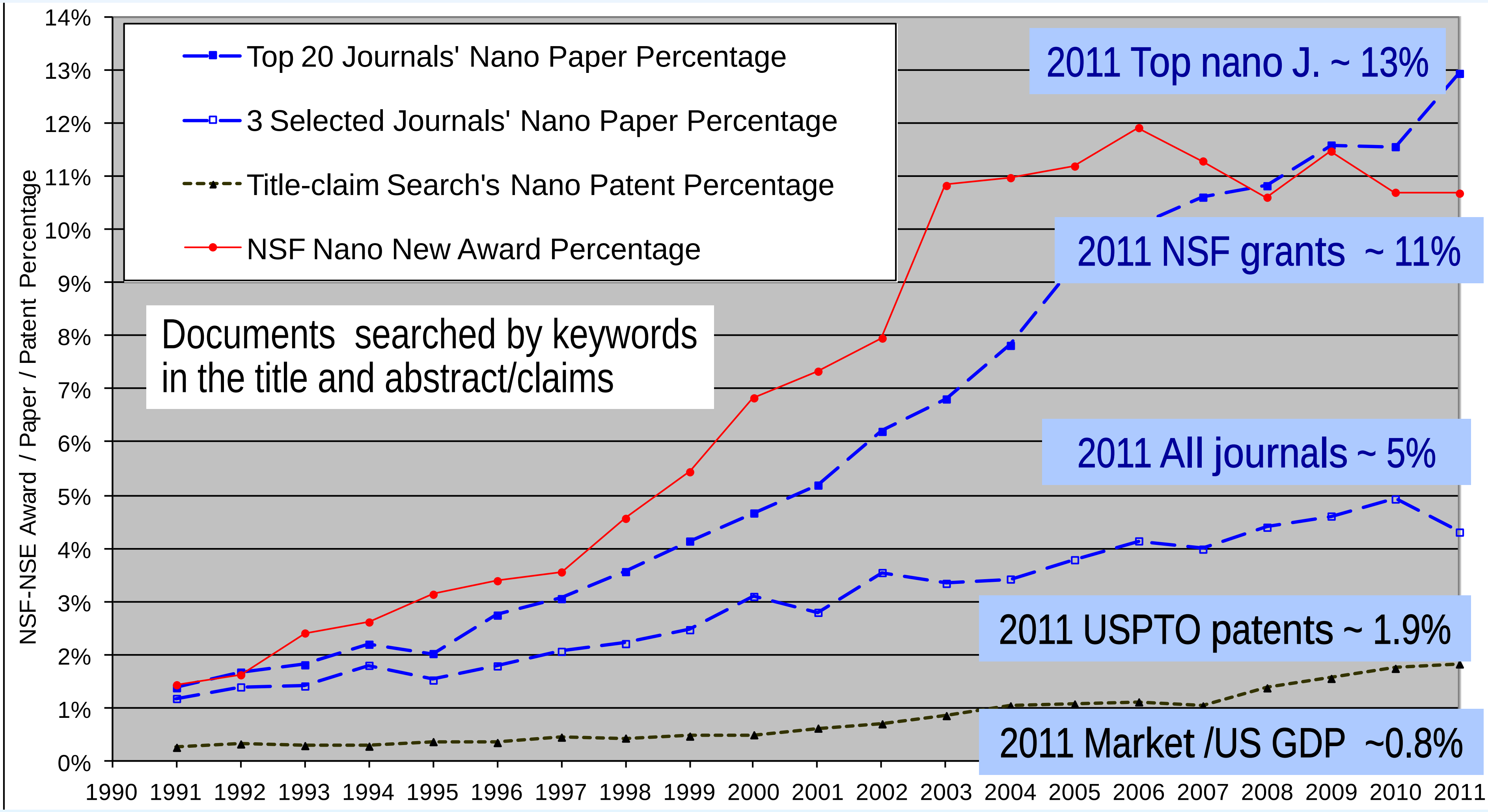
2000-2010
Estimates show an average growth rate of key nanotechnology indicators of 16% - 33%

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*					

MC Roco, Sept 5 2012

Percentage of nanotechnology content in NSF awards, ISO papers and USPTO patents (1991-2011)

(update after Encyclopedia Nanoscience, 2012)



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

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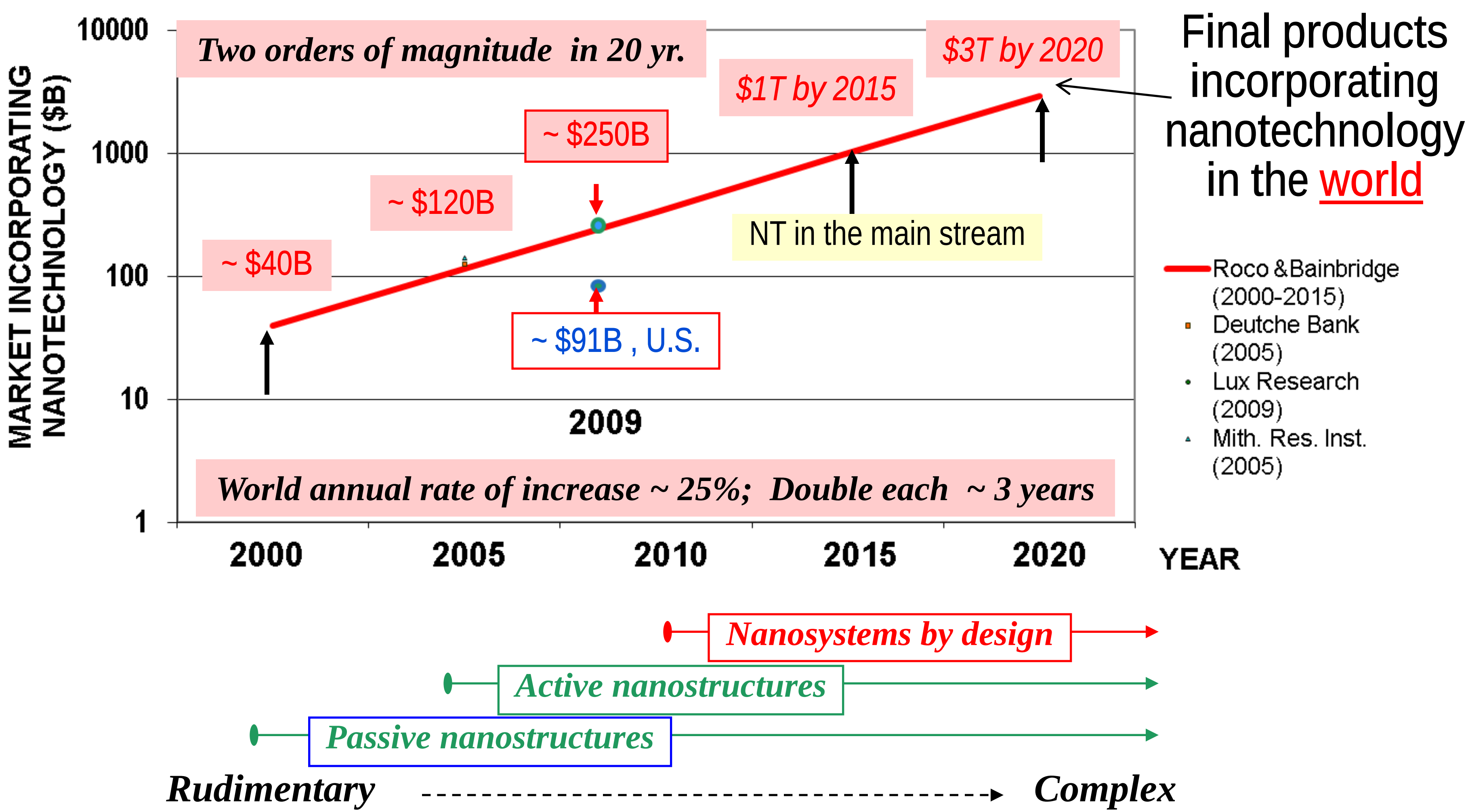
WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

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



Reference: Roco and Bainbridge, Springer, 2001

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Main nanotechnology outcome at 10 years

- ***Foundational knowledge of nature*** by control of matter at the nanoscale
- ***Global interdisciplinary community*** (~ 600,000) for R&D, nano-EHS and ELSI
- ***Science & technology (S&T) breakthroughs***
- ***Novel methods and tools***
- ***Extensive multi-domain infrastructure***
- ***New education & innovation ecosystems***
- ***New industries*** with increased added value
- ***Solutions for sustainable development***

(A) 2000-2010 S&T Outcomes

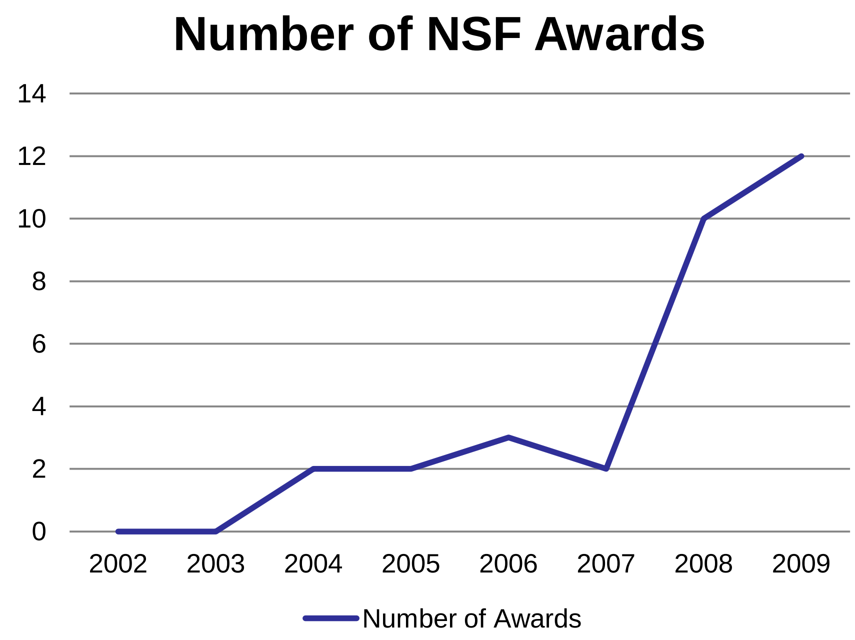
- *Remarkable scientific discoveries* than span better understanding of the smallest living structures, uncovering the behaviors and functions of matter at the nanoscale, and creating a library of 1D - 4D nanostructured **building blocks for devices and systems; Towards periodical table for nanostructures.**

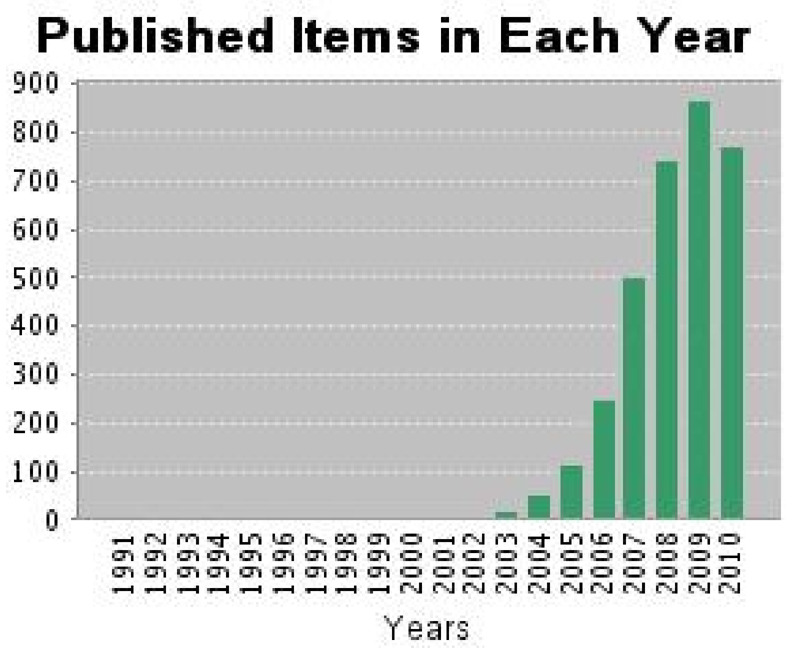
- *New S&E fields have emerged* such as: *spintronics (2001), plasmonics (2004), metamaterials, carbon nanoelectronics, molecules by design, nanofluidics, nanobiomedicine, nanoimaging, nanophotonics, opto-genetics, synthetic biology, branches of nanomanufacturing, and nanosystems*

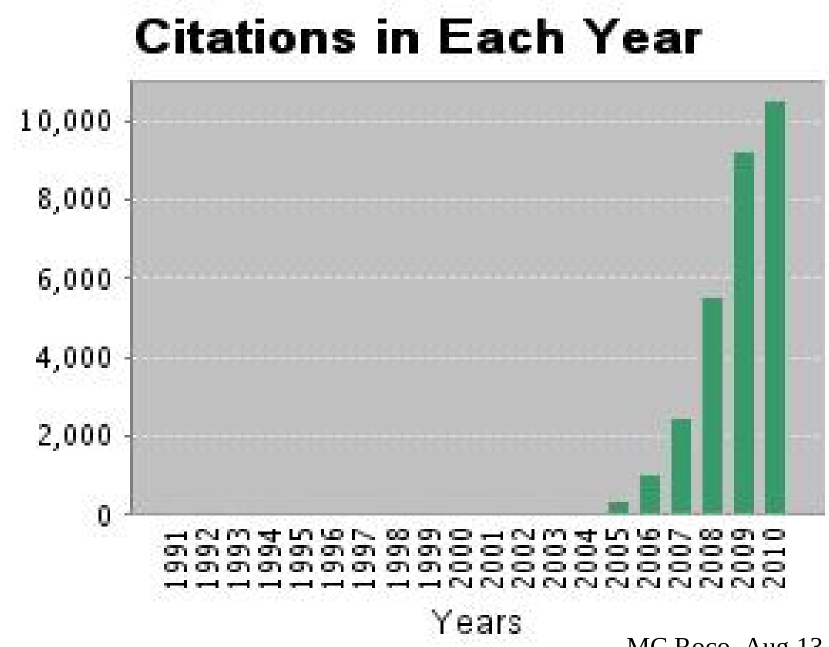
- *Technological breakthroughs* in advanced materials, biomedicine, catalysis, electronics, and pharmaceuticals; **expansion into** energy resources and water filtration, agriculture and forestry; and **integration of nanotechnology with other emerging areas** such as quantum information systems, neuromorphic engineering, and synthetic and system nanobiology

Example: Emergence of Plasmonics after 2004

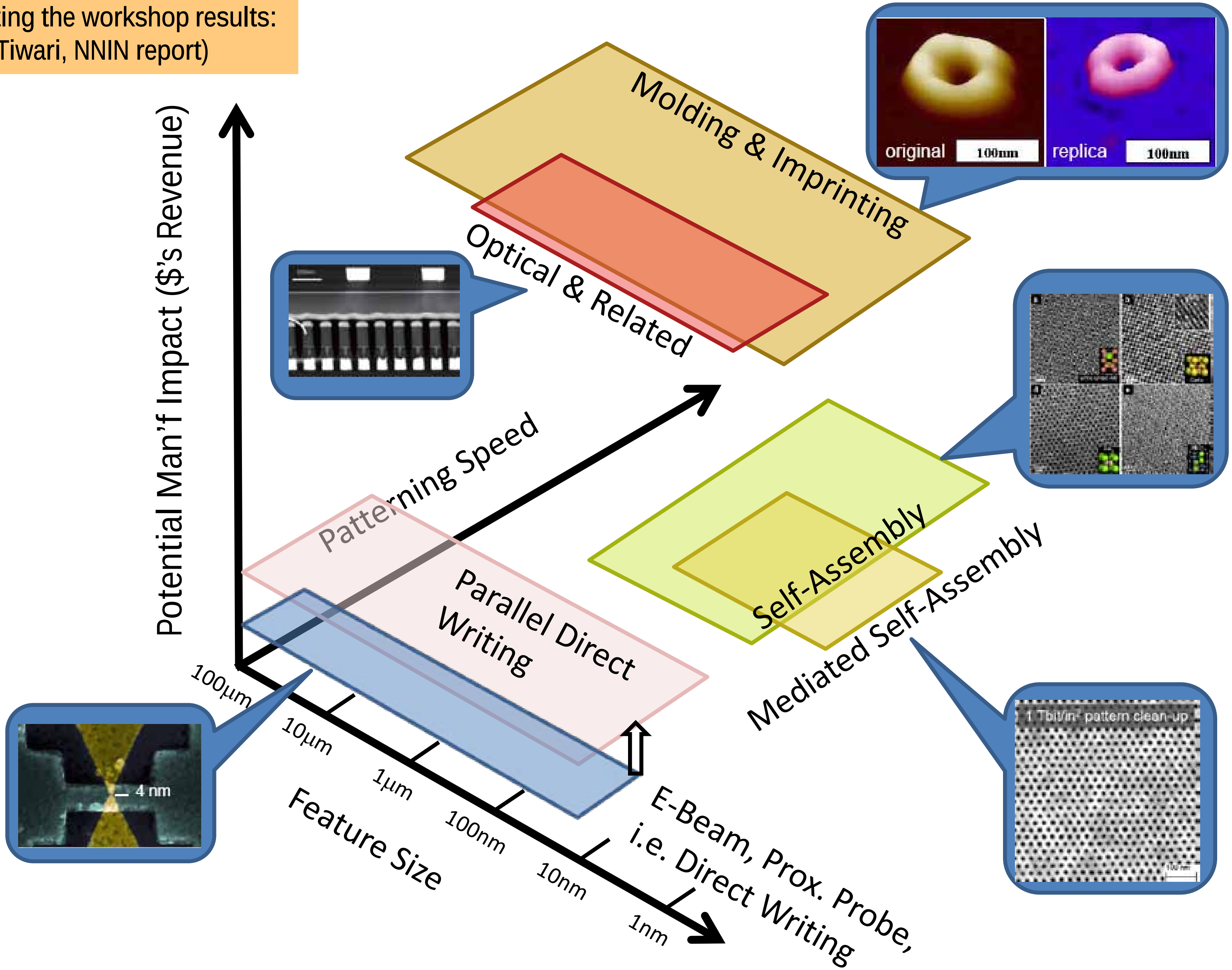
Plasmonics: Merging photonics, electronics and materials at nanoscale dimensions







Model for reporting the workshop results: synthetic view (Tiwari, NNIN report)



Nanopatterning on surfaces

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 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

Article citations by NSF Principal Investigators

```
                                  Individual 95% CIs For Mean Based on Pooled StDev
Level           N    Mean   StDev  -------+---------+---------+---------+--
NSF          3615   166.0   693.5                                      (*-)
IBM          1877    53.8   158.8           (*-)
TOP10       33071    27.0   160.2     (*
UC          10097    42.4   233.9         (*
US          85669    31.6   183.2       *
EntireSet  260880    26.2   147.1     (*
Japan       22358    24.2    85.5     *)
European   118429    20.5    94.9    *
Others      63654    15.1    74.5  (*
                                   -------+---------+---------+---------+--
                                         40        80        120       160
```

Chen at al. (2012)

NSF-funded PIs (1991-2010) have a higher number of citations (166 in average) than researchers in other groups: IBM, UC, US (32 in average), Entire world Set (26 in average), Japan, European, Others

Number of patent citations by NSF P.I.-Inventors

```
                                        Individual 95% CIs For Mean Based on Pooled StDev
Level          N   Mean   StDev   ---------+---------+---------+---------+
NSF         1887  30.93  113.90                                   (--*-)
IBM         3614  10.21   30.04             (-*-)
TOP10      14076  11.65   87.53                (*)
UC          2497  10.29   35.08             (-*-)
US         96962   9.04   51.08             *)
EntireSet 140855   7.32   44.04           *
Japan      20562   3.43   19.43     (*)
European   20211   1.79    9.03   (*)
Others      8133   2.10    9.99   (-*)
                                  ---------+---------+---------+---------+
                                         8.0      16.0      24.0      32.0
```

Chen at al. (2012)

NSF-funded PI-Inventors (1991-2010) have more citations (31 in average) than inventors in the TOP10, UC, IBM, US (9 in average), Entire World Set (7 in average), Japan, Others, and European group

(B) 2000-2010: Novel Methods and Tools

- *Femtosecond measurements* with atomic precision in domains of biological and engineering relevance
- *Sub-nanometer measurements* of molecular electron densities
- *Single-atom and single-molecule* characterization methods
- *Scanning probe tools for printing*, sub-50 nm "desktop fab"
- *Simulation* from basic principles has expanded to *assemblies of atoms 100 times larger than in 2000*
- New measurements: negative index of refraction in IR/visible wavelength radiation, Casimir forces, quantum confinement, nanofluidics, nanopatterning, teleportation of information between atoms, and biointeractions at the nanoscale. Each has become the foundation for new domains in science and engineering

(C) 2000-2010 Infrastructure and R&D - NNI illustrations -

- Infrastructure
  - Developed an *extensive infrastructure* of interdisciplinary research of ~ 100 large centers, networks and user facilities
  - *Educate and train > 10,000 students and teachers* per year ~ 1,000 new curricula in accredited research universities ; ~ 30 associate degree nanotechnology programs
  - *Established networks for ELSI and public awareness*

- R&D&I Results

With ~22% of global government investments, U.S. accounts for

~ 70% of startups in nanotechnology worldwide

> 2,500 U.S. nanotech companies with products in 2010, with $110B (~38% of the world) products incorporating nano parts

(D) 2000-2010: Ten highly promising products incorporating nanotechnology

- *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*

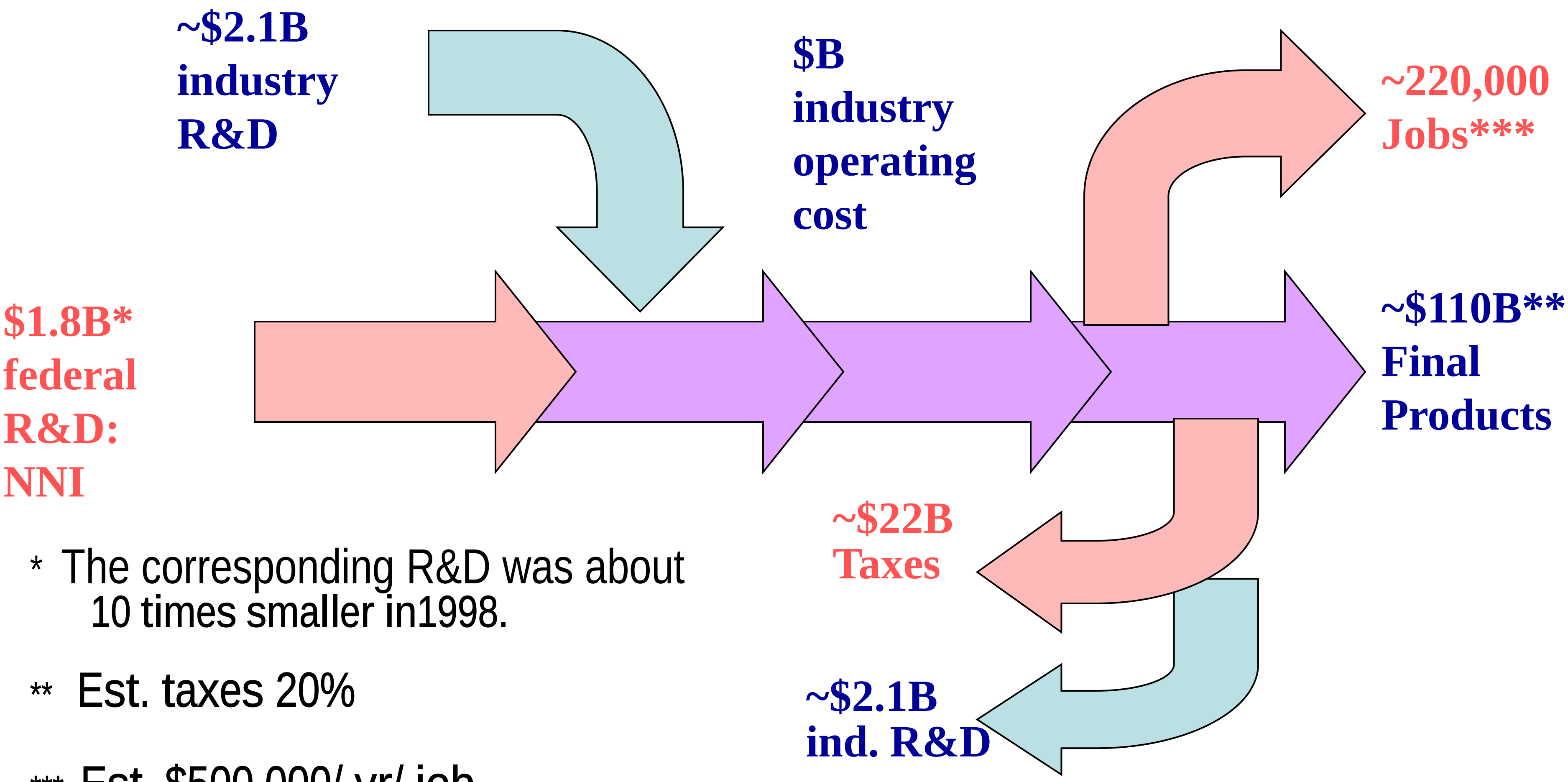
Leading to new industries, some with safety concerns: cosmetics, food, disinfectants,..

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

(E) 2000-2010: Sustainable Development

- Nanotechnology has provided solutions for about half of the new projects on energy conversion, energy storage, and carbon encapsulation in the last decade
- Entirely new families have been discovered of nanostructured and porous materials with very high surface areas, including metal organic frameworks, covalent organic frameworks, and zeolite imidazolate frameworks, for H storage and CO_2 separations
- A broad range of polymeric and inorganic nanofibers for environmental separations (membrane for water and air filtration) and catalytic treatment have been synthesized
- Testing the promise of nanomanufacturing for sustainability
- Evaluating renewable materials and green fuels

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

MC Roco, Sept 5 2012

nano2

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

Manufacturing: **Transforming raw materials into products with desired properties and performance – generally in large quantities**

Defining Nanomanufacturing (1) :

Aims at building material structures, components, devices/ machines, and systems with nanoscale features in one, two and three dimensions. It includes

- **bottom-up directed assembling** of nanostructure building blocks (from the atomic, molecular, supramolecular levels),
- **top-down high-resolution processing** (ultraprecision engineering, fragmentation methods, positioning assembling),
- **engineering of molecules and supramolecular systems** (molecules as devices "by design", nanoscale machines, etc.),
- **hierarchical integration** with larger scale systems.

Atoms, molecules ⇨ **nanostructures** (intermediate) ⇨ **materials/ devices/ machines/ systems**

Nanomanufacturing: typical bottom-up processes

- Controlled nucleation and growth
  - Aerosol and colloidal dispersions; deposition on surfaces
- Selfassembling
  - Natural process in living systems and biomimetics
  - Chemistry/chemical manufacturing
  - Guided by electric, magnetic, optical fields, DNA controlled ..
- Templating: Al and C nanotubes; by substrate; local reactors; . .
- Engineered molecules and molecular assemblies
  - Designed molecules as devices or for selfassembling
  - New molecular architectures by design
- Bio methods - Selectivity, selfassembling, synthetic biology, ..
- Bottom-up modular nanosystems
- Control replicating structures (ex: cellular approach)

Nanomanufacturing: other typical processes

- Lithography: optical, ultraviolet, electron-beam, SPM based (1-10 nm)
- Nano-machining
- Nano-manipulation of atoms, molecules, nanoparticles
- Fragmentation: mechanical milling, spark erosion, etc.
- Sintering of nano precursors
- Thermal treatment of metals, ceramics, composites
- Mixing of nanocomposites and their processing
- Fluidics
- Nanoscale robotics
- Bio-evolutionary approaches, ..

Twelve opportunities for pre-competitive nanomanufacturing R&D

1. Guided molecular assembling on several length scales (using electric and magnetic fields, templating, imprinting, additive, chemical methods, etc.)
2. Modular and platform-based nanomanufacturing for nanosystems
3. Use micro/nano environments: microreactors, microfluidics, deskfactories
4. Designing molecules with new structures and functionalities

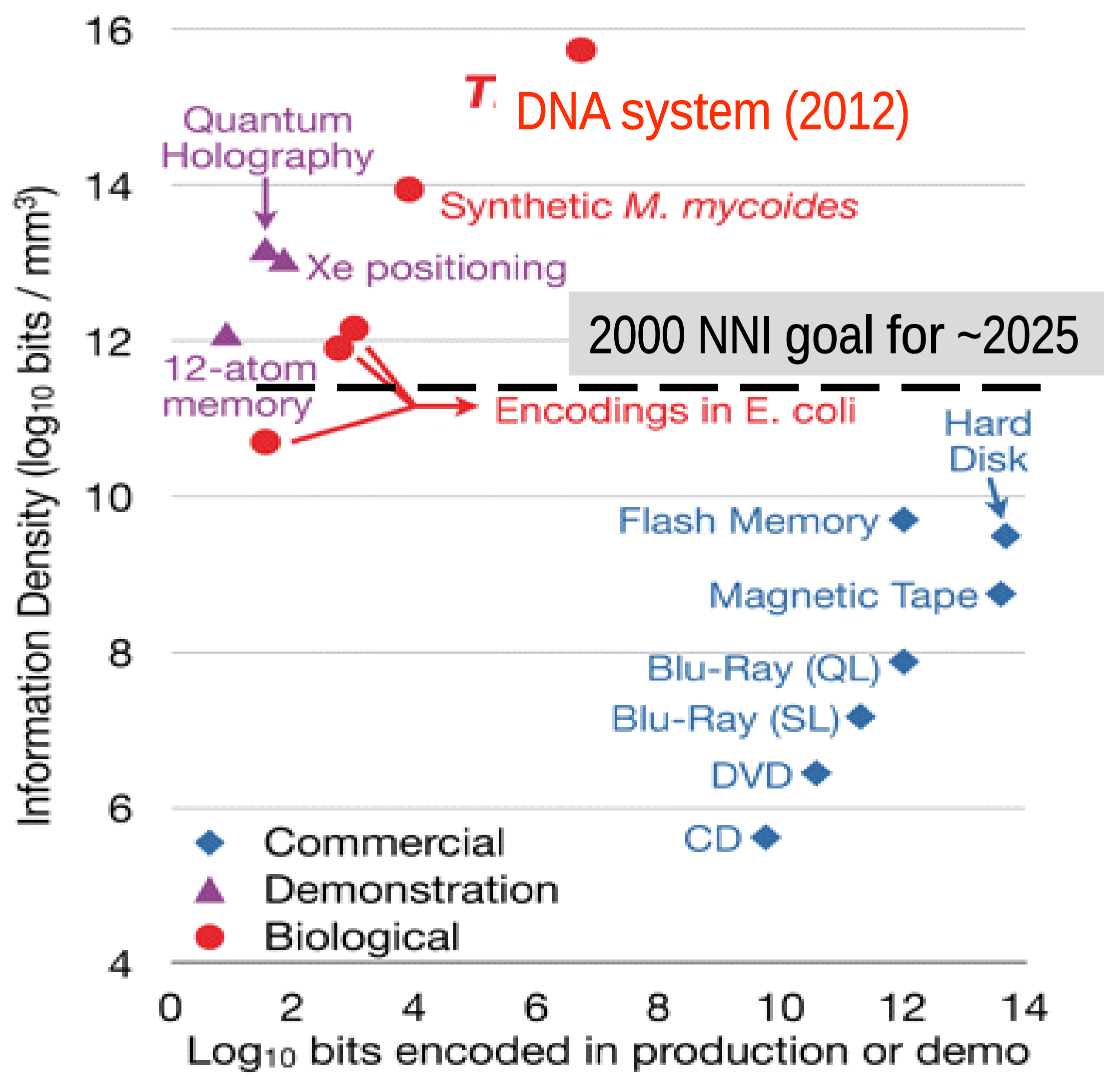
5. Nanobio-manufacturing - harnessing biology for nanomanufacturing (using living cells directly, borrowed, or bio-inspiration such as folding)
6. Manufacturing by nanomachines - advances catalysts, DNA machines, ..
7. Hierarchical nanomanufacturing - integrate in 3D, diff. materials, functions
8. Scale-up, high-rate, distributed continuum manufacturing processes

9. Standardized tools for measurements and manufacturing
10. Predictive simulation of nanomanufacturing processes
11. Predictive approach for toxicity of nanomaterials (ex: oxidative stress)
12. Development and use of nanoinformatics and intellectual property

DNA data memory system (Harvard U.)

2020: NNI goal for ~2025 - all information from Library of Congress in a device of size of sugar cube (Pros Clinton) – was labeled as too ambitious

2012: DNA system could store it in about 1mm cube (Science, Aug. 2012)



2. Modular and platform-based fabrication of nanosystems

- Modules for measuring nanoscale processes (SNL)
- Biotic-abiotic nanomodules (ex: with parts of viruses and bacteria) for sensors, energy conversion, nanomachines (Ex: Cornell U., Carnegie Mellon U.)
- Platforms for nanomanufacturing processes with various applications in larger companies
- Platforms by relevance of R&D: energy, water, sustainability, food, cancer research, forestry, concrete
- Combinatorial approaches for new architectures and nanoscale networks

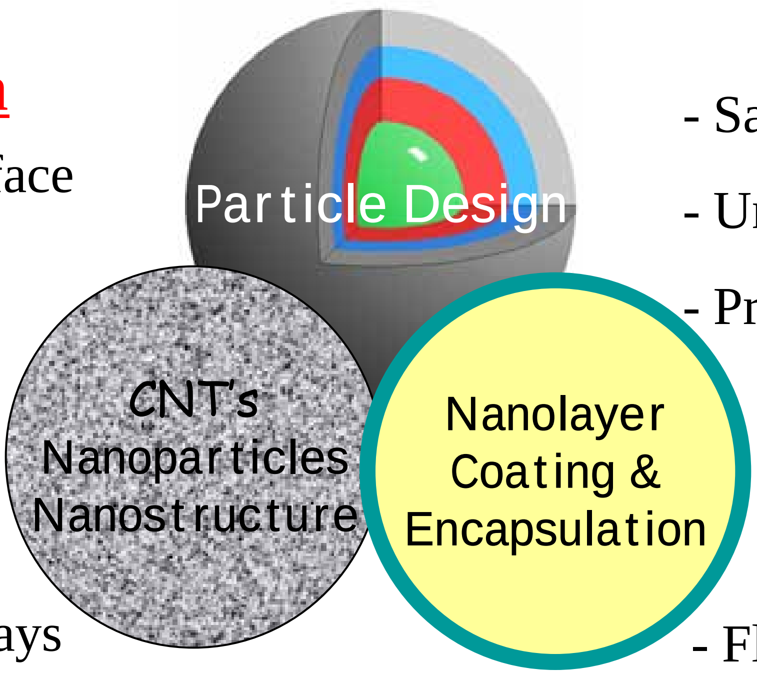
DuPont: Process Engineering & Manufacturing

for synthesis (CVD, Aerosol, Crystallization, precipitation), size reduction, surface treatment, coating, encapsulation, dispersion, incorporation

Nanotechnology platform for various particle technologies

Characterization

- PSD, morphology, surface
- Defects
- End-use performance



Manufacturing

- Safety
- Unit operations & Scale up
- Process integration

Applications

Films, Electronics, Displays

EP, Coatings, Personal care, Sensors, N&H

Assembly

- Fluid dynamics
- Field (E&M)
-Molecular template
- Biomolecule assisted

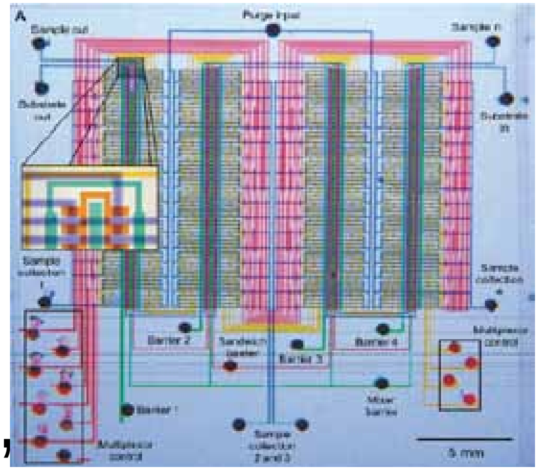
Modeling&Simulation

Molecular, Meso, Macro, CFD,

Example 3rd generation

Platforms for systems nanotechnology

- Create controllable systems built from nano components: unifying principles that enable control of emergent behavior in complex nanosystems
- Wide application: revolutionary new products, petascale computing, organ regeneration, sensors for health monitoring
- Enable other goals for: nanomanufacturing, efficient use of energy; sensor capabilities
- Development of a new framework for risk assessment



Ex UIUC: Microfluidics systems incorporating nanocomponents

Ex UCB: nano radio = antenna, filter, amplifier

3. Use nano/micro-environments:
microreactors, microfluidics, deskfactories

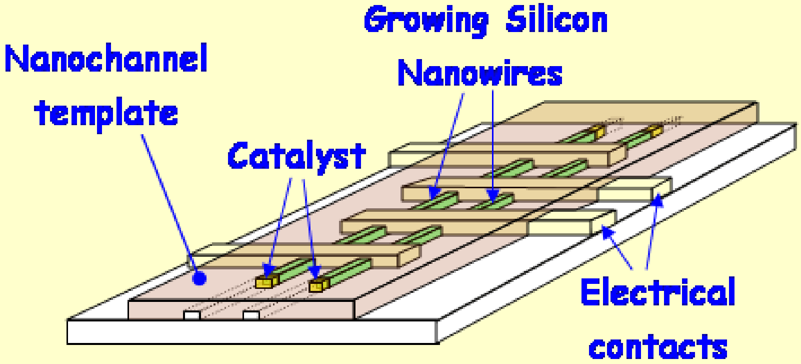
For process control, process intensified, with less waste, parallel production, potentially continuous, at the point of use

- Microchannels for reactors (for large specific surface area; for precise manufacturing larger macromolecular yield and controlled nanoparticle size distribution)
- Microfluidic devices for nanoscale assembling
- Desk size factories for processing nanomaterials
- In-situ synthesis of nanostructures (ex. Nanoscale channels for in-situ manufacturing, Fonash, Penn State)
- Simultaneous, multiple processes in same environment

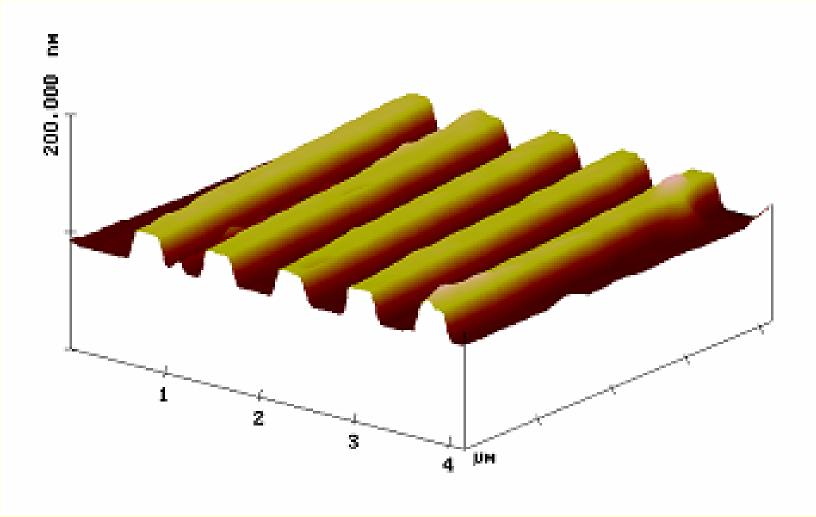
Example 1st generation

"Grow in place" for Nanowire Devices

(S. Fonash, Penn State)



(a)



(b)

a. Manufacturing nanowire "in situ". "Grow-in-place" method keeps assembled together all nanostructured materials during processing

b. AFM image of grown silicon nanowires

Cyborg-like Tissue Monitors Cells
Nanoelectronic scaffolding supports living tissue

Lieber, Langer et al. (Harvard U) have constructed a material that merges nanoscale electronics with biological tissues into a mesh of transistors and cells

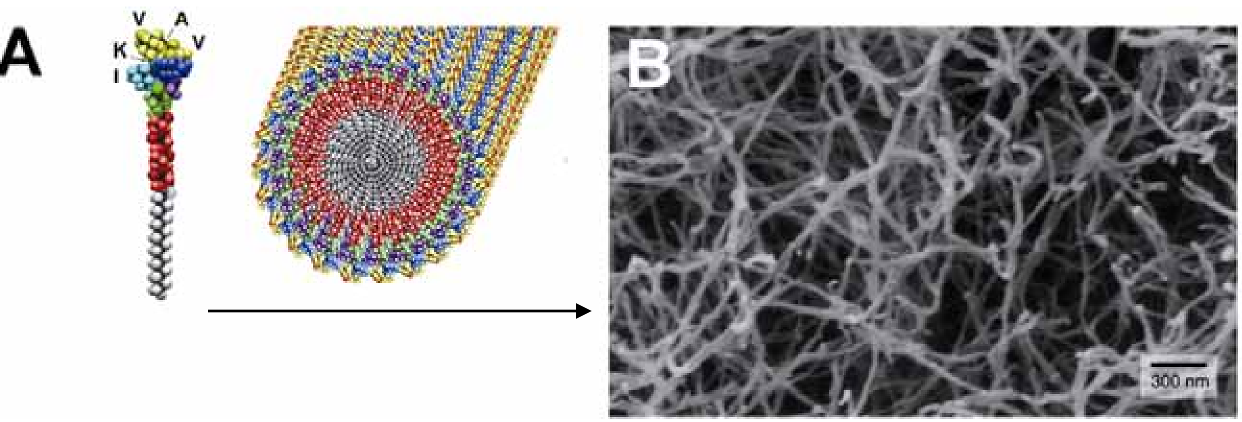
- The cyborg-like tissue, supports cell growth while simultaneously monitoring the activities of those cells
- It could improve *in vitro* drug screening by allowing researchers to track how cells in a three-dimensional environment respond to drugs in real time
- It may also be a step toward prosthetics that communicate directly with the nervous system, and tissue implants that sense and respond to injury or disease (Nature Materials, Aug 2012)

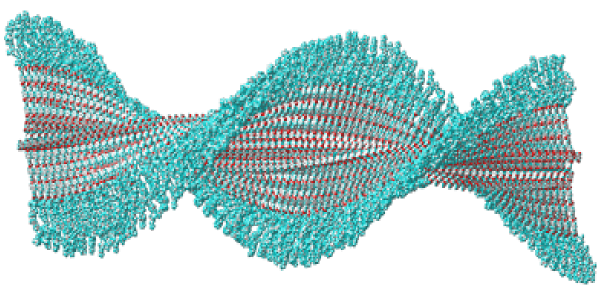
4. Designing molecules

with new structures and functionalities

Example for hierarchical selfassembling - 4th NT generation (in research)

EX: - Biomaterials for human repair: nerves, tissues, wounds (Sam Stupp, NU)





- New nanomachines, robotics - DNA architectures (Ned Seeman, Poly. Inst.)
- Designed molecules for self-assembled porous walls (Virgil Percec, U. PA)
- Self-assembly processing for artificial cells (Matt Tirrell, UCSB)
- Block co-polymers for 3-D structures on surfaces (U. Mass, U. Wisconsin)

Need for nanomanufacturing in the U.S.

- Service work alone is not sufficient for a modern economy
- Nano - broad based technology to enhance or replace mature technologies in order to maintaining high paying jobs
- Better opportunities for nanomanufacturing in US when:
  - Need of advanced infrastructure and multidisciplinary teams
  - Highly automated processes
  - Linked to biotechnology, medicine and overall converging technologies
  - Adapting existing manufacturing infrastructure
  - Requiring an ecology of innovation
  - Signs of an industrial policy (re: co-investment, partners, tax)

NNI "signature initiatives"
2012-2013

Sustainable Nanomanufacturing

Nanoelectronics for 2020 and Beyond

Nanotechnology for Solar Energy

Nanotechnology Knowledge Infrastructure

Nanotechnology for Sensors

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)

FY 2012 at NSF
Three system oriented nano centers

Nanosystems Engineering Research Centers

for 5 + 5 years (~ $4M / year per center)

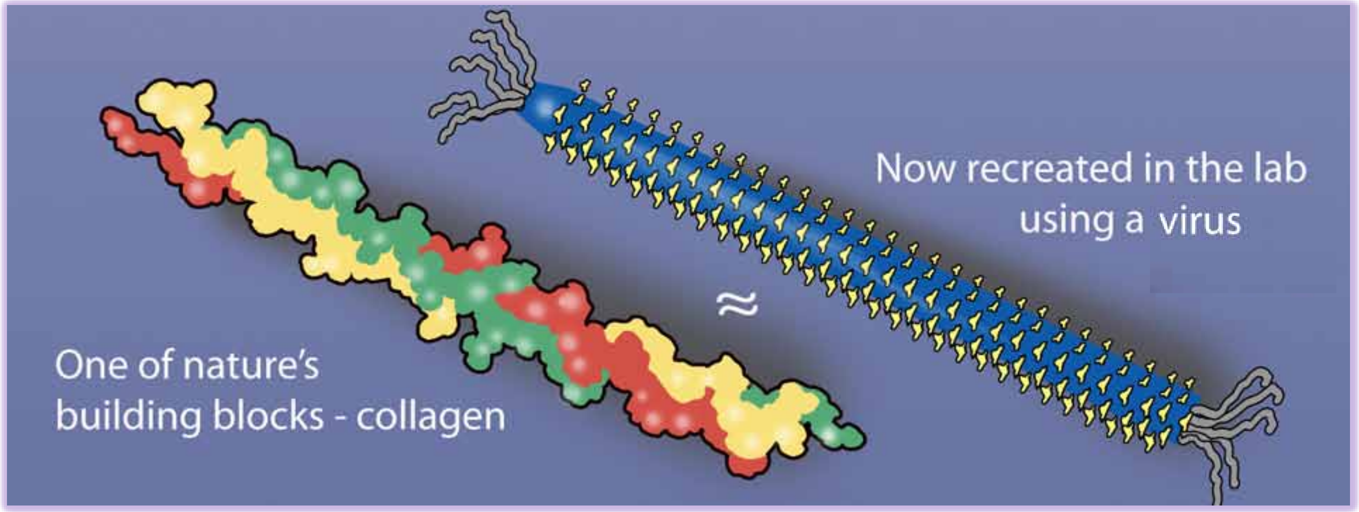
Three awards in 2012 $55.5M for 5 years

Address major topics from discovery to innovation

NSF is a contributor to Advanced Manufacturing

- **Cyber-Enabled Materials, Manufacturing, and Smart-Systems (CEMMSS)**

$110 M for CEMMSS In 2012



Credit: Zina Deretsky, National Science Foundation

Defining Convergence

Convergence is the process / approach to achieve reciprocal compatibility & synergism of different disciplines, technologies and communities by integrated application of knowledge at all length (e.g. starting from atom, gene, and neuron scale), time, complexity and societal levels, for common goals.

Levels of convergence

Nanotechnology – integrate knowledge of material world

NBIC – integrate foundational emerging tools (nano-bio-IT-cogno)

NBIC2 – integration of essential convergence platforms in knowledge, technology and society

NSF (2001-): Converging technologies (NBIC) - Examples of new transdisciplinary domains

- **Quantum information science** (IT; Nano and subatomic physics; System approach for dynamic/ probabilistic processes, entanglement and measurement)
- **Eco-bio-complexity** (Bio; Nano; System approach for understanding how macroscopic ecological patterns and processes are maintained based on molecular mechanisms, evolutionary mechanisms; interface between ecology and economics; epidemiological dynamics)
- **Neuromorphic engineering** (Nano, Bio, IT, neurosc.)
- **Cyber-physical systems** (IT, NT, BIO, others)
- **Synthetic & system biology** (Bio, Nano, IT, neuroscience)
- **Cognitive enhancers** (Bio, Nano, neuroscience)

Converging Technologies for Societal Benefit

Workshop June 2012, Report presentation: Dec 2012 (NSF)

10 Innovative & responsible governance

CONVERGENCE IMPLEMENTATION

5 Human health & Physical potential

6 Cognition & communication

7 Societal collective outcomes: Manu

8 Prepare people & infrastructure

9 Sustainable development

CONVERGENCE OUTCOMES DOMAINS

1 Foundational Tools - NBIC

2 Earth scale

3 Human scale & quality of life

4 System approach & synergism

CONVERGENCE PLATFORMS

MC Roco, Sept 5 2012

Covergence of knowledge and technology – several implications

- Shift manufacturing capabilities from the hands of few to the hands of the many contributors with many skills
  - that may increase innovation
- Distributed, multi-approach manufacturing
  - that may alter how knowledge is being created
- Multi-functional NBIC nanomanufacturing, with bio-systems, robotic and design by simulation dimensions
  - that may increase efficiency and added-value