Proceedings of the WTEC Workshop

Nanotechnology Long-term Impacts and Research Directions: 2000-2020

National Science Foundation
Arlington, VA 22203
September 30, 2010

Nanotechnology Long-term Impacts and Research Directions: 2000-2020

Sponsored by the National Science Foundation (NSF).

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WTEC Mission

WTEC provides assessments of international research and development in selected technologies under awards from the National Science Foundation (NSF), the Office of Naval Research (ONR), and other agencies. Formerly part of Loyola College, WTEC is now a separate nonprofit research institute. Michael Reischman, Deputy Assistant Director for Engineering, is NSF Program Director for WTEC. Sponsors interested in international technology assessments and related studies can provide support for the program through NSF or directly through separate grants or GSA task orders to WTEC. WTEC2 is a sister small business.

WTEC's mission is to inform U.S. scientists, engineers, and policymakers of global trends in science and technology. WTEC assessments cover basic research, advanced development, and applications. Panels of six to nine technical experts conduct WTEC assessments. Panelists are leading authorities in their field, technically active, and knowledgeable about U.S. and foreign research programs. As part of the assessment process, panels visit and carry out extensive discussions with foreign scientists and engineers in their labs.

The WTEC staff helps select topics, recruits expert panelists, arranges study visits to foreign laboratories, organizes workshop presentations, and edits and publishes the final reports. R. D. Shelton is the WTEC point of contact: telephone 410-467-9832 or email Shelton@ScienceUS.org.

WTEC Proceedings Report on

NANOTECHNOLOGY LONG-TERM IMPACTS AND RESEARCH DIRECTIONS: 2000-2020

September 2010

Mihail Roco (Coordinator)
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Nanotechnology Long-term Impacts and Research Directions: 2000-2020

NSF, Stafford II, room 565

Public Presentation of the Final Report

September 30, 2010

Final draft report: http://wtec.org/nano2/; *draft report will be posted on this website.*
Public Comment: http://www.nano2review.org/; *input will be accepted from September 30 to October 15, 2010.*
Webcast Access: www.tvworldwide.com/events/NSFnano2/100930*; to view the webcast, access the website and provide your email address; the webcast may be viewed in Room 370 during the workshop.*

Agenda

8:00 Registration and Coffee
8:30 Welcome, Tom Peterson, NSF
8:40 Overview of the Study, Mark Hersam, NU
8:50 Long-term View of Nanotechnology Development, Mike Roco, NSF
9:10 Scientific, Engineering, and Societal Challenges for Nanotechnology, Chad Mirkin, NU
9:30 ***Chapter 1.*** Enabling and Investigative Tools: Theory, Modeling, and Simulation
Mark Lundstrom, Purdue U.
9:50 ***Chapter 2.*** Enabling and Investigative Tools: Measuring Methods, Instruments, and Metrology
Dawn Bonnell, U. Pennsylvania

10:10-10:20 Break

10:20 ***Chapter 3.*** Synthesis, Processing, and Manufacturing of Nanoscale Components, Devices, and Systems, Mark Tuominen, University of Massachusetts Amherst (and Chad Mirkin, NU)
10:40 ***Chapter 4.*** Nanotechnology Environmental, Health, and Safety Issues
Andre Nel, University of California Los Angeles
11:00 ***Chapter 5.*** Nanotechnology for Sustainability: Environment, Water, Food, and Climate
Mamadou Diallo, California Institute of Technology (and Jeff Brinker, SNL and UNM)
11:20 ***Chapter 6.*** Nanotechnology for Sustainability: Energy Conversion, Storage, and Conservation
Jeff Brinker, SNL and UNM (and Jim Murday, USC)

11:40-1:00 Lunch

12:00-12:30 Press conference (Room 110)

1:00 ***Chapter 7.*** Applications: Nanobiosystems, Medicine, and Health
Chad Mirkin, NU (and Andre Nel, UCLA)
1:20 ***Chapter 8.*** Applications: Nanoelectronics and Nanomagnetics
Jeff Welser, IBM and Nanoelectronics Research Initiative (and Stuart Wolf, UVA)
1:40 ***Chapter 9.*** Applications: Photonics and Plasmonics
Evelyn Hu, Harvard University (and Stuart Wolf, UVA; Jeff Welser, IBM and NRI)
2:00 ***Chapter 10.*** Applications: Nanostructured Catalysts
Evelyn Hu, Harvard University
2:20 ***Chapter 11.*** Applications: High-performance Nanomaterials and Other Emerging Areas
Mark Hersam, NU
2:40 ***Chapter 12.*** Preparation of People and Physical Infrastructure
James Murday, University of Southern California (and Mark Hersam, NU)
3:00 ***Chapter 13.*** Innovative and Responsible Governance
Mike Roco, NSF
3:20 Overarching Conclusions
3:30 General Questions and Answers
4:30 Adjourn

Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

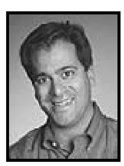
Introduction and Overview of the Nano2 Study

National Science Foundation
Arlington, Virginia
September 30, 2010

Mark C. Hersam
Professor of Materials Science and Engineering
Northwestern University
http://www.hersam-group.northwestern.edu/

Panel Members


Mike Roco (NSF)

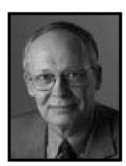

Chad Mirkin, Co-Chair (Northwestern)


Mark Hersam, Co-Chair (Northwestern)


Dawn Bonnell (Penn)


C. Jeffrey Brinker (Sandia)


Evelyn Hu (Harvard)


Mark Lundstrom (Purdue)


André Nel (UCLA)


Jeffrey Welser (IBM)

Additional Committee Members

Mark Tuominen, University of Massachusetts Amherst
(Synthesis, Assembly, and Processing)

Mamadou Diallo, California Institute of Technology
(Sustainability of Environment and Industry)

Jim Murday, University of Southern California
(Needs for R&D and Education; Sustainability)

Stuart Wolf, University of Virginia
(Nanoelectronics and Nanosystems)

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Introduction to the Nano2 Study

History (Advent of the NNI)

- International Study (Siegel, Hu, Roco, 1999)
- Research Agenda Workshop (Roco, Williams, Alivisatos, 2000)
- Helped formulate and justify the NNI

Other Recent Studies (Reviewing the NNI)

- National Academies, PCAST
- Assessment of the NNI, primarily focused on USA

Goals of the Nano2 Study

- **International assessment of nanoscale science, engineering, and education**
- **Vision and opportunities for the future (5-10 years)**
- **Report speaks to many audiences on a global scale (e.g., policy makers, investors, researchers, students, etc.)**

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Nano2 Workshops

Chicago Workshop
- March 9-10, 2010
- Participants primarily from North America

Hamburg Workshop
- June 23-24, 2010
- Participants primarily from the European Union

Tsukuba Workshop
- July 26-27, 2010
- Participants primarily from Japan, Korea, and Taiwan

Singapore Workshop
- July 29-30, 2010
- Participants primarily from Singapore, China, Australia, India, and Saudi Arabia

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Nano2 Study Topics: Fundamentals

Enabling principles and infrastructure
- Theory, modeling, and simulation
- Measuring methods, instruments, and metrology
- Synthesis, processing, and nanomanufacturing

Oversight and workforce development
- Proactive and responsible governance
- Environment, health, and safety
- Education at all levels

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Nano2 Study Topics: Applications

- Sustainability (environment, water, food, climate)
- Energy conversion, storage, and conservation
- Nanobiosystems, medicine, and health
- Nanoelectronics and nanomagnetics
- Photonics and plasmonics
- Catalysis (efficient chemical processing)
- High-performance nanomaterials

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Conclusions and Acknowledgments

Primary attributes of the Nano2 study:

- International perspective
- Assessment of the past decade (2000-2010)
- Vision for the next decade (2010-2020)

Thank you:

- All attendees, observers, media
- Sponsors
- Panelists and committee members
- WTEC and NSF staff

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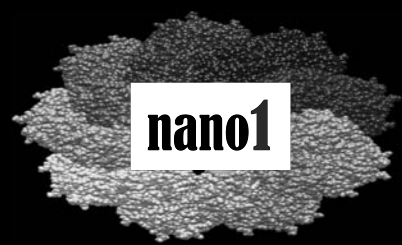
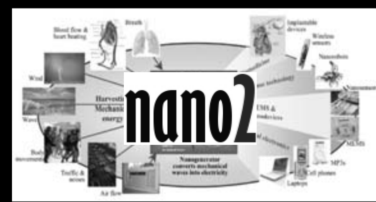




Long-term View of Nanotechnology Development

Mike Roco

NSF and NNI

Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

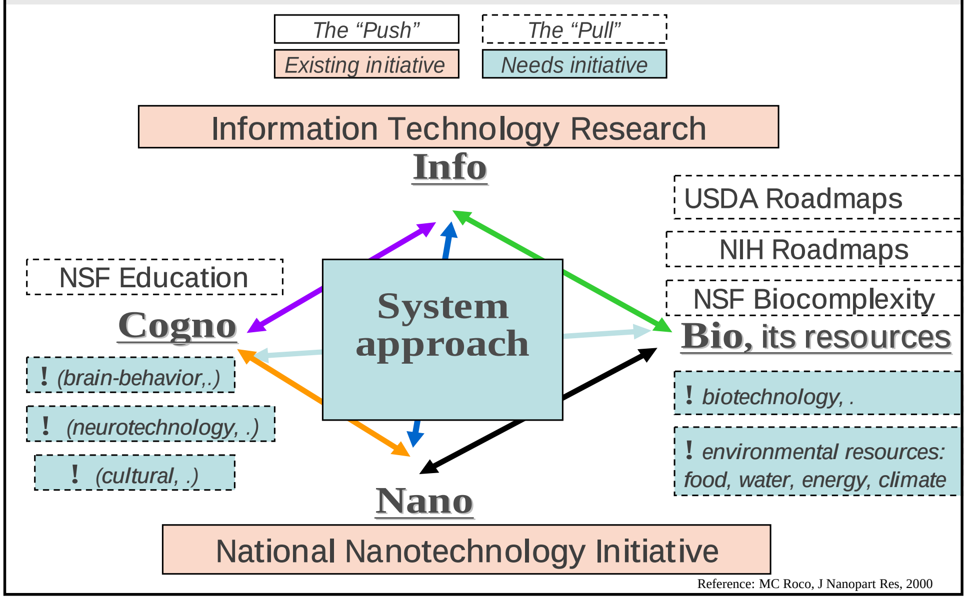
NSF, September 30 2010

2000-2008 Estimates show an average growth rate of key nanotechnology indicators of ~ 25%

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/
2008 *(actual)*	~ 400,000 /150,000/	65,000 /15,000/	12,776 /3,729/	~ $200 B /$80 B/	~ $14 B /$3.7 B/	~ $1.4 B /$1.17 B/
2000 - 2008 average growth	~ 25%	~ 23%	~ 35%	~ 25%	~ 35%	~ 30%
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 30 2010

Nanotechnology at the core of convergence of new emerging technologies (overview 2000)



Benchmark with experts in over 20 countries in 1997-1999

"Nanostructure Science and Technology"

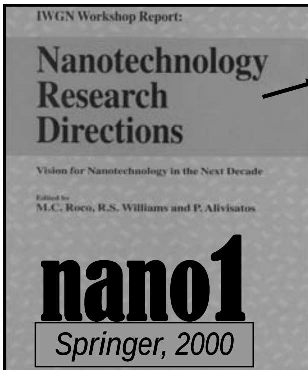
NNI preparatory Report, Springer, 1999

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 fundamentally new properties and functions because of their small structure

- NNI definition encourages new R&D that were not possible before:
  - ***the ability to control and restructure matter at nanoscale***
  - ***new phenomena, properties leading to novel applications***
  - ***integration along length scales, systems and applications***

MC Roco, WH, March 11 1999



"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

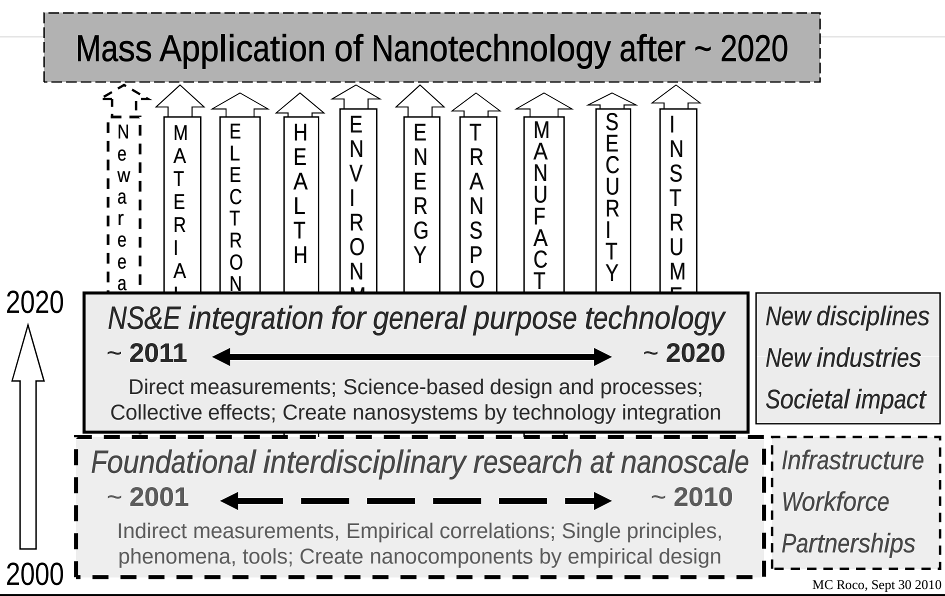
- *Change the foundations from micro to nano*
- *Create a general purpose technology (similar IT)*

More important than miniaturization itself:

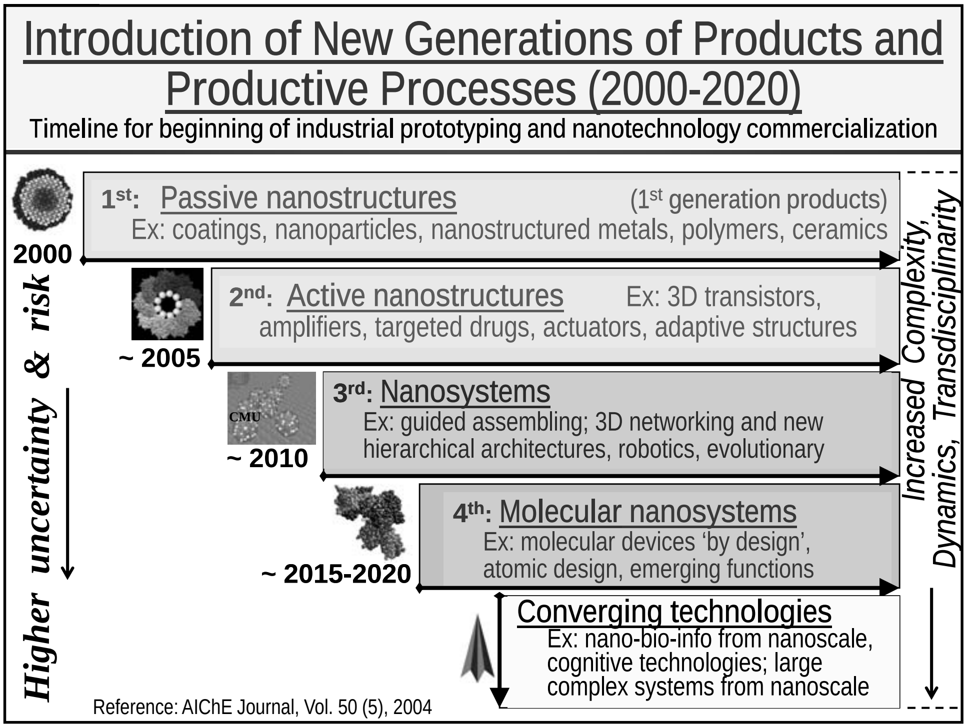
- Novel properties/ phenomena/ processes/ natural threshold
- Unity and generality of principles
- Most efficient length scale for manufacturing, biomedicine
- Show transition from basic phenomena and components to system applications in 10 areas and 10 scientific targets

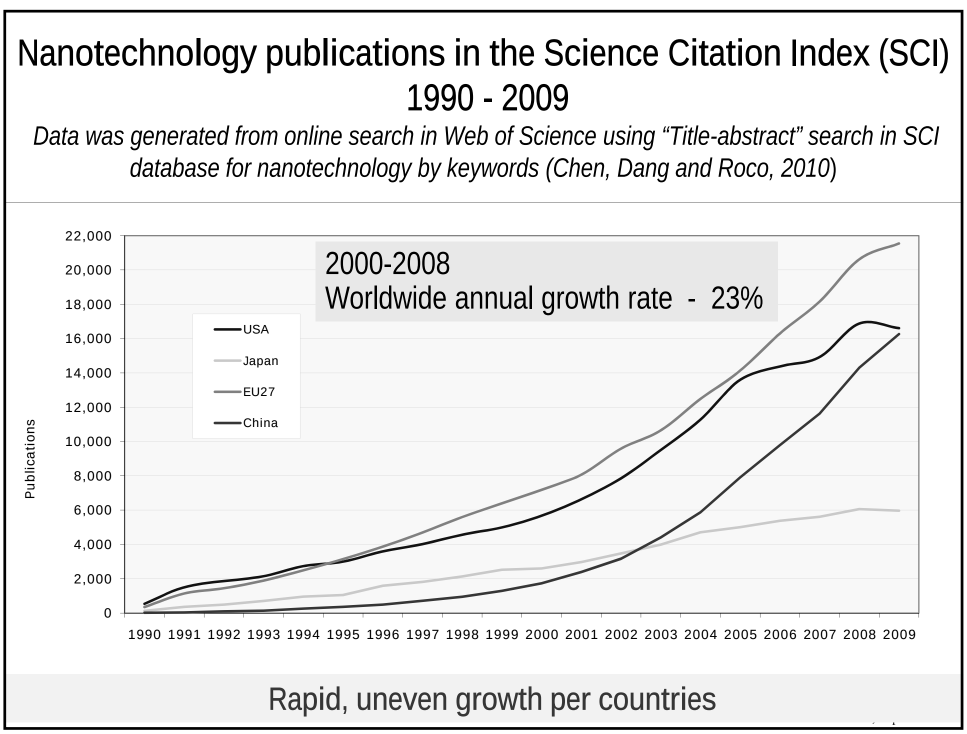
MC Roco, WH, March 11 1999

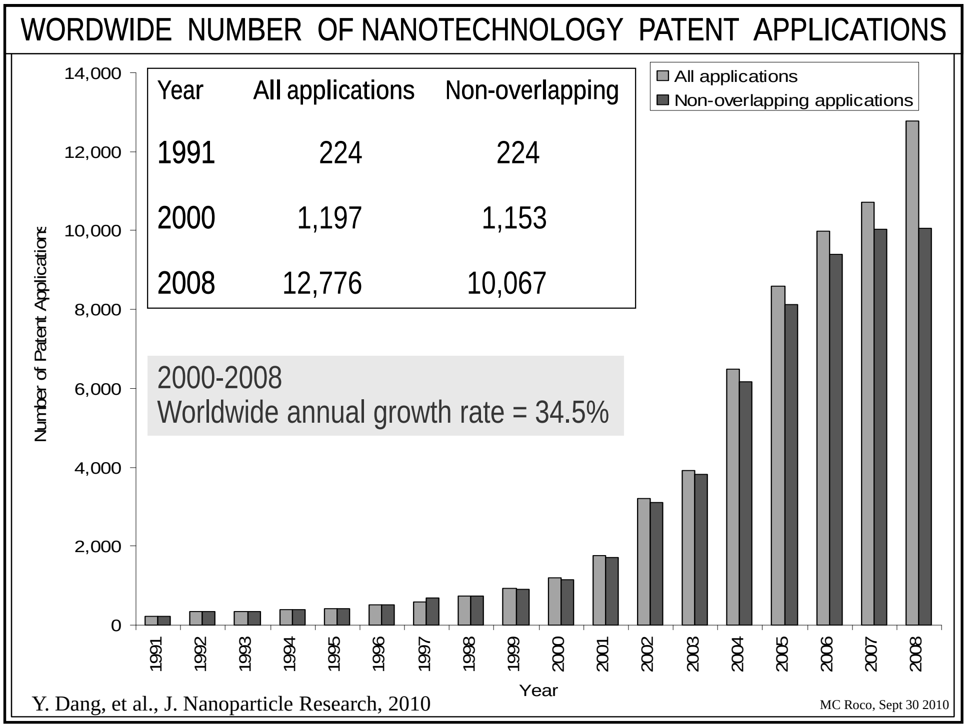
CREATING A NEW FIELD AND COMMUNITY IN TWO FOUNDATIONAL STEPS (2000~2020)

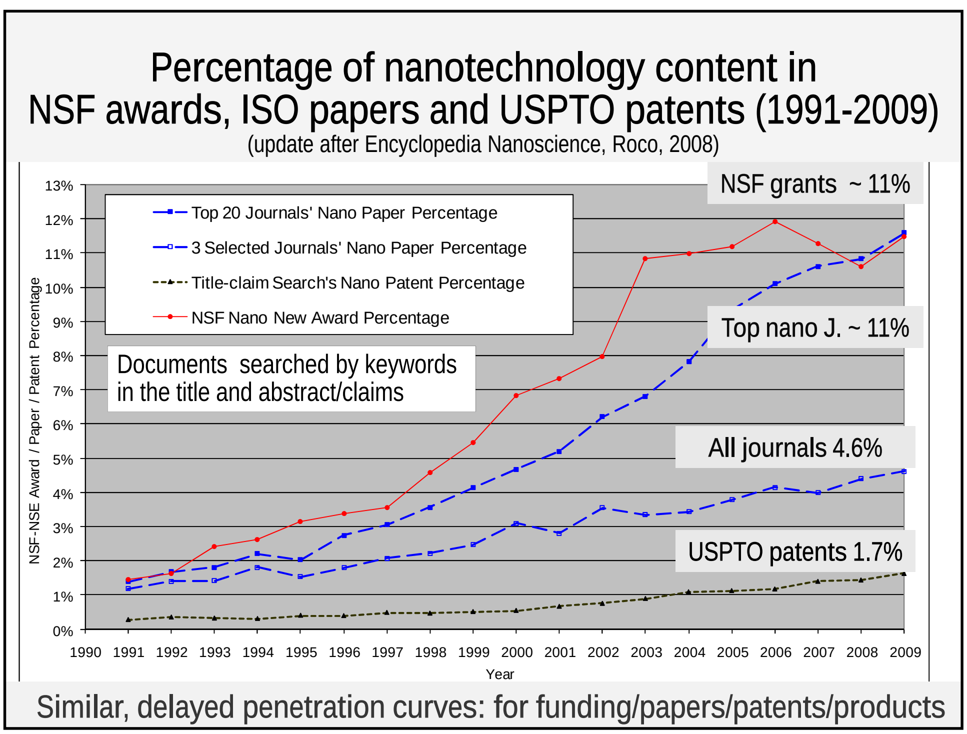


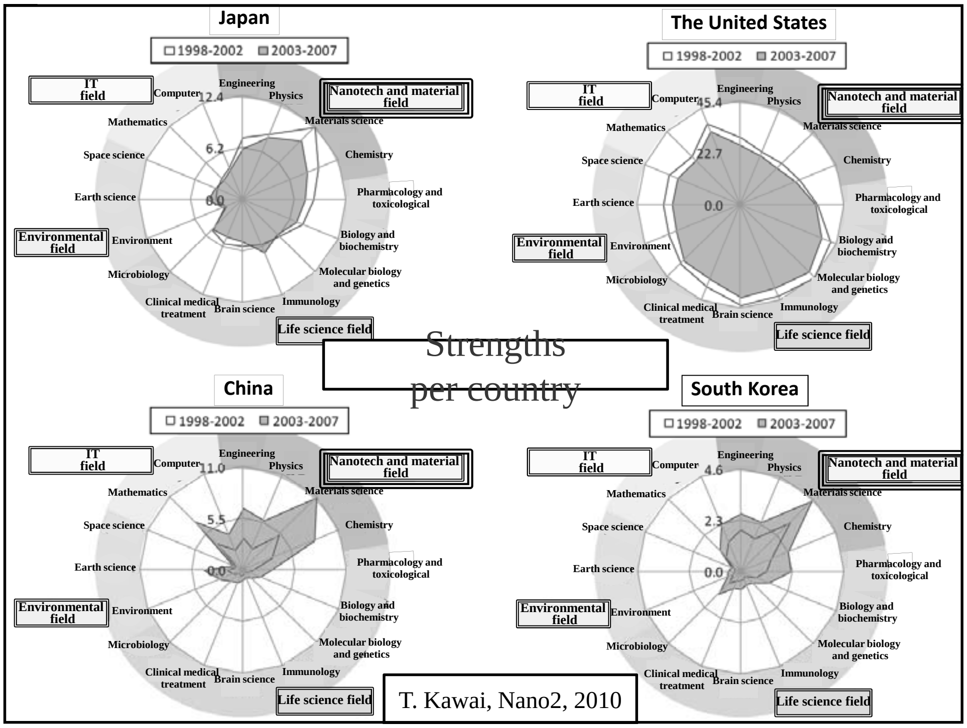
MC Roco, Sept 30 2010

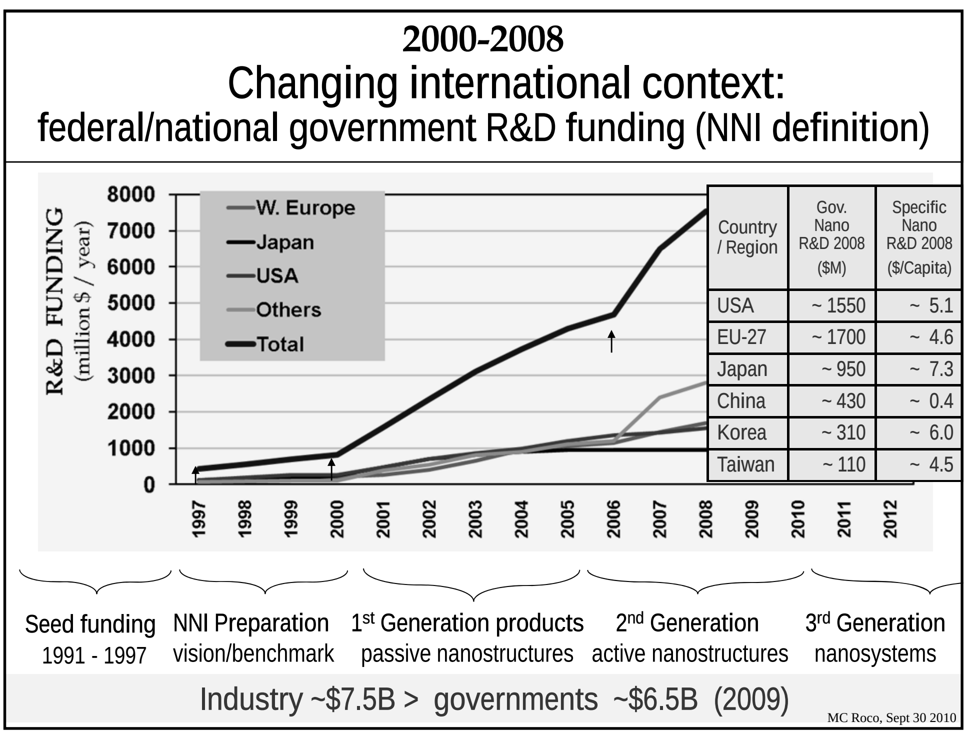

Introduction of New Generations of Products and Productive Processes (2000-2020)
Timeline for beginning of industrial prototyping and nanotechnology commercialization
1st: Passive nanostructures (1st generation products)
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics
2000
2nd: Active nanostructures Ex: 3D transistors, amplifiers, targeted drugs, actuators, adaptive structures
~ 2005
3rd: Nanosystems
Ex: guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary
CMU
~ 2010
4th: Molecular nanosystems
Ex: molecular devices 'by design', atomic design, emerging functions
~ 2015-2020
Converging technologies
Ex: nano-bio-info from nanoscale, cognitive technologies; large complex systems from nanoscale
Higher uncertainty & risk
Increased Complexity, Dynamics, Transdisciplinarity
Reference: AIChE Journal, Vol. 50 (5), 2004


Nanotechnology publications in the Science Citation Index (SCI) 1990 - 2009
Data was generated from online search in Web of Science using "Title-abstract" search in SCI database for nanotechnology by keywords (Chen, Dang and Roco, 2010)
2000-2008
Worldwide annual growth rate - 23%
USA
Japan
EU27
China
Publications
22,000
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
Rapid, uneven growth per countries


WORDWIDE NUMBER OF NANOTECHNOLOGY PATENT APPLICATIONS
Year All applications Non-overlapping
1991 224 224
2000 1,197 1,153
2008 12,776 10,067
All applications
Non-overlapping applications
2000-2008
Worldwide annual growth rate = 34.5%
Number of Patent Applications
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008
Year
Y. Dang, et al., J. Nanoparticle Research, 2010
MC Roco, Sept 30 2010


Percentage of nanotechnology content in
NSF awards, ISO papers and USPTO patents (1991-2009)
(update after Encyclopedia Nanoscience, Roco, 2008)
NSF grants ~ 11%
Top 20 Journals' Nano Paper Percentage
3 Selected Journals' Nano Paper Percentage
Title-claim Search's Nano Patent Percentage
NSF Nano New Award Percentage
Documents searched by keywords
in the title and abstract/claims
Top nano J. ~ 11%
All journals 4.6%
USPTO patents 1.7%
NSF-NSE Award / Paper / Patent Percentage
13%
12%
11%
10%
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
Year
Similar, delayed penetration curves: for funding/papers/patents/products


Japan
The United States
China
South Korea
1998-2002
2003-2007
IT field
Nanotech and material field
Environmental field
Life science field
Computer
Engineering
Physics
Materials science
Chemistry
Pharmacology and toxicological
Biology and biochemistry
Molecular biology and genetics
Immunology
Brain science
Clinical medical treatment
Microbiology
Environment
Earth science
Space science
Mathematics
Strengths per country
T. Kawai, Nano2, 2010


2000-2008
Changing international context:
federal/national government R&D funding (NNI definition)
R&D FUNDING (million $ / year)
W. Europe
Japan
USA
Others
Total
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
Industry ~$7.5B > governments ~$6.5B (2009)
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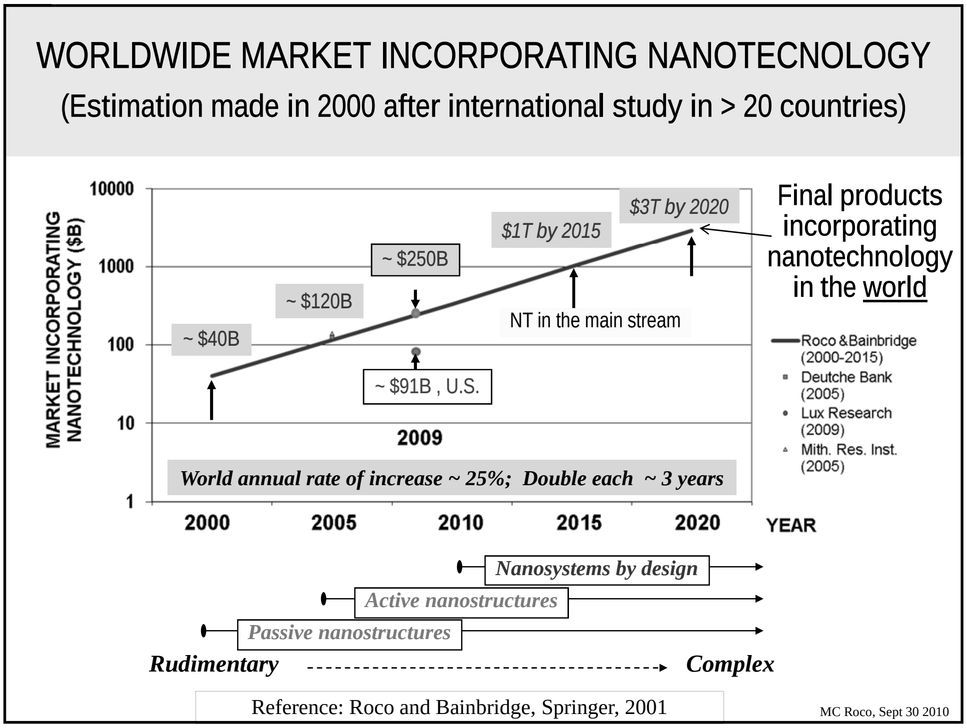
WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY
(Estimation made in 2000 after international study in > 20 countries)
MARKET INCORPORATING NANOTECHNOLOGY ($B)
10000
1000
100
10
1
~ $40B
~ $120B
~ $250B
~ $91B , U.S.
$1T by 2015
$3T by 2020
NT in the main stream
2009
Final products incorporating nanotechnology in the world
Roco & Bainbridge (2000-2015)
Deutche Bank (2005)
Lux Research (2009)
Mith. Res. Inst. (2005)
World annual rate of increase ~ 25%; Double each ~ 3 years
2000
2005
2010
2015
2020
YEAR
Nanosystems by design
Active nanostructures
Passive nanostructures
Rudimentary
Complex
Reference: Roco and Bainbridge, Springer, 2001
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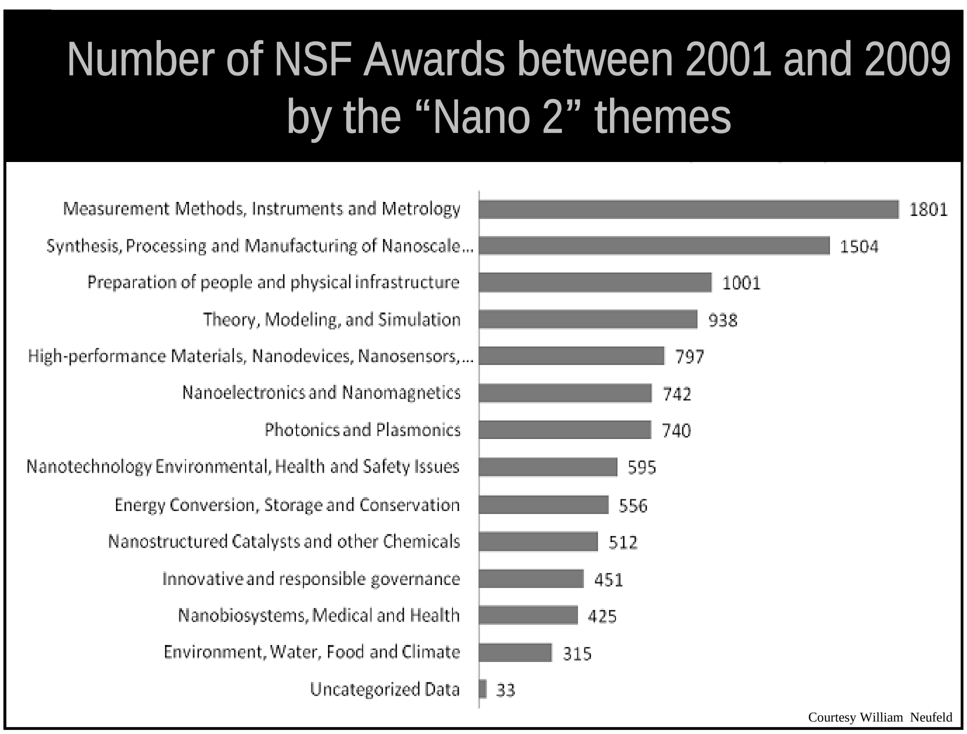
Number of NSF Awards between 2001 and 2009 by the "Nano 2" themes
Measurement Methods, Instruments and Metrology 1801
Synthesis, Processing and Manufacturing of Nanoscale... 1504
Preparation of people and physical infrastructure 1001
Theory, Modeling, and Simulation 938
High-performance Materials, Nanodevices, Nanosensors,... 797
Nanoelectronics and Nanomagnetics 742
Photonics and Plasmonics 740
Nanotechnology Environmental, Health and Safety Issues 595
Energy Conversion, Storage and Conservation 556
Nanostructured Catalysts and other Chemicals 512
Innovative and responsible governance 451
Nanobiosystems, Medical and Health 425
Environment, Water, Food and Climate 315
Uncategorized Data 33
Courtesy William Neufeld

The long-term view drives NNI
2000-2020

- <u>NNI was designed as a science project</u> after two years of planning without dedicated funding in 1997-1999:
  - Long-term view ("Nanotechnology Research Directions")
  - Definitions and international benchmarking ("Nanostructure S&T")
  - Science and Engineering Priorities and Grand Challenges ("NNI")
  - Societal implications ("NSF Report", 2000)
  - Plan for government agencies ("National plans and budgets")
  - Public engagement brochure ("Reshaping the word", 1999)
- <u>Combine four time scales in planning (2001-2005)</u>
  Vision - 10-20yrs, Strategic plan – 3 yrs, Annual budget - 1yr, and Management decisions - 1 month;
  at four levels: program, agency, national executive, legislative

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Nanotechnology in 2010 - still in an earlier formative phase of development

- <u>Characterization</u> of nanomodules is using micro parameters and not internal structure
- <u>Measurements and simulations</u> of a domain of biological or engineering relevance cannot be done with atomic precision and time resolution of chemical reactions
- <u>Manufacturing Processes</u> – empirical synthesis/processing, better control for one chemical component in steady state
- <u>Nanotechnology products</u> are using only rudimentary nanostructures (dispersions in catalysts, layers in electronics) incorporated in existing products or systems
- <u>Enabling new technologies (QIS, Syn Bio, CT. .)</u> – in formation
- <u>Knowledge for risk governance</u> – in formation

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Twelve trends to 2020

- 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, selfrepariting, 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 - economic by 2015, mass use
- Enabling and integrating with new areas – bio, info, cognition
- Earlier preparing nanotechnology workers – system integration
- Governance of nano for societal benefit - institutionalization

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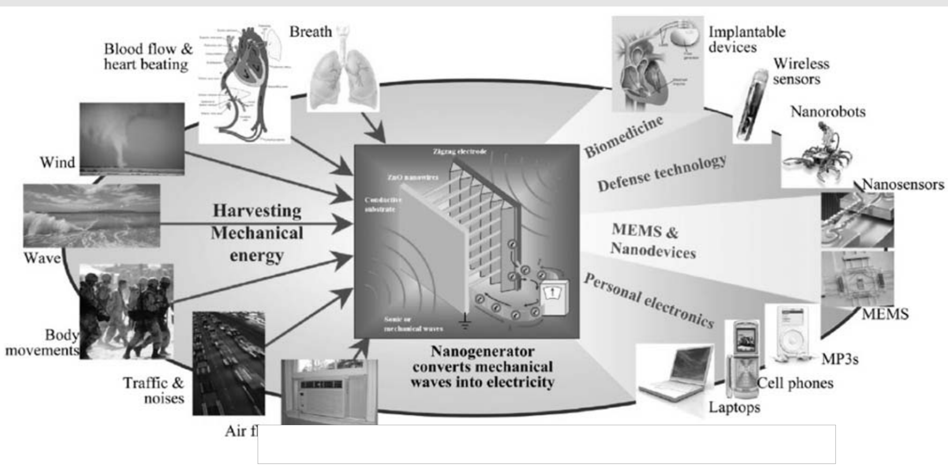
Ex: Self-powered nanosystems

Multifunctional, self-powered nanosystems (using fluid motion, temperature gradient, mechanical energy..) in wireless devices, biomedical systems...



Reference: Z. L. Wang, Adv. Funct. Mater., 2008

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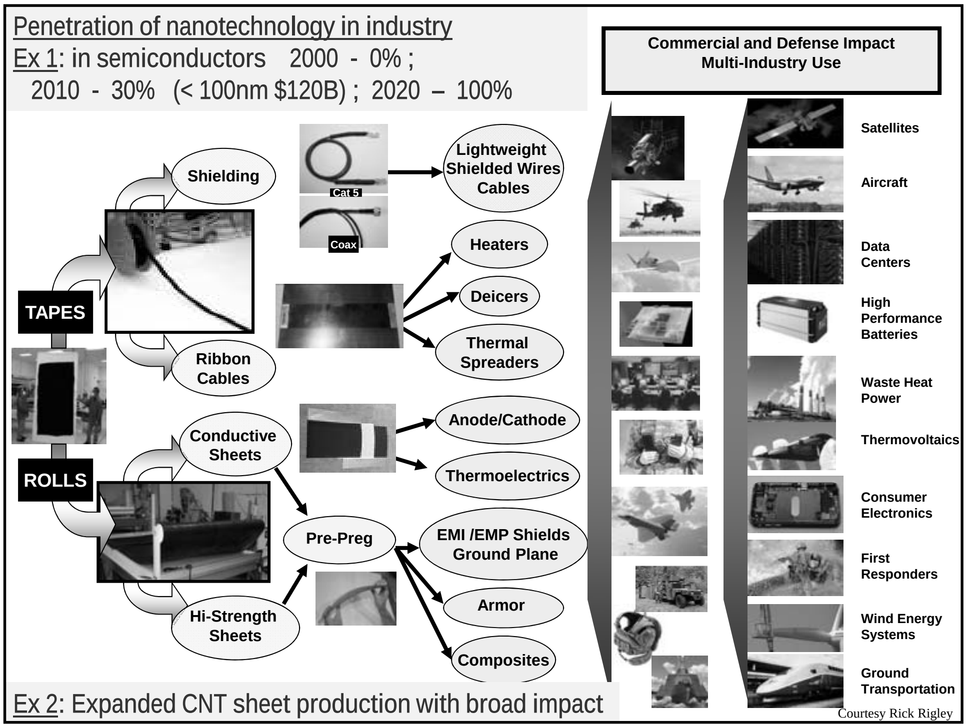
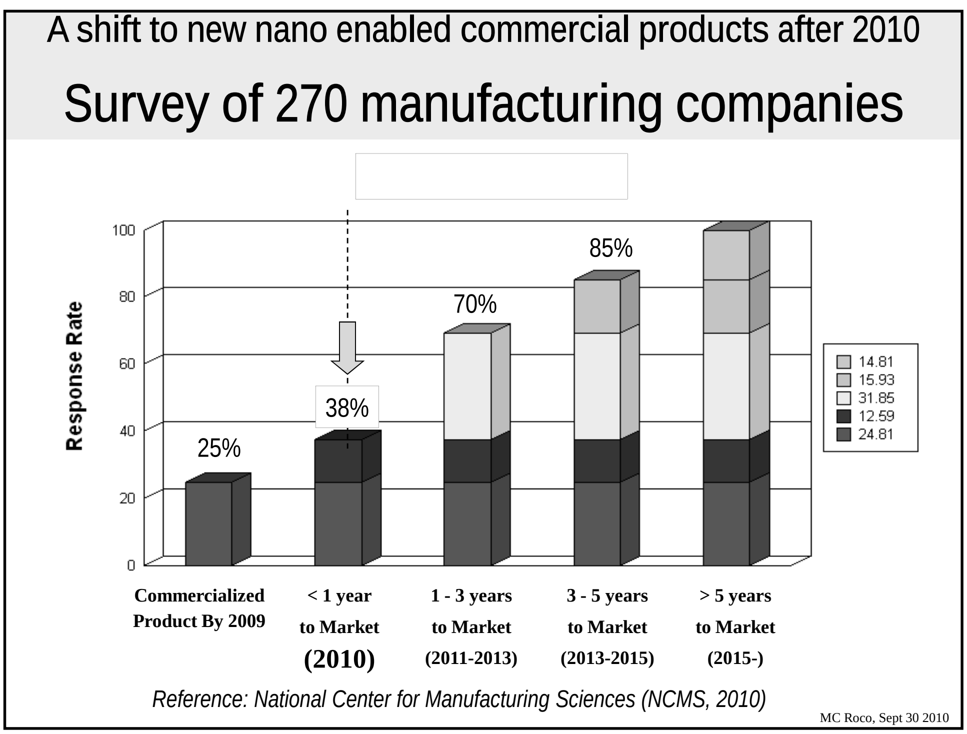

Penetration of nanotechnology in industry
Ex 1: in semiconductors 2000 - 0% ;
2010 - 30% (< 100nm $120B) ; 2020 – 100%
Commercial and Defense Impact
Multi-Industry Use
TAPES
ROLLS
Shielding
Ribbon Cables
Conductive Sheets
Hi-Strength Sheets
Cat 5
Coax
Lightweight Shielded Wires Cables
Heaters
Deicers
Thermal Spreaders
Anode/Cathode
Thermoelectrics
Pre-Preg
EMI /EMP Shields Ground Plane
Armor
Composites
Satellites
Aircraft
Data Centers
High Performance Batteries
Waste Heat Power
Thermovoltaics
Consumer Electronics
First Responders
Wind Energy Systems
Ground Transportation
Ex 2: Expanded CNT sheet production with broad impact
Courtesy Rick Rigley


A shift to new nano enabled commercial products after 2010
Survey of 270 manufacturing companies
Response Rate
100
80
60
40
20
0
25%
38%
70%
85%
14.81
15.93
31.85
12.59
24.81
Commercialized Product By 2009
< 1 year to Market (2010)
1 - 3 years to Market (2011-2013)
3 - 5 years to Market (2013-2015)
> 5 years to Market (2015-)
Reference: National Center for Manufacturing Sciences (NCMS, 2010)
MC Roco, Sept 30 2010

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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

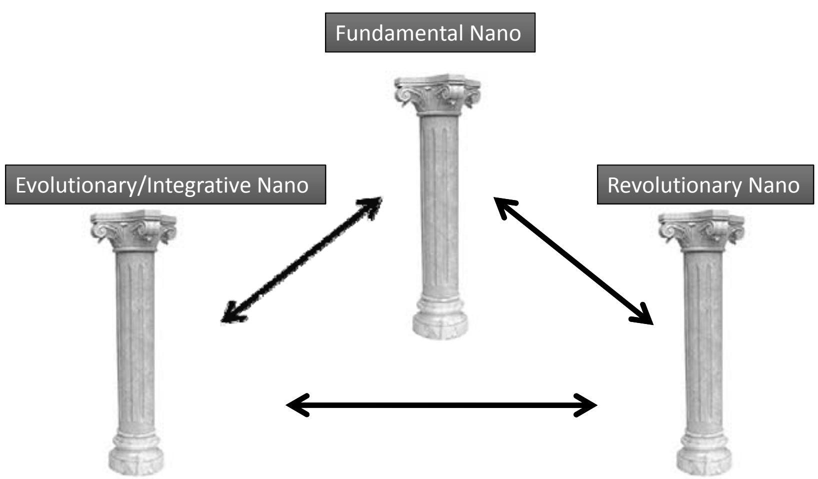
Scientific, Engineering, and Societal Challenges for Nanotechnology

Chad A. Mirkin and Mark Hersam

NSF, September 30, 2010

Pillars of Nanotechnology

The needs and discoveries of one subsection of Nanotechnology inspires and fuels innovation in the others



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Pillars of Nanotechnology

Fundamental Nano

Tool and Materials Development

- Fabrication (two and three-dimensional)
- New Nanostructures (colloids, graphene, anisotropic structures)
- Modeling (predicting structure-property relationships)
- Novel properties and strategies (self-assembly, plasmonics, surface chemistry)
- Single atom, molecule, and single particle spectroscopies enable fundamental studies of biology, chemistry and physics.

Concept Development

- Classification – Creating a clear set of meaningful and teachable rules
- The Nanotech Periodic Table – Atom to Molecule, Nanoparticle to Assembly Analogy
- Moving beyond spherical nanostructures - Anisotropic Structures
- Building valency into a nanostructure – the equivalent of a coordination environment
- Hierarchical design

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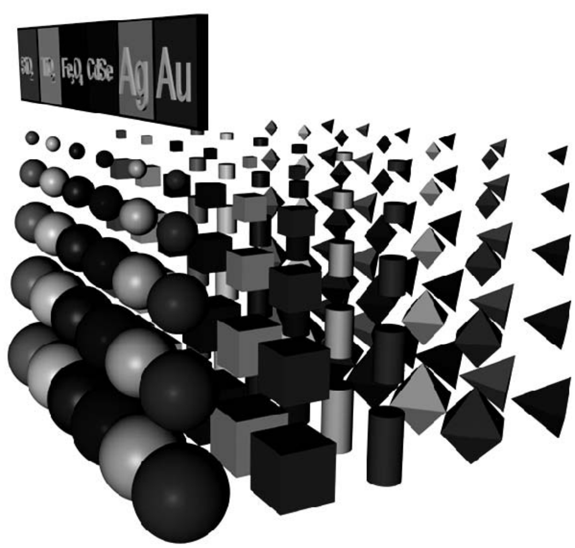
Fundamental Nanotechnology

Nanoscale Building Blocks and Tools for Miniaturization

A Multidimensional "Periodic Table"



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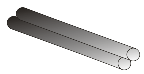
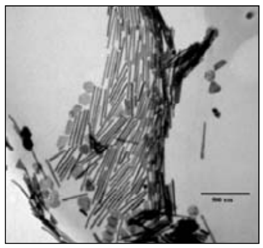
Well Defined Anisotropic Nanostructures

How do we move beyond spherical particles?

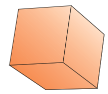


Rods and Wires

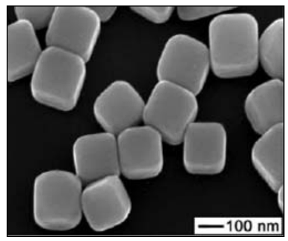


- Thermal
- Photochemical
- Electrochemical

1. Murphy, C.J. et al. *Adv. Mater.* 2003, *15*, 414.
Yang, P. et al. *J. Am. Chem. Soc.* 2002, *124,* 14316.
Martin, C. R. *Science* 1994, *266*, 1961.

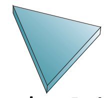


Platonic Solids

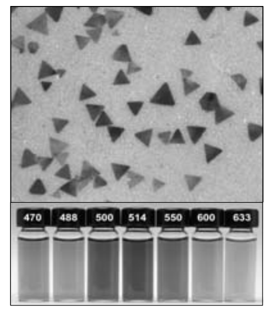


- Thermal

2. El-Sayed, M. A.. Science, 1996, *272*, 1924.
Xia, Y. *Science* 2002, *298*, 2176.
Yang, P. *Angew. Chem.* 2004, *43*, 3673.



Triangular Prisms



- Thermal
- Photochemical

3. Mirkin, C. , Schatz G. *Science*, 2003, *425,* 487. *Nature,* 2003, 425, 487-490

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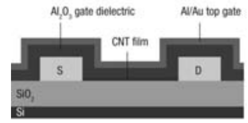
Optically Pure SWNTs By Ultracentrifugation

Materials Today, **10**, 59 (2007).

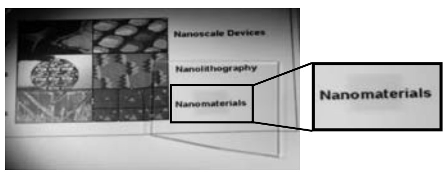
A wide range of optically pure SWNT samples are produced in one density gradient ultracentrifugation step

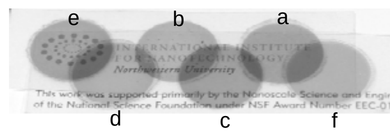
(Raw material = HiPco SWNTs)

Payoff From Carbon-based Nanomaterials Separation Capabilities



- **High Performance Semiconducting FETs**
- **Light Emitting, Aligned Semiconducting FETs**
- **80 GHz Semiconducting SWNT Thin Film FETs (Unaligned)**
- **Transparent Conductors from Metallic SWNTs**
- **Visibly Colored Translucent Metallic SWNT Films**





Pillars of Nanotechnology

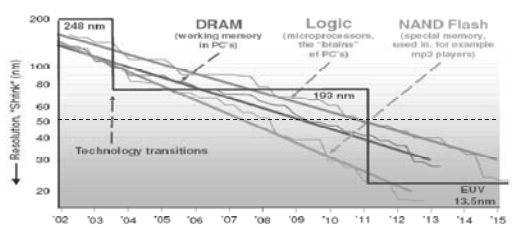
Evolutionary/Integrative Nano

Tool and Materials Development

- Take established methods and materials from Fundamental Nano and Revolutionary Nano to make incremental improvements (titanium dioxide for sunscreen, incremental but important fabrication improvements for semiconductors (.eg. Reduction in feature size of transistor)

Concept Development

- "Drop-In" Technology (adding nanotechnology components to existing modular systems)
- Defined evolutionary technology goals (Moore's law for transistors)
- Rapid integration into existing paradigms



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Pillars of Nanotechnology

Revolutionary Nano

Tool and Materials Development

- Imaging (combining spectroscopy with physical probing)
- Detection (high sensitivity and selectivity)
- Nanomedicine (treatment strategies, tissue engineering, regenerative and reconstruction strategies)

Concept Development

- Lateral application of fundamental observations made in fundamental Nano, which causes disruptive advances in a related field
- Paradigm shifting technology platforms fueled by discovery made in Fundamental Nano (SERS)
- Emergent, surprising properties only accessible through nanotechnology (polyvalency, meta materials)

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Modern Printing Tools Revolutionized the World

Desk Top Printer

Information transfer, the semiconductor industry, the microelectronics revolution, and gene chips

It is exceedingly difficult to print with molecules and many materials on the "nanometer scale"

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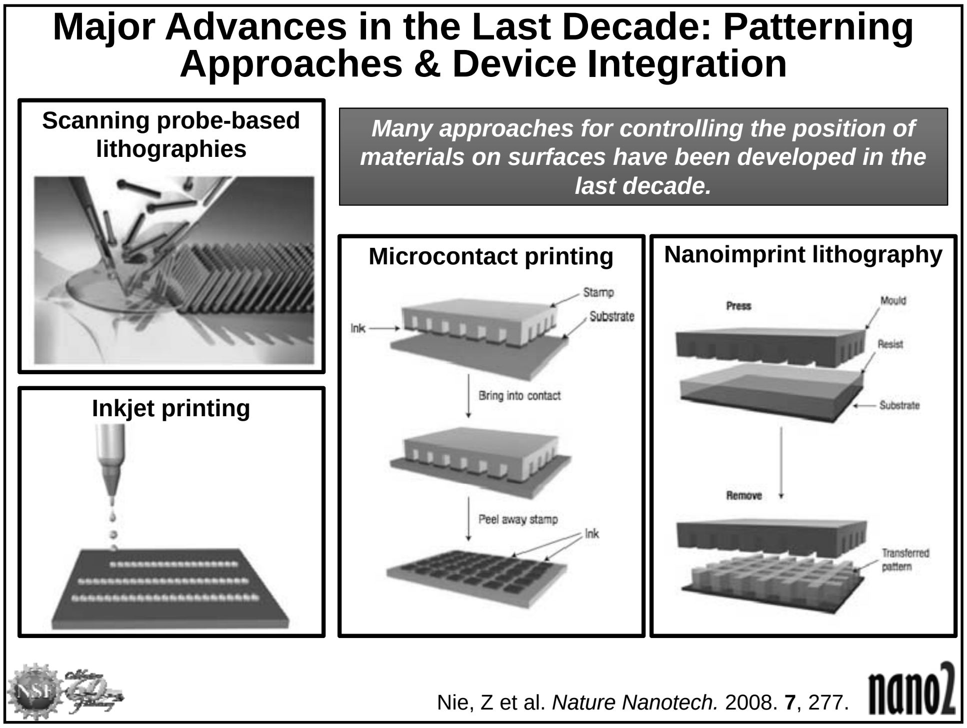
Major Advances in the Last Decade: Patterning Approaches & Device Integration
Scanning probe-based lithographies
Many approaches for controlling the position of materials on surfaces have been developed in the last decade.
Microcontact printing
Stamp
Substrate
Ink
Bring into contact
Peel away stamp
Ink
Nanoimprint lithography
Press
Mould
Resist
Substrate
Remove
Transferred pattern
Inkjet printing
Nie, Z et al. Nature Nanotech. 2008. 7, 277.
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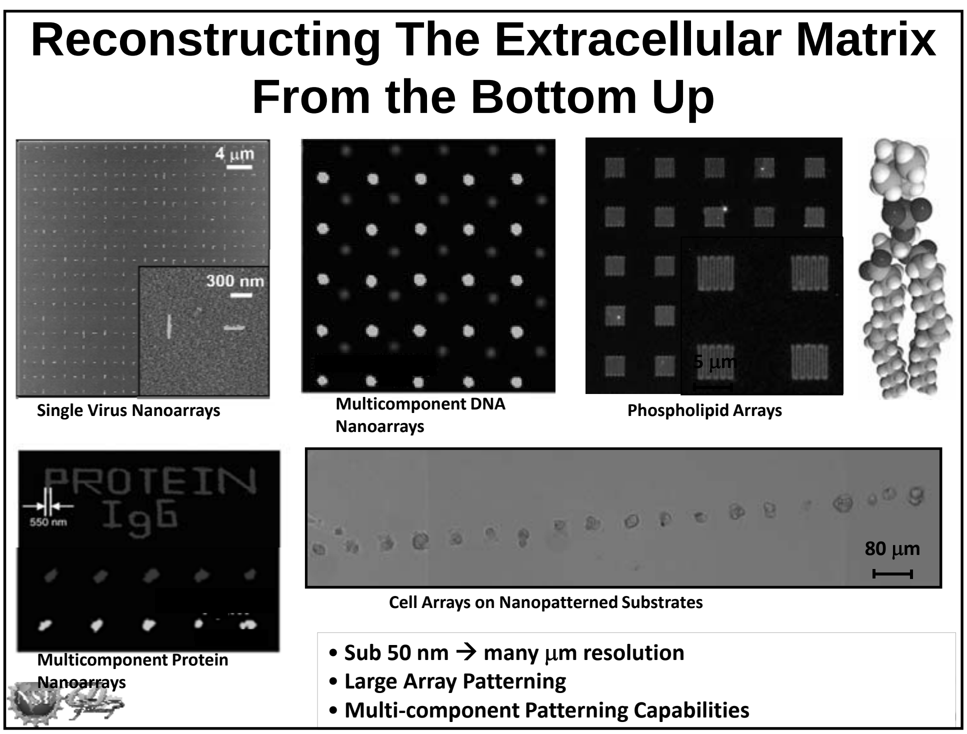
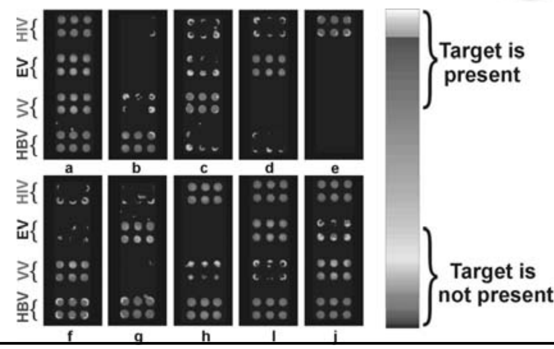

Reconstructing The Extracellular Matrix From the Bottom Up
4 μm
300 nm
Single Virus Nanoarrays
Multicomponent DNA Nanoarrays
5 μm
Phospholipid Arrays
PROTEIN
IgG
550 nm
Multicomponent Protein Nanoarrays
80 μm
Cell Arrays on Nanopatterned Substrates
• Sub 50 nm → many μm resolution
• Large Array Patterning
• Multi-component Patterning Capabilities

Examples of Major Advances in the Last Decade

FDA-approved and commercially available point-of-care diagnostic methods can enable early disease detection.



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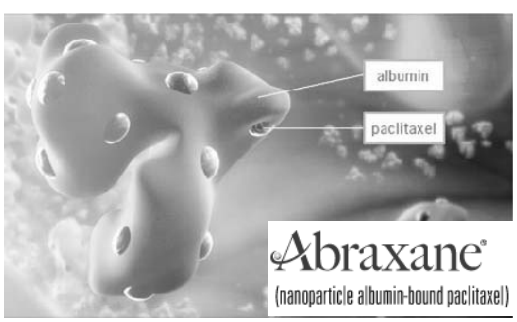
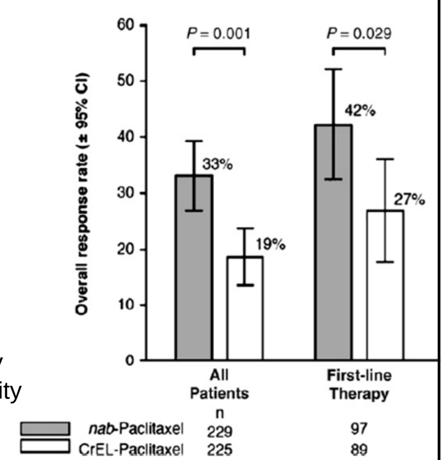
Examples of Major Advances in the Last Decade

Abraxane is a FDA-approved therapeutic which relies on albumin protein nanoparticles as a paclitaxel carrier for more efficient drug delivery to tumor sites.





- Solvent based administration of chemotherapeutic agents has allowed delivery of hydrophobic drugs but has associated toxicity
- Allows delivery of a 49% higher dose of paclitaxel vs solvent-based paclitaxel

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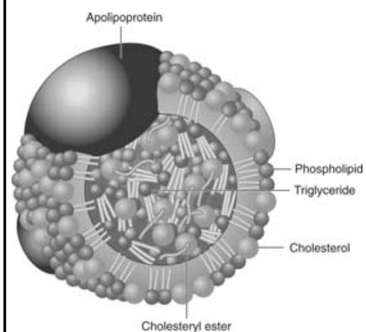
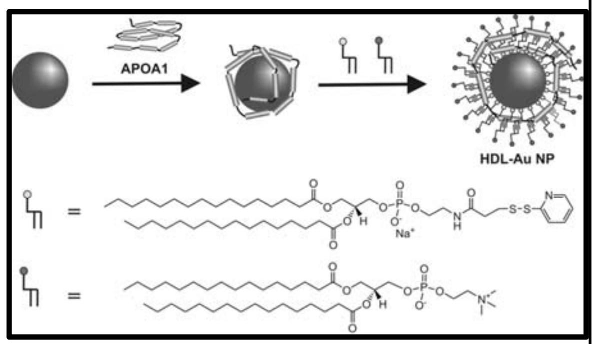
Examples of Major Advances in the Last Decade

Synthetic replacements as therapies in the context of HDL, a model example demonstrating that nanomaterials can mimic size, shape, and activity of biological analogs.

Natural high density lipoprotein (HDL)



Synthetic HDL analog using nanomaterials

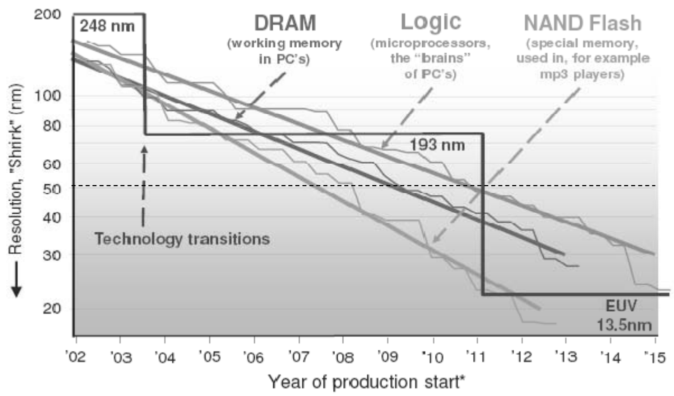


Libby, P. Braunwald's Heart Disease 8th ed., 2008
Schaefer, E. and Asztalos, B. 2007 *Curr Opin Cardiol* 22:373-378.
Singh, I. et al. 2007 *J. Am. Med. Assoc.* 298: 786-798.

Opportunities and Challenges Looking Forward

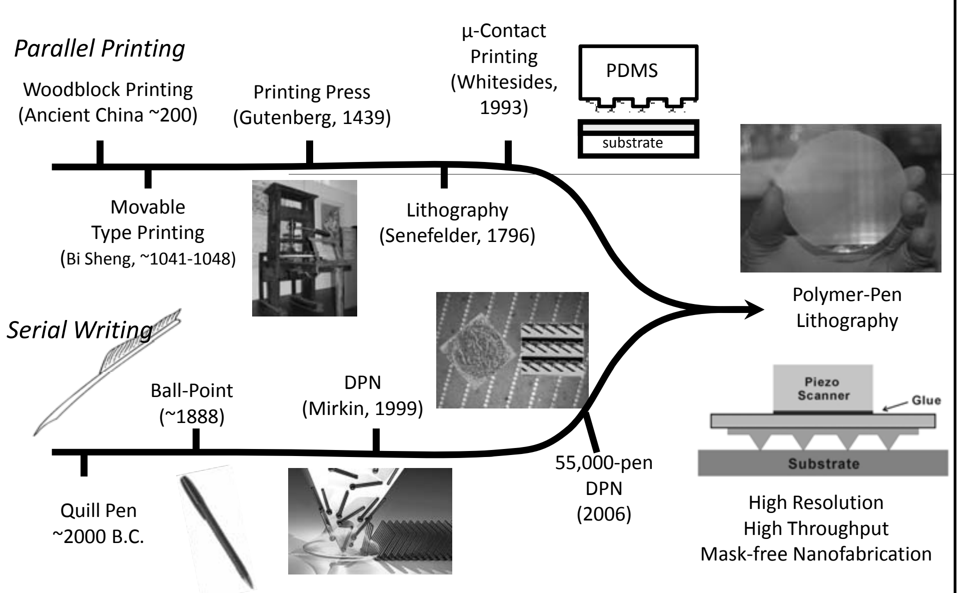
- Nanotechnology, built on a firm foundation of fundamental and basic science and engineering understanding, will impact almost every aspect of human life in the context of both evolutionary and revolutionary technologies.
- Many of the early discoveries on the revolutionary pillar are well-poised for scaling to widely used, manufacturable technologies.
- The field needs to communicate the structure, opportunities, and challenges for the three pillars in the context of textbooks for all levels of education and public outreach. The message has been diluted, in part because of the extraordinary breadth of the field.
- The cost-benefit analysis to the general public needs to be clearly communicated with an appropriate level of expectation with respect to timeline.

Parallel Writing: Lithography gets sub-50 nm



Developing a new lithography technique isn't something that a single company can achieve on its own – it requires effort and investment from across the industry.

Timeline of The Development of Molecular Printing



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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

Chapter 1. Enabling and Investigative Tools: Theory, Modeling, and Simulation

M. Lundstrom, P. Cummings, M. Alam
With collaboration from:
M. Ratner, W. Goddard, S. Glotzer, M. Stopa, B. Baird, R. Davis
International workshop moderators:
Lars Pastewka, Akira Miyamoto, Julian Gale

NSF, September 30, 2010

2

preface

Theory: A set of scientific principles that succinctly describes a class of problems.

Simulation: Application of theory to faithfully render a physical problem in the greatest possible detail.

Modeling: Application of theory to solve specific problems. *Insight*, *intuition*, *simplification* are key factors.

Multi-scale modeling and simulation:

1) **Investigative tools**
2) **Exploratory tools**
3) **Design tools**

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nano2 workshops…

- Tremendous progress in nanoscience TMS over the past 10 yrs.
- Many successes with isolated building blocks
- Need for continued investments in research on fundamentals, methods, computing, …
- Focus now shifting from science to science ***and*** applications
- Applications require multi-scale / multi-phenomena simulation

Moving nanoscience to nanotechnology will require new approaches that relate complexity on the macroscale to structure on the nanoscale.

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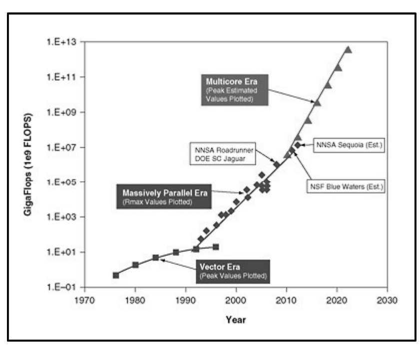
2000 – 2010: Progress in TMS…

- Advances in ab initio theory beyond DFT
- Development of quantum transport approaches
- Applications of NEGF to transistors
- Ability to treat devices and material synthesis at the atomistic scale
- 1000 X increase in computational efficiency.
- Reactive force fields
- Enhanced sampling techniques
- Applications of NEGF to transistors
- Statistical theories for conduction in nanostructured materials
- Advances in automatic upscaling
- Theoretical prediction of spin torque
- Multi-million atom simulations of electronic devices
- Simulation of self-assembly
- etc.



NRC study on modeling, simulation and games

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Self Assembly: 2000 - 2020

2000: Simple assembly (liquid crystals, block copolymers,…). Nanoparticles of limited shape, functionality, in small quantities, polydisperse). Colloid shapes mostly spheres - crystals mostly cubic, self-assembled DNA-coated gold nanospheres demonstrated. **Little TMS – simple models 100's of particles.**

2010: Wide diversity of nanoparticle and colloid shape, material, interaction anisotropy, functionality. Self-assembly into moderately complex crystal structures. **Promising TMS** approaches provide qualitative / quantitative guidance. (**1000's of particles**, enabled by 1000-fold cpu speed up since 2001.)

2020: "Programmed materials" that self-repair, change shape. Coatings that change color. Sensors that detect, trap and dispose of pathogens, etc. Assembly "science becomes assembly "engineering" with buckets of building blocks.

TMS manufacturing tools for on-the-fly screening, building block design and prototyping, and materials by design. Requires **1,000,000's** of particles - at least 1000X increase in cpu speed.

Tethered and "patchy" particles
Glotzer, ACS Nano 5, 2010

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Electronic Devices: 2000 - 2020

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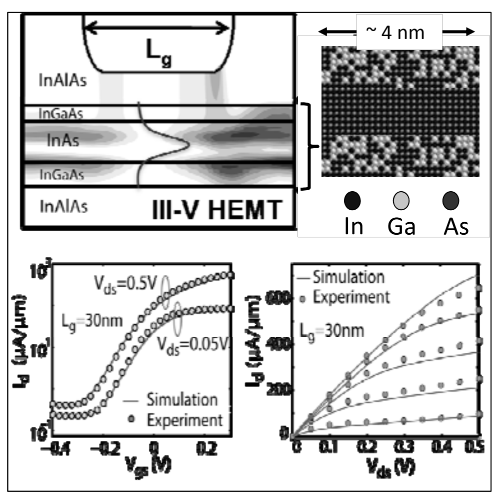
2000: first simulations of molecular electronics, 1D RTDs, eff. mass treatment of transistors. Mostly ballistic. (**100's of atoms**).

2010: Simulations of quantum dots with **50M atoms** ($101nm^3$).

"Full atomistic" (TB) simulation of "nanotransistor" (~**40,000 atoms** on Jaguar with 220,720 cores- 15 min vs. 5.7 yrs).

Similar applications to NW's, NT's, graphene, Si, Ge, III-V BTBT transistors, spintronic devices…

2020: First principles (beyond DFT) simulation of 10nm x 10 x 10 qdot. Full atom simulation of complete transistor. **10,000X challenge**.



G. Klimeck, M. Luisier, et al.

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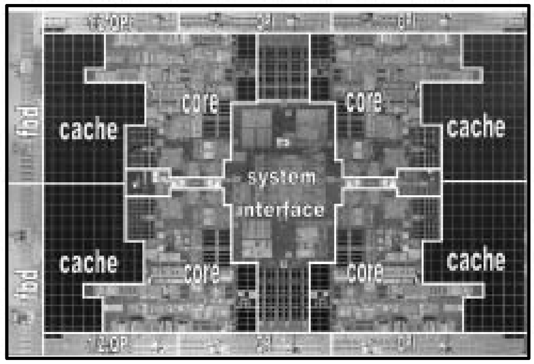
multi-scale modeling and simulation example



Intel Itanium (65nm, 2.05B transistors)

Blaine Stackhouse, et al, IEEE J. of Solid-State Circuits, Vol. 44, No. 1, Jan. 2009

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lessons from microelectronics

- Begin with applications – not atoms
- Develop the appropriate conceptual models for different scales, high-level abstractions, connections, generalizations, organizing principles. (***key challenge***)
- Support with physically detailed / atomistic / first principles simulations.
- Hand-crafted solutions are expensive and take time to develop. Is there ***a*** general framework for multi-scale modeling and simulation?

It's all about understanding complex systems

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challenges and opportunities for TMS

1) Harnessing the power of new computing technology to increase the power of simulations (e.g. gpu chips)
2) Increasing use of simulation by non-experts (e.g. designers, in metrology, etc.)
3) Continuing to clarify nanoscience concepts and fundamentals and improving the physical fidelity of simulations.
4) Turning nanoscience into nanotechnologies to address society's grand challenges (energy, environment, health, security…)

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strategies

1) Support research on fundamentals, methods, etc.
2) Strengthen infrastructure for TMS (leadership class supercomputers, methods development, data archiving, community SW, ***cyberinfrastructure***
3) ***Application-driven***, team-based research to connect experts in TMS, experiments, applications (centers and problem-specific institutes)
4) ***Simulation-driven*** exploration leading to new technologies. (multi-scale, multi-phenomena computational prototyping)

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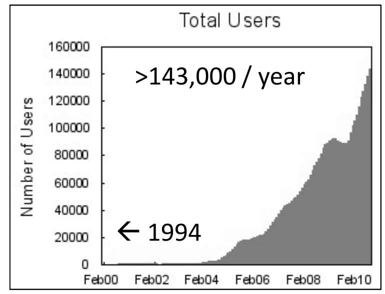
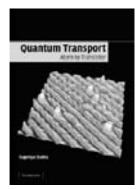
cyberinfrastructure

www.nanoHUB.org



"fingertip access to:"
- -simulations
- -data
- -research methods
- -educational resources
- -tools for collaboration



Atom to Transistor (Datta 2005)

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Goals for 2020

2000-2010:

Developing building blocks, techniques for synthesis and assembly, tools, concepts and organizing principles, education. Setting the stage for innovation in nanotechnology.

2010-2020:

- Achieve 10,000X increase in computational capacity to increase physicial fidelity and to support next-decade research and design (e.g. full HF 100nm^3 quantum dot, full atom simulation of nanotransistors, >self-assembly with > 1M complex particles, etc.)
- **Application-focused**, **simulation-driven** technology exploration that leads to technology development and manufacturing.
  Outcomes: nanotechnologies
  progress in multi-scale/multi-phenomena simulation

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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

Chapter 2. Enabling and Investigative Tools: Measurements, Instruments, and Metrology

Dawn A. Bonnell, Vinayak P. Dravid, Paul Weiss
With collaboration from:
David Ginger, Keith Jackson, Don Eigler, Harold Craighead, Eric Isaacs
International workshop moderators:
Liam Blunt, Dae Won Moon, John Miles

NSF, September 30, 2010

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Probing Structure and Properties at the Nanoscale

The ability to quantify nanoscale behavior is a limiting factor in understanding new physics and is a prerequisite to manufacturing.

It is a basic tenet of science that, “If it can’t be measured, it can’t be understood.”

In manufacturing, if specifications can’t be determined, reliable manufacturing is not possible

The decade 2000 to 2010 witnessed a geometric expansion of the variety of properties that can be measured at the nanoscale, some aimed at advancing fundamental science and some developed in support of technology commercialization

2000 to 2010

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Science Enabled by Scanning Probes

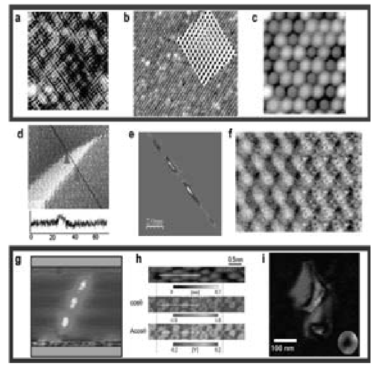
Exciting Advances

Single charge detection
Single electron spin resolution
Room temperature atom manipulation

Atomic resolution polarization
Dielectric function of molecular layers
Work function of atoms and molecules
Vibrational spectroscopy of single molecules

Single molecule tracking of protein motion
Optical and force imaging of a single ribosome
Quantification of protein folding energies

Goldman et al



Spatially resolved properties of nanoscale materials and phenomena "mapped" and/or imaged using a variety of atomic-scale characterization tools

Bonnell, ACS Nano 2008,
Brukman et al Physics Today 08

2000 to 2010

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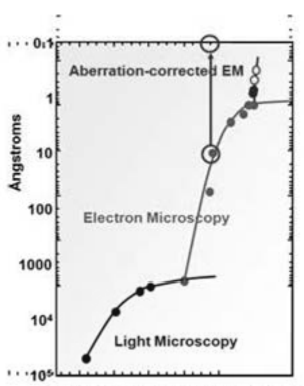
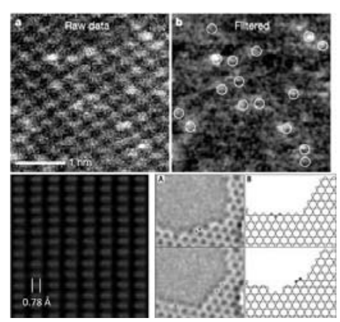
Aberration Correction Revolutionizing Structural Imaging In Electron Microscopy





Montage of atomic-scale images and phenomena enabled by aberration-corrected S/TEM.

Batson, P.E., et al , Nature, 2002., Kisielowski, C., et al.,. Microscopy and Microanalysis, 2008.
Krivanek, O.L., et al.,. Ultramicroscopy, 2008.. Muller, D.A., et al., Science, 2008.., Pennycook, S.J., et al., MRS Bulletin, 2006. Smith, D.J.,. Microscopy and Microanalysis, 2008..,Zhu, Y., et al. Nature Materials, 2009.

2000 to 2010

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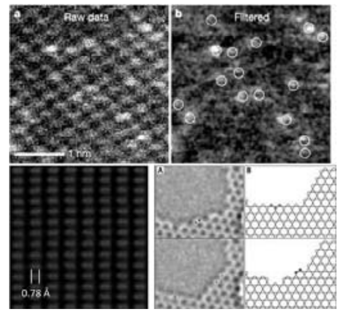
Aberration Correction Revolutionizing Structural Imaging In Electron Microscopy

Impact by
- **atomic resolution**
- **electron tomography**
- **in situ platforms**



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Batson, P.E., et al , Nature, 2002., Kisielowski, C., et al.,. Microscopy and Microanalysis, 2008.
Krivanek, O.L., et al.,. Ultramicroscopy, 2008.. Muller, D.A., et al., Science, 2008.., Pennycook, S.J., et al., MRS Bulletin, 2006. Smith, D.J.,. Microscopy and Microanalysis, 2008..,Zhu, Y., et al. Nature Materials, 2009.

2000 to 2010

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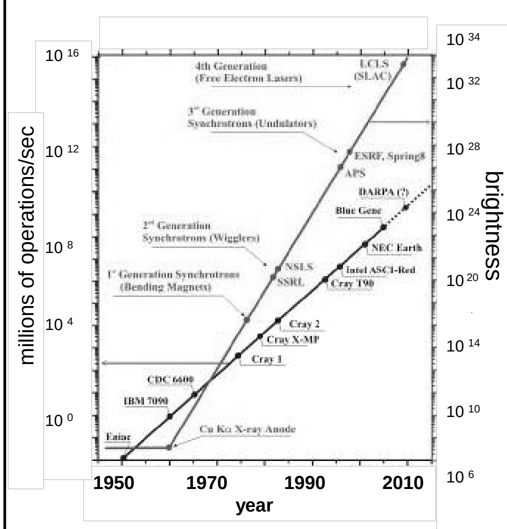
Synchrotron Radiation Reaching New Space and Time Regimes



Atto second snapshots of electronic disturbances in water produced by a diffusing gold ion based on inelastic x-ray scattering measurements

P. Abbamonte, K.D. Finkelstein, M.D. Collins, S.M. Gruner, Imaging density disturbances in water with a 41.3-attosecond time resolution, Phys. Rev. Lett. ***92****, 237401 (2004).*

2000 to 2010

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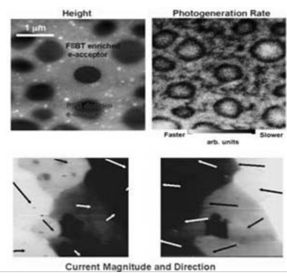
Nano Fabrication, Patterning and Manufacturing

Novel processes for fabricating and patterning nanodevices have been invented and scaled up in the last decade

In situ device characterization is in its infancy
Standards and metrology tools almost non existent



Imaging photo current generation in an organic solar cell and current size of vector across an operating oxide device

D. C. Coffey and D. S. Ginger, Nature Materials , (2006)
. Kalinin, S. et al Solid State Phenomena 33047 20011

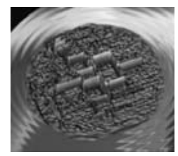
Nanoimprint and Step&Flash Lithographies

Scanning Probe Lithographies

Microcontact Printing

Dip Pen Lithgraphy

Ferroelectric Nanolithography



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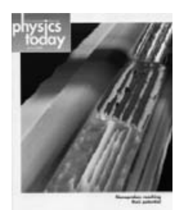
On the Horizon

The next decade will see unanticipated new discoveries of nanoscale phenomena along with the implementation of early nanoscience into novel applications.

New challenges will arise in direct measurement of dynamic processes in nanoscale systems, nanomanufacturing, integration of biosystems, and in higher levels of device and system complexity.

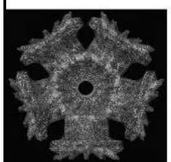
At the dawn of this decade the scope of our ability to probe local phenomena is vastly increased. Researchers now envision capabilities that were unimaginable ten years ago.



Opportunities

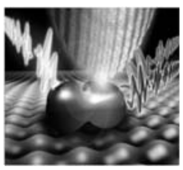
Most advances have been along the length scale or time scale axis.

Recent developments point to pathways to combined methods that access the interior region

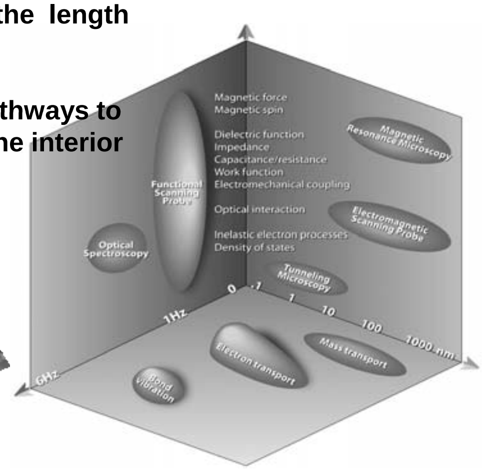


Emi et al. 2009

Nikiforov et al 2009



Courtesy of S. Jesse ORNL



Relation of advances probes to space, time and complexity. The future is in extending these probes into the regions in the center where spatial resolution, time resolution, and complexity can be simultaneously probed

Goals for 2020

Science

Atomic resolution of the 3-D structure of a single protein with chemical specificity

Mapping (so called) continuum properties of individual atoms in a solid and bridging continuum and quantum regimes

Discovery of stable new compounds by the manipulation of atoms at room temperature

Tracking electrons with sufficient speed to observe intermediate steps in chemical reactions

Concurrent imaging of processes throughout and entire cell

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Goals for 2020

Manufacturing

Physical infrastructure and human resource development for Nanomanufacturing

New portable and inexpensive nanoscale instruments capable of operating in an industrial environment

Instruments capable of measuring nanomaterials in matrices such as water, soil, food and living tissue, etc

Globally accepted traceable standards for measurement

Routine online measurements suitable for a production environment
Metrology across the process chain
.

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Goals for 2020

Infrastructure

A national structure for the development and operation of mid sized instrumentation and metrology capabilities, providing access to advanced tools and facilitated by centers of excellence and international networking

Institutional engagement between national measurement institutes, documentary standards developers, and the R&D community to produce reference materials and standards.

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Conclusions

Advanced capabilities in investigative, fabrication, and metrology tools will be a primary factor that enables new scientific discovery, as well as the translation of nanoscience to nanotechnology.

In the absence of these new critical instruments and tools, the full potential of nanotechnology cannot be realized.

The previous decade produced concepts and approaches that provide a platform for a new generation of localized measurement tools that could once again revolutionize our understanding of inorganic, organic, and biological systems.

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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

Chapter 3. Synthesis, assembly, and processing of components, devices, and systems

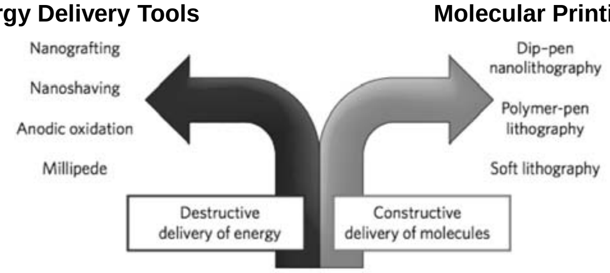
C.A. Mirkin, M. Tuominen
With collaboration from:
R. Siegel, J. Ruud, F. Ebrahimi, S. Murdock, R. Wang, X. Zhang, J. Milner, J. Belk, M. Davis, T. Shibata

NSF, September 30, 2010

Changes of the vision in the last decade

- Exciting period of discovery in the synthesis and processing of nanostructures
- Many new nanomaterials emerged, along with new fabrication processes
- Widespread use of nanotechnology including commercial products (e.g. nanostructured coatings, cosmetics, textiles, magnetic storage devices)
- While inorganic devices and sensors have required top-down lithography tools, which rely on high-energy destructive methods, there have been transformational developments for patterning surfaces with soft materials that would otherwise be damaged; these are the so-called molecular printing techniques
- As top-down approaches meet fundamental resolution limits, it is necessary to look at bottom-up synthesis of materials at the single molecule level for higher order assemblies and material property testbeds

Energy Delivery Tools **Molecular Printing**



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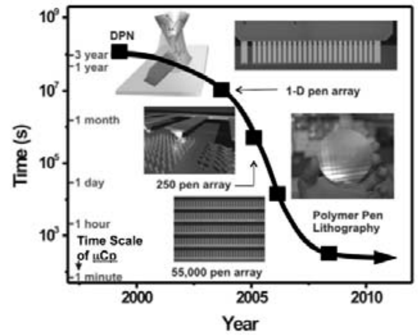
Vision for the next decade: Methods

- Arrange desired materials over large areas with sub-10 nm resolution and materials flexibility (e.g. hard and soft matter) will require the **integration of top-down and bottom-up techniques**
- Develop **low-cost processes** that can be scaled to high throughput (e.g., roll-to-roll) manufacturing
- Understand fundamental approaches for **materials synthesis and relevant properties** that arise (e.g. one-dimensional wires, design rules for DNA-nanoparticle assemblies, process kinetics)
- Improve **resolution and sensitivity** of imaging, measurement, and characterization techniques.



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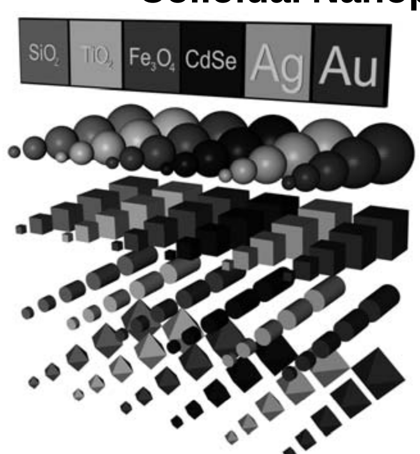
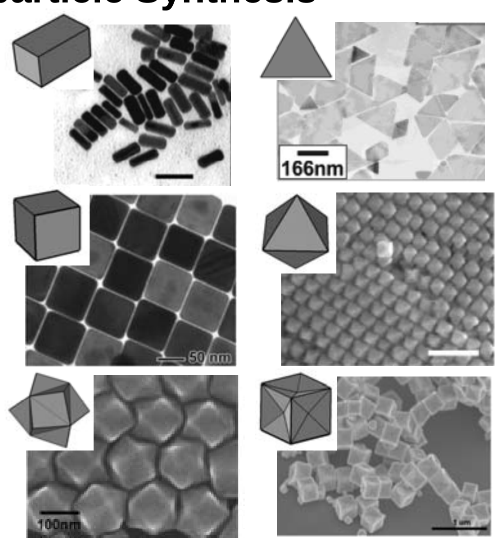
Major Advances in the Last Decade: Colloidal Nanoparticle Synthesis





The availability of a range of new nanostructures has been facilitated by synthetic control over composition, size and shape.

Nikoobakht, B. et al. *Chem. Mater.* 2003. **15,** 1957.
Xia, Y. et al. *Angew. Chem. Int. Ed.* 2009. **48,** 60.
Yu, Y. et al. *J. Phys Chem. C.* 2010. **114,** 11119.
Millstone, J. E. et al. *J. Am. Chem. Soc.* 2005. **127,** 5312.
Niu, W. et al. *J. Am. Chem. Soc.* 2009. **131,** 697.
Zhang, J. et al. *J. Am. Chem. Soc.* 2010. ASAP.

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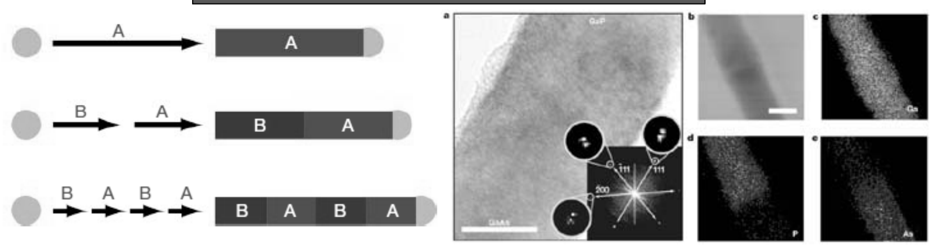
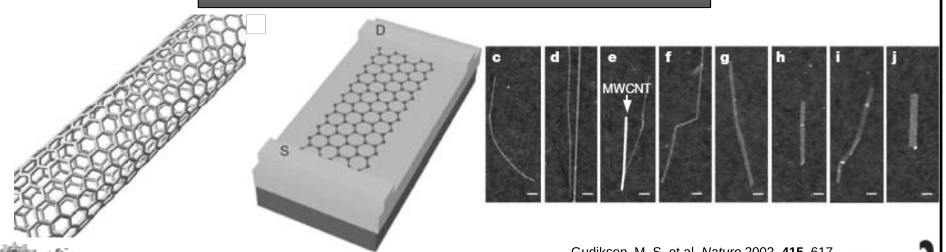
Major Advances in the Last Decade: One and Two Dimensional Nanostructures

Inorganic Silicon Nanowires



Carbon-Based Nanomaterials



Gudiksen, M. S. et al. *Nature* 2002. **415,** 617.
Jiao, L. et al. *Nature* 2009. **458,** 877.
http://www.3dchem.com/imagesofmolecules/Buckytubes2.jpg

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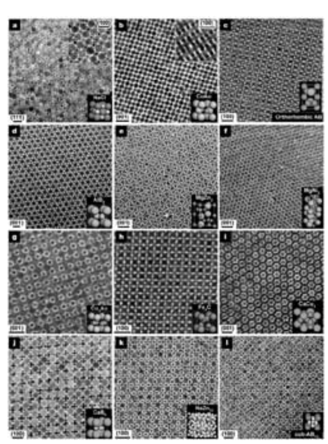
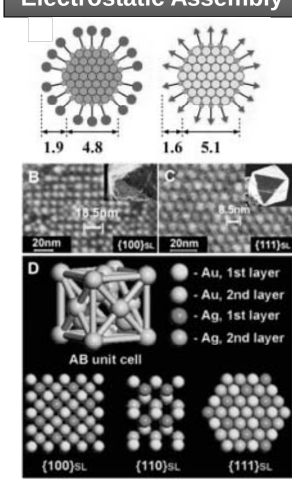
Major Advances in the Last Decade: Superlattice Formation and Assembly of Nanostructures

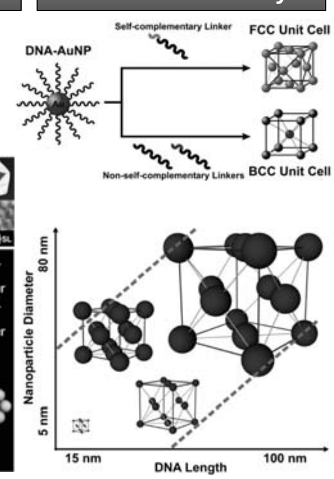
Entropic Drying Effects



Electrostatic Assembly



Directed Assembly



Shevchenko, E. V. et al. *Nature* 2006. **439,** 55.
Kalsin, A. M. et al. *Science* 2006. **312,** 420.

Park, S. Y. et al. *Nature* 2008. **451,** 553.
Macfarlane, R. J. et al. *Angew Chem. Int. Ed.* 2010. **49,** 4589.

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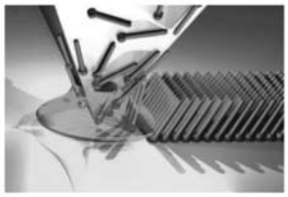
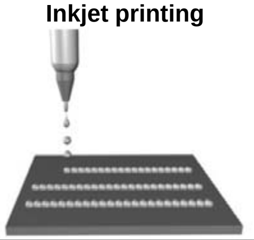
Major Advances in the Last Decade: Patterning Approaches & Device Integration

Many approaches for controlling the position of materials on surfaces have been developed in the last decade.

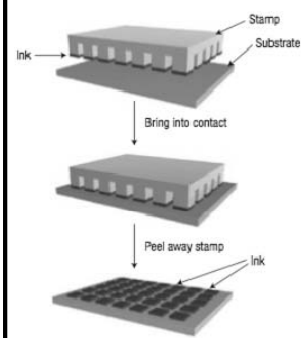
Scanning probe-based lithographies



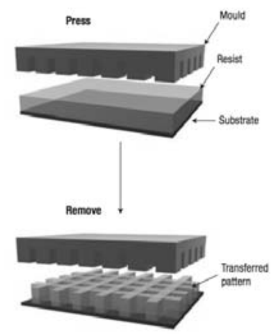
Inkjet printing



Microcontact printing



Nanoimprint lithography



Nie, Z et al. *Nature Nanotech.* 2008. **7**, 277.

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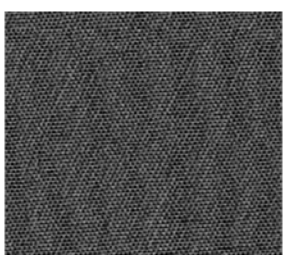
Major Advances in the Last Decade: Patterning Approaches & Device Integration

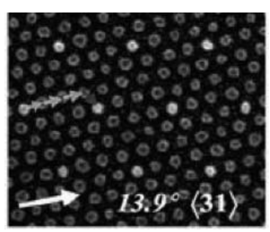
Block "A"

Block "B"

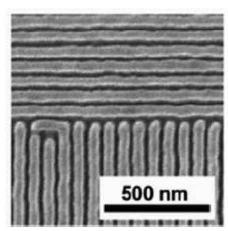
Block copolymer lithography: A hierarchical-friendly method



UMass Amherst/ UC Berkeley

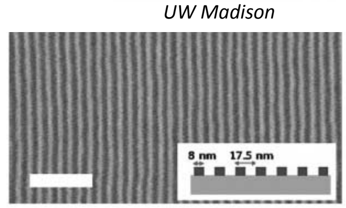


MIT



UW Madison

Directed self-assembly for nanoscale patterning down to 3 nm



MIT

S. Park, et al. *Science* 2009. **323**, 1030.
I. Bita, et al. *Science*. 2008. **321**, 939.

Y.S. Jung, et al. *Nano Lett.* 2010. **10**, 1000.
K. Galatsis, et al. *Adv. Mater*. 2010. **22**, 769.

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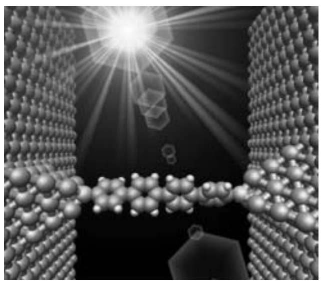
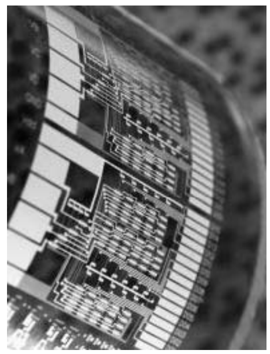
Major Advances in the Last Decade: Advanced Manufacturing

It is important to develop tools and methods for integrating nanoscale patterning of soft materials with industry standards and practices. This work would be important for flexible electronics and highly sensitive gene chips.

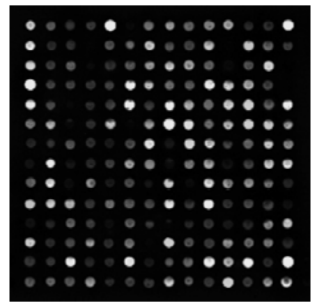
Molecular electronics



Flexible devices

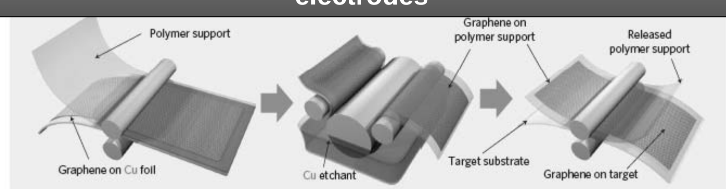


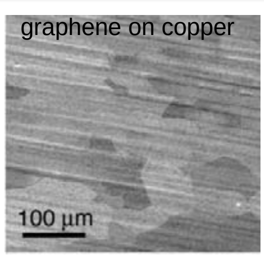
DNA and protein chips



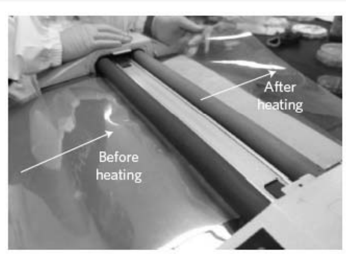
Major Advances in the Last Decade: Advanced Manufacturing

Roll-to-roll production of graphene for transparent conducting electrodes





U. Texas Austin



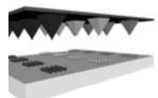
Korea/Japan/Singapore Collaboration

X. Li, et al. Science 2009. **324**, 1312
S. Bae, et al. *Nature Nanotech*. 2010. **5,** 574.

Expected Major Advances in the Next Decade

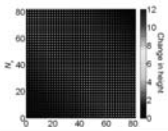
Advances in nanomaterials synthesis and assembly will lead to new insights in combinatorial chemistry, plasmonic materials, and carbon-based materials.

Synthesis, assembly, and characterization



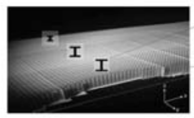
Develop and understand methods for controlling nanostructures (size, shape) and positioning them with nanometer precision over large areas.

Combinatorial chemistry & biology



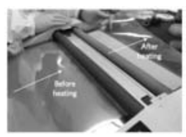
Enable rapid and low-cost screening of materials (catalysts, biologics) in high sensitivity and high throughput platforms.

Plasmonic metamaterials



Understand and model the structure-property relationships (optical, electrical) and design rules that arise from periodic structures in plasmonic metamaterials.

Graphene & carbon-based devices



Fabricate large-scale high-performance devices in a robust manner that can be integrated with established nanomanufacturing procedures

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Synthesis, Assembly and Processing: Goals for 2020

- A robust platform of inherently **scalable processes**—including self-assembly, directed assembly and bioinspired synthesis—for high volume nanomanufacturing, including roll-to-roll production.
- Infrastructure for fabrication of low cost **carbon nanoelectronics**
- A library of building-block processes to fabricate **complex and multicomponent 3D nanosystems**, having designed heterogeneous structure and different spatial properties.
- Science-based **process-structure-property relationships** for nanoscale synthesis and processing -- enabling scale up, process control, modeling and optimization.

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R&D Investment and Implementation Strategies

• **Pilot projects and manufacturing test beds** to establish critical data on the pathway to full scale nanomanufacturing

• Establish a robust **strategic roadmap for nanomanufacturing** and its value chain; identify and fill current gaps and strengthen weaknesses

• Develop **training programs and nanomanufacturing education** curriculum, promoting integrative research and innovation practices

• Accessible **databases** with information on nanomaterial properties, nanomanufacturing process data, and safety, and **workflow tools** to use them

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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

Chapter 4. Nanotechnology Environmental, Health, and Safety Issues

André Nel, David Grainger
With collaboration from:
Pedro Alvarez, Santokh Badesha, Vincent Castranova, Mauro Ferrari, Hilary Godwin, Piotr Grodzinski, Jeff Morris, Nora Savage, Norman Scott, Mark Wiesner
International workshop moderators:
Bengt Fadeel, Tatsujiro Suzuki, Yuliang Zhao

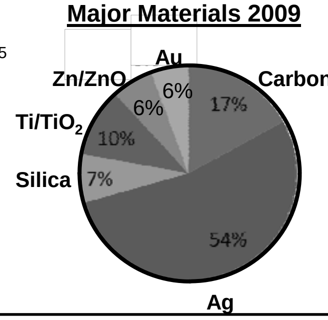
NSF, September 30, 2010

The nano EHS Challenge:

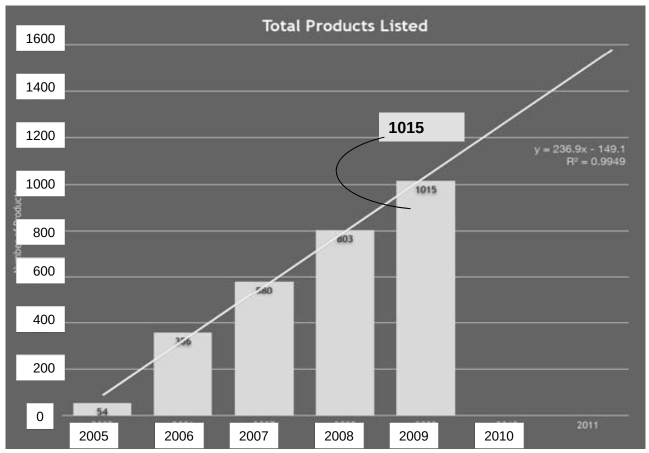
- **What is the reality?**
- **Is the glass half empty or half full?**

- We do not currently know of any specific human disease or serious environmental impact due to ENM
- However, there is experimental evidence of ENM hazard
- Currently, 6 base materials constitute >90% of all manufactured nano products (by number)
- Presently ~ 10^3 consumer nano products - could grow to $>10^4$ in the next decade, ultimately to 10^5
- Knowledge generation will take time and will be incremental
- Decision making currently proceeding on a material by material basis but regulatory awareness is gaining ground and ability to make decisions are improving

Major Materials 2009



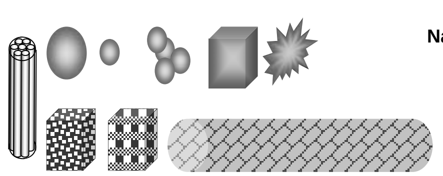
Number of Consumer Products that include Nano-based components

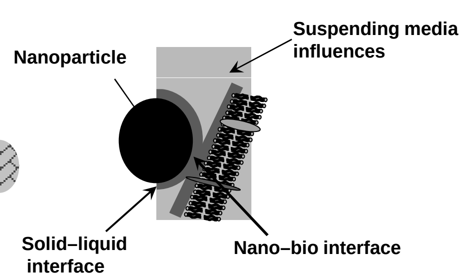


Source: Project on Emerging Nanotechnologies

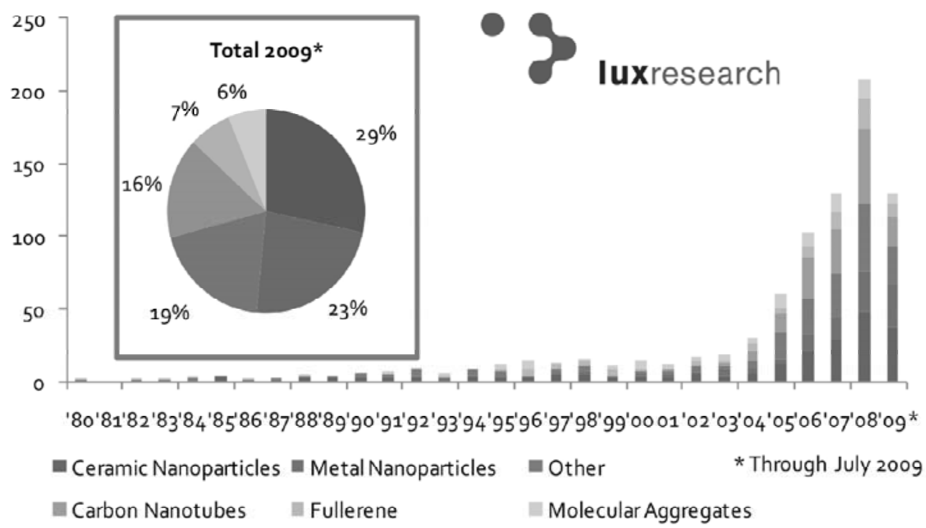
Changes of the vision in the last 10 years

- Nano EHS advanced from awareness level to implementation of the science of "nano safety" and "nanotoxicology"
- "Small Is Dangerous" was replaced by the recognition that the specific material compositions and properties determine the events at the nano-bio interface that could be responsible for toxicity





Peer-reviewed Journal Articles on nano EHS

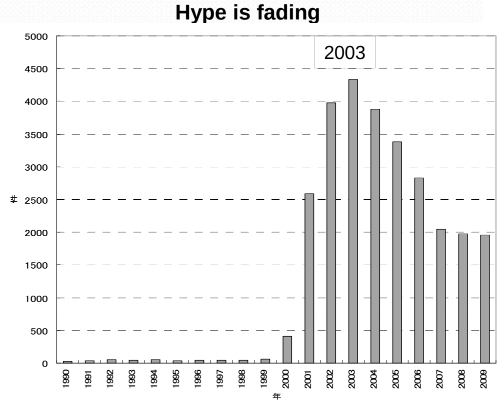


Lux Research LRNI-R-09-05

Impact on Public Perception of the technology at large vs coverage of risk in Japan

Nanotechnology

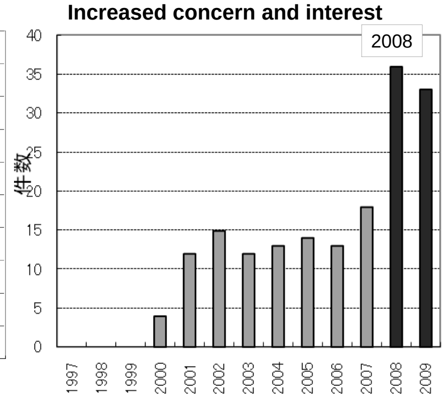
Hype is fading



Frequency of nanotechnology-related articles appeared in domestic mass media

Nano Risk

Increased concern and interest



Frequency of articles on carbon nanotube risk appearing in domestic mass media after publication of data in mouse model

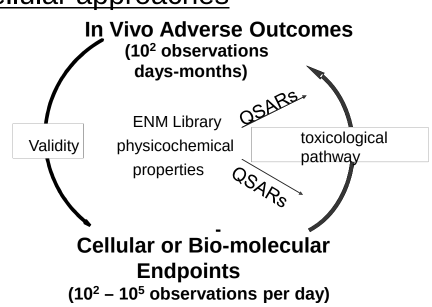
(Source Data: Nikkei-telecon, Analyzed by M. Ata)

Changes of the vision in the last ten years

- Nanotechnology is a new science and new knowledge is required to understand how novel materials may react with bio-molecules and biological processes
- Knowledge generation will be incremental and will take time but is worthwhile because it will lead to evidence-based decision making, safe design, and sustainability
- Knowledge generation is a multidisciplinary exercise that demands a new approach to scientific integration
- Recognize that we will have to make stepwise decisions as knowledge generation and data collection on commercial nano products proceed
- Nano EHS should be an integral part of ENM design and not as a *post facto* add-on or imposed cleanup cost

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



Vision for the next 10 years

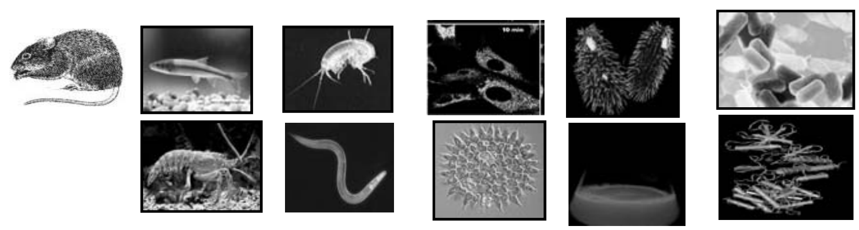
- Build a nano EHS enterprise with the capacity to keep pace with the rate of growth of nanotechnology
- Develop computational methods, nano-informatics, modeling and decision-making tools to speed up nano EHS knowledge generation
- Develop safe-by-design approaches as an integral part of product development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

Examples of the major advances over the last 10 years

- Transitioning from nano EHS awareness to action on the research and regulatory fronts
- Progress in understanding the mechanisms of hazard generation, how to perform toxicity testing on the major classes of materials and some risk profiling
- Formulation of real and perceptual risk profiling for CNT and a few high volume materials
- Acute hazard data collection for inhalable MWCNTs and SWCNTs is being used by NIOSH to implement hazard prevention in the workplace

Expected major nano EHS advances in the next 10 years

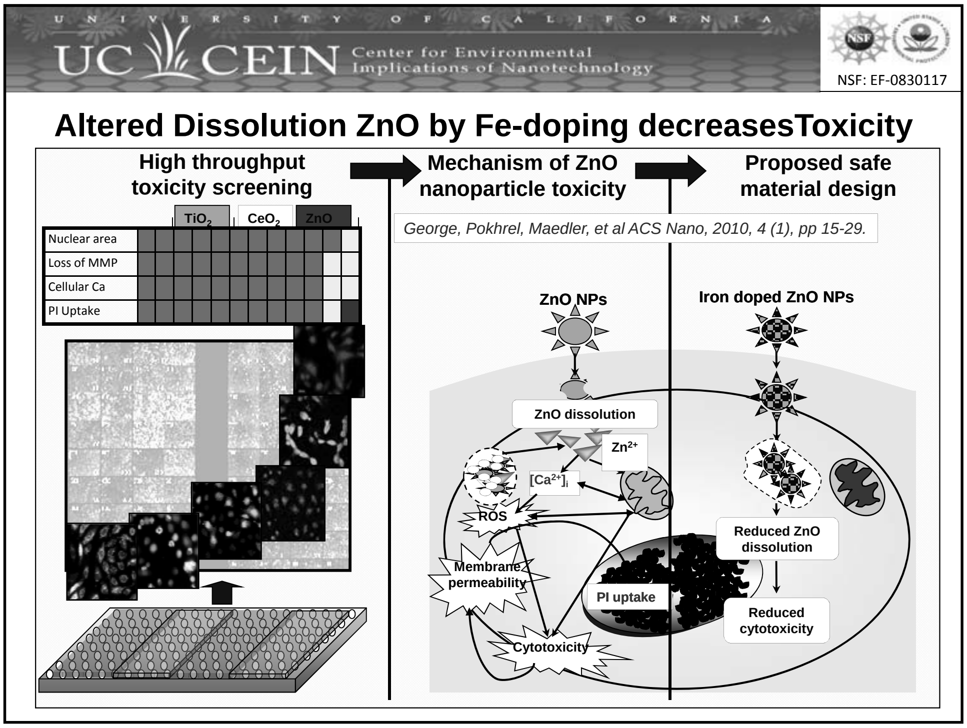
- Develop <u>validated screening methods</u>, harmonized protocols and risk reduction strategies
  (requires correct balance between in vitro/in vivo, appropriate dosimetry metrics, improved technology to track fate/transport & exposure)
- Develop <u>predictive toxicological approaches</u> that utilize the correct balance between in vitro and in vivo testing



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

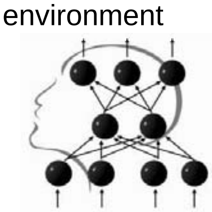
Expected major nano EHS advances in the next 10 years

- Develop a <u>stepwise approach to nano EHS governance</u> that takes into consideration incremental progress (see example)
- Develop <u>computational analysis</u> and *in silico* decision-making tools (computational biology, nano informatics, modeling)
- Develop <u>high throughput and high content screening</u> as a universal tool for studying ENM toxicity, hazard ranking, in vivo prioritization and designing safer materials

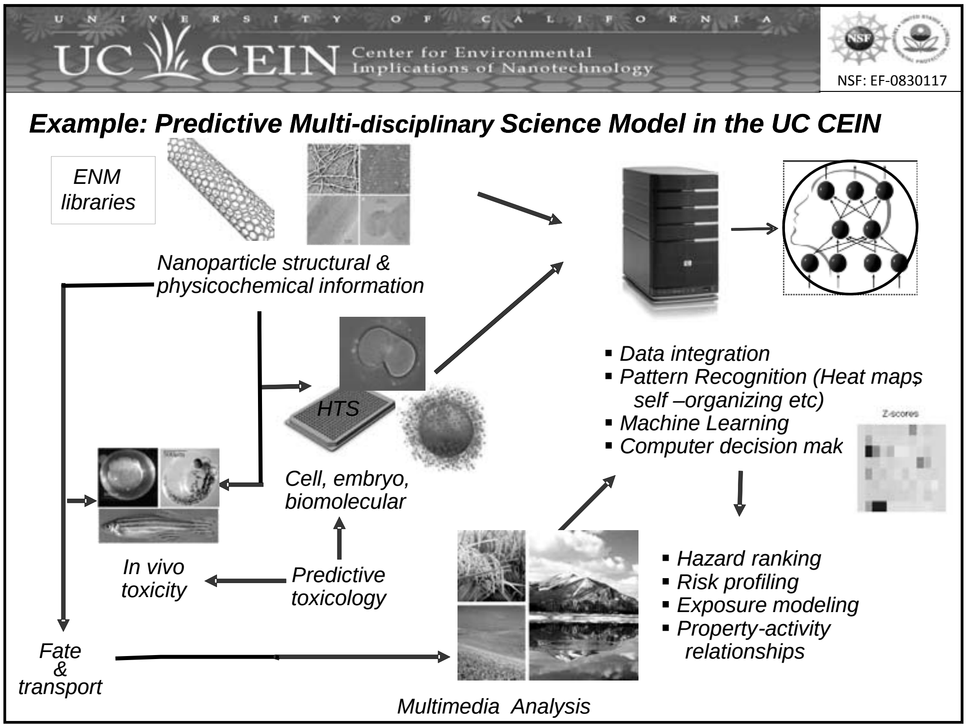


Scientific and Technological Infrastructure Needs

- Instrumentation that will improved tracking and identification of the ENM in biological tissues and the environment
- Computational models, algorithms, artificial intelligence



- Public-private partnerships to allow knowledge generation on nano safety to be incorporated by industry, including the recognition that this can lead to new intellectual property and product generation
- Need a multidisciplinary workforce that is capable of meeting the needs for safety assessment, safe implementation and development of a sustainable technology



R&D Investment and Implementation Strategies

- Increase the <u>federal budget</u> to improve nano safety assessment, implementation, and coordination
- <u>Standardized nomenclature</u> & standard reference materials
- Validated, standardized <u>methodology for the assessment</u> of ENM hazard
- <u>Industry</u> needs to play an <u>active role</u> in investing in nano EHS R&D

  (rewards: facilitated access to marketplace, safely designed and improved materials, new intellectual property and applications)
- <u>Regional nano EHS user facilities</u> to assess and design safer materials by product category

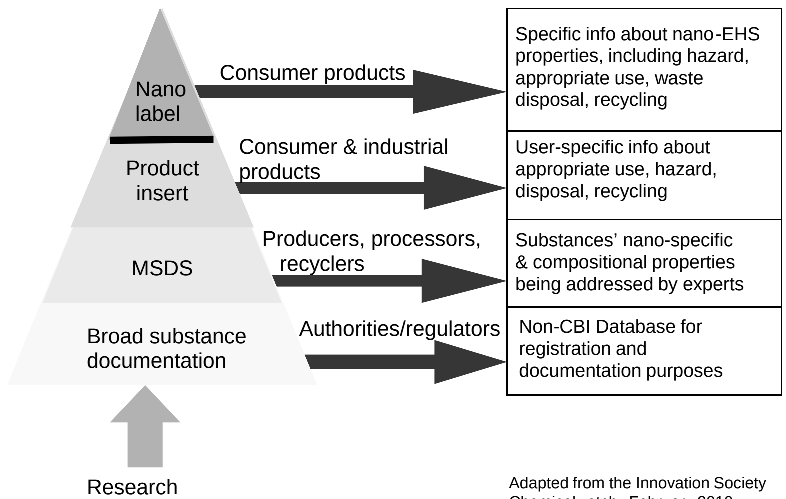
Emerging Topics and Priorities

- The important role of nanotechnology in environmental remediation
- Green manufacturing and green nanotechnology
- Safe-by design approaches to develop safer and improved products
- Nanotechnology as a pervasive technology with a great promise of helping to develop sustainable technologies
- Key role of nano for providing clean water, renewable energy and improved food supply

Broad Societal Implications

- The public stands to benefit from nanotechnology providing better consumer products, medicines, and stimulation of the economy
- Important contributions of nanotechnology to sustainability
- The safety and potential hazard of nanomaterials needs to be conveyed to the public in a balanced and responsible manner
- Where potential hazards are identified it is important to consider responsible product safety disclosure, e.g., the nano-pyramid

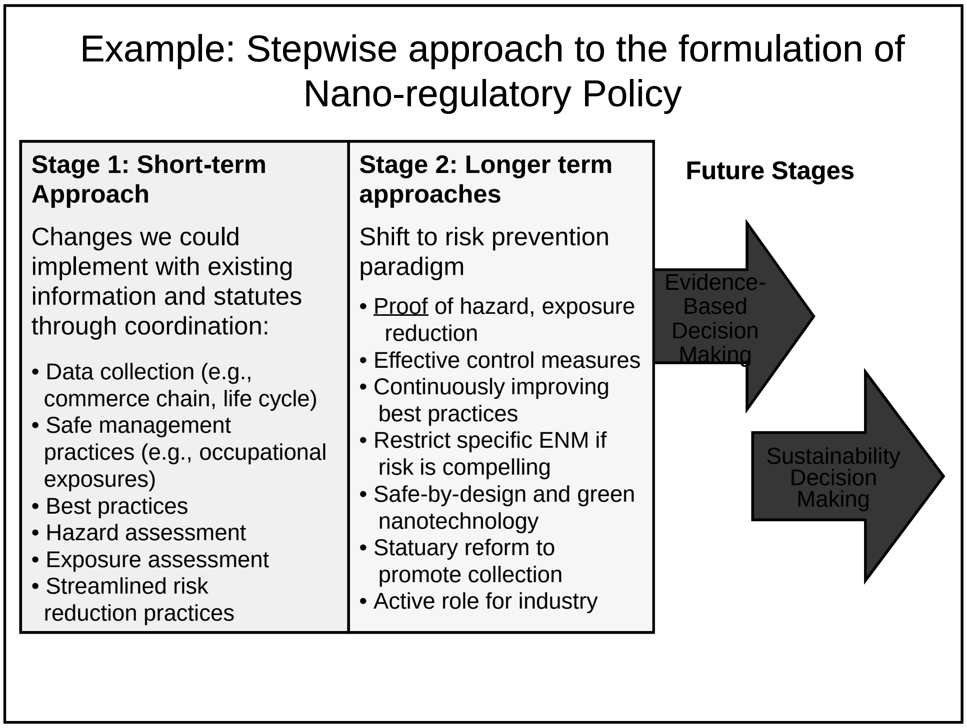
Example: Proposed Nano-pyramid for Product Information Disclosure

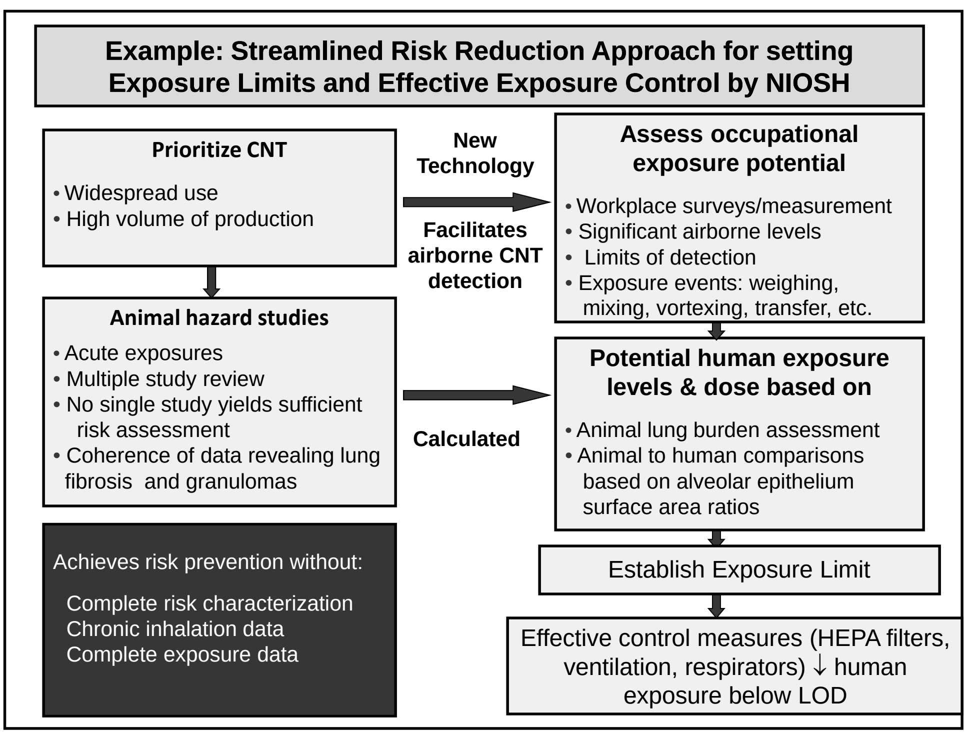


Adapted from the Innovation Society
Chemicalwatch. February 2010

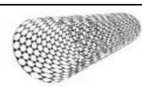
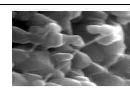
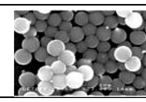
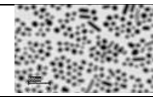
Major positions amongst stakeholders regarding nano-regulatory philosophy

- The existing regulatory situation is adequate. If scientific evidence indicates the need for modification, the regulatory framework will be adapted
- Specific guidance and standards must be developed to support existing regulations but the existing regulatory situation is generally adequate
- Regulation should be amended (on a case by case basis) for specific ENM and their applications. When a high potential risk is identified, a precautionary approach should be chosen
- The existing regulatory situation is not adequate. Nanomaterials should be subject to mandatory, nano-specific regulation


Example: Stepwise approach to the formulation of Nano-regulatory Policy
Stage 1: Short-term Approach
Changes we could implement with existing information and statutes through coordination:
• Data collection (e.g., commerce chain, life cycle)
• Safe management practices (e.g., occupational exposures)
• Best practices
• Hazard assessment
• Exposure assessment
• Streamlined risk reduction practices
Stage 2: Longer term approaches
Shift to risk prevention paradigm
• Proof of hazard, exposure reduction
• Effective control measures
• Continuously improving best practices
• Restrict specific ENM if risk is compelling
• Safe-by-design and green nanotechnology
• Statuary reform to promote collection
• Active role for industry
Future Stages
Evidence-Based Decision Making
Sustainability Decision Making


Example: Streamlined Risk Reduction Approach for setting Exposure Limits and Effective Exposure Control by NIOSH
Prioritize CNT
• Widespread use
• High volume of production
New Technology
Facilitates airborne CNT detection
Assess occupational exposure potential
• Workplace surveys/measurement
• Significant airborne levels
• Limits of detection
• Exposure events: weighing, mixing, vortexing, transfer, etc.
Animal hazard studies
• Acute exposures
• Multiple study review
• No single study yields sufficient risk assessment
• Coherence of data revealing lung fibrosis and granulomas
Calculated
Potential human exposure levels & dose based on
• Animal lung burden assessment
• Animal to human comparisons based on alveolar epithelium surface area ratios
Achieves risk prevention without:
Complete risk characterization
Chronic inhalation data
Complete exposure data
Establish Exposure Limit
Effective control measures (HEPA filters, ventilation, respirators) ↓ human exposure below LOD

Example: Real and Perceptual Risk Profiles of Major Materials

	Carbon nanotubes	TiO_2 nanoparticles	ZnO nanoparticles	Ag nanoparticles
				
Consumer, occupational & human risk	Regarded as pulmonary toxicant by NIOSH; effective. workplace prevention feasible	Among best characterized ENM since the '80's; effective workplace risk management	Reasonably safe consumer profile; inadvertent lung exposure leads to metal fume fever	Modest risk to workers and consumers but some concern to developers
End-of-life and environment risk	Uncertain: capping agents promote spread Nano-composites may disintegrate	Ultimate disposal risk uncertain but likely not more than micron sized pigments	Reasonably high concern because Zn^{++} regarded as extremely toxic in the environment	Possible high environmental impact, especially aquatic systems
Perceptual risk	Relatively high based on analogy to asbestos	Sunscreen ingredient but no clinical data indicating toxicity	Same as for TiO_2 in sunscreens; Does it reach the environment?	High perceptual risk due to environmental concerns
Regulatory position	Under TSCA, CNT are new chemicals requiring a PMN. EPA regulating with consent order/SNUR.	Existing chemical under TSCA. EPA developing a SNUR for nano forms of existing chemicals.	Existing chemical under TSCA. EPA developing a SNUR for nano forms of existing chemicals.	EPA uses FIFRA for antibacterial claims.

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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

Chapter 5. Nanotechnology for Sustainability: Environment, Water, Food, and Climate

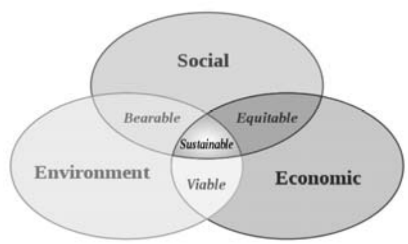
Mamadou Diallo, Jeffrey Brinker
With collaboration from:
Mark Shannon, Nora Savage, Norman Scott, James Murday
International workshop moderators:
Antonio Marcomini, Chul-Jin Choi, Murali Sastry

NSF, September 30, 2010

Background: the three pilars of sustainability

- **Brundtland's Commission (Brundtland, 1987) defined sustainable development as:**
  - "that which meets the needs of the present"
  - "without compromising the ability of future generations to meet their own needs."

The three pilars of sustainability (Brundtland, 1987).



1. *Sustainability entails considerations of people, the environment and the economy.*

1. *Every human being needs food, water, energy, shelter, transportation, healthcare and employment to live and prosper on Earth.*

2. *One of the greatest challenges facing the world in the 21st century is to continue to provide better living conditions to people while minimizing the impact of human activities on Earth's ecosystems and global environment.*

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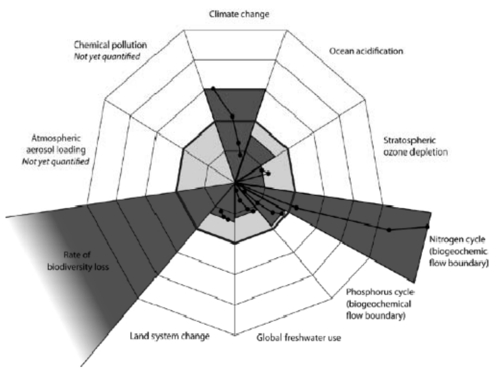
Background: A global environment under siege

- **Resilience Alliance (http://www.resalliance.org/)**
  - Defined "**Earth System**" as the the set of coupled and interacting physical, chemical, biological and socioeconomic processes that control the environmental state of Planet Earth.
  - Proposed a new conceptual framework **"Planetary Boundaries"** for "estimating a safe operating space for humanity with respect to the functioning of the Earth System".



Planetary Boundaries

(Rockstrom, J. et al.A safe operating space for humanity. Nature 461, 472-475, 2009)

The inner green shading represents the proposed safe operating space for nine planetary systems.

The red wedges represent an estimate of the current position for each variable.

The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle), have already been exceeded.

Nanotechnology and sustainability: vision and focus areas

- **As nanotechnology looks toward the next 10 years and beyond, two key questions arise:**

  -How can nanotechnology help address the challenge of global sustainability?

  - Can nanotechnology be developed in a sustainable manner?

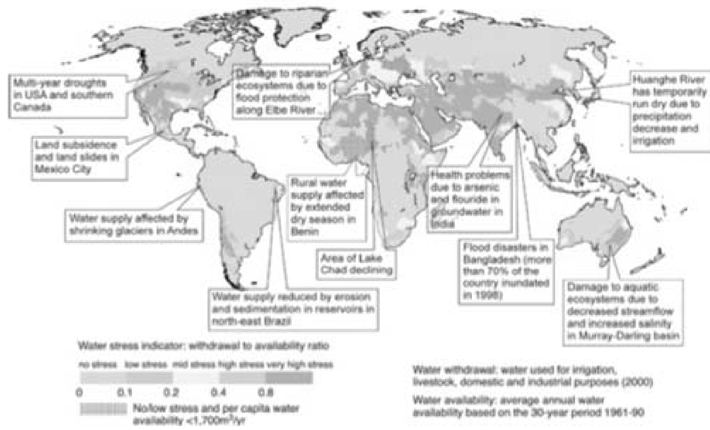
- **Very early in the US National Nanotechnology Initiative (NNI), it was envisioned that nanotechnology could provide more cost effective and environmentally acceptable solutions to address global sustainability challenges including:**
  - **Water**
  - **Food**
  - **Habitats**
  - **Transportation**
  - **Mineral Resources**
  - **Environment (Nano EHS Issues Not Included)**
    - **Green Manufacturing**
    - **Environmental monitoring, clean-up and remediation**
  - **Climate Change**
    - **CO_2 separations and transformations [Priority Research Area]**
    - **Geoengineering**
  - **Biodiversity**

Overall results of our study and input from the European Union and Asia workshops suggest that priority research areas critical to the solutions of the global sustainability problems in the next 5-10 years are:

1. Water Reuse and Desalination
2. CO_2 Capture and Conversion
3. Green Manufacturing

- **The United States as well as many regions of the world are facing multiple challenges in sustainably supplying potable water for human use and clean water for agriculture, food processing, energy generation, mineral extraction, chemical processing and industrial manufacturing.**

Priority Research Area



2.3 billion people (40% of the word population) currently live in water-stressed areas.

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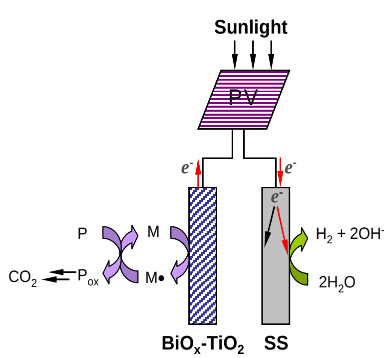
Beyond Reverse Osmosis: Extracting Clean Water, Energy, Organics, Nutrients and Minerals from Wastewater, Brackish Water and Seawater

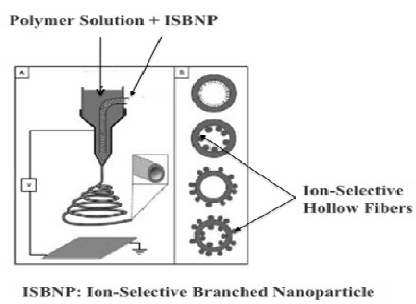
A. Wastewater as a source of clean water, energy and nutrients

– Solar-powered nanoelectrochemical or photo-catalytic systems, which can extract clean water and produce energy (e.g. hydrogen) from wastewater).



B. Saline water as a source of clean water and minerals

-Nanocomposite fibers and membranes with tailored “ion channel” mimics that can selectively extract ions using low pressure (<5 bar) and less energy than conventional RO membranes (< 1.0 KWh per m^3 of clean water produced)



Michael Hoffmann (Caltech) **Priority Research Area** Mamadou Diallo (Caltech)

- **The world will continue to face significant challenges in meeting the global demand for food as the world population reaches 9 billion by 2050.**
- **Viable solutions to these challenges will require a radical transformation of the agriculture and food industries by producing more food while:**
  - Minimizing the environmental impact of the agriculture and food industries.
  - Managing the impact of global climate change.

- **Key goals the next 5-10 years will include :**
  - Nanobiosensors for identification of pathogens, toxins and bacteria in foods.
  - Nanoscale biofilms for food packaging and contact materials that extend shelf life, retained quality and reduce cooling requirements.
  - Nano-enabled identification systems for tracking animal and plant materials from origination to consumption
  - Nano-enabled systems for controlled release of nutrients, fertilizers and pesticides in soil systems.

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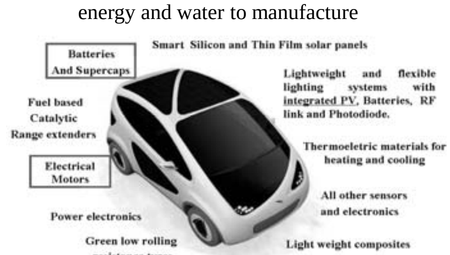
Beyond Remediation and Clean-up: Reducing the Environmental Footprint of Industry

- **Green manufacturing is arguably the most efficient way to fabricate high performance products at lower cost while reducing and (eventually) eliminating the release of toxic pollutants in the environment.**
- **Green manufacturing encompasses a broad range of approaches that are being used to:**
  - Design and synthesize environmentally benign chemical compounds and processes (Green Chemistry)
  - Develop and commercialize environmentally benign industrial processes and products (Green Engineering)

Priority Research Area

- **Priority R&D areas include**
  - Nano-enabled, environmentally benign manufacturing processes and products for the semiconductor industry.
  - High performance and environmental benign nanocatalysts for the chemical, pharmaceutical and petroleum industries
  - High performance nano-enabled consumer products (e.g. cars) that use less materials, energy and water to manufacture



Nanomaterials as components of the next generation of automobiles (courtesy of Pietro Perlo, Fiat, http://www.gennesys2010.eu/).

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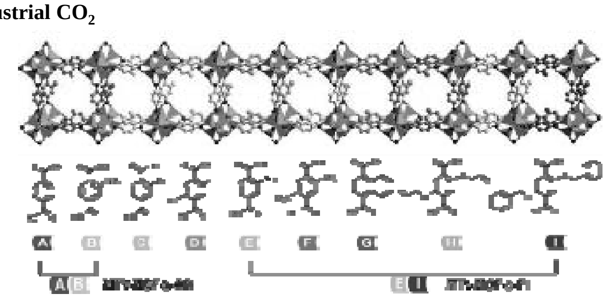
Climate Change: Vision and goals for 2020

Beyond CO_2 Capture and Storage: Reducing the Carbon Footprint of Industry

- **Although several alternative energy sources and generation technologies are being developed (See Chapter 6), the world will continue to burn significant amounts of fossil fuels to produce energy in the foreseeable future.**
- **Thus, carbon capture and conversion is emerging as viable alternative for reducing the amounts of industrial CO_2 released in the atmosphere.**
- **Current CO_2 capture media only perform a single function, i.e. CO_2 separation from flue gases. Need to develop:**
  - Media and membranes with multifunctional and size/shape selective nanocages that can capture CO_2 from flue gases and convert it to useable products.



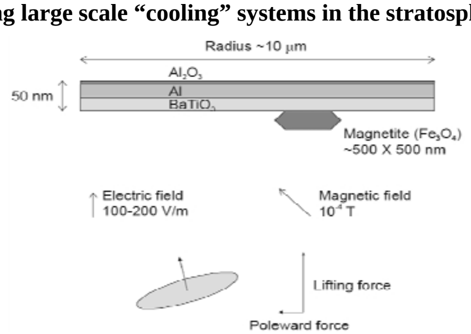
Priority Research Area

Multivariate (MTV) metal organic frameworks (MOFs) as building bocks for the next generation of CO_2 capture and conversion technologies (Yaghi and co-workers, Science. 2010, 327, pp 846-850).

Climate Change: Vision and goals for 2020

Beyond CO_2 Capture and Storage: Climate Mitigation Through Geoengineering

- **The ultimate goal of geoengineering is to reduce global warming by developing and deploying large scale "cooling" systems in the stratosphere.**



Conceptual design of a self-levitated nano-disk for geoengineering (Keith, 2008). This nano-disk configuration is theoretically designed to have 3 properties: (1) the aluminum layer ~25 nm thick would be reflective in the visible and transparent in the infrared portion of the electromagnetic spectrum; (2) the nano-disks would self-levitate in the stratosphere due to the interaction of the barium titanate ($BaTiO_3$) with the natural electric-field (100-200 V/m) in the stratosphere; and (3) the nano-disks would "tilt" due to the off-center presence of the magnetic iron oxide (Fe_3O_4) interacting with the Earth's magnetic field in the stratosphere, leading to the nano-disks being pushed by Brownian forces in the direction of the Earth's magnetic poles and concentrating the particles over the Arctic. All of the material layers and size scales indicated in this figure could be produced using existing nanofabrication techniques.

Scientific and technological infrastructure needs

- **During the last 10 years, there has a gradual shift from the discovery, characterization and modeling of nanoscale materials and phenomena toward the development of nano-enabled systems, devices and products.**
- **Need to advance the science and engineering knowledge required to manufacture the next generation of nano-enabled sustainable products, processes and technologies.**
- **Key science and technological infrastructure needs and R&D investment needs include:**
  - Holistic investigations of all interdependent aspects of sustainable development including cost-benefit-environmental risk assessments.
  - Nanomaterial scale-up and manufacturing facilities/hubs for sustainability applications.
  - Computer-aided modeling and process design tools for nano-enabled sustainability applications.
  - Test-beds for nanotechnology-enabled sustainability technologies

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R&D investment and implementation strategies

- **Nanotechnology solutions for sustainable development cannot be addressed at the level of small and single-investigator funded research grants.**
- **Sustainability R&D needs to be integrated with broader research goals to be carried by dedicated nanoscale interdisciplinary research teams (NIRT) and Federally Funded Research and Development Centers.**
- **To achieve these objectives, we will need to:**
  - Establish interdisciplinary teams and centers to develop and implement nanotechnology solutions to key aspects of sustainability, as well as to develop suitable open source databases and partnerships
  - Develop new funding mechanisms to advance promising early-stage research projects, e.g. automatic supplemental funding for projects with commercial potential.
  - Involve industry at the outset of programs.
  - Accelerate knowledge and technology transfer from academic/government laboratories (e.g. academic spin-off companies.

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Summary and Conclusions: Goals for 2020

- **Nanotechnology has emerged as a powerful platform technology for addressing global sustainability challenges in energy, water, food, habitat, transportation, mineral resources, green manufacturing, clean environment, climate change and biodiversity.**
- **Priority areas include**

  -Nanostructured membranes for water reuse and desalination with high water recovery (>95%) that use low pressure (< 5 bar) and less energy than conventional reverse osmosis membranes (<1.0 KWh per m^3 of water produced)

  -Multifunctional media and membranes with tailored nanocages that can capture CO_2 fron flue gases and transform it into valuable products.

  -Nano-enable building blocks, catalysts and processes for green manufacturing.

- **Because sustainability entails considerations of social, economic and environmental factors, it is critical in all cases to integrate:**
  - Fundamental science (e.g. materials synthesis, characterization and modeling) with
  - Engineering research (e.g. system design, fabrication and testing), Commercialization (e.g. new products)
  - Societal benefits (e.g. new jobs and cleaner environment)
- **This can only be achieved by forming targeted and focused partnerships between academia, industry, government, non-governmental organizations and the venture capitalist community.**

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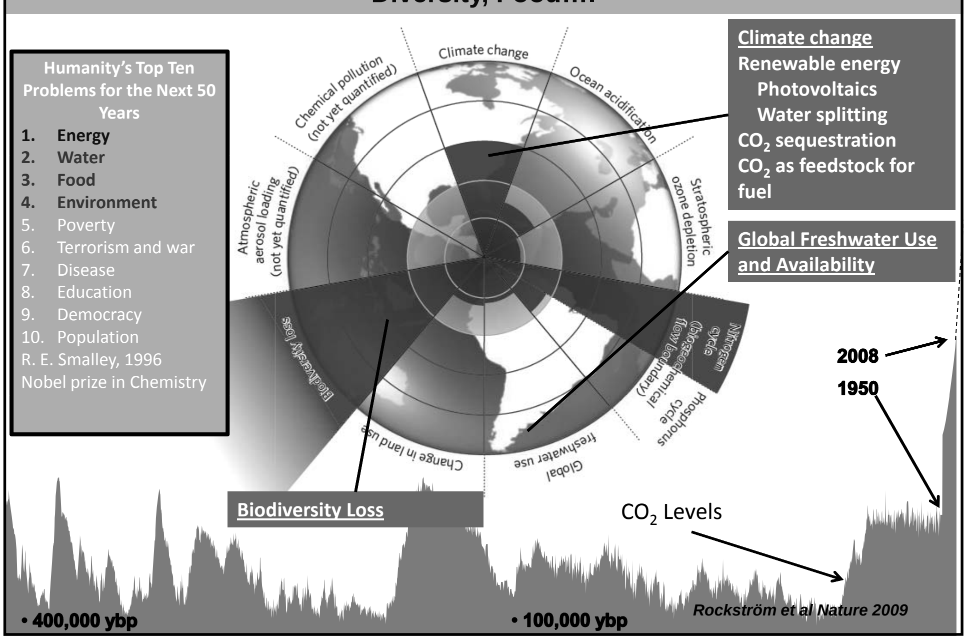
Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

Chapter 6. Nanotechnology for Sustainability: Energy Conversion, Storage, and Conservation

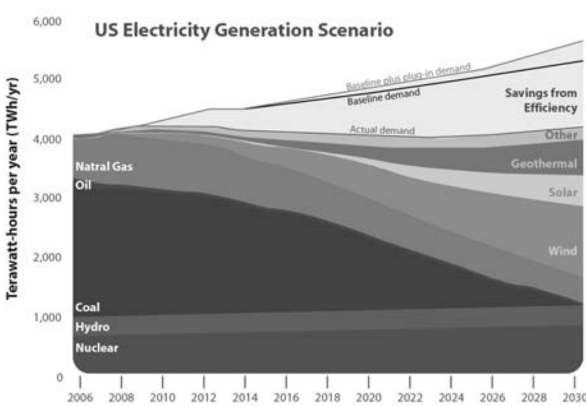
Jeff Brinker, David Ginger
With collaboration from:
Yet-Ming Chiang, MIT
…
International workshop moderators:
Bertrand Fillon, Wei-Fang Su, Subodh Mhaisalkar

NSF, September 30, 2010

It has been recognized for more than a decade that Energy is intimately related to Sustainability – Climate Change, Water Availability, Bio-Diversity, Food….



Nanotechnology is uniquely poised to enable the sustainable production and efficient consumption and storage of energy needed to be supplied at TW scale



This projection will allow us to reduce:

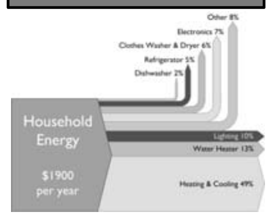
- Fossil **fuel-based electricity generation by 88%**
- Vehicle **oil consumption** by 44%
- Dependence on imported oil (currently 10 million barrels per day) by 37%
- Electricity-sector CO2 emissions by 95%
- Personal vehicle sector CO_2 emissions by 44%
- US **CO_2 emissions** overall by 49% (41% from today's CO_2 emission level)

(Adapted from google's "Clean energy 2030")

Consumption/Efficiency
Solid state lighting
Nano-insulation
Power transmission
Transportation
Thermoelctrics and Electrocalorics

Energy production
Advanced Photovoltaics
Artificial photosynthesis
H_2O splitting via sunlight
Biofuels
CO_2 as a feedstock

Energy and storage
Hydrogen storage
Ultracapacitors and CNTs
Batteries



How So?

- The dimensional scale of physical phenomena related to the capture, conversion, storage, transmission, and dissipation of energy is inherently NANO
  - Exciton (electron hole pair) dimension - PV
  - Bandgap engineering by quantum confinement – energy absorption, multi-exciton
  - Photocatalytic reaction center – photosynthesis, water splitting
  - Specific Surface Area – energy storage, bulk heterojunction interface, catalytic activity
  - Pore Size – molecular separations and water desalination
  - Friction/Lubricity/Adhesion
  - Diffusion and Convection – thermal, electrical, chemical transport
  - Defects - nanoscale

- But the energy future will require manufacturable/scalable, integrated systems coupling multiple nanoscale phenomena to enable low cost sustainable energy production, storage, and utilization on massive scale

Example 1: Solar Energy - *more solar energy strikes the earth in 1 hour than all energy consumed in 1 year* – ***must be captured, converted, and stored cost effectively***

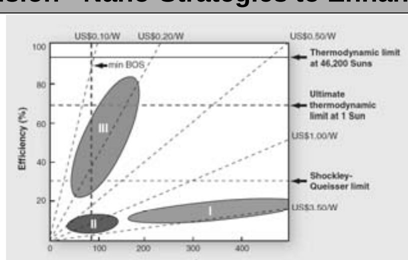
10 yr vision: nanotechnology enables ***scalable*** solar at ~10X below current cost due to tremendous scale of problem

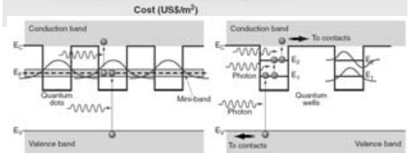
Relevance and Needs of Nanoscience and Nanotechnology:

- critical physical length scales (exciton diffusion lengths, minority carrier diffusion lengths)
- optical engineering for light harvesting: plasmonics, near-field energy transfer, and band gaps depend on size, shape, composition on nanoscale
- nanostructured colloids, and organic macromolecules, enable low-temperature, scalable, solution processing methods
- multiscale modeling in heterogeneous environments – understanding electron transfer at complex interfaces, transport over 10 or 100 nanometers
- scalable nano-to- macro scale manufacturing of nanostructures over large areas (imperfect OK)

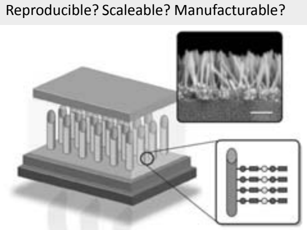
Vision - Nano-Strategies to Enhance Efficiency and Lower Cost of PV

DOE, 2005, Nate Lewis, *Science* 2007

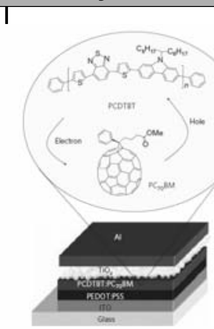


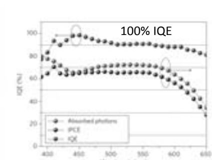


Strategies to circumvent 31% limit involve multiple excitons (e.g. PbSe QDs, Klimov et al APL 2005), mini-bands, and quantum wells. Reproducible? Scaleable? Manufacturable?



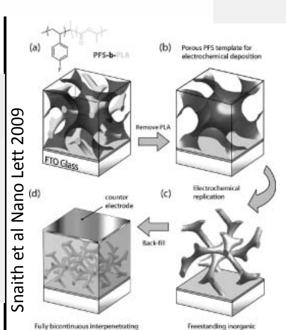
Overcome cost-thickness-purity constraint: Oriented nanostructures allow orthoganalization of the directions of light absorption and charge carrier collection





Bulk heterojunctions with nano-phase separated electron donating conjugated polymer and electron accepting fullerene, nano-optical spacer layer. 6% Power conversion efficiency - *Nature Phot.* 2009; > 8% reported Solarmer 2010

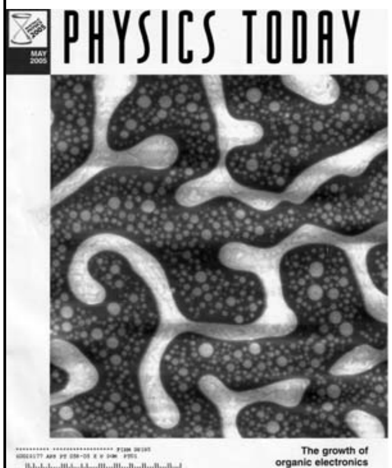
Snaith et al Nano Lett 2009



Bicontinuous double gyroid bulk hetero-junction – dye sensitized cell
– 1.7% PCE so far, 400-nm, thick

Vision: Can Nanostructured Polymer – Based Solar Cells Provide a Scalable Route to Cheap PV?

Hierarchical assembly – can we control molecular to nanoscale structure over large areas, in a scalable (roll-to-roll) manufacturing process?



In a bulk heterojunction solar photovoltaic a nanostructured donor/acceptor interface is used to dissociate excitons while providing co-continuous transport paths

Review by Malliaras and Friend

Trajectory

2000 Efficiency <1%
Lifetime= ~ hours
crazy to discuss as viable technology

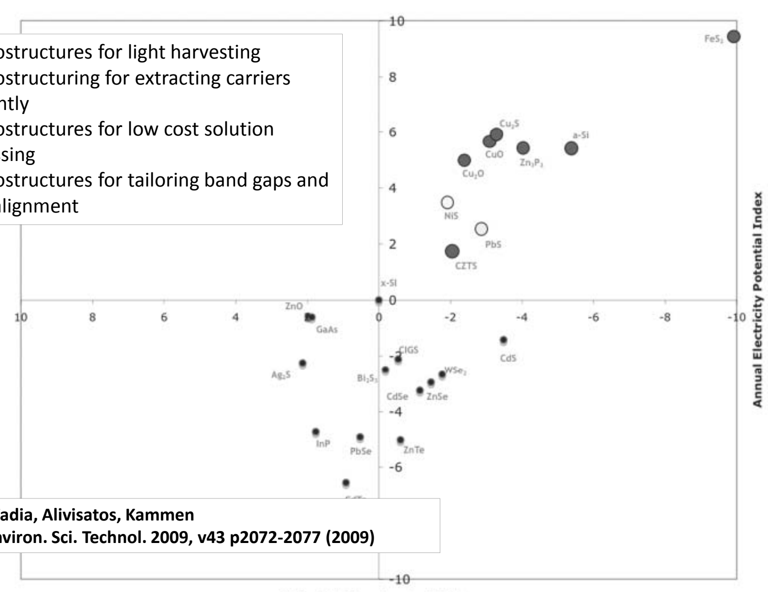
2010 Efficiency ~8% (certified lab scale NREL)
(enabled by new nano-materials, better control over nanoscale morphology)
Lifetime = unknown: months-years?
Industrial startups, Solarmer,

2020 Efficiency 10-15%
Low cost production
Lifetime= years+
Successful, transformative technology

This will require combination of new materials, light harvesting, modeling, scalable manufacturing, barrier materials

Vision: Can nanotechnology enable the use of cheap and abundant materials in new ways for low cost scalable and sustainable solar PV?

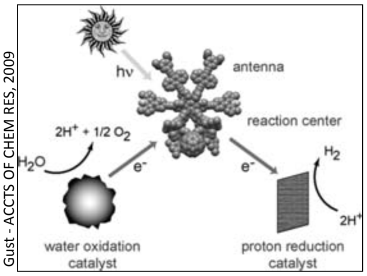
- Nanostructures for light harvesting
- Nanostructuring for extracting carriers efficiently
- Nanostructures for low cost solution processing
- Nanostructures for tailoring band gaps and band alignment



Wadia, Alivisatos, Kammen
Environ. Sci. Technol. 2009, v43 p2072-2077 (2009)

Example 2 Artificial Photosynthesis/Water Splitting – direct conversion and storage of solar energy in fuel – <u>Photosynthesis provides a blueprint for sustainable energy conversion and storage – But….is low efficiency and requires supporting architecture and multi-electron redox catalysts</u>

Gust - ACCTS OF CHEM RES, 2009

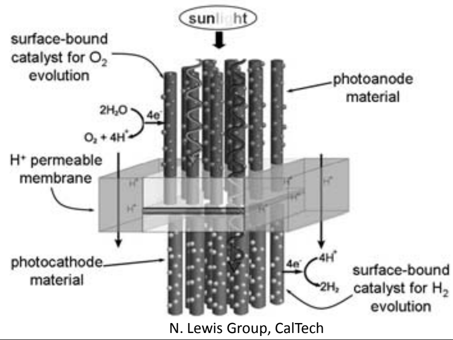


P. Yang Group LBL/UCBerkeley

Semiconductor nanowires and their heterojunctions can have optimized light absorption, high charge mobility, efficient charge separation and collection, and reduced recombination –

The n/n heterojunction is a promising structure for solar water splitting since the photovoltage at the junction can compensate for the lower energy level of the conduction band of the shell semiconductor

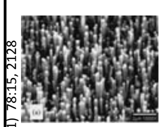
Require dramatic improvements in efficiency and durability before they can be considered for practical application - Gust

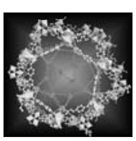


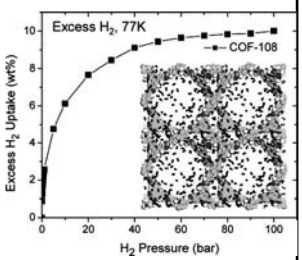
N. Lewis Group, CalTech

Example 3. Energy storage| nanomaterial storage of electrical energy and hydrogen

Appl. Phys. Lett. (2001) 78:15, 2128







Yaghi *JACS* 2008

2010 DOE targets 45 g H_2 per L (~6 wt%) temperature range -30 to 50˚C and low P

- **CNT** promised high H_2 uptake (5-7%) at modest pressures (10atm)…later disputed/invalidated.
- H_2 uptake 10.0 total wt% and 66 g/L has been observed for **MOF** $Zn_4O(BDC)_3$ at 77K and 100 bar
- **COFS** (>3000m²/g) show promise (predict that COF-105 and COF-108 lead to a reversible excess H_2 uptake of 10.0 wt % at 77 K)

•Nano-Solutions:

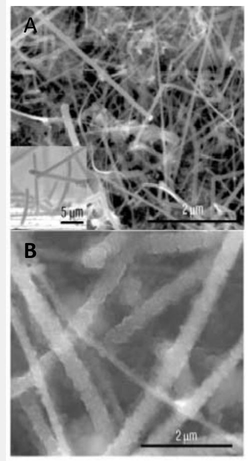
-Continue development of high, engineered, surface area, pore structure, and pore volume

-High hydrogen adsorption enthalpy - 22-25 kJ/mol interactions for hydrogen storage at room temperature via engineered charge-induced dipole interactions at surface

But: Will hydrogen pressure vessel technology win out? We are far from room temperature storage

Example 3: Energy Storage: Batteries Trajectory

- **(2000)** Li-ion batteries adopted for cellphones and laptops, but had safety issues, low performance (100 Wh/kg) unclear for use in automotive applications
- **(2010)** Nanotechnlogy enables engineered high surface area interfaces, efficient diffusion, and efficient displacement reactions in new battery materials
  -Toyota Prius is highest-selling hybrid car in U.S., Chevy Volt PHEV and Nissan Leaf EV ready to launch
  -Performance:150 Wh/kg
- **(2020)** Target Cell level performance of 400 Wh/kg, 800 Wh/L, <$100/kWh to enable 200 mile battery electric vehicles, nanotech enables new performance – PHEV's standard



Low-dimensional nanostructured materials, such as these Si nanowires used as an anode in a Li ion battery before (A) and after (B) electrochemical cycling (Nature Nanotech, v3, pp31-35, 2008) have the potential to increase the performance of batteries by 10X or more.

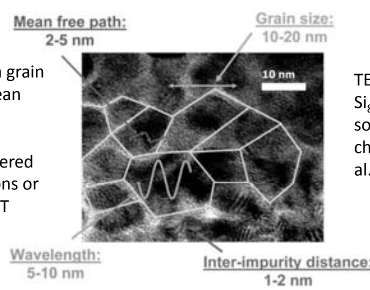
Example 4 – Energy Conservation - Thermoelectrics - the direct conversion of temperature differences to electric voltage – utilize 'wasted' heat energy from low efficiency power generation, etc.

Thermoelectric materials are ranked by a figure of merit, *ZT*, defined as:

$ZT = (S^2\sigma/k)T$ has increased barely above 1 in last decade

where *S* is the thermopower or Seebeck coefficient, σ is the electrical conductivity, *k* is the thermal conductivity, and *T* is the absolute temperature. *The challenge lies in the fact that S, σ, and k are interdependent*

Because the nanostructure has a grain size smaller than the phonon mean free path but greater than the electron or hole mean free path, phonons are more strongly scattered by grain boundaries than electrons or holes yielding a net increase in ZT



TEM image (3) of a heavily doped $Si_{80}Ge_{20}$ nanocomposite along with some important numerically calculated characteristic lengths. Dresselhaus et al. Appl. Phys. Lett. 2008

But…Vining CB (2009) An inconvenient truth about thermoelectrics. *Nat Mater* 8(2):83-85. Not as efficient as mechanical systems – limited to smaller scale – even for *ZT* = 4. **Nanosolution:** Decouple *σ/k with electrocalorics and heat switches, f*or example, a high contrast thermal switching material employing CNTs and LCs.

Example 5 – Energy Conservation - Solid-State Lighting

In 2001, **22% of the US energy** use was spent on artificial lighting – the equivalent of $50 B/yr and about 7% of the annual CO_2 emissions. 50% efficient SSL devices would save more than 400 billion-killowatt hours per year – ~50 nuclear power plants worth

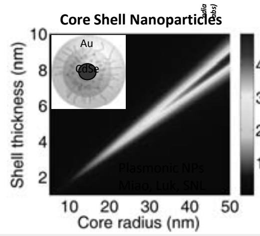
NEEDS

- Understand degradative energy conversion pathways, e.g. Auger recombination, where an electron-hole pair recombines, but instead of the energy going to create a photon, it goes to excite another carrier.
- Understand the relationship between energy quantization and dimensionality
- Clever ideas regarding device packaging and manufacturing – e.g. coupling with photonic lattices

Beyond 2-D

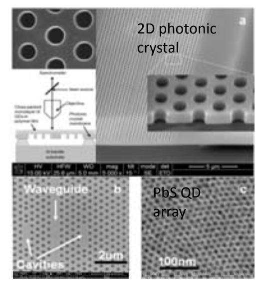
Luminescent nanowires and nanodots

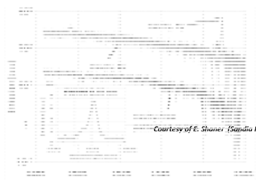
Core Shell Nanoparticles



Beyond Spontaneous Emission

Plasmonic routes to exciton-photon conversion





Xiong et al. *Small* 2010

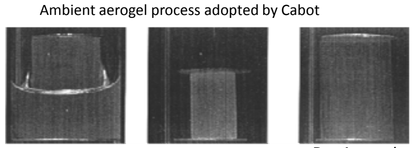
Nanostructures can result in enhanced field intensity and emission rate – coupling of fields can result in <u>efficient conversion of excitons to photons</u>

Example 6,7 – Energy Conservation – Super-Insulation and Power Transmission

Manufacturable Nano-Structured Thermal insulation

$$\mathrm{Si{-}OH + ClSi(CH_3)_3 \longrightarrow Si{-}O{-}Si(CH_3)_3}$$

Ambient aerogel process adopted by Cabot



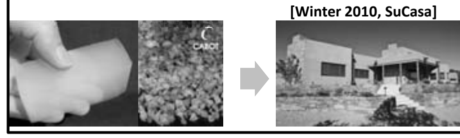
Modified Wet Gel — *Solvent-Filled Fully Shrunken Gel* — *Dry Aerogel Without Autoclave*

- Heating and cooling account for 50% residential energy – insulation can save 30%
- Nanostructured permeation barriers will allow new vacuum packaged nanostructured insulations – biggest area for immediate impact on energy sustainability

~~Ultraporous nanomaterials, where the pore size << the~~ mean free path, minimize conduction, convection, and radiation of heat

Su casa house uses half as much energy to heat/cool than average

[Winter 2010, SuCasa]



Power transmission

Significant amounts of energy are lost through the power distribution grid. This problem can be alleviated through the implementation of clever power allotment strategies. However, real contributions to efficiency can only be realized with a complete overhaul of the transmission pathways.

The development of **CNT strands on reels** is rapidly nearing production and may serve as a solution to this problem.

Vision/Challenges for the Next Ten Years:

- Improve the efficiency of photovoltaic devices beyond Shockley-Queisser limit (31%) through **Nano-enhanced light coupling, engineered interfaces, multi-exciton effects, and bandgap engineering**

- Develop scalable, low-cost manufacturing methods for photovoltaic fabrication, e.g. roll-to-roll, **through self-assembly** and other bottom-up approaches **utilizing non-precious, abundant and 'impure' materials** resources, e.g FeS_2.

- Increase efficiency of scalable organic PVs to 15-20% via **Self-Assembly and Nano-engineered phase separation of copolymers – Nano to Macro architectures**

- Increase stability of organic PVs for extended periods of time (>10 years) – Stability in general is a crucial issue for nano – nano-related defects and will require **Nanostructured barrier coatings**

- Improve battery power and energy density **through Nano-interfacial engineering** as well as lifetime for electrified transportation and grid-connected renewables: 400 Wh/kg, <$100/kWh to enable 200 mile battery electric vehicles

Vision/Challenges for the Next Ten Years

- Develop economical, efficient catalysts and nano- to microscale architectures to convert electricity and/or sunlight to chemical fuels with efficiencies exceeding natural photosynthesis
  - – risky, inefficient requires two multi-electron redox catalysts
  - - no manmade catalysts come close to hydrogenase and photosystem II

- Increase significantly the figure of merit for thermoelectric and electrocaloric materials to >3; develop **new Nano-systems that decouple σ/k**

- Increase efficiency of Solidstate Lighting - **Nanostructures can result in enhanced field intensity and emission rate** – coupling of fields can result in <u>efficient conversion of excitons to photons</u>

- Continue development of nanostructured materials for improved energy efficiency in everything from buildings to industrial separations – **Nanostructured thermal insulation vacuum-packaged in nanobarrier coatings** may have highest immediate impact

R&D impact on society

- Energy is a central pillar supporting sustainable development, economic growth, and national security
- Energy intimately connected with water availability, world health, climate change, and biodiversity (through water quality availability and climate change) and health (air and water quality and climate change)
- Impacting energy with nanotechnology will provide direct tangible examples that can be understood by students and the general public (similar to nanomedicine)

Infrastructure needs

- Certified performance measurements/standards/facilities (for solar, utility scale storage, etc.)
- Test platforms for large area multiscale manufacturing
- Expand computational resources (both hardware and software) for tackling multiscale systems function and manufacturing
- Metrics and codes for predictive self-assembly as a manufacturing tool
- For computation: need more energy related codes maintained by topical experts
- Infrastructure to accelerate development and adoption of nanotechnologies for targeted energy applications (e.g. hubs for efficient buildings, fuel conversion, etc.)

R&D Strategies

- What R&D investment and implementation strategies would you suggest?
  - Is there something to be learned from the "SRC" model that can be implemented in energy?
  - Award more student and postdoctoral fellowships in nanoscience and nanotechnology for energy
  - Crosscutting nature of problems demands synergy and integration between federal agencies, will require less exclusive "ownership" of ideas and programs
  - More small team awards –important to encourage connections between computation and experiment, unique opportunities for convergence in nanotech
  - Initiate international collaboration on energy which is a worldwide need for sustainability of mankind

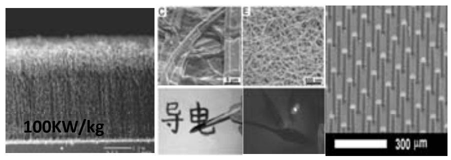
International Perspective

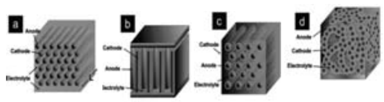
- Conduct an inventory of facilities (infrastructures, pilot lines, etc.)
- Develop an international roadmap "nano for energy applications"
- Improve the efficiency, stability, and life of fuel cells/batteries. Need to work on the system level rather than on single components such as electrodes, think about battery recycling
- Work out the details of total system cost of the various approaches for generation and storage of energy. The life-cycle issues need to be addressed.
- China will soon publish a plan for what it called "newly developing energy industries" that will involve 5 trillion yuan ($739 billion) in investment through 2020. -the *China Securities Journal*, 8 Aug 2010
- glazings, heat rejection coatings, phase-change materials, high reflectivity coatings, and alternate building construction materials (e.g., high-performance concrete reinforced by nanomaterials). New concepts in air conditioning (e.g., magnetocaloric cooling, absorption / adsorption chillers), dehumidification, and solid-state lighting will also be enabled by research in nanomaterials.

Example 3. Energy storage| nanomaterial storage of electrical energy and hydrogen

Electrical energy storage. Solid state batteries and ultra-capacitors benefit from engineered ultra-high surface area nanoscale interfaces and optimized pore architectures

PNAS (2006) **106**:51, 21490





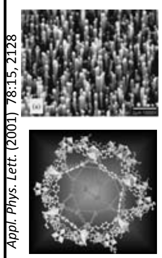
- CNT Ultracapacitor forests show >100times the power density of conventional Li-ion at 100kW/kg – but low energy density 60Wh/kg
- Li Ion – Li metal phosphate NPs 3kW/kg
- 3D battery assemblies on porous nanomaterial architectures

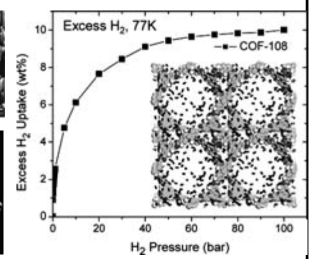
Chem. Rev. (2004) **104**, 4463 *IET Power Eng.* (2006)

Murray, Leslie J.; Dincă, Mircea; Long, Jeffrey R. (2009). Chemical Society Reviews 38 (5): 1294–1314

H_2 Storage using high surface area materials

Appl. Phys. Lett. (2001) 78:15, 2128





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- **Need:**

-High, engineered surface area, pore structure
- High hydrogen adsorption enthalpy - 22-25 kJ/mol interactions are ideal for hydrogen storage at room temperature; engineer charge-induced dipole interactions

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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

Chapter 7. Nanobiosystems, Medicine and Health

C.A. Mirkin, A. Nel
In collaboration with:
Barbara Baird, C. Carl Batt, David Grainger, Sanjiv Sam Gambhir, Demir Akin, Otto Zhou, J. Fraser Stoddart, Thomas J. Meade, Piotr Grodzinksi, Dorothy Farrell, Harry F. Tibbals, Joseph De Simone, Shad Thaxton

NSF, September 30, 2010

U.S. Contributors

Chad Mirkin[1], André Nel[2], Barbara Baird[3], Carl Batt[3], David Grainger[4], Sanjiv Sam Gambhir[5], Demir Akin[5], Otto Zhou[6], J. Fraser Stoddart[1], Thomas J. Meade[1], Piotr Grodzinksi[7,8], Dorothy Farrell[7,8], Harry F. Tibbals[9], Joseph De Simone[6], C. Shad Thaxton[1]

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7. NCI
8. NIH
9. University of Texas, Southwestern

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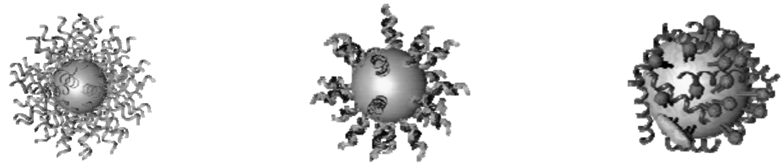
What is Nanomedicine?



The design and synthesis of biologically interactive nanoscale systems that enable medicinal technology advances in:

- **Prevention, diagnostics, treatment of diseases, including personalized, point of care modalities**
- **Preservation and improvement of human health**
- **Chronic and acute pain relief** by leveraging significant advantages nano-systems hold over traditional methods for sensing, imaging, reconstruction, delivery and interactivity of biological systems.

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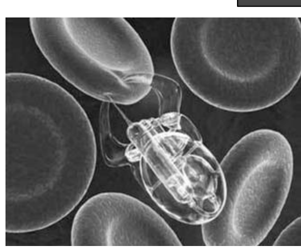
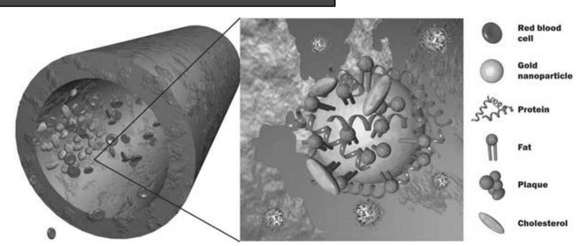
Changes of Vision in the Last Decade

From Nano-Robots to Nano-Realities





Fundamental research and diagnostic tools have been developed from nanoscale building blocks, some of which have been FDA cleared and approved.

Nanomaterials face increased scrutiny due to their unknown interactions in the environment.

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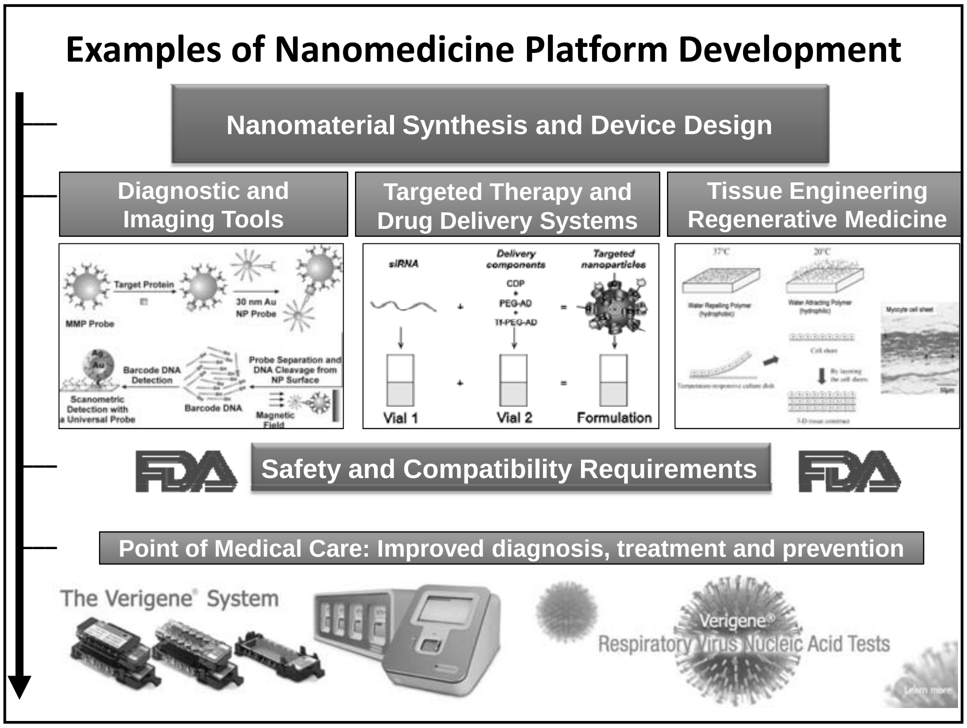
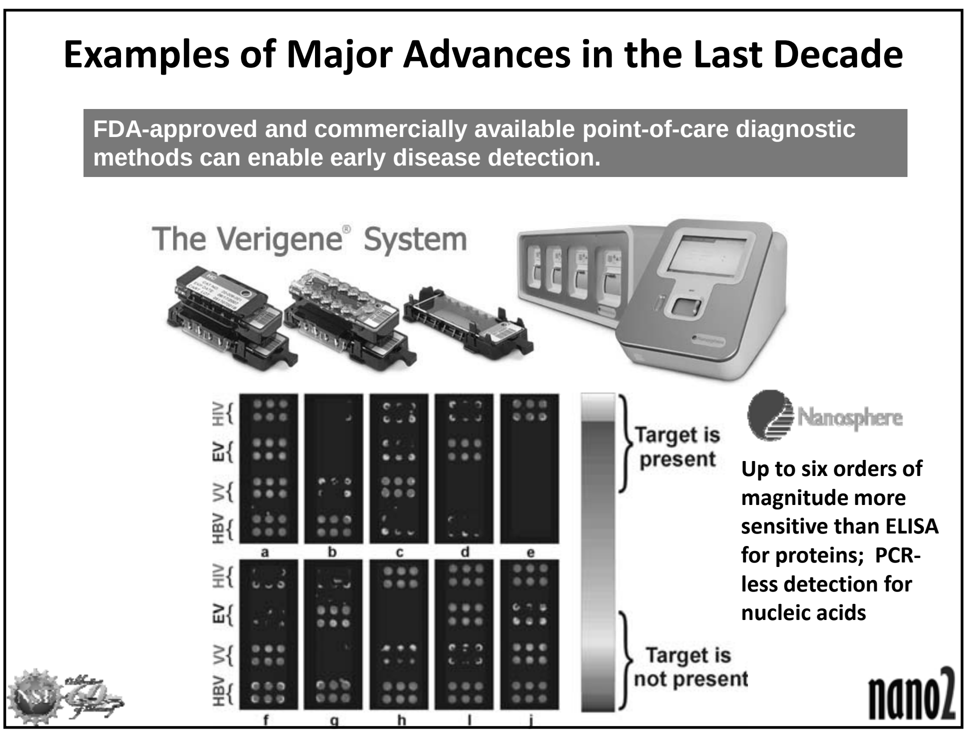
Challenges Nanomedicine Researchers Seek to Overcome

- Diagnostics
  - High sensitivity – comparable to or exceeding PCR, ELISA
  - Speed, multiplexing, portability, and decreased cost
  - Application of ultra high sensitivity systems in the clinic for improved disease diagnosis
- Imaging
  - Non-invasive monitoring of disease occurrence and progression
- Therapeutics
  - Improved specificity for drug delivery
  - Enabling nucleic acids and biologics for therapies
- Regenerative Medicine
  - Architectures that induce tissue regeneration as well as bone and organ repair

Vision for the next decade

	Screening	Diagnosis & Staging	Treatment & Monitoring	Follow-up
Current	• Relatively non-specific markers • Limited number • Macroscale imaging • Established disease	• Macroscale site imaging • Diagnostic surgery/biopsy • Intervention • Batch testing insensitive	• Surgery • Cath lab • Radiation • Debilitating chemo • Whole-body pharmaco-kinetics	• Macroscale site imaging • Relatively non-specific markers • Relatively late • Intervals
Nano Impact	[redacted]	[redacted]	[redacted]	[redacted]


Examples of Nanomedicine Platform Development
Nanomaterial Synthesis and Device Design
Diagnostic and Imaging Tools
Targeted Therapy and Drug Delivery Systems
Tissue Engineering Regenerative Medicine
Target Protein
30 nm Au NP Probe
MMP Probe
Barcode DNA Detection
Probe Separation and DNA Cleavage from NP Surface
Scanometric Detection with a Universal Probe
Barcode DNA
Magnetic Field
siRNA
Delivery components
Targeted nanoparticles
CDP
PEG-AD
Tf-PEG-AD
Vial 1
Vial 2
Formulation
FDA
Safety and Compatibility Requirements
FDA
Point of Medical Care: Improved diagnosis, treatment and prevention
The Verigene® System
Verigene®
Respiratory Virus Nucleic Acid Tests


Examples of Major Advances in the Last Decade
FDA-approved and commercially available point-of-care diagnostic methods can enable early disease detection.
The Verigene® System
HIV
EV
VV
HBV
a
b
c
d
e
f
g
h
i
j
Target is present
Target is not present
Nanosphere
Up to six orders of magnitude more sensitive than ELISA for proteins; PCR-less detection for nucleic acids
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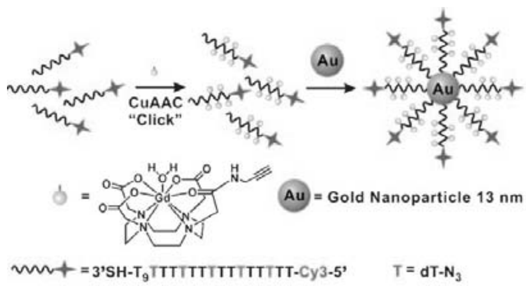
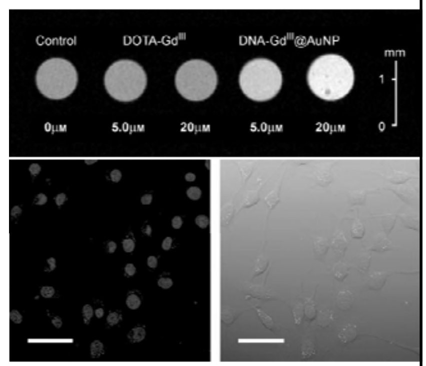
Examples of Major Advances in the Last Decade

Polyvalent DNA-Au nanoparticle conjugates as multifunctional gene regulation and magnetic resonance imaging agents. These constructs require no transfection agents, making them ideal candidates for drug delivery and imaging.

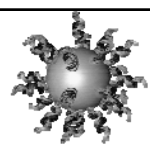


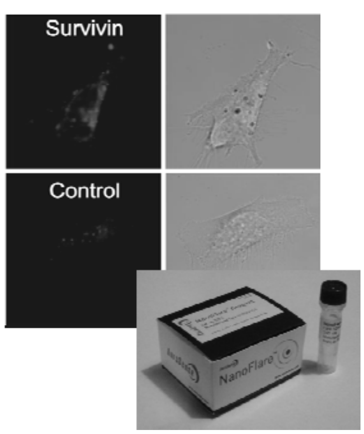


Northwestern

100 times more sensitive than molecular probes

NanoFlare™ Platform





NanoFlare™ Constructs

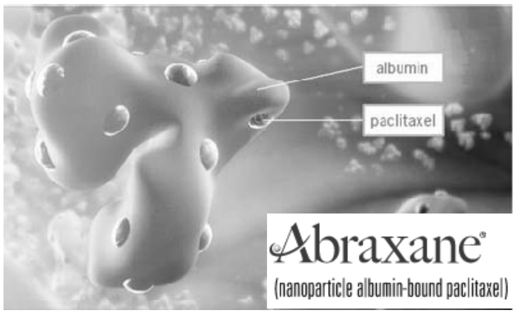
Key Advantages

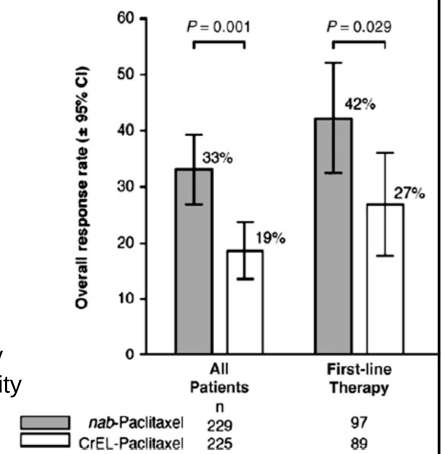
- ***A unique method for quantifying mRNA and small molecules inside living cells***
- Easy to use with existing equipment and no special preparations
- Meaningful alternative to ubiquitous RT-PCR platform
- Carrier free, non-toxic
- High uptake and stability
- High signal to noise ratio
- Enables genetic- and small molecule-based cell-sorting assays

AuraSense

Examples of Major Advances in the Last Decade

Abraxane is a FDA-approved therapeutic which relies on albumin protein nanoparticles as a paclitaxel carrier for more efficient drug delivery to tumor sites.





- Solvent based administration of chemotherapeutic agents has allowed delivery of hydrophobic drugs but has associated toxicity
- Allows delivery of a 49% higher dose of paclitaxel vs solvent-based paclitaxel

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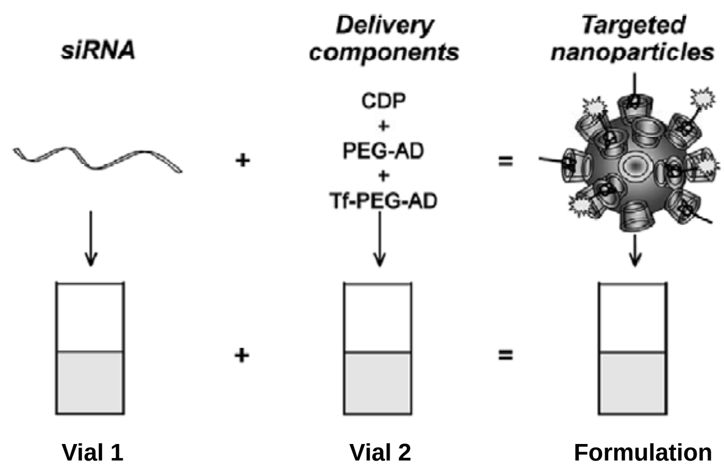
Examples of Major Advances in the Last Decade

First demonstration of RNA interference in humans via targeted delivery of siRNA in a self-assembled nanoparticle construct.



Cal Tech

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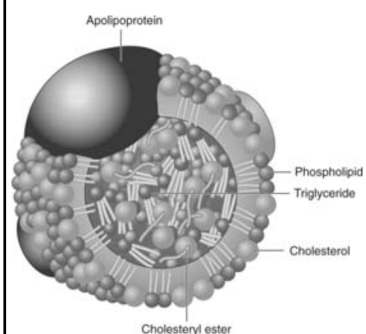
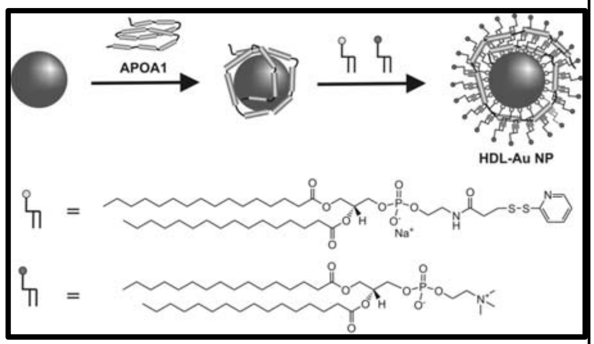
Major Advances in the Last Decade

Synthetic replacements as therapies in the context of HDL, a model example demonstrating that nanomaterials can mimic size, shape, and activity of biological analogs.

Natural high density lipoprotein (HDL)



Synthetic HDL analog using nanomaterials

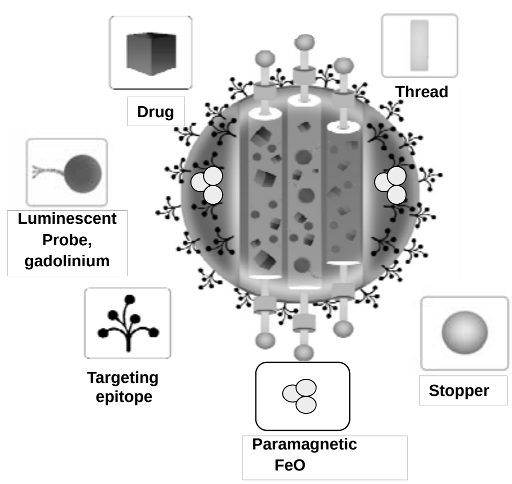


Libby, P. Braunwald's Heart Disease 8th ed., 2008
Schaefer, E. and Asztalos, B. 2007 *Curr Opin Cardiol* 22:373-378.
Singh, I. et al. 2007 *J. Am. Med. Assoc.* 298: 786-798.

AuraSense nano2

Examples of Major Advances in the Last Decade

Targeted nanotherapies with controlled drug release mechanisms via light, pH, temperature controls allow one to enhance disease treatments. The multifunctionality of the nanoparticle is enabling.



Stimuli

- Light
- pH
- Enzymatic
- Temp
- Redox

UCLA, Northwestern nano2

Expected Major Advances in the Next Decade

- Medical Diagnostics – many order of magnitude increased sensitivity, selectivity, and multiplexing capabilities at low cost will enable **point-of-care diagnosis** and treatment. Moreover, these capabilities will allow clinicians to **track and treat disease,** in some cases, **years earlier than with conventional tools**. **Nanodiagnostic tools will become the backbone of clinical medicine by 2020, making the transition from remote labs to hospitals and then eventually the home.**

- Biological Diagnostics – **Routine live cell imaging with the ability to identify and quantify the key components of a cell (nucleic acids, small molecules, and metal ions) will become possible and enable a new way of studying, diagnosing, and treating some of the most debilitating diseases (cancer, cardiovascular, and Alzheimer's disease).**

- Nanotherapeutics – Many challenges such as pharmacokinetics, biodistribution, targeting, tissue penetration, *etc.* will be overcome, and **major nanotherapeutics will be adopted by industry. At least 50 percent of all drugs used in 2020 will be nanoenabled. Many of these will be for diseases like glioblastoma, pancreatic cancer, and ovarian cancer, where patient prognosis is grim with current therapies.**

- Stem Cells – Nanobiology and nanomedicine will aid in the **understanding and control of stem cell differentiation and the transition of stem cells to widespread medicinal application**. These advances will be fueled by advances in diagnostics, intracellular gene regulation, and high-resolution patterning tools. **Nanoenabled stem cell-based therapies for spinal cord regeneration will be in wide-spread use by 2020.**

- Tissue Engineering – Nanotechnology strategies will rapidly enable the growth of **clinically relevant tissue regeneration and repair strategies. Nanoenabled tissue constructs for cardiac damage repair (heart attack victims) will be in wide-spread use by 2020.**

- Economic Impact– Many bionanomaterials will be translated to the medical arena, and **the market size for these nanomedicine advances is estimated to grow to $200 billio by 2020 by varying estimates. In the process, these technologies will dramatically lower health care costs.**

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Scientific & Technological Infrastructure Needs

- Centralized Research Centers – Focused research infrastructures (e.g. CCNE, NSEC) with targeting funding approaches are needed to expedite key discoveries. The FDA needs its own Nano-based infrastructure for evaluation purposes.
- Investment in Education – K-12 outreach programs are necessary to foster and enhance matriculation to careers in science. Enhanced communication between researchers, clinicians, industry is necessary for enhanced collaboration, and understanding and overcoming of major hurdles facing nanotechnology.
- Quality Control – Reproducible, large scale production and characterization of nanomaterials is necessary. High quality production platforms, and broad access to characterization tools of nano-bio interactions are required for evaluative purposes. Standardized safety tests are needed for the evaluation of nanomaterials *in vitro* and *in vivo.*
- Clinical Trials – A more rapid mechanism for establishing and funding of clinical trials for promising nanodiagnostics and therapeutics must be established.

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R&D Investment and Implementation Strategies

- Substantial Investments, Substantial Returns – Nanotechnology is poised to drastically alter the economic and efficacy landscape of medicine with tremendous job creation in the United States. Large investments and financial incentives are necessary for the key drivers of these innovations (often universities and small start-up companies).
- Enhanced Communication – By increasing communication between healthcare professionals, pharmaceutical industry experts, and academics, nanomedicinal efforts may be streamlined to facilitate early interest and enhanced likelihood of translating intellectual curiosities to tangible medical impacts.
- Access to Information – As Nano transitions from an empirical science to a predictive technological platform, standards and a centralized knowledge base are needed to avoid redundancy and to enhance understanding of core nanomedicine challenges and solutions.

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Conclusions and Priorities

- 10 years of substantial growth – We have moved Nanomedicine to a lab based science to FDA approved diagnostic, therapeutic, and imaging nanomedicine platforms. Nanomedicine has impacted siginificantly other core medical endeavors such as tissue engineering and stem cell research.
- Much more to be gained – Large, focused investments coupled with scientific advances in related fields such as biomarker identification are needed to sustain growth.
- Collaborative synergy – Nanomedicine is an inherently collaborative endeavor. Communication pathways and relationships must be fostered between scientists, engineers, industrialists, clinicians and regulators to ensure safe, rapid introduction of nanomedicine to fully gain the advantages nanomedicine promises. Centers that focus on interdisciplinary themes are essential for the development of the field.

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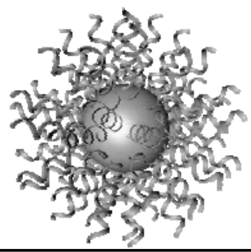
Broad Societal Implications

- Looking toward the future – Society stands to greatly benefit from the advantages of nanomedicine. **Early detection and monitoring of diseases, coupled with more effective therapies will drastically reduce the overall cost of healthcare.** Modular nanosystems will enable personalized medicine, targeted disease treatment, and tissue engineering at the point-of-care.
- Larger Economic Implications – Innovation in this sector will spur significant job creation, which will drive a revolution in the United States akin to the industrial revolution**. It will maintain our position as the world's innovation leader.**



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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

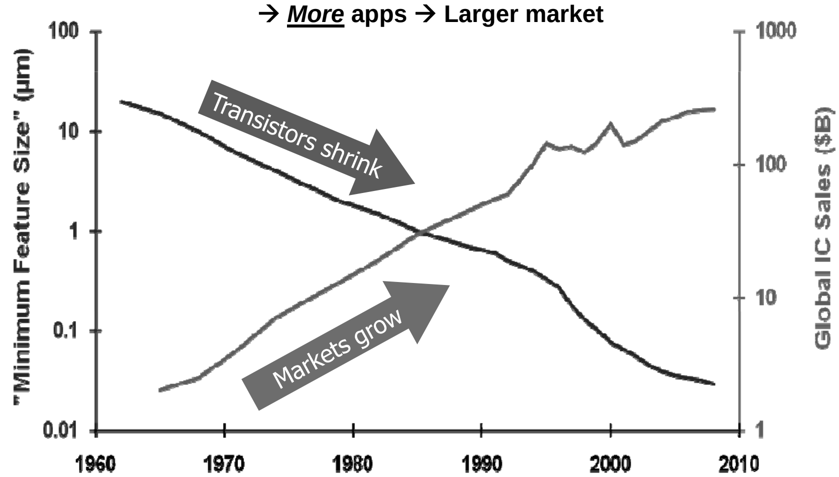
Chapter 8. Applications: Nanoelectronics and Nanomagnetics

J. Welser, S. Wolf, P. Avouris, T. Theis
With collaboration from:
….
International workshop moderators:
Clivia Sotomayor Torres, Ming Huei Hong, Andrew Wee

NSF, September 30, 2010

Nanoelectronics Most Visible Impact:
Scaling Drives the Semiconductor Industry

Smaller features → Better performance & cost/function
→ *More* apps → Larger market



Courtesy of R. Doering, Texas Instruments;
Data from Semiconductor Industry Association, http://www.sia-online.org

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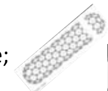
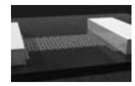
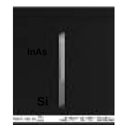
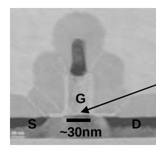
Advances in Last Ten Years:
From Science to Product

- Science/Engineering Level:
  - Expansion of Carbon Electronics: (Re-)discovery of graphene; advances in nanotube fabrication and selection
  - Emergence of Spintronics:
    - Demonstration of Spin Torque switching
    - Discovery of magnetoelectric / multiferroic materials
    - Discovery of the Spin Hall Effect
    - Demonstrations of spin injection and readout from semiconductors
  - Advances in resistive memory: Phase-Change, metal oxides
  - Fundamental understanding of semiconductor nanowire growth
- Product Level:
  - CMOS and FLASH scaled down to ~30nm
  - Magnetic Tunnel Junctions (MTJs)
    - Read Heads for Magnetic Recording; Magnetic RAM
  - Phase Change High Density Memory









Insulator:
SiON ~ 1nm or
High-k ~3nm

- Impact: Exponential increase in the capability and mobility of electronic devices:
  A cellphone is now a computer, internet access device, stereo, video camera, game machine, GPS, etc.

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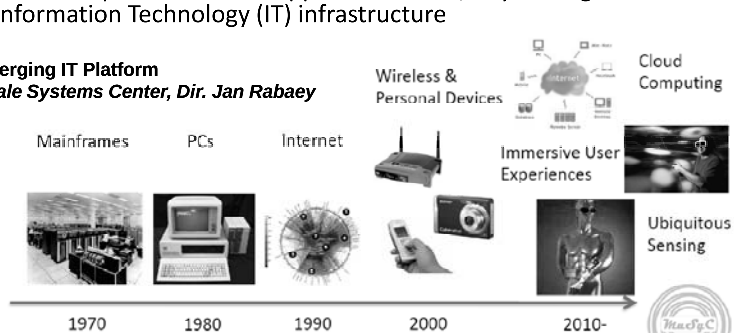
Vision Changes in Last Ten Years:
From How to Build → What to Build

- Barrier to future scaling changing from just "how do we make them smaller?" to "how do we reduce their power to make them usable?"
  - Shift from breaking below 100nm Si CMOS to breaking below 10nm
- Discovery of myriad new materials with new physics and properties driving new ideas for device functionality
- Shift from single device focus to circuits and architecture integration
- Increased emphasis on other application areas, beyond logic and memory for Information Technology (IT) infrastructure

The Emerging IT Platform
Multiscale Systems Center, Dir. Jan Rabaey



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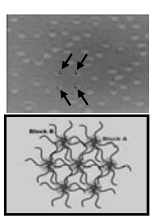
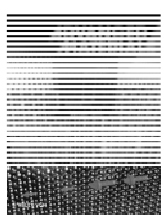
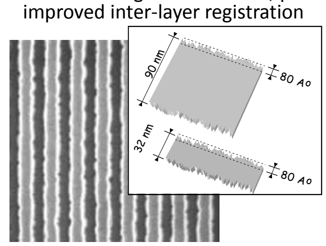
Vision for the Next Ten Years:
Major Directions

- Increased focus on utilizing new nanoscale physics for device functionality, rather than just fighting it to continue current device scaling
  - Alternate state variables for logic & memory
- Increased focus on architecture and alternative ways to do computation
  - Dealing with lower speeds for lower power: Multi-bit logic? Increased parallelism?
  - Dealing with increased variability: Analog / Statistical / “Almost Right” computation?
  - Tighter integration – and blurring – between memory and logic: Non-volatile transistors, memristors, memory-in-logic, reconfigurable logic, FPGAs
- Increased focus on spin, magnetics, Magnetic Tunnel Junctions – especially spin torque based structures
  - STT-RAM, Nano-oscillators, Magnetic Sensors, Spin Torque MTJ Logic, magnetic cellular automata, reconfigurable arrays
- Increased focus on Carbon based devices
  - Exploiting physics of graphene, carbon nanotubes, fullerenes, defects in diamond
- Increased focus on non-IT applications – future driver of the industry
  - Energy, healthcare, sensors everywhere, always-on connectivity, mobile devices

Goals for 2020:
Fabrication

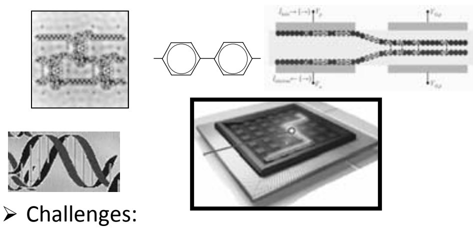
- Achieve 3D near-atomic-level control of reduced-dimensional materials
  - Includes mono-layer growth, nano wire/tube/dot growth and placement, custom materials (e.g. complex metal oxides, multiferroics), and meta-materials (e.g. ferroelectric lattice with embedded ferromagnetic particles)
- Combine lithography and self-assembly to pattern semi-arbitrary structures down to 1nm precision
  - Requires both top-down control of litho for ~10nm-scale arbitrary structures, and bottoms-up control of self-assembly of 1nm-scale regular structures, plus improved inter-layer registration

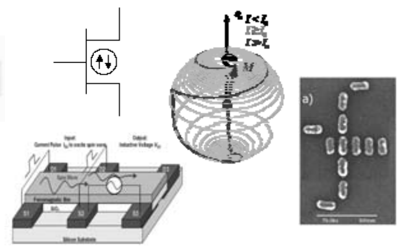




- Requires continued advances in:
  - Tools for growth, etching and placement at near-atomic levels
  - Chemistries for self-assembly
  - Metrology tools, including in-situ, dynamic characterization & in-line, non-invasive monitoring
  - Predictive modeling of materials and interfaces from atomic level up

Goals for 2020:
Devices

- Discover devices for logic and memory that operate with greatly reduced energy dissipation: 10,000kT → ~10kT
  - Power density is the primary limiter of future scaling. Requires:
    A device with a lower energy, room temperature switching mechanism
    and/or
    A system that operates out of equilibrium or recovers operation energy as part of the logic computation
- Exploit spin for memory, logic, and new functionality
  - Spin and nano-magnetics offer unique attributes (non-volatility, precession, low power, spin-spin interaction) already utilized in memory and storage
  - New materials and nano-scale control should enable logic, solid state quantum computing, oscillators, sensors, and other functionality

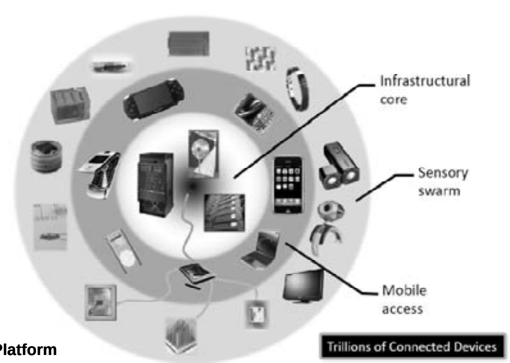




- Challenges:
  - Finding appropriate architectures and state variables (spin, charge, collective effects, etc.)
  - Maintaining speed, noise robustness, signal strength, gain/drive

Goals for 2020:
Architectures

- Integrate architecture and nanoscale device research for unique computation functionality
- Increase focus on emerging, non-IT applications
  - Previous research has focused on the device first, but most challenges are in the large-scale integration of any new device
  - Energy, healthcare, security, communications, sensors, flexible electronics all drive different needs at device and architecture level
  - Drives need for interdisciplinary teams – materials, chem/bio/physics, engineering, circuit design – working together on basic research driven by the application



The Emerging IT Platform
Multiscale Systems Center, Dir. Jan Rabaey

International Perspective
Insights from the EU and Asia Workshops

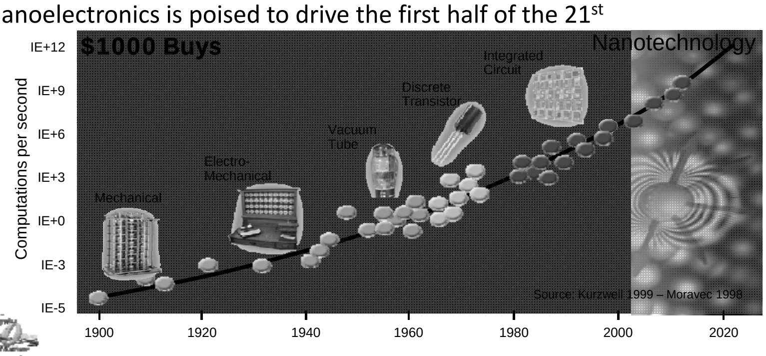
- International workshops reinforced the primary goals, and added additional emphasis in complementary areas
  - Potential to work together on common themes and build off each other's work
- EU Workshop, Hamburg, Germany (C. Sotomayor Torres, J. Welser)
  - Increased emphasis on "More-than-Moore" applications of nanoelectronics, particularly in analog devices, to enhance functionality
  - Strong focus on basic science research to discover new phenomena
- Japan-Korea-Taiwan Workshop, Tsukuba, Japan (M.-H. Hong, S. Wolf)
  - Also emphasized "More-than-Moore", but with more focus on exploring novel state variables and materials (e.g. topological insulators, orbitronics, superconductivity, etc.)
  - Strong interest in quantum computing
- Australia-China-India-Singapore, Singapore (A. Wee, S. Wolf)
  - Strong emphasis on full quantum information systems, for computation and communication
  - Increased interest in molecular electronics, as well as heterogeneous materials integration
- All groups emphasized the need for interdisciplinary teaming, focusing on the application as the driver, and continued strong investment in both research and infrastructure for nanoelectronics work

R&D Strategy & Infrastructure Needs:
Investing for Success

- Scientific and Technology Infrastructure Investment Priorities
  - Provide readily accessible tools – at low cost – to fabricate, characterize, and model *active* nanoelectronic structures at the atomic scale
    - Modeling: Multi-scale models that span from first-principles, atomic scale material simulations to macroscopic device & circuit relevant structures, including new state variables – readily accessible (e.g. NanoHub)
  - Expand nano-tools at Universities, regional centers (e.g. NNIN), and at National User facilities for rapid fabrication and characterization cycles
  - Enable infrastructure to look at both single device prototypes, as well as larger scale nano-manufacturing strategies, to expedite implementation
- R&D Team Strategies
  - Form strongly interacting, multidisciplinary teams working on projects that start from specific applications
  - Increase funding for small, high-risk projects that can launch new innovation directions and larger centers in the future
  - Partner early with industry (e.g. NRI) – Goal-Oriented, Basic-Research
    - Utilize industry scientists/engineers as evaluators, liaisons for reality checks
    - Include industry funding, as appropriate for the focus and timeline of the research, to insure buy-in – and expedite transfer from lab to product

Nanoelectronics Impact on Society:
To Continue the Benefits, Continue the Curve

- Nanoelectronics plays a major role in tackling most of society's challenges
  - High Performance Computing: behind every major scientific advance
  - Energy: low energy devices, sensors, "smart" appliances & energy grid
  - Bio / Health: in vivo sensors, health monitoring, drug delivery, drug discovery
- Increased proliferation of mobile devices, sensors, and always-on connectivity will alter how we interact with each other and the planet
  - More remote interactions, workforce globalization, remote delivery of services
  - Continued focus on environmental & societal impact of embedded devices
- Microelectronics was THE economic driver for the last half of the 20th century Nanoelectronics is poised to drive the first half of the 21st



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Two-page Overview Slides

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Nanoelectronics & Nanomagnetics

- Nanoelectronics is arguably the most mature application of "nano" to date, with the largest impact on the economy
- Major breakthroughs in materials and devices over the past 10 years have opened up new fields for future research and product innovation
  - Expansion of Carbon Electronics: (Re-)discovery of graphene; advances in nanotubes
  - Emergence of Spintronics for applications beyond storage: memory, logic, oscillators
  - Advances in resistive memory, and commercialization of phase change memory
- The focus has been on "how-to-build" IT devices at the nanoscale; the next 10 years are likely to focus on "what-to-build" beyond the IT roadmap
  - Requires a focus on reducing power, exploiting (rather than fighting) quantum effects, and letting specific applications drive the research
- Will result in greater impact in more diverse fields
  - Continued advancement of High Performance Computing, the underpinning of almost every major advance in all areas of science
  - New products incorporating advanced communications, sensors, flexible electronics, etc. helping to build solutions in every sector of society, including energy, healthcare, and security

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Nanoelectronics & Nanomagnetics

- Primary Goals for Nanoelectronics by 2020:
  - **Fabrication:** Achieve 3D near-atomic-level control of reduced-dimensional materials
  - **Fabrication:** Combine lithography and self-assembly to pattern semi-arbitrary structures down to 1 nm precision
  - **Devices:** Discover devices for logic and memory that operate with greatly reduced energy dissipation
  - **Devices:** Exploit spin for memory, logic, and new functionality
  - **Architecture:** Integrate architecture and nanoscale device research for unique computation functionality
  - **Architecture:** Increase focus on emerging, non-IT applications
- Achieving these goals will require:
  - Interdisciplinary teams, particularly with domain experts in specific application areas such as bio, health, energy, and security
  - Increased investment in nanoelectronics infrastructure for fabrication and metrology, including dynamic characterization
  - Increased investment in modeling tools that can span from atoms to systems
- Public-private partnerships – even for basic research – can help to guide the work and expedite transfer to new product innovations
- *Microelectronics was THE economic driver for the last half of the 20th century Nanoelectronics is poised to drive the first half of the 21st*

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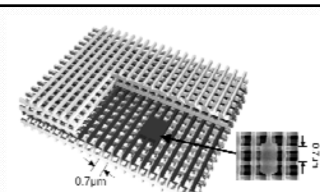
Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

Chapter 9. Applications: Photonics and Plasmonics

E.L. Hu, M. Brongersma, A. Baca
With collaboration from:
....
International workshop moderators:
Fernando Briones Fernandez-Pola, Satoshi Kawata, Paul Mulvaney

NSF, September 30, 2010

Some Definitions



S. Noda

Photonic Crystal Cavity

- ***Nanophotonics :*'the science and engineering of light-matter interactions that take place on wavelength and subwavelength scales where the physical, chemical or structural nature of natural or artificial nanostructure matter controls the interactions'.**

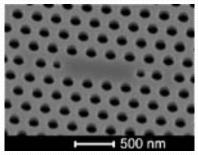
'Nanophotonics', NRC Report 2008

Plasmonics: exploits the unique optical properties of metallic nanostructures to enable routing and active manipulation of light at the nanoscale.

Plasmonic Modulator

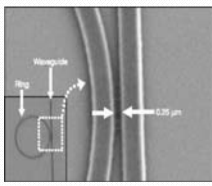
Thomas Nikolajsen et al., Optics Commun. (2005).

Advances in the Last Decade: New Semiconductor Nano-optics

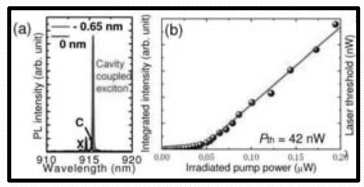


Dielectric Nanocavities with Ultra High Quality Factors (10^4 – 10^6)

- **On-demand control of photons**
- **Ultra-low threshold lasers**
- **'slowed light'**
- **New quantum mechanical states**
- **Higher speed, lower power information switching**



Silicon-based waveguides & optical switches



Nomura, Arakawa et al., *Optics Exp.* **17**, 815975 [2009]

Single Quantum Dot Laser

Advances in the Last Decade: New Imaging Capabilities

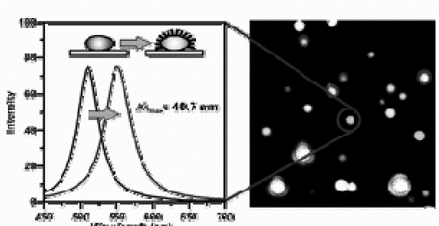
Imaging & detection with exceptional spatial & spectral resolution, at the level of single molecules

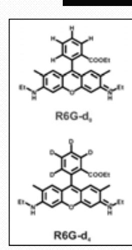
Scanning Near-Field Optical Microscopy

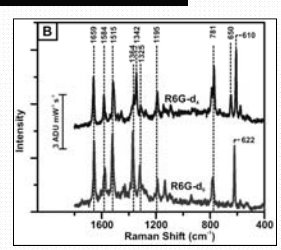
Taminiau, et al. Nano Lett. 7, (2007)

R. Van Duyne

Single Molecule SERS





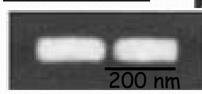


Single Nanoparticle Biosensor

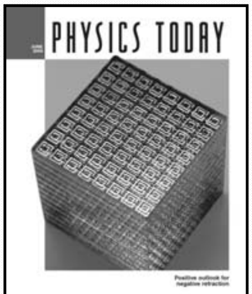
Advances in the Last Decade: the emergence of plasmonics

- Photonic devices at 10's of nanometers
- Highest resolution detection and excitation
- Applications for solar cells, medicine, imaging….

Nanoscale Antennas

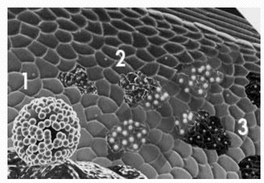


D.W. Pohl et.al, 308, 1607, Science(2005)



METAMATERIALS

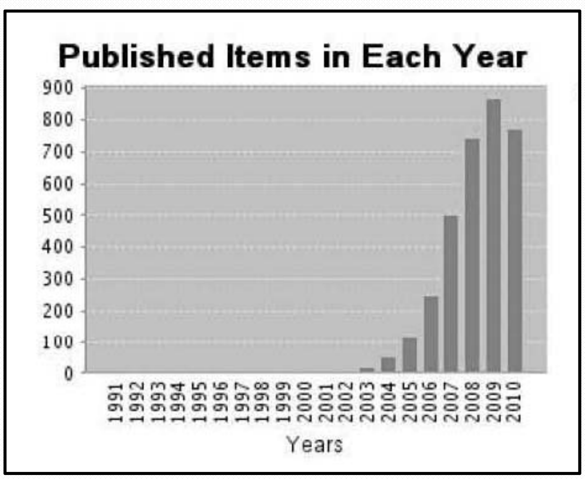
'Cloaking', lensless focussing



New Medical Therapeutics

Kelleher, *Popular Sci.* 2003

The rapid emergence of plasmonics



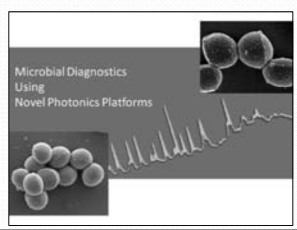
ISI Web of Science, key word = plasmonic*

How has the vision (& expectation) changed in the past 10 years?

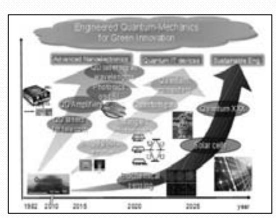
- **The realization of photonic devices 10's of nanometers dimensions (much less than the wavelength of light)**
- **Development of new photonic materials by design.**
- **Integration of nanophotonics and plasmonics into a <u>broader range of applications</u>**
  - ✓ **Photovoltaics, catalysis, biomedical therapies . . .**
- **Gaining increased control of photons**
  - ✓ **'slowed light', photons on demand, change in lifetimes**

The International Perspective

European Roadmap
For Photonics & Nanotechnologies



Photonic Platforms for Biomedical Applications, Taiwan



Quantum Dot Technologies, Japan

Lessons from the past decade

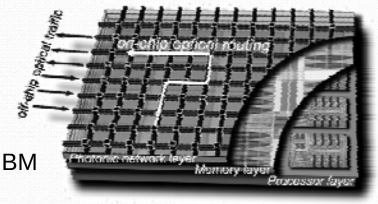
- **Rapid (& surprising) developments of new science & technology can take place *if the right infrastructure is in place***
- **'Holy Grails' are obtainable**
  - ✓ **Slowed light**
  - ✓ **'Thresholdless' lasers, lasing from a single quantum dot**
  - ✓ **Sub-wavelength imaging**
- **Photonics at the <u>nanoscale</u> produces greater opportunities for integration into other platforms and applications**

Infrastructure needs to ensure continued progress

- **Develop simple *design rules* & *coupled optical simulations* for nanophotonics and plasmonics**
- **Support expanded use of state-of-the-art fabrication facilities**
  - ✓ **Access to silicon-based fabrication**
  - ✓ **Develop low-cost patterning & assembly of heterogeneous materials & devices**
- **Expand & Develop Characterization Capabilities for Nanophotonic & Plasmonic Materials & Devices**
- **Build new educational systems that promote diversity, interdisciplinarity and collaboration.**

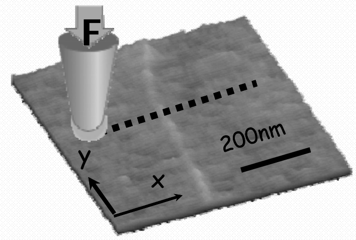
A vision of Nanophotonics & Plasmonics for 2020

True Integration of Photonics with Electronics



IBM

super-resolution microscopy



Tip-enhanced Raman imaging
(plasmonic probe)
Yano/Kawata, Nature Photon 2009

- **Photo-active nano-materials**
- **Instrumentation for 1nm-resolution imaging/analysis**
- **Three-dimensional photo-generated fabrication**
- **Selective medical photo-therapies**
- **New light-matter states for quantum information processing**

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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

Chapter 10. Applications: Nanostructured Catalysts

Evelyn Hu, S. Mark Davis, Robert Davis, Erik Scher

NSF, September 30, 2010

Changes in Vision for Nanostructured Catalysis

- **Earlier vision: Potential for breakthroughs in high selectivity & high yield**
  - ✓ **Demonstration of unusual catalytic properties at the nanoscale**
- **The new vision: Nanoscience-inspired design, synthesis & formulation of industrially important catalytic materials**
- **Grand Challenge:**

  'to control the composition and structure of catalytic materials over length scales from 1 nanometer to 1 micron and to provide catalytic materials that accurately and efficiently control reaction pathways'

  2003 NSF Workshop on *Future Directions in Catalysis*

The economic impact of nanostructured catalysis

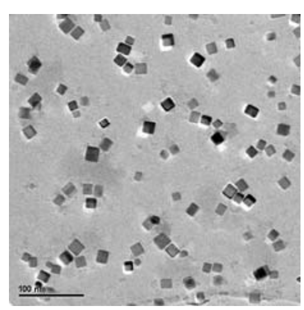
- **Global catalyst business: $18 – $20 billion/year**
- **Synthetic methods derived from modern nanotechnology currently utilized in 30-40% of global catalyst products**
- **Innovations in product selectivity & energy efficiency for conversion of petroleum to transportation fuels & petrochemicals: economic impacts: several $ trillion annually**
- **Looking to have an impact on 'Holy Grail' reactions (selectivity, conversion efficiency, temperature)**
  - ✓ **Highly selective oxidation of hydrocarbons (methane to ethylene)**
  - ✓ **Conversion of CO_2 to useful products (carbon dioxide reforming)**
  - ✓ **Catalytic after-treatment of waste**

Advances in the Past Decade: synthesis of nanostructured catalysts

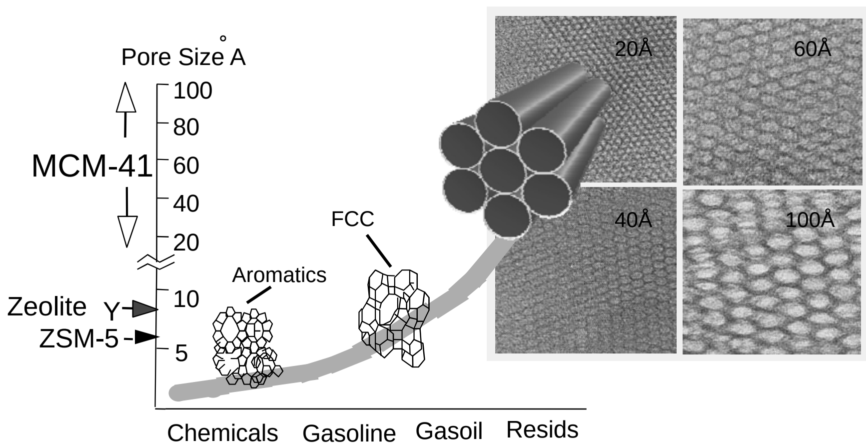
Natural reaction vessels for catalysis AND transport

- Control of porosity at different length scales
- Increased control of size, shape and surface orientations

Cubic Pd nanoparticles

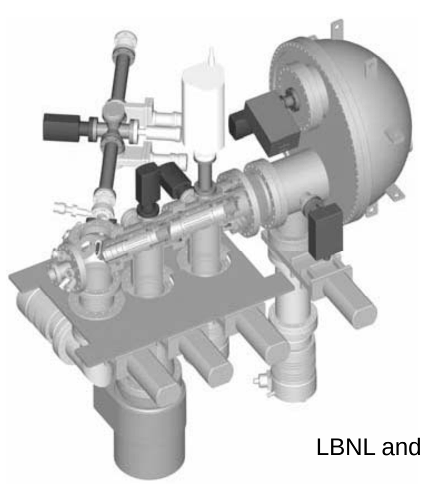


Advances in the Past Decade: control of porosity at different length scales



- ***MCM-41 Recent Commercial Nanotechnology Example***

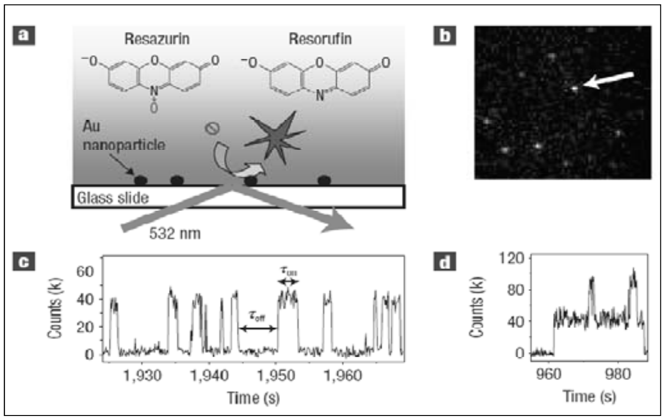
Advances in the Past Decade: characterization of catalysis in the 'working state'



X-ray Photoelectron Spectroscopy (XPS) at millibar pressures, under high flux

LBNL and Fritz Haber Ins.

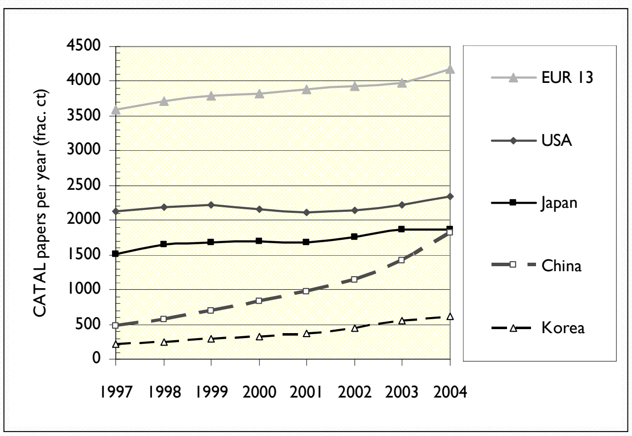
Advances in the Past Decade: single-turnover detection of Au-nanoparticle catalysis



Xu et al., 2008

The International Perspective

Earlier (2009) International Assessment of Nanostructured Catalysis



EUR13 = Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands Norway, Spain, Sweden, Switzerland, UK

What have we learned from the past decade?

- Tremendous advances in synthesis and characterization…
  - Possible to control size, shape, crystalline faces of nanoparticle catalysts
  - Possible to engineer hierarchical structure in nanoporous catalysts
  - Possible to monitor catalysis in 'working conditions', and as single turnover events

BUT

- The Grand Challenge so far remains elusive

  'to control the composition and structure of catalytic materials over length scales from 1 nanometer to 1 micron and to provide catalytic materials that accurately and efficiently control reaction pathways'

- The involvement and benchmarking by industry has been and will continue to be critical

Goals for the Next Decade

- Design & Synthesis:
  - ✓ Materials with controlled meso-microporosity & stability
  - ✓ Metal and metal oxide particles with preferential exposure of surface planes
  - ✓ Hierarchical design of catalysts with multiple functions
  - ✓ Materials that will scale up to perform in large-scale industrial processes
- Characterization of Catalysts in Working State
  - ✓ Improve state-of-the-art resolution (temporal & spatial) spectroscopy
  - ✓ Combined catalysis and microscopy
- Improvements in Theoretical Methods
  - ✓ Improve method accuracy
  - ✓ Connect ab initio methods and atomistic simulations
  - ✓ Begin to predict materials synthesis

Vision for 2020

- Demonstrate impact on 'Holy Grail' reactions
  - ✓ Highly selective oxidation of hydrocarbons (methane to ethylene)
  - ✓ Conversion of CO_2 to useful products
  - ✓ Catalytic after-treatment of waste

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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

Chapter 11. Applications: High-performance Nanomaterials and Other Emerging Areas

Mark Hersam, Paul Weiss
With collaboration from:
Richard Siegel, Phil Jones, Fereshteh Ebrahimi, Chris Murray, Sharon Glotzer, James Ruud, John Belk, Santokh Badesha, Adra Baca, David Knox
International workshop moderators:
Peter Degischer, Sang-Hee Suh, Jan Ma

NSF, September 30, 2010

Evolution from 2000 to 2010

- **How has this definition/vision of nanostructured materials evolved over the last ten years? What is the state of the art now versus ten years ago?**

In 2000, most work focused on studies of individual nanoparticles, nanowires, and nanotubes.

In 2010, ensembles of monodisperse nanomaterials are available, thus enabling them to be incorporated into coatings and bulk nanocomposites with clearly identifiable applications including:

(a) Nanofibrous filters and nanofluidic systems

(b) Aerospace/transportation nanocomposites

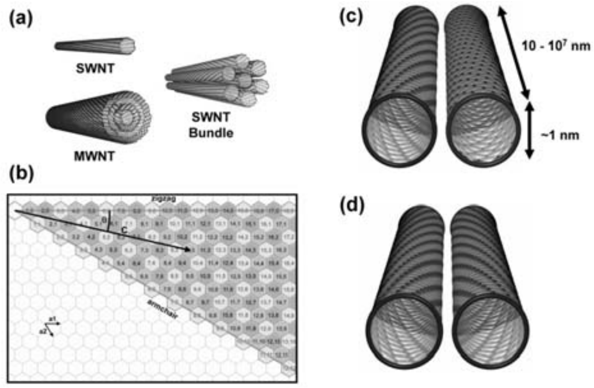
(c) Thin film electronic and optoelectronic devices

(d) Transparent conductors

nano2

Carbon Nanotube Polydispersity

Reviews: *Nature Nanotechnology*, **3**, 387 (2008); *MRS Bulletin*, **35**, 315 (2010).



- Current synthetic methods yield polydisperse mixtures of CNTs.
- Post-synthetic methods for sorting by diameter, electronic type, chiral handedness, and number of walls are highly desirable.

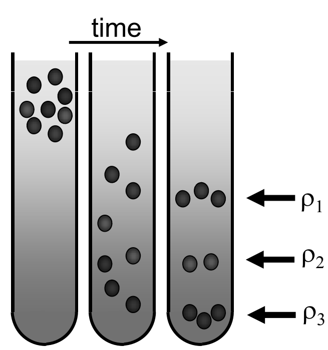
Density Gradient Ultracentrifugation (DGU)

Nano Letters, **5**, 713 (2005).

$$v = \frac{d^2(\rho_p - \rho_l)g}{18\mu}.$$

$$\mathbf{g = \omega^2 r}$$

v = particle velocity
d = particle size
μ = viscosity
g = centrifugal force
ρ = density

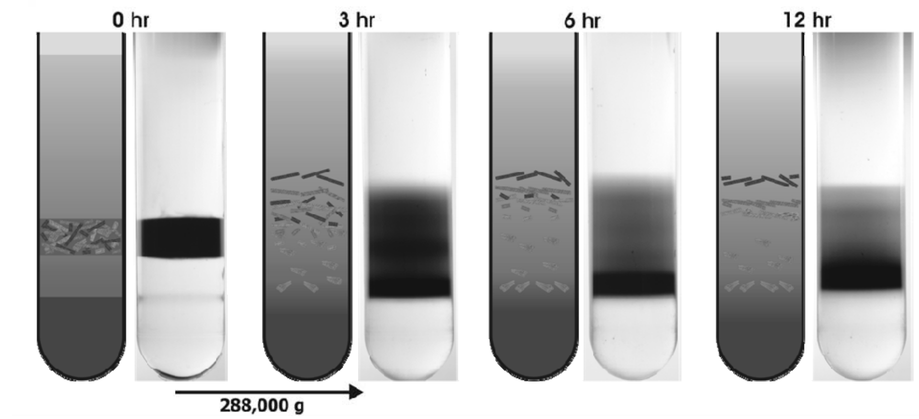


A preformed density gradient is used, and nanotubes move until their density matches that of the local density of the gradient.

As a function of surfactant chemistry, isopycnic sorting can be achieved by CNT diameter or electronic type.

Isopycnic Separation by CNT Diameter

Materials Today, **10**, 59 (2007).



Separation by CNT diameter (and therefore optical properties) occurs when using a single component surfactant.

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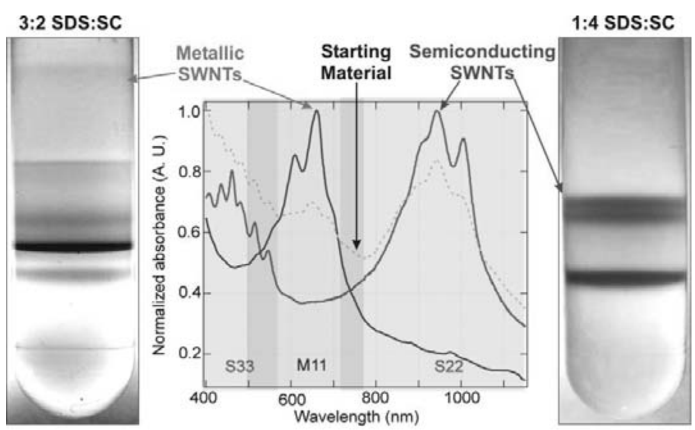
Electronic Type Separation with Co-Surfactants

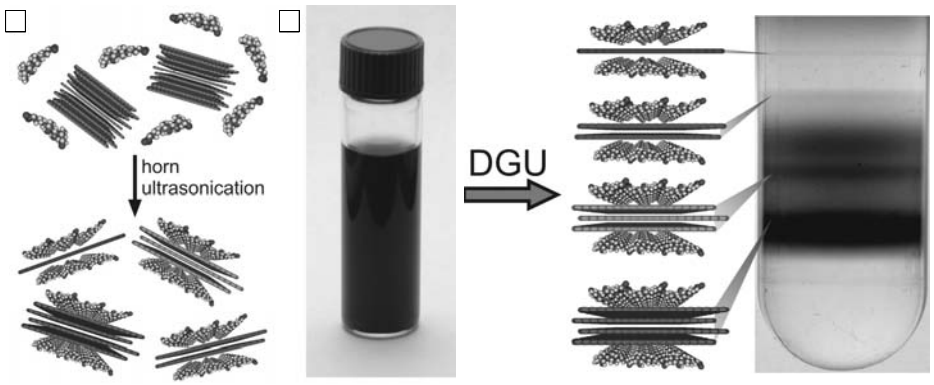
Nature Nanotechnology, **1**, 60 (2006).



Metal and semiconductor purities exceeding 99% are routinely achieved using co-surfactants.

Monodisperse Graphene

Nano Letters, **9**, 4931 (2009).



• Exfoliate graphite powder via sonication in aqueous solution with the planar surfactant sodium cholate.
• DGU enables sorting by the number of graphene layers.

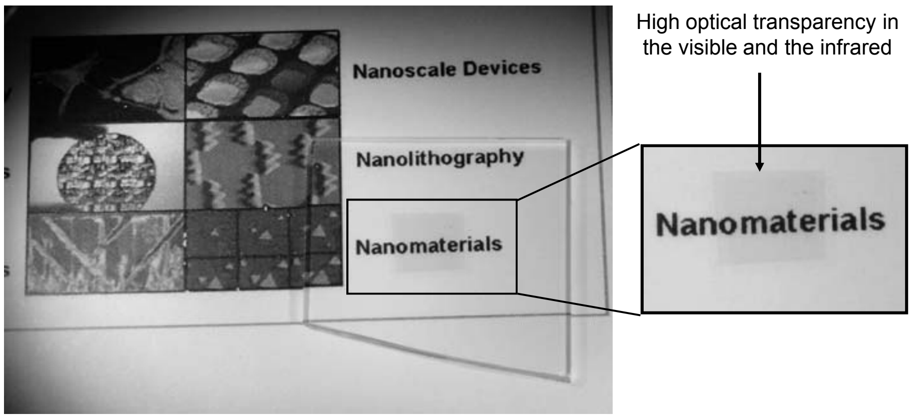
Scalability of Density Gradient Ultracentrifugation

http://www.nanointegris.com/

~10,000x scale up of metal and semiconductor IsoNanotubes™ and graphene PureSheets™

Transparent Conductors from Metallic CNTs

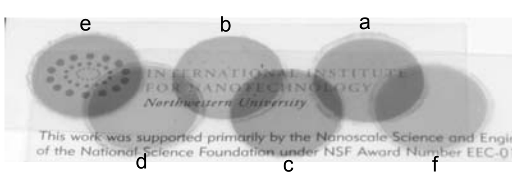
Nano Letters, **8**, 1417 (2008).

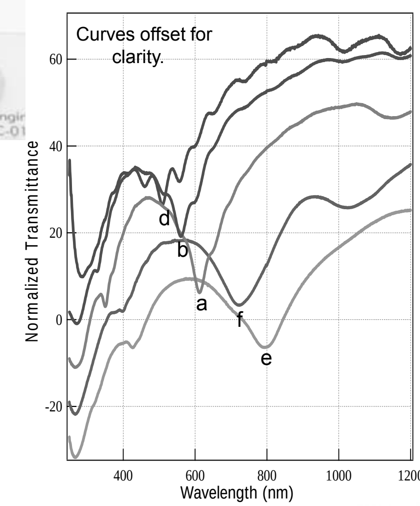


Conductivity increases by ~10x when using metal CNTs sorted via density gradient ultracentrifugation.

Visibly Colored Translucent Metallic CNT Films

Nano Letters, **8**, 1417 (2008).

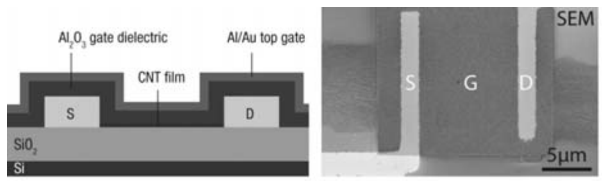


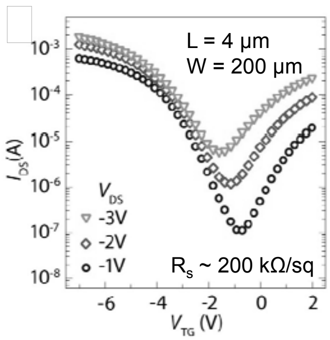


- The range of metallic CNT diameters allows transparency control over most of the visible.
- High transparency can also be achieved in the near IR.
- The absence of doping implies high environmental stability.
- Compatible with flexible substrates (e.g., polymers).

Aligned, Semiconducting CNT FETs

ACS Nano, **2**, 2445 (2008).

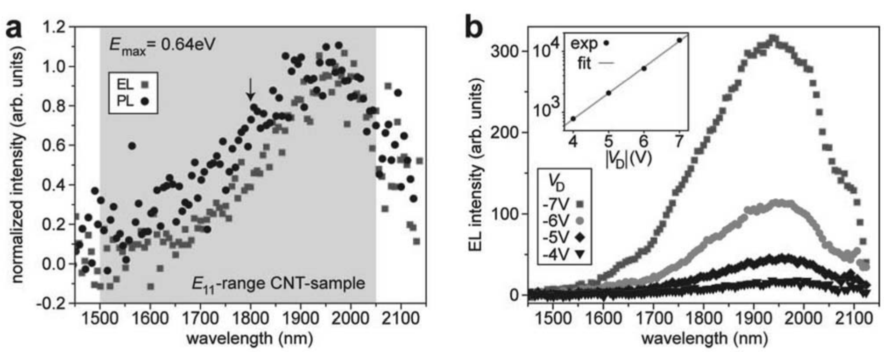




- The inherent tradeoff between drive current and I_{on}/I_{off} is minimized with 99% pure semiconducting CNTs.
- 1 mA drive current with $I_{on}/I_{off} = 10^3$ has been achieved, which is sufficient for display applications (e.g., OLEDs).

Light Emission from Semiconducting CNT FETs

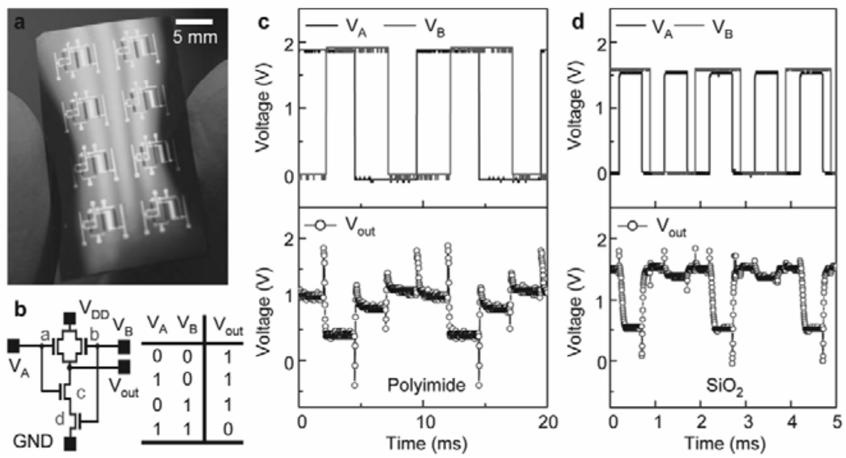
ACS Nano, **2**, 2445 (2008).



- Infrared photoluminescence and electroluminescence is observed in thin film devices due to the absence of metallic CNTs.
- Enables optoelectronic applications for thin film CNT devices.

Printed, Flexible Circuits from Aqueous CNT Inks

ACS Nano, **4**, 4388 (2010).

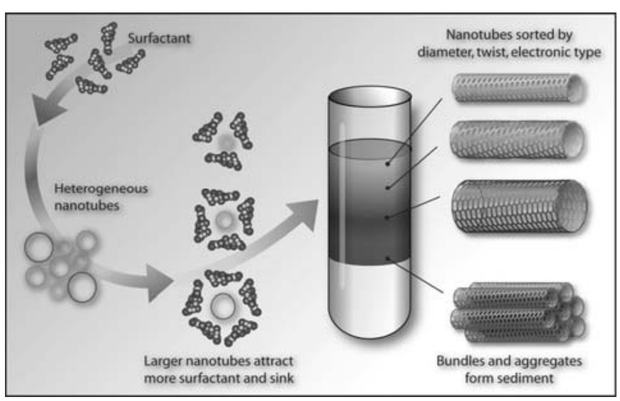


V_A	V_B	V_{out}
0	0	1
1	0	1
0	1	1
1	1	0

Flexible inverters, ring oscillators, and NAND gates have been achieved.

Goals for 2020

- Synthesis, separation, fractionation, and purification in an effort to realize a library of nanomaterials with monodispersity in composition, size, and shape.



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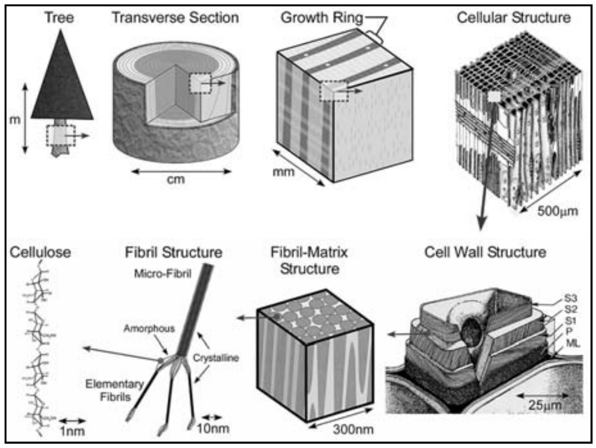
Goals for 2020

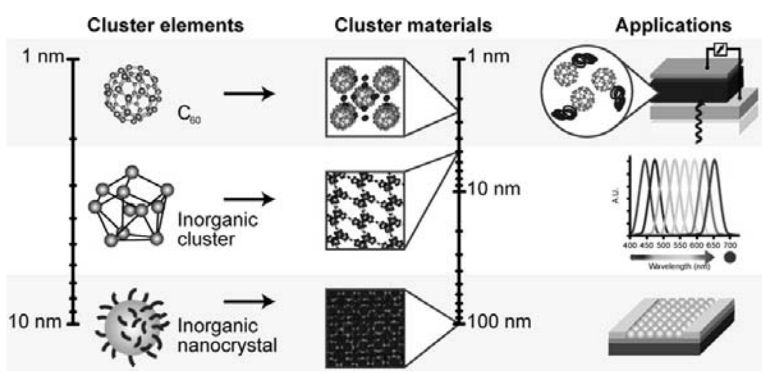
- Harvesting nanostructures from natural, sustainable, and abundant raw materials (e.g., wood, clay, etc.).



nano2

Goals for 2020

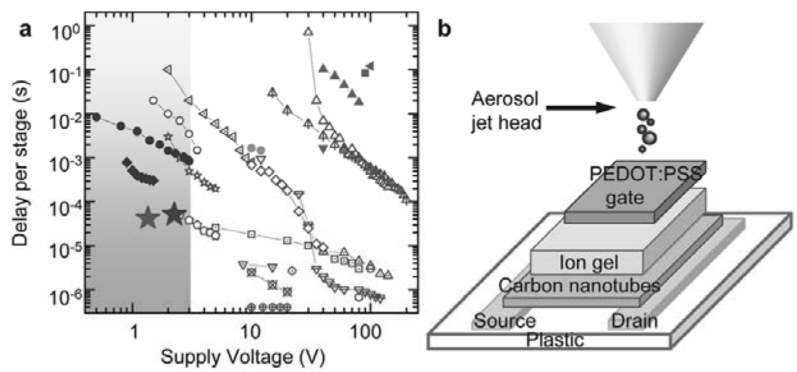
- The realization of hierarchical nanostructured materials with independent tunability of previously coupled properties.



nano2

Goals for 2020

- Improvements in nanomanufacturing issues including scale-up, cost, sustainability, energy efficiency, process control, and quality control.



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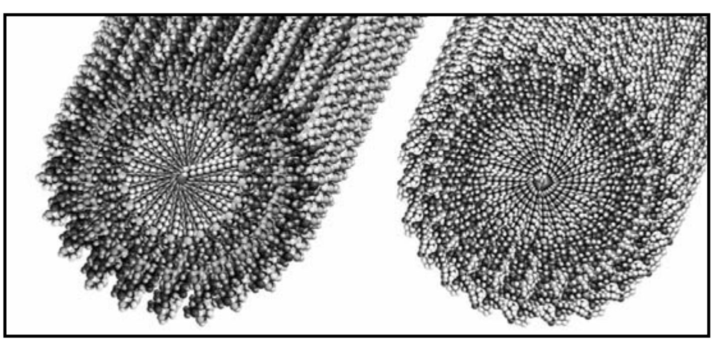
Goals for 2020

- Realization of nanomaterials with biologically inspired attributes including non-equilibrium, self-healing, reconfigurable, and defect-tolerant structures in hybrid organic/inorganic media.



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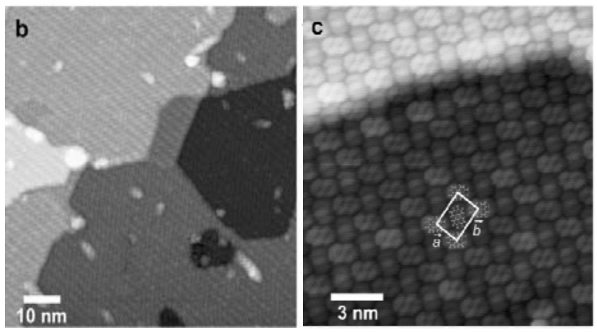
Goals for 2020

- Combinatorial and computational approaches that enable efficient exploration of the vast phase space for nanocomposites including the size, shape, and composition of the nanoconstituents, role of defects, surface functionalization, and matrix.



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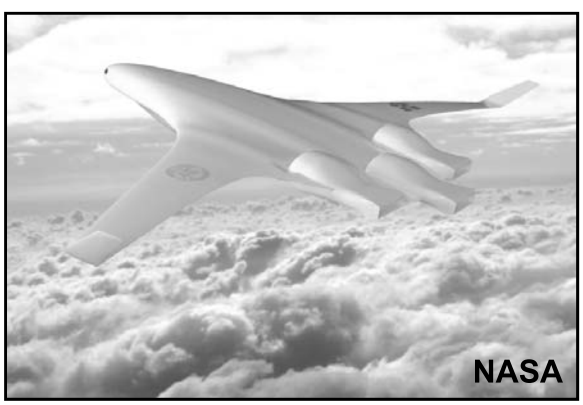
Goals for 2020

- Utilization of new nanocomposite materials with unprecedented properties and unique combinations of properties in emerging and converging technologies.



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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

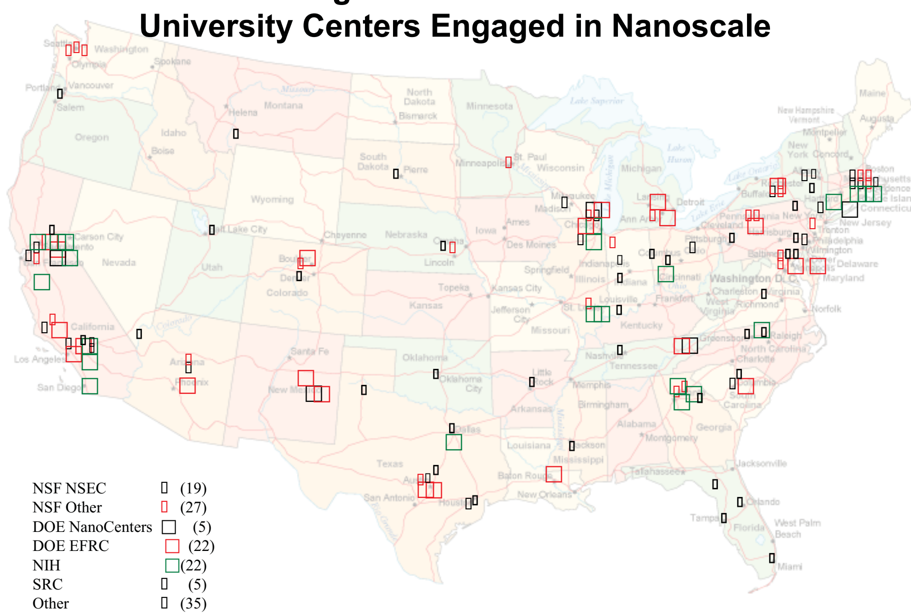
Chapter 12. Preparation of People and Physical Infrastructure

James Murday, Mark Hersam, Robert Chang, Steve Fonash, Larry Bell
With collaboration from:
....
International workshop moderators:
Costas Charitidis, Hiroyuki Akinaga, Hans Griesser

NSF, September 30, 2010

U.S. Research Infrastructure

Changes in Past Ten Years
University Centers Engaged in Nanoscale

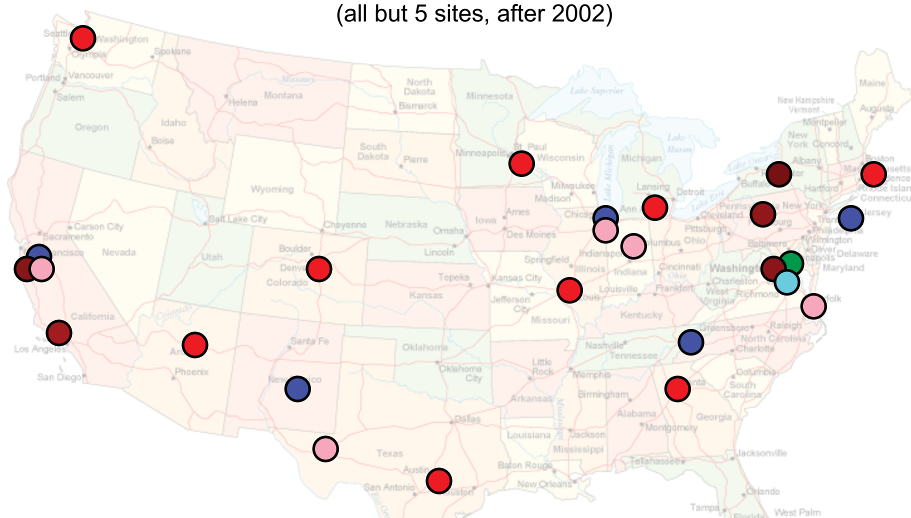


2

U.S. Research Infrastructure

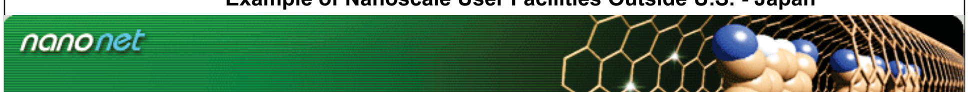
R&D User Facilities

(all but 5 sites, after 2002)



NSF National Nanotechnology Infrastructure Network (NNIN) (pre 2002) **www.nnin.org/**
NSF Network for Computational Nanotechnology (NCN) **nanohub.org/**
DOE NanoCenters **www.er.doe.gov/bes/user_facilities/dsuf/nanocenters.htm**
NIST Center for Nanoscale S&T (CNST) NanoFab **www.cnst.nist.gov/nanofab/nanofab.html**
NIH National Cancer Inst Nanotechnology Characterization Lab (NCL) **ncl.cancer.gov/** 3

Example of Nanoscale User Facilities Outside U.S. - Japan



User Facilities
Individual research organizations and universities often find it difficult to install specialized, large-scale equipment that is required for nanotechnology research. For this reason, the use of the Japanese top research institutions, **Ultra-HV TEM, Nano Foundries, Synchrotron Radiation, and Molecular Synthesis and Analysis** is available for researchers as one of activities of **MEXT Nanotechnology Support Project**. Research collaborations and technological consulting are also available through these institutions.

User Supports

1. Facility Use
   Be able to use facilities for making samples, doing measurement and analysis.
   (Only available for users obtaining experience.)

2. Research Collaborations
   Be able to set up the collaboration for research obtaining high research values.

3. Measurements/Sample Preparation on Request
   Some facilities are able to measure and analyze elements for users as well as provide samples.

4. Technical Consultation
   Staffs of facilities are able to provide technical help.

* Some facilities may not cover all of the above.
Please contact each facility or nanonet for details.

4

International Workshop Perspectives on Research Infrastructure

R&D User Facilities: Next Decade

Challenges	Options
Operating funds	Agency budgets incorporate funding for operations, renovations, and local experts
Facility expertise available to users	
	Attention to innovative instrumentation development
State-of-art instrument additions	International collaboration on more expensive items
	Rapid development of International standards / reference materials
Technology test-bed facilities	Morph selected user facilities
Ready Industry Access	

5

Education Infrastructure

"Nanotechnology" in Education

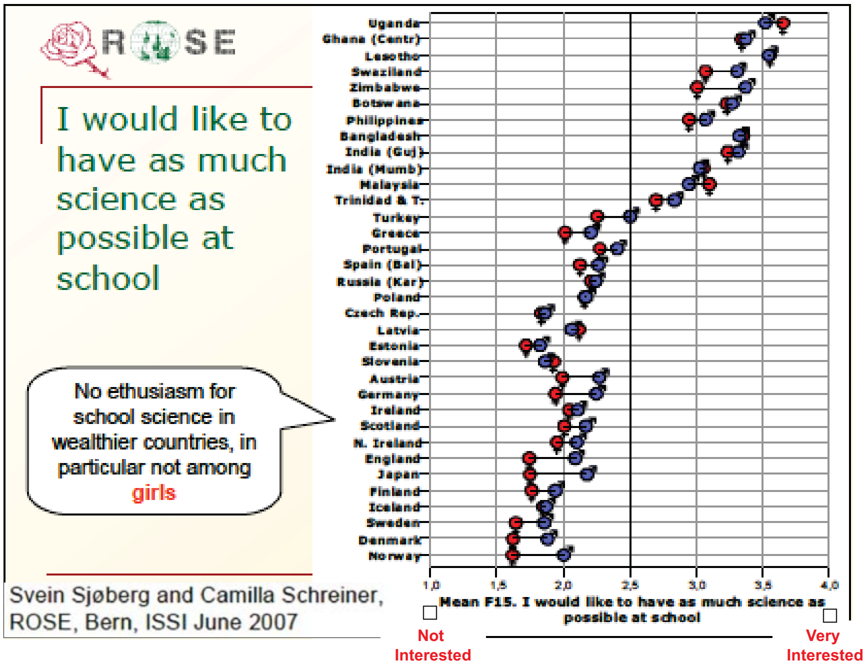
Why Now

- New knowledge to be incorporated into the educational corpus
- Nano-enabled technologies have growing presence in economy/society
- Need for an informed, skilled workforce
- Workers and the general public sufficiently knowledgeable to understand the benefits and risks
- The nanoscale holds sufficient novelty to engage Science/Technology/ Engineering/Mathematics (STEM) interest in students

Overarching Challenges/Opportunities in next ten years

- Nanoscale science and engineering is largely transdisciplinary and challenges traditional education taxonomies
- "Nano" evolving into mainstream S&T and beyond "nano" focused programs
- "Nano" is presently an "engine for change" – how to exploit it to engage students
- A wealth of new, underutilized instructional materials (funded by NSF and others)
- STEM education stakeholder communities marginally engaged in "nano"

Global Challenge to STEM Education



Teaching materials for K-12 - Taiwan

Nanotechnology Symphony-Physics, Chemistry and Biology (Senior High)

"The Tiny but Beautiful Nano World "
(the first brailed material specially designed for blind students)

"Nanotechnology Teaching Material of Southern Center for K-12 Nanotechnology Center"

Nano Blaster Man

Dr. Fuh-Sheng Shieu, National Chung Hsing Univ

Illustrations of Other K-12 Nanoscale Resources

The Adventure of Nano

Adventure of Nano

Nanotechnology, technology in the small world, which we cannot see, is going to change our lives.

* Introduction
* What is nanotechnology?
* Biology Version
* IT Version
* Environment/Energy Version

National Institute of Materials Science, **Japan**

Become a NANOYOU school!

Schools from all over **Europe** are already teaching NT in their classrooms with videos, animations, games, virtual dialogues, and virtual experiments based on current research.

Register here to become a NANOYOU school!
http://nanoyou.eu/

NanoBioNet, **Saarbrucker** Kompetenznetzwerk fur Nano- und Biotechnologie

NanoEd Resource Portal
A repository for the collection and dissemination of information for the NSEE community
NCLT US

NSF sponsored

Partnership for Nanotechnology Education Workshop

University of Southern California, 26-28 April, 2009

www.nsf.gov/crssprgm/nano/reports/nsfnnireports.jsp

Goals

- Identify and examine the present status of "nano" education efforts (K – Gray), including international perspectives
- Identify the infrastructure needed to carry out effective "nano" education
- Lay the groundwork for functional stakeholder partnerships that will address the needs and identify the opportunities
- Identify mechanisms for the partnerships to provide information for the:
  - National Science and Technology Council (NSTC)
  - Nanoscale Science, Engineering, and Technology (NSET) Subcommittee
  - Other interested parties to use in developing funding goals, strategies, and programs.

Workgroups (tasked to identify options)

K-12 Education:
- Standards of Learning: Local, State, and National Involvement
- Teacher Education and Training
- Development of Curricula and Teaching Aids

Post-Secondary Education:
- University and Community College
- Industry Workforce Needs
- Cyber and Virtual Innovation (cross-cutting all categories)

Public Education:
- Informal Education: Museums
- Press, Radio, Television, and Web-based
- Local Community Outreach and Engagement

10

Next Decade: Overarching Education Need
Creation of a NanoEducation Ecosystem

Finding: A focal point is needed to identify, validate, and integrate the many NanoEducation capabilities that presently exist and to assess what is additionally needed.

Options:

- The Nanoscale Science, Engineering and Technology subcommittee create a multiagency Nanotechnology Education and Workforce working group
- An education and workforce-focused consultative board to the NSET should be created, comprising the various principal stakeholders.

Principal Stakeholders include:

The National Science and Technology Council (NSTC)
NNI participating Federal agencies with education interests - NSF, DoEd, DoL,…
National Science Teachers Association (NSTA)
National Education Association
STEM Education Coalition
Professional Science and Engineering Societies
NanoBusiness Alliance
International partners

International Workshop Perspectives on Education Infrastructure

Next Decade Education: K-12

Challenges	Options
Low STEM career choices by students, especially underrepresented populations	Utilize nanoscale contributions to solutions of societal issues as student STEM motivator
Poor showing of U.S. students in international STEM testing	Internationally Benchmarked Common Core Standards including the nanoscale
Disparity in standards among the states and school districts	Establish partnerships to create vetted curricula and teacher training materials from the various NSF funded NanoCenters (and other sources)
Incorporation of appropriate nanoscale material into standards and curricula	Formalize hand-off of NSF STEM nanoeducation innovation to Department of Education for continuation
Inadequate teacher training / knowledge	Exploit cyber-learning opportunities
Transdisciplinary approaches to STEM education	

NCLT National Center for Learning and Teaching in Nanoscale Science and Engineering

International Workshop Perspectives on Education Infrastructure

Next Decade Education: 2 and 4 year College

Challenges	Options
Defining workforce needs	Monitor job opportunities vice degree certifications (minor, certificates, degrees)
Building curricula/degrees to meet workforce needs	Continued attention to course development
Transdisciplinary Integration	
Community/Technical College (2 yr) transition to College/University(4 yr), especially with minority populations	Widely accepted articulation agreements Web-controlled remote access of costly laboratory instruments
K-12 STEM teacher education	Utilize graduate/undergraduate students in K-12 education

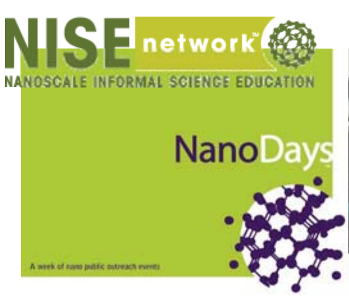
Nano4Me.org EDUCATION & CAREERS IN NANOTECHNOLOGY

13

International Workshop Perspectives on Education Infrastructure

Next Decade Education: Informal (General Public)

Challenges	Options
Well-informed, nano-literate citizens	Upgrade wikipedia entries
Risk-management perspectives	Utilization of e-media such as Facebook, YouTube, Second Life,...
Captivating museum displays	Museum presentations linked with nano-enabled technology solutions to societal problems



Deutsches Museum München
Nanotechnology and Biotechnology
Exhibition

Summary of Options for Next Decade Laboratory Infrastructure

Past ten years has seen significant growth in Centers and User Facilities addressing NSE, both in the US and globally

While user facilities have been created, it is essential for Agency budgets to incorporate funding for operations, renovations, and local experts

Mechanism(s) for insertion of newly developed innovative instrumentation into user facilities.

As nanoscale instrumentation becomes more sophisticated and expense, there must be International collaboration on inserting the more expensive items into user facilities.

Rapid development of International standards / reference materials is important for reliable interpretation of instrumental responses - funding for participation.

User facilities are needed that will enable technology demonstrations, i.e. provide means for fabricating prototype device/systems.

Continued attention must be paid to easy, rapid access by companies/industry into user facilities, in particular proposal competitions may not fit commercial time frames.

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Summary of Options for Next Decade Education Infrastructure

Overarching

- The Nanoscale Science, Engineering and Technology subcommittee create a multiagency Nanotechnology Education and Workforce working group
- **An education and workforce-focused consultative board to the NSET should be created, comprising the various principal stakeholders.**

K-12

- **Utilize the nanoscale to recast STEM education and career motivation**
- Internationally Benchmarked Common Core Science/Engineering Standards
- Establish partnerships to create vetted curricula and teacher training materials from the various NSF funded Centers (and other sources)
- Formalize hand-off of NSF STEM education innovation to Department of Education continuation
- Exploit cyber-learning opportunities

Community/Technical College and University

- **Course and degree development, reflecting evolving knowledge and workforce needs**
- Widely accepted and implemented articulation agreements (under-represented minority)
- Web-controlled remote access of costly laboratory instruments
- Utilize graduate/undergraduate students in K-12 education

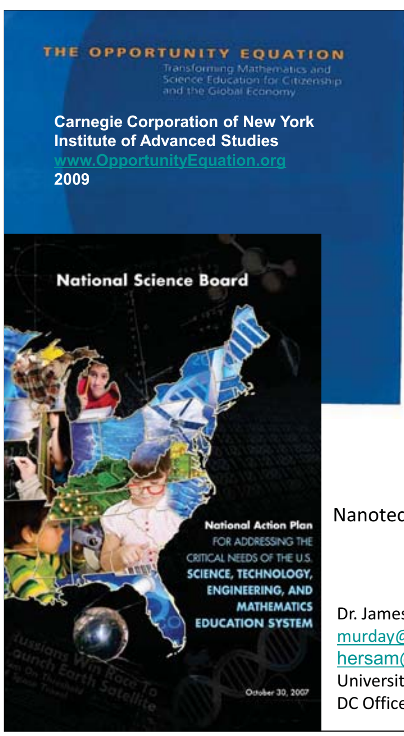
Public / Informal

- Upgrade wikipedia entries on nanoscale science/engineering/technology
- Utilization of e-media such as Facebook, YouTube, Second Life,…
- Museum presentations linked with nano-enabled technology solutions to societal problems

16

Begin Supplemental

17



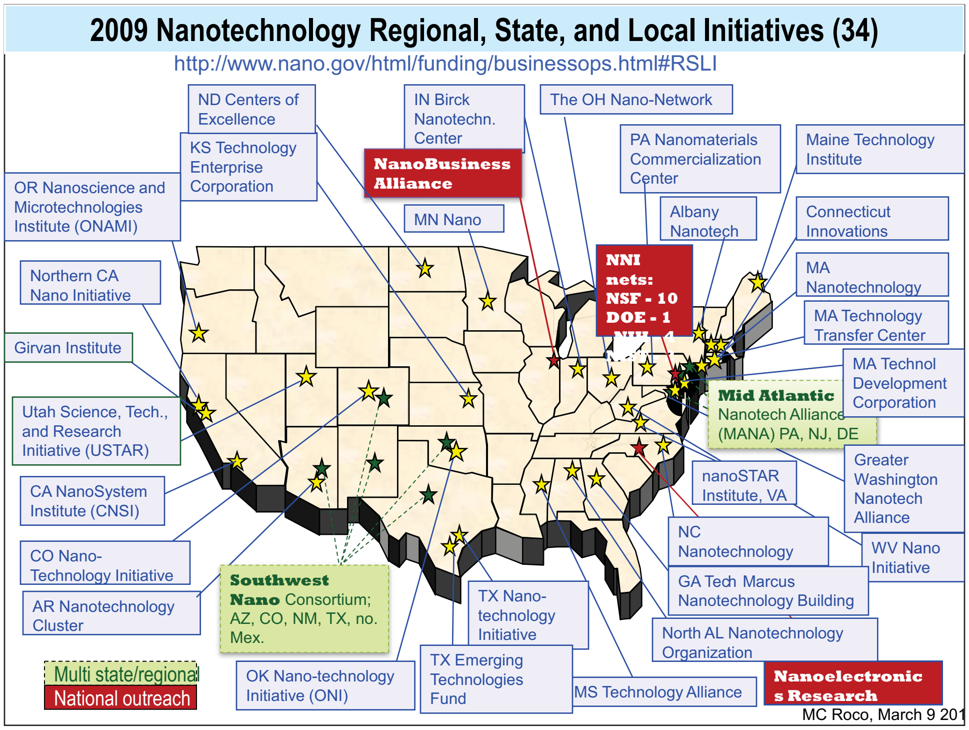
Preparation of People and Physical Infrastructure

Nanotechnology Long-term Impacts and Research Directions: 2000-2020

September 30, 2010

Dr. James S. Murday
murday@usc.edu
University of Southern California
DC Office of Research Advancement

Dr. Mark C. Hersam
m-hersam@northwestern.edu
Northwestern University
Department of Materials Science and



Where is Nano Taking us?

Integrated Science Base for Materials and Technology by Design:

A new Era in Biology, Chemistry, Engineering, and Physics

~1750 - 2000	2000 - 2025?	2025?
• Old (atomic) World • **Building Blocks:** • **109 Elements** (→ molecules →)	**Transition (nano)** **Dendritic** **Fullerenes** **Carbon Nanotubes** **Quantum Dots** **Nanoclay** **Superlattices**	New (multi-scale) World **Building Blocks:** Elements/molecules, plus **effectively unlimited variety of quality dots, clusters, macromolecules** **wires, tubes** **films, ribbons**
• **Assembly Rules:** • **Periodic Table Groupings** • **Ionic Bonds** • **Covalent Bonds** • **"Metallic" Bonds**	**Colloidial Devices** **Block Copolymer** **Metamaterials** **Biomimetic** **Atomic Layer Epi**	**Assembly Rules:** Atomic bonding, plus **Van-der-Waal forces** **Coulomb forces** **Magnetic forces** **Molecular recognition** **Steric hindrance** **Fluid drag**
• **Guidance:** • **Atomistic or Continuum** • **Models explain experiment**	**Multi-Scale** **Supercomputer** **Projects**	**Guidance:** **Predict Composition/Structure to get the Desired Property**

Figure 3: Schematic of NSF Investment in NanoEducation.

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Partnership for Nanotechnology Education Workshop

Industry Needs for Nanotechnology Education

Finding: Preparation for employment is an important aspect of the educational process and there will likely be strong competition for nano-trained people between the U.S. and other countries.

Option:

- Department of Labor work with industry groups and with professional science and engineering societies develop accurate assessments of domestic workforce needs, including the effects of growing overseas education and job opportunities.

Principal Stakeholders include:

DoL, Department of Commerce (DoC)
Professional science and engineering societies
NanoBusiness Alliance

K-12 Nanoscale Learning Standards

Finding: The National Governors Association (NGA) has approached Achieve Inc. with the task of preparing common core learning standards in the physical sciences that might be adapted by each state for its own learning standards. The NAS/NRC report "Conceptual Framework for New Science Education Standards" is due early 2011.

Options:

- The NSET initiate contact with the NGA, the Council of Chief State School Officers (CCSSO), and Achieve Inc. to introduce the nanoscale into the common core standards. *[On-going – Dec 6-7 Workshop on International Benchmarks]*
- Participants in the many U.S. NanoCenters work with their own State Education Departments toward science learning standard revisions.

Principal Stakeholders include:

OSTP/NSTC
National Research Council (NRC)
NSF, Department of Education (DoEd)
CCSSO, NGA, Achieve Inc.
NSET's Nanotechnology Public Engagement and Communications Working Group (NPEC)
Association of Science and Technology Centers (ASTC)
NSTA and the state-based affiliates
International Technology Education Association (ITEA) and the state-based affiliates
American Association for the Advancement of Science (AAAS)
International Community

K-12 Common Standards
NanoEducation Notional Way Forward

1. "Workshop(s)" to develop ideas on what/where/why "nano" concepts should be inserted into college/career readiness standards and into K-12 standards.

2. Work with CCSSO/Achieve Common Core State Standards Process to insert "nano" into College & Career Readiness Standards.

2. Work with CCSSO/Achieve Common Core State Standards Process to insert "nano" into K-12 Standards

- Curriculum Development
- Web-based enrichment modules for use in present curricula
- Information/modules for use with proposed common physical science standards

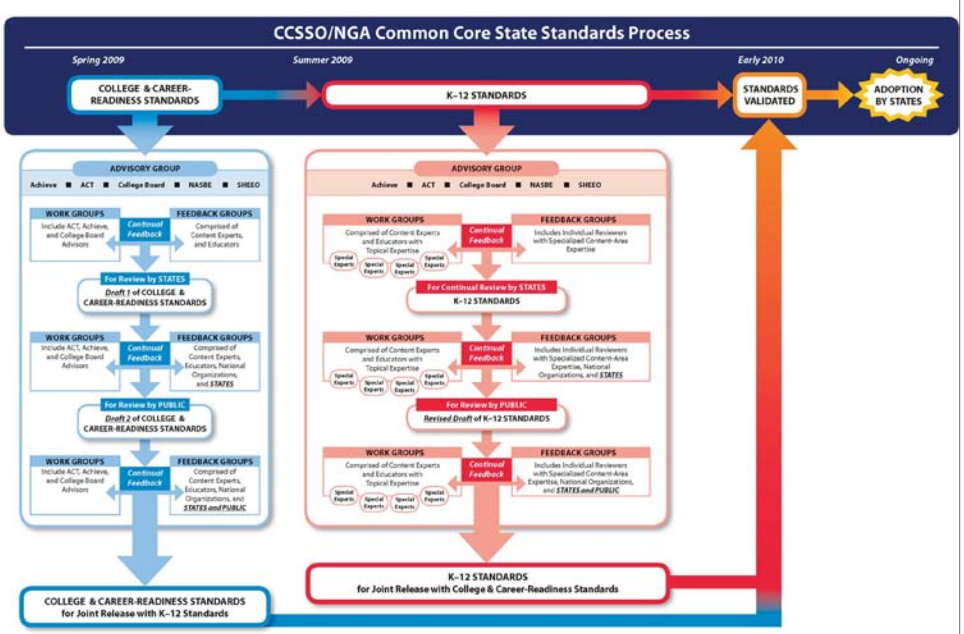
- Teacher Training in how to utilize "nano" modules

Partnership for Nanotechnology Education Workshop

Stakeholders

General public
Federal government agencies
State and local education, workforce, and economic development authorities
Foundations
Industry leadership and workforce
K-12 teachers and administrators
Technical and community colleges
Undergraduate colleges and universities (BS/BA, majors/minors)
Graduate degree universities (MS/PhD)
Continuing education institutions - including industrial, individual, and distance learning
Professional Science and Engineering Societies
Professional groups, such as NSTA, EDUCAUSE, the STEM Education Coalition
Computer and web-based education groups
Publishers and media for outreach
International perspectives

English Language Arts and Mathematics



Partnership for Nanotechnology Education Workshop

Curricula and Teaching Aid Development

Finding: To regain prominence in science, technology, and engineering the U.S. must gain a common approach to curriculum development.

Options:
- Funding is needed to allow for the design, development, testing, and implementation of a coherent curriculum that would allow 7 to 16 year-old students to develop an integrated understanding of core science ideas that underpin nanoscience and engineering.
- Such a curriculum would focus on helping students develop progressively deeper understanding of core ideas.
- Such a process calls for change in the standards that focus on teaching big ideas with a focus on developing a deeper understanding of these ideas.

Principal Stakeholders include:

NSF, DoEd, and other appropriate Federal agencies
NSTA
Professional science and engineering societies

Partnership for Nanotechnology Education Workshop

Curricula and Teaching Aid Development

Finding: The NSF-funded Nanoscale Science and Engineering Centers (NSEC) have been very productive at developing innovative approaches to NanoEducation. However, the materials are widely dispersed, are of non-uniform format, and have varying degrees of refinement.

Options:
- The DoEd, working closely with the NSTA and cyber-oriented curriculum developers, create a central web site.
- The NSTA should serve as the evaluator for quality control to ensure web site materials :
  - are of high quality,
  - are in a format readily utilized by K-12 teachers,
  - are carefully indexed to the various state learning standards, and
  - can be readily accessed from the NSTA web site.
- Additional well-designed, highly interactive, media-rich, online learning tools should continue to be developed.

Partnership for Nanotechnology Education Workshop

Curricula and Teaching Aid Development

Finding: Some laboratory learning may be beyond the capability and/or budget of local schools and personnel.

Option:

- NNIN, NSEC, DoE NanoCenters, and the National Institute of Standards Technology (NIST) Center for Nanoscale Science and Technology work with the NSTA and the DoEd toward the preparation of on-site and/or remote access to higher end facilities that might contribute to the K-12 education process.

Finding: Person to person contact remains the most effective approach to education.

Options:

- The various university-based NanoCenters mobilize their undergraduate and graduate students to engage in K-12 education at the nanoscale.
- Federal funding agencies must provide an adequate budget allowance for this work.
- Universities must recognize the supervisor faculty efforts in tenure and promotion decisions.

Partnership for Nanotechnology Education Workshop

Teacher Education and Training

Finding: Teachers will need to be trained to use the learning resources for K-12 audiences that address nanoscale science, engineering, and technology.

Option:

- The various NanoCenters can be a vital resource to provide materials, training, and information. They should be encouraged to be more proactive toward K-12 teacher training.

Principal Stakeholders include:

NSTA
DoEd, NSF, other Federal agencies supporting teacher training & workforce development
CCSSO
ASTC
ITEA

Partnership for Nanotechnology Education Workshop

University and Community College

Finding: Since 40% of college students get their start in community colleges – there need be closer interaction between community colleges and the universities.

Options:

- Foster nanotechnology curricula development and evaluation that is appropriate for community colleges
- Ensure meaningful collaborations between the community colleges and the NanoCenters.
- Ensure nanotechnology is included in the DoEd's Department of College and Career Transitions articulation program

Principal Stakeholders:

NSF, DoEd, Department of Labor (DoL)
Universities
National Association of Community College Entrepreneurship (NACCE)

Partnership for Nanotechnology Education Workshop

Informal Education - Museum

Finding: It is timely to develop exhibits and programs associated with the impact of those nano-enabled technologies.

Options:

- NSF should take the lead in establishing links between museums and the national and international research communities for new exhibit development.
- Other Federal funding agencies and industry representatives must also be contributors since they will be engaged in the translational efforts that lead to technology impact.

Principal Stakeholders include:

NSF, other relevant mission-oriented Federal funding agencies
Museums
ASTC
NanoBusiness Alliance

Partnership for Nanotechnology Education Workshop

Public Education – TV, Radio, Press, Books, Magazines, and Web

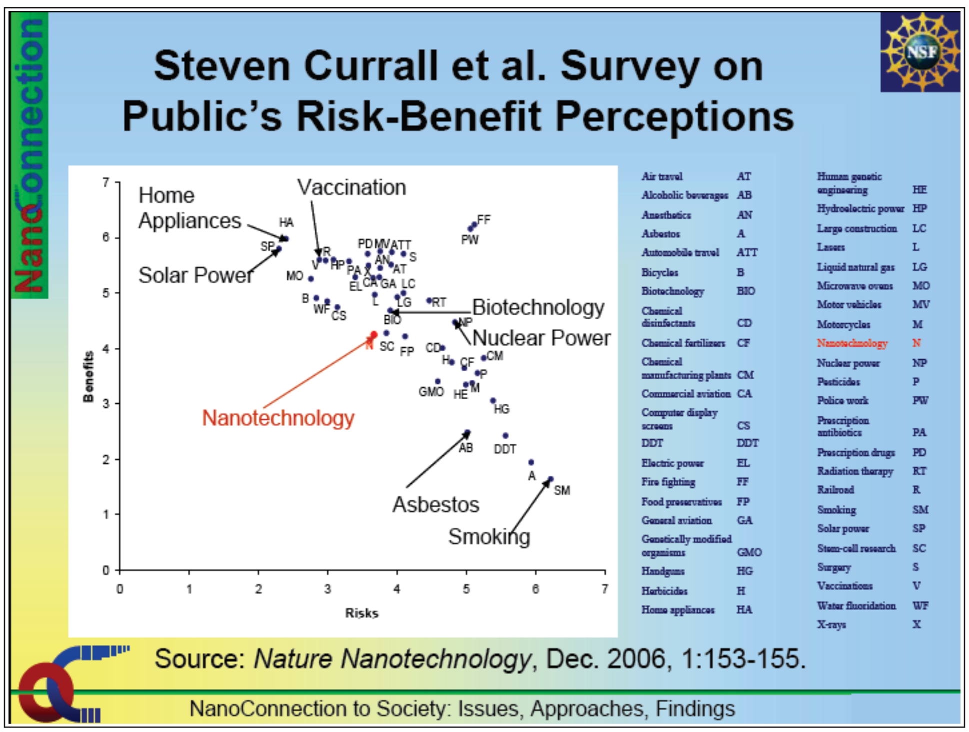
Finding: With the decline in the number of science journalists, there is an opportunity for the NNCO, University and Industrial programs, and other stakeholder groups to develop a continuing stream of information that can inform the public of the benefits and risks emanating from progress at the nanoscale. The rapid growth in information technologies is creating new interaction paradigms that might be exploited using electronic media.

Options:

- Cyber-education should be included in the suite of learning venues to engage students. NSF, with its interest in cyberlearning, should take the initiative but the DoEd must be engaged to ensure a continuing effort.
- The Wikipedia entries on nanotechnology should be routinely updated and expanded. K-12 science teachers should be involved to ensure the information is structured in ways that can be readily absorbed at the various grade levels.

Principal Stakeholders include:

NSF, DoEd and other agencies with relevant missions
NSTA
ASTC



Partnership for Nanotechnology Education Workshop

Local Community Outreach and Engagement

Finding: The national media plays an important role in informing people. However, local and personal engagement is often more effective.

Options:

- Existing NanoCenters should expand their outreach activities to local and state communities
- The NSEE forum should be expanded to engage all federally/state funded NanoCenters

Principal Stakeholders:

NSET/NNCO
ASTC
NGA.

Partnership for Nanotechnology Education Workshop

Cyber and Virtual Innovations

Finding: The emerging NanoEducation community must be able to exploit existing cyber-infrastructure resource investments more effectively.

Options:

- NNI resources need to be better publicized regarding accessibility, targeted user-levels, customizability both in terms of targeted audiences and user interface, interoperability with other systems, and service and training offerings.
- Consideration should be given to the research and development of an overall mechanism for efficient search, access, and use of cyber-infrastructure resources focused on nanoscience and technology with potential relevance to education at all levels

Principal Stakeholders include:

NSF, other Federal agencies with relevant missions
NSET/NNCO
NSTA
Open Education Resources (OER)
NanoTechnology Group Inc.

NanoEducation Provisions in NNI Reauthorization (H.R. 554 and S. 1482)

- Name an OSTP Associate Director as Coordinator for Societal Dimensions
- NSTC to establish an Interagency Education Working Group under NSET
- All NNI education efforts to include environmental/safety/health (ESH) and other societal aspects
- NNCO develop/maintain database for NNI education
- NSF authorized to fund Nanotechnology Education Partnerships to:
- Enable professional development activities for secondary school teachers;
- Enrichment programs for students, including access to facilities;
- Identify secondary school educational materials and curriculum
- NSF authorized to fund Undergraduate Education Programs for:
- Interdisciplinary courses or modules to existing courses
- Faculty professional development
- Acquire instrumentation / equipment for education and research
- Remote internet access by secondary students / teachers to "nano" facilities

U.S. Federal Education Programs with Potential for NanoEducation Interest

NSF	Education and Human Resources	www.nsf.gov/dir/index.jsp?org=EHR
DoEd		www.ed.gov/index.jhtml
DoD	National Defense Education Program	www.ndep.us/
DoE	Energy Education National Labs	www1.eere.energy.gov/education/ www.energy.gov/morekidspages.htm
EPA	Teaching Center	www.epa.gov/teachers/
NASA	Education Program	www.nasa.gov/offices/education/programs/index.html
NIH	Office of Science Education	science.education.nih.gov/home2.nsf/feature/index.htm
USDA	NRCS AFSIC CSREES	soils.usda.gov/education/resources/k_12/ www.nal.usda.gov/afsic/AFSIC_pubs/k-12.htm www.agclassroom.org/

Web sites with NanoEducation Content

Accessnano	www.accessnano.org/
American Chemical Society	community.acs.org/nanotation/
European Nanotechnology Gateway	www.nanoforum.org
Exploring the Nanoworld	www.mrsec.wisc.edu/Edetc/modules/index.html
Institute of Nanotechnology	www.nano.org.uk/CareersEducation/education.htm
McREL Classroom Resources	www.mcrel.org/NanoLeap/
Multimedia Educ. & Courses in Nanotech	www.nanopolis.net
NanoEd Resource Portal	www.nanoed.org
NanoHub	nanohub.org/
Nanotech KIDS	www.nanonet.go.jp/english/kids/
Nanotechnology News, People, Events	www.nano-technology-systems.com/nanotechnologyeducation/
NanoTecNexus	www.Nanotecnexus.org
Nanozone	nanozone.org/
NASA Quest	quest.nasa.gov/projects/nanotechnology/resources.html
National Science & Technology Education Partnership	nationalstep.org/default.asp
Nano&me	www.nanoandme.org/home/
NanoYou	nanoyou.eu/
Nanoscale Informal Science Education Network Network	www.nisenet.org
Nanotechnology Applications and Career Knowledge	www.nano4me.org
National Nanotechnology Initiative Education Center	www.nano.gov/html/edu/home_edu.html
National Nanofabrication Infrastructure Network Educ Portal	www.nnin.org/nnin_edu.html
NSF Nanoscience Classroom Resources	www.nsf.gov/news/classroom/nano.jsp
PBS – Dragonfly TV	pbskids.org/dragonflytv/nano/
Taiwan NanoEducation	www.nano.edu.tw/en_US/
The Nanotechnology Group Inc	www.tntg.org
Wikipedia	en.wikipedia.org/wiki/Nanotechnology_education
UVA Virtual Lab: Nanoscience Class Homepage	www.virlab.virginia.edu/Nanoscience_class/Nanoscience_class.htm

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Nanotechnology Long-term Impacts and Research Directions: 2000 – 2020

Chapter 13. Innovative and Responsible Governance

Mihail Roco, Barbara Harthorn, David Guston, Philip Shapira
With collaboration from:
Skip Rung, Sean Murdock, Jeff Morris, Nora Savage, David Berube, Larry Bell, Jurron Bradley, Vijay Arora
International workshop moderators:
Alfred Nordmann, Tsung-Tsan Su, Graeme Hodge

NSF, September 30, 2010

Changes of the vision in the last ten years

Nanotechnology governance *has evolved considerably* :

- The viability and societal importance of nanotechnology has been confirmed, while extreme predictions have receded
- An international community has been established
- Greater recognition to nanotechnology EHS and ELSI after 2004
- The 2001 vision of international collaboration – reality after the first International Dialogue on Responsible Development of Nanotechnology (Arlington, 2004)
- Nanotechnology has become a model for governance issues (transformative/responsible/inclusive/visionary) of other emerging technologies. Increasing role of innovation.

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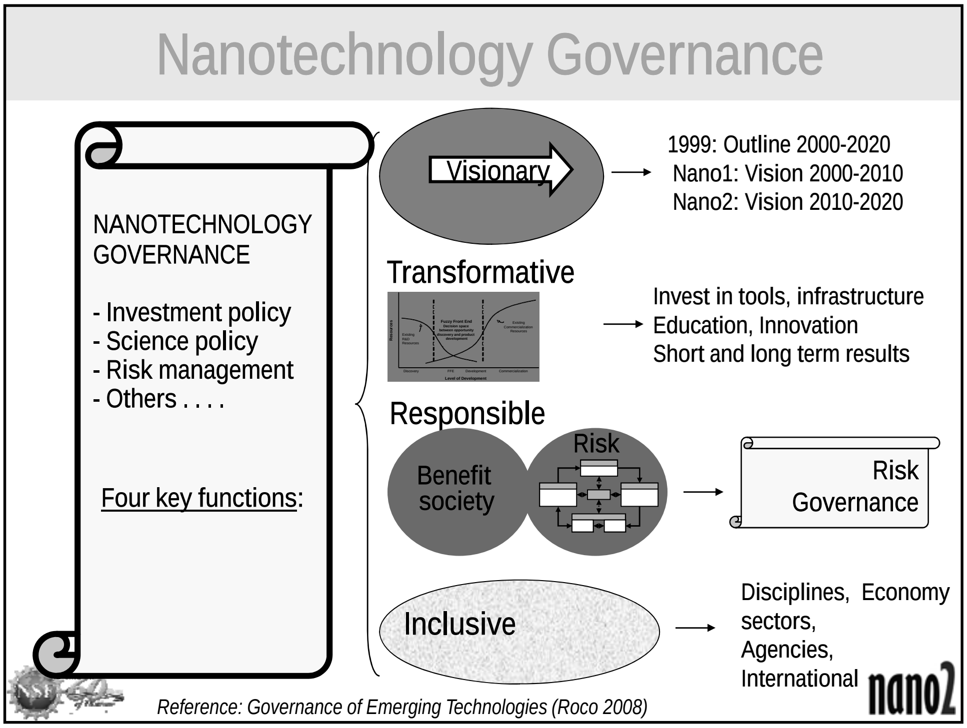
Nanotechnology Governance
NANOTECHNOLOGY GOVERNANCE
- Investment policy
- Science policy
- Risk management
- Others . . . .
Four key functions:
Visionary
1999: Outline 2000-2020
Nano1: Vision 2000-2010
Nano2: Vision 2010-2020
Transformative
Invest in tools, infrastructure
Education, Innovation
Short and long term results
Responsible
Benefit society
Risk
Risk Governance
Inclusive
Disciplines, Economy sectors,
Agencies,
International
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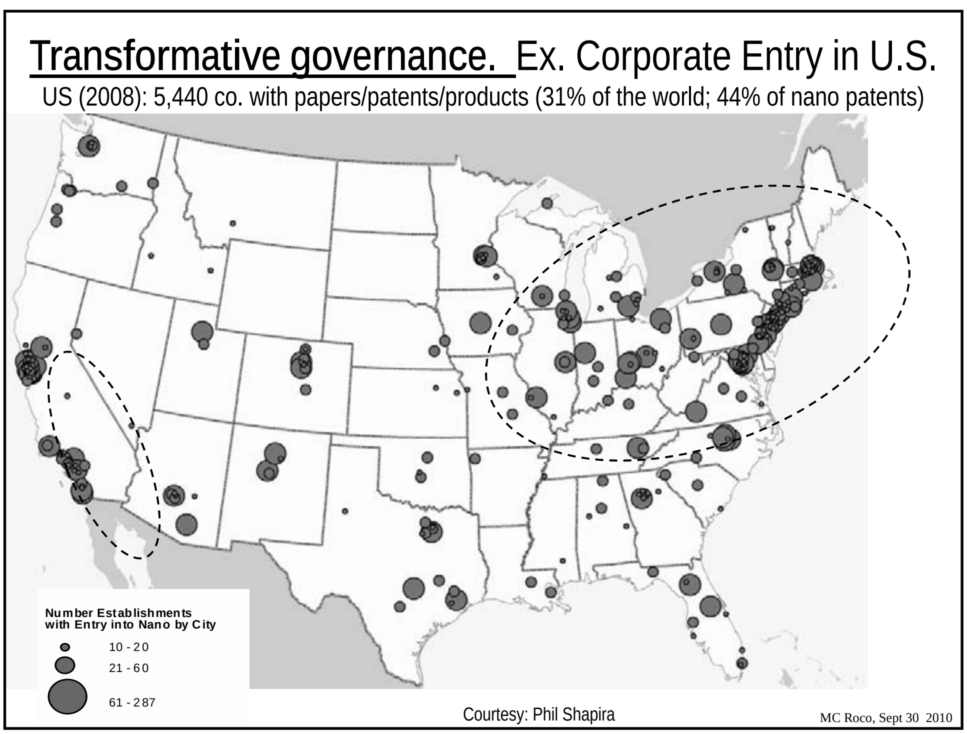
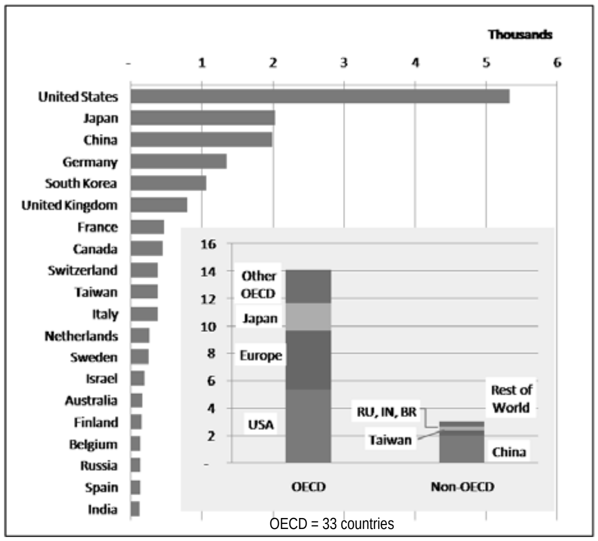
Reference: Governance of Emerging Technologies (Roco 2008)


Transformative governance. Ex. Corporate Entry in U.S.
US (2008): 5,440 co. with papers/patents/products (31% of the world; 44% of nano patents)
Number Establishments with Entry into Nano by City
10 - 20
21 - 60
61 - 287
Courtesy: Phil Shapira
MC Roco, Sept 30 2010

Transformative governance

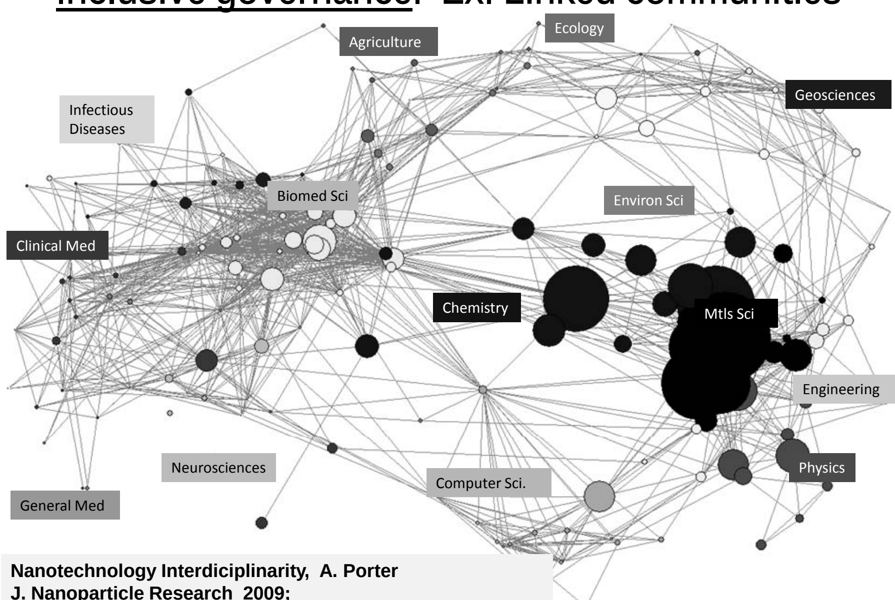
Ex.: Corporate Entry in leading countries (has products, articles and/or patents), 1990-2009



Courtesy Phil Shapira, Jan Youtie and Luciano Kay

MC Roco, Sept 30 2010

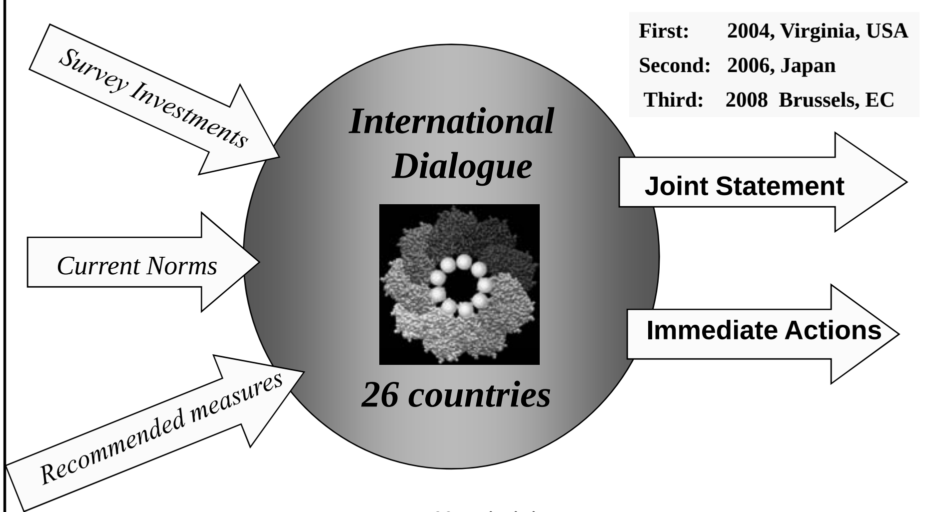
Inclusive governance. Ex. Linked communities



Nanotechnology Interdiciplinarity, A. Porter
J. Nanoparticle Research 2009;
Searched on Web of Science 93233 Documents
Overlay of distribution on map conveys diversity

MC Roco, Sept 30 2010

Inclusive governance - Ex: International Dialogue on Responsible Nanotechnology R&D since 2004



June 2004, Virginia

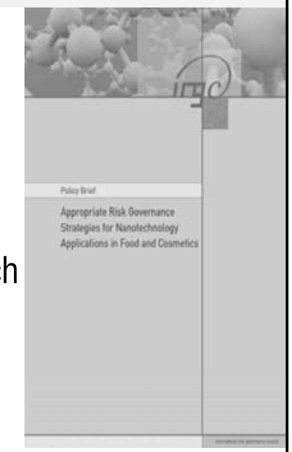
http://www.nsf.gov/home/crssprgm/nano/dialog.htm

First International Dialogue on Responsible Nanotechnology R&D (2004)

Coordinated activities after the June 2004 International Dialogue

- October 2004 / October 2005 - Occupational Safety Group (UK, US,.)
- November 2004 - OECD / EHS group on nanotechnology begins
- December 2004 - Meridian study for developing countries
- December 2004 - Nomenclature and standards (ISO, ANSI)
- February 2005 - North-South Dialogue on Nanotechnology (UNIDO)
- May 2005 - International Risk Governance Council (IRGC)
- May 2005 - “Nano-world”, MRS (Materials, Education)
- July 2005 - Interim International Dialogue (host: EC)
- October 2005 - OECD Nanotechnology Party in CSTP
- June 2006 - 2nd International Dialogue (host: Japan)
- 2006 Int. awareness for: EHS, public participation, education
- 2007-2010 - new activities

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

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Advances in 2000-2010

Creation of new community of multidisciplinary researchers

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*

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)

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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

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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

MC Roco, Sept 30 2010

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

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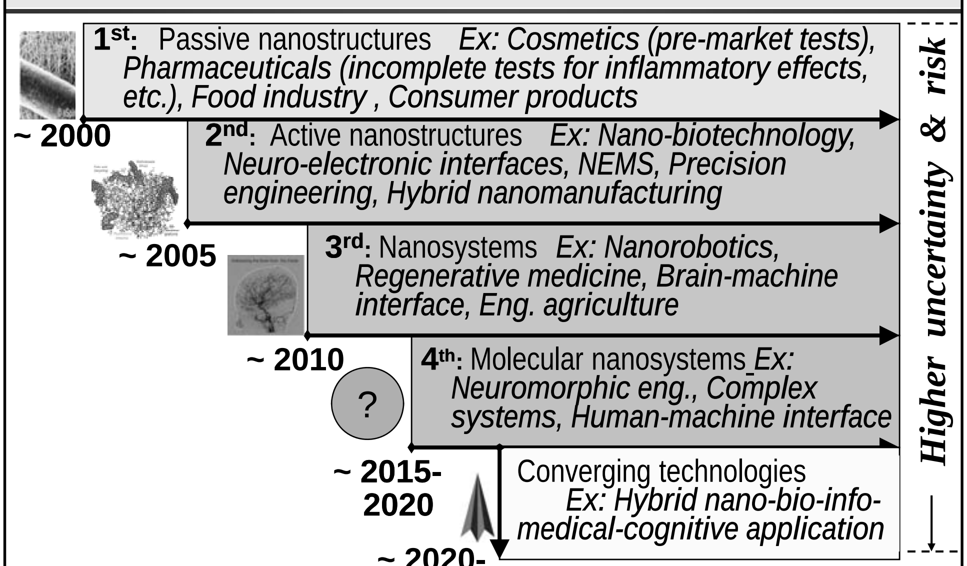
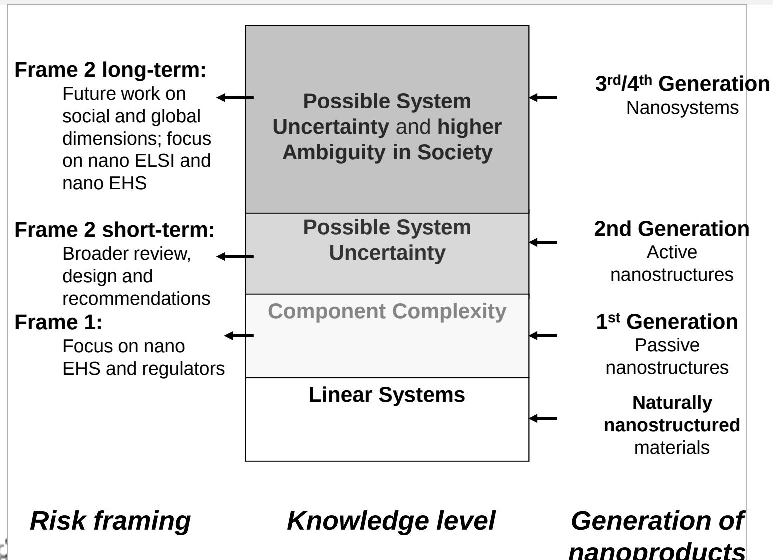
Perceived Higher Risks Areas (2000-2020; 2020-) as a function of nanotechnology generation



MC Roco, Sept 30 2010

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



Reference: Roco and Renn (2008)

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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"

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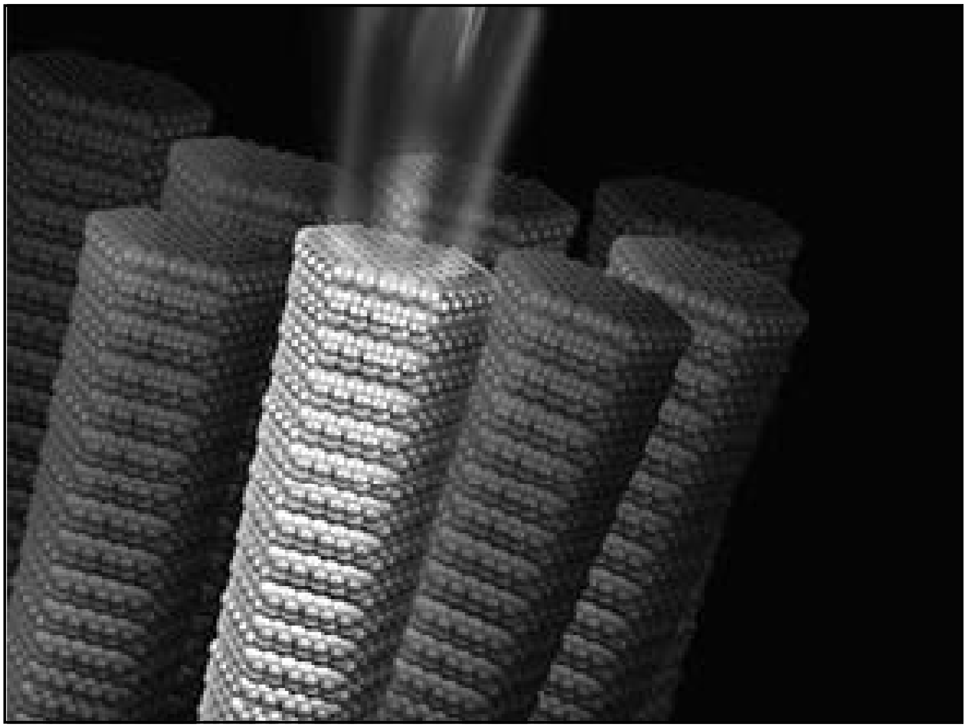

WTEC Books:

Brain-computer interfaces: An international assessment of research and development trends. Ted Berger (Ed.) Springer, 2008.

Robotics: State of the art and future challenges. George Bekey (Ed.) Imperial College Press, 2008.

Micromanufacturing: International research and development. Kori Ehmann (Ed.) Springer, 2007.

Systems biology: International research and development. Marvin Cassman (Ed.) Springer, 2007.

Nanotechnology: Societal implications. Mihail Roco and William Bainbridge (Eds.) Springer, 2006. Two volumes.

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Tissue engineering research. Larry McIntire (Ed.) Academic Press, 2003.

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Societal implications of nanoscience and nanotechnology. Mihail Roco and William Brainbridge (Eds.) Kluwer Academic Publishers, 2001.

Nanotechnology research directions. M.C. Roco, R.S. Williams, and P. Alivisatos (Eds.) Kluwer Academic Publishers, 1999. Russian version available.

Nanostructure science and technology: R & D status and trends in nanoparticles, nanostructured materials and nanodevices. R.S. Siegel, E. Hu, and M.C. Roco (Eds.) Kluwer Academic Publishers, 2000.

Advanced software applications in Japan. E. Feigenbaum et al. (Eds.) Noyes Data Corporation, 1995.

Flat-panel display technologies. L.E. Tannas, et al. (Eds.) Noyes Publications, 1995.

Satellite communications systems and technology. B.I. Edelson and J.N. Pelton (Eds.) Noyes Publications, 1995.

Other Selected WTEC Panel Reports:

(Imperial College Press will publish the first three reports)

Research and development in simulation-based engineering and science (1/2009)

Research and development in catalysis by nanostructured materials (11/2008)

Research and development in rapid vaccine manufacturing (12/2007)

Research and development in carbon nanotube manufacturing and applications (6/2007)

High-end computing research and development in Japan (12/2004)

Additive/subtractive manufacturing research and development in Europe (11/2004)

Microsystems research in Japan (9/2003)

Environmentally benign manufacturing (4/2001)

Wireless technologies and information networks (7/2000)

Japan’s key technology center program (9/1999)

Future of data storage technologies (6/1999)

Digital information organization in Japan (2/1999)

Selected Workshop Reports Published by WTEC:

International assessment of R&D in stem cells for regenerative medicine and tissue engineering (4/2008)

Manufacturing at the nanoscale (2007)

Building electronic function into nanoscale molecular architectures (6/2007)

Infrastructure needs of systems biology (5/2007)

X-Rays and neutrons: Essential tools for nanoscience research (6/2005)

Sensors for environmental observatories (12/2004)

Nanotechnology in space exploration (8/2004)

Nanoscience research for energy needs (3/2004)

Nanoelectronics, nanophotonics, and nanomagnetics (2/2004)

Nanotechnology: Societal implications (12/2003)

Nanobiotechnology (10/2003)

Regional, state, and local initiatives in nanotechnology (9/2003)

Materials by design (6/2003)

Nanotechnology and the environment: Applications and implications (5/2003)

Nanotechnology research directions (1999)

All WTEC reports are available on the Web at http://www.wtec.org.