Nanotechnology Research
Trends in the U.S.

Mihail C. Roco
National Science Foundation and National Nanotechnology Initiative

Topics

- 2000-2030 - establishing nanotechnology
- Funding nanotechnology at NSF
- Several research trends in: nanomanufacturing, composite materials and systems, and convergence (including brain research)
Current trends

• Nanotechnology is an essential megatrend in S&E, the most exploratory field as a general foundation as compared to IT and BIO

• Nanotechnology continues exponential growth by vertical science-to-technology transition, horizontal expansion to areas as agriculture/ textiles/ cement, and spin-off areas (~20) as spintronics/ metamaterials/…

• After 2020, nanotechnology promises to become the primary S&T platform for investments & venture funds once design & manufacturing methods are established
Converging foundational technologies - NBIC

Information Technology Spin-offs: Large-data bases, topical computer-aided design, cyber networks, ...

Brain simulation
Cyber networking
Personalized education...

Nanobioinformatics
DNA computing
Proteomics, ....

Neuromorphic engng.
Synapses to mind
Smart environments,
Cogno aid devices ..

Nanobiomedicine
Nanobiotechnology
Synthetic biology
Bio-photonics, ....

Nanotechnology Spin-offs: Nanophotonics, plasmonics, materials genome, mesoscale S&E, metamaterials, nanofluidics, carbon electronics, nanosustainability, wood fibers, DNA NT, ..
Conceptualization of “Nanomanufacturing” and “Digital Technology” megatrends
(GAO-14-181SP Forum on Nanomanufacturing, Report to Congress, 2014, Fig. 3)

Nanomanufacturing
- Has characteristics of a general purpose technology
- Could eventually match or outstrip the digital revolution in terms of economic importance and societal impact
Vision inspired research is essential for the long-term view of nanotechnology

Modified Stokes diagram

- Pure Basic Research (Bohr)
- Use-inspired Basic Research (Pasteur)
- Vision-inspired Basic Research (added in CKTS, 2013)
- Empirical, less useful
- Pure Applied Research (Edison)

Relevance for the advancement of knowledge

- High
- Low

Relevance for applications

- Low use
- Known use
- New use

Roco and Bainbridge, 2013, Fig 9 [1]
Nanotechnology: from scientific curiosity to immersion in socioeconomic projects


30 year vision to establish nanotechnology: changing focus and priorities

Reports available on: www.wtec.org/nano2/ and www.wtec.org/NBIC2-report/ (Refs. 2-5)
OVERVIEW: CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES (2000 – 2030) 

(Refs. 2-5)

**Foundational interdisciplinary research at nanoscale**

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

Create passive and active nanocomponents by semi-empirical design

**NS&E integration for general purpose technology**

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

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

**New convergence platforms & economy immersion**

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

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

**FIVE GENERATIONS NANOPRODUCTS**

1. **Passive Nanostructures**
2. **Active Nanostructures**
3. **Nanosystems**
4. **Molecular Nanosystems**
5. **NBIC Technologies Platforms**

~ 2030

New convergence platforms & economy immersion

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

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

**NS&E integration for general purpose technology**

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

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

**Foundational interdisciplinary research at nanoscale**

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

Create passive and active nanocomponents by semi-empirical design

MC Roco, Sept 29 2014
National Nanotechnology Initiative

A U.S. Government research and development (R&D) initiative involving 20 Federal Departments and Independent Agencies working together toward the shared and challenging vision of "a future in which the ability to understand and control matter at the nano-scale leads to a revolution in technology and industry that benefits society."
2000-2030 Convergence-Divergence Cycle for global nanotechnology development

CONVERGENCE stage

Knowledge confluence

Disciplines
Bottom-up & top-down

Materials
Medical, ...

Sectors

Tools & Methods

Creative phase

Assembly of interacting parts
Control of matter at the nanoscale

Idea, discovery

Integration/Fusion phase

Five NT Generations

Product, invention

Innovation phase

New Products & Applications - $30 T

Spin-off disciplines, and productive sectors

New applications & business

New expertise and methods

Decision-making

Based on Roco and Bainbridge, 2013, Fig. 8 [1]
## Global and US revenues from Nano-enabled products

### Total world revenues

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2010-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total world revenues</td>
<td>339 (10 yr ~ 25%)</td>
<td>514</td>
<td>731</td>
<td>1,014</td>
<td>+ 676</td>
</tr>
</tbody>
</table>

### US

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2010-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>US (10 yr ~ 24%)</td>
<td>109.8</td>
<td>170.0</td>
<td>235.6</td>
<td>318.1</td>
<td>+ 208</td>
</tr>
</tbody>
</table>

### World annual increase

<table>
<thead>
<tr>
<th>Year</th>
<th>10 yr ~ 25%</th>
<th>2010-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-2013</td>
<td>52%</td>
<td>39%</td>
</tr>
</tbody>
</table>

### US annual increase

<table>
<thead>
<tr>
<th>Year</th>
<th>10 yr ~ 24%</th>
<th>2010-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-2013</td>
<td>55%</td>
<td>35%</td>
</tr>
</tbody>
</table>

### US / World

<table>
<thead>
<tr>
<th>Year</th>
<th>10 yr ~ 35%</th>
<th>2010-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-2013</td>
<td>32.4%</td>
<td>31%</td>
</tr>
</tbody>
</table>

**Total nanotechnology product revenues annual growth > 40% in 2010-2013**

MC Roco, Sept 29 2014
FY 2015 Budget Request - $412 million

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

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

- Training and education
  > 10,000 students and teachers/y; ~ $30M/y
Funding mechanisms (1) of research, education and infrastructure

- **NNI is a NSF-wide initiative**: funding for individual or small-group awards in all directorates BIO, CISE, GEO, E,H.R., ENG, MPS, SBE and offices (e.g. international, integrative activities) – in order to get synergism with all areas on a competitive basis and increase fundamental aspects in research and education

- **Dedicated programs in key areas**: in Chemistry (Macromolecular/Supramolecular/Nanochemistry Program), DMR (Metals and Metallic Nanostructures), CBET (Environmental Health and Safety of Nanotechnology), CMMI (Nanomanufacturing), BIO (Environmental Biology –CEIN)
Funding mechanisms (2) of research, education and infrastructure

- **Research and education centers** (5 year + 5 year awards)
  - cross directorates: NSECs, MRSECs, NERC, NISE, STCs,..
  - focused on topics in Molecular Chemistry Centers, Physics,..
- **Cross-directorate NSF solicitations**: such as Nanoscale Interdisciplinary Teams (NIRT), Nanoelectronics for 2020 and Beyond (NEB), Scalable Nanomanufacturing, Two-dimensional nanomaterials, and Nanotechnology Applications and Career Knowledge for technological education
- **National user facilities**: NNIN, NCN-nanoHUB
- **SBIR / STTR, I-Corps, GOALI, PFI (spectrum of programs)**
Sustainable Nanomanufacturing
Nanoelectronics for 2020 and Beyond
Nanotechnology for Solar Energy
Nanotechnology for Sensors and Sensors for Nanotechnology
Nanotechnology Knowledge Infrastructure

New topics under consideration for 2015:
  nanomodular systems, water filtration, nanocellulose,
  nanophotonics, nano-city…
Nanomanufacturing

• A part of National Nanotechnology Initiative and supporting Advanced Manufacturing (NSF, NASA, DOE, DOD, NIST, USDA, ..)

• Nanotechnology Signature Initiative: Sustainable Nanomanufacturing
  www.nano.gov/NSINanomanufacturing
  - NSF National Nanomanufacturing Network (NSF, NNN), http://www.internano.org/content/;
    Newsletter newsletter-bounces@nanomanufacturing.org
Twelve opportunities 2010-2020 for pre-competitive nanomanufacturing R&D

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

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

9. Standardized tools for measurements and manufacturing
10. Predictive simulation of nanomanufacturing processes
11. Predictive approach for toxicity of nanomaterials (ex: oxidative stress)
12. Development and use of nanoinformatics and intellectual property
National Nanomanufacturing Network (2006-)  
Its core: Four Nanomanufacturing NSECs

- **Center for Hierarchical Manufacturing** (CHM)  
  - U. Mass Amherst/UPR/MHC/Binghamton  
    Integrated *roll-to-roll* printed nanoelectronics

- **Center for High-Rate Nanomanufacturing** (CHN)  
  - Northeastern/U. Mass Lowell/UNH  
    Large-scale, directed assembling of nanostructures

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

- **Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems** (Nano-CEMMS)  
  - UIUC/ Caltech/ NC A&T. Combined methods and materials for manufacturing, using e.g. *nanofluidics*
Nanosystems Engineering Research Centers
Three NSF awards of $55.5 million (2012-2017)


- **Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies**, UT-Austin: high-throughput, reliable, and versatile nanomanufacturing process systems with illustration to mobile nanodevices.

- **Transformational Applications of Nanoscale Multiferroic Systems**, UCLA: exploit nanoscale phenomena to reduce the size and increase the efficiency of components and systems whose functions rely on the manipulation of either magnetic or electromagnetic fields.
Opportunities to advance nano-informatics

Nanotechnology Knowledge Infrastructure for fundamental collaborative research, a cyber-toolbox, and data infrastructure for nanotechnology.

To create a community-based, solution-oriented knowledge infrastructure for nanoinformatics:
- for design,
- manufacturing,
- nano-EHS, ....

MC Roco, Sept 29 2014
Nanocomposite 2D materials beyond graphene

- Other layered 2D materials exist: oxides, nitrides, sulfides
- Van der Waals solids: e.g. 2D MoS2
- MoS2 turns from indirect band-gap semiconductor to direct band-gap

- Bulk MoS2 crystal, like graphite – Molybdenite – earth abundant
- Modular materials and systems
- 3D assembling
Modular Nanosystems
Example: using 2D electronic materials

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

Graphene Family (C, Si, BN)
MX₂ (TMD) Family (>88 members)

- Half-metal ($E_g$: 0-1 eV)
  - Example: CrO₂, CrS₂

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

- Semiconductor ($E_g$: 1-2 eV)
  - Channel Material
  - Example: MoS₂, WSe₂

- Metal
  - Interconnect, Gate, etc.
  - Example: VO₂, VS₂

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

- Superconductor
  - Example: NbSe₂

All 2D Circuits

2D Metal
2D Dielectric
2D Channel
2D Interconnect

Courtesy Kaustav Banerji (UCSB)
<table>
<thead>
<tr>
<th>Prop ID</th>
<th>PI Last Name</th>
<th>Project Title</th>
<th>Submitting Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1433311</td>
<td>Terrones</td>
<td>Design, Synthesis, and Device Fabrication of Transition Metal Dichalcogenides for Active and Nonlinear Photonics</td>
<td>Rensselaer Polytech Inst</td>
</tr>
<tr>
<td>1433510</td>
<td>Lauhon</td>
<td>EFRI 2-DARE: Scalable Growth and Fabrication of Anti-Ambipolar Heterojunction Devices</td>
<td>Northwestern University</td>
</tr>
<tr>
<td>1433541</td>
<td>Huang</td>
<td>Scalable Synthesis of 2D Layered Materials for Large Area Flexible Thin Film Electronics</td>
<td>U of Cal Los Angeles</td>
</tr>
<tr>
<td>1433378</td>
<td>Redwing</td>
<td>2D Crystals Formed by Activated Atomic Layer Deposition</td>
<td>PA St U University Park</td>
</tr>
<tr>
<td>1433395</td>
<td>Balandin</td>
<td>Novel Switching Phenomena in Atomic MX2 Heterostructures for Multifunctional Applications</td>
<td>U of Cal Riverside</td>
</tr>
<tr>
<td>1433467</td>
<td>Goldberger</td>
<td>Enhancing Thermal and Electronic properties in Epitopotaxial Si/Ge/Sn Graphene Heterostructures</td>
<td>Ohio State University</td>
</tr>
<tr>
<td>1433307</td>
<td>Robinson</td>
<td>Ultra-Low Power, Collective-State Device Technology Based on Electron Correlation in Two-Dimensional Atomic Layers</td>
<td>PA St U University Park</td>
</tr>
<tr>
<td>1433496</td>
<td>Cobden</td>
<td>Spin-Valley Coupling for Photonic and Spintronic Devices</td>
<td>U of Washington</td>
</tr>
<tr>
<td>1433490</td>
<td>Xing</td>
<td>Monolayer Heterostructures: Epitaxy to Beyond-CMOS Devices</td>
<td>University of Notre Dame</td>
</tr>
<tr>
<td>1433459</td>
<td>Ye</td>
<td>Phosphorene, an Unexplored 2D High-mobility Semiconductor</td>
<td>Purdue University</td>
</tr>
</tbody>
</table>
Five convergence principles for progress applied in five human activity platforms.
Tissue Engineering meets 3-D Printing

- 3D printing technology
- Tissue engineering
- Nanotechnology
- Additive manufacturing enables printing of scaffolds with nanoscale precision for tissue engineering

Coincidental convergence of four very different research directions

Novogen MMX Biprinter
Credit: Organovo, Inc.
Develop experimental and computational tools for understanding, and controlling the complex functional behaviors of interacting cell clusters or biological machines.

Understand fundamental cellular behaviors that are guided by integrated biological, biochemical, and physical (geometrical, mechanical, electrical, thermal) processes.

Lead MIT (Kamm); Georgia Tech, Illinois, Morehouse, UC Merced, City College NY are partner institutions.
Cyborg-like Tissue Monitors Cells
Nanoelectronic scaffolding supports living tissue

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

- The **cyborg-like tissue** supports cell growth while simultaneously monitoring the activities of those cells, drug effects

- Step toward **prosthetics that communicate directly with the nervous system, and tissue implants** (Nature Materials, Aug 2012)

SEM images of a mesh nanoES/alginate scaffold, top (I) and side (II) views. The epoxy ribbons from nanoES are false-colored in brown for clarity
Cellulose nanomaterials

Nanofibrillar cellulose (NFC)

Films, packaging, barrier materials

Composites (reinforcing)

Rheology modifiers, paintings, pharma and food

Biomedical materials

Coatings

Flexible, soft electronics
Circuit board base (electronic packaging)
Conductive/magnetic or piezoelectric films (sensors, actuators, RTDs)

Bacterial Cellulose (BC)

Cellulose Nanocrystals (CNC)

O.J. Rojas, NCSU, 2014
Understanding the brain
First step: Mapping and engineering the brain

www.nsf.gov/BRAIN

<table>
<thead>
<tr>
<th>Neuroscience &amp; Cognitive Science</th>
<th>Genetic &amp; Molecular Cell Biology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neuro-engineering</td>
<td>Computation &amp; Bioinformatics</td>
</tr>
<tr>
<td>Biophysics &amp; Control</td>
<td>Bioimaging &amp; Biosensing</td>
</tr>
<tr>
<td>Nanomedicine &amp; Nanofabrication</td>
<td></td>
</tr>
</tbody>
</table>

Integration

Deciphering

mechanisms underlying the brain adaptation to changing environment, and genetic and epigenetic landscape

neural representations and coding, and principles of brain organization and decision making

mechanisms underlying dynamic decisions and communication within and across scales

neural circuits and signal pathways that regulate the regrowth, repair of nerve tissues and cells

Engineering

Intelligent Systems

Brain Circuit Control Network

Artificial Intelligence

Intelligent Robotics
Twelve global 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, self repairing, dynamic
- Penetration of nanotechnology in industry - toward mass use; catalysts, electronics; innovation– platforms, consortia
- Nano-EHS – more predictive, integrated with nanobio & env.
- Personalized nanomedicine - from monitoring to treatment
- Photonics, electronics, magnetics – new capabilities, integrated
- Energy photosynthesis, storage use – solar economic by 2015
- Enabling and integrating with new areas – bio, info, cognition
- Earlier preparing nanotechnology workers – system integration
- Governance of nano for societal benefit - institutionalization
Long-term opportunity and challenge:

**NBIC systems with emerging behavior**

- Evolutive nano-bio-robotic systems
- Hybrid viruses, bacteria and other organisms
- Nanosystem, synthetic biology & neurotechnology
- Control and manipulation of DNA at the nanoscale
- Human enhancement, including physic-medical, brain potential, behavior, individualized medicine, others
- Artificial organs, legal aspects & life expectancy
- Intelligent working and urban environments
- Numerous emerging NBIC platforms (see Ref [1-6])
Related publications

1. “The new world of discovery, invention, and innovation: convergence of knowledge, technology and society” (Roco & Bainbridge, JNR 2013a, 15)


3. NANO2: “Nanotechnology research directions for societal needs in 2020” (Roco, Mirkin & Hersam, Springer, 690p, 2011a)


5. NBIC2: “Convergence of knowledge, technology and society: Beyond NBIC” (Roco, Bainbridge, Tonn & Whitesides; Springer, 604p, 2013b)

6. “Nanotechnology: from discovery to innovation and socioeconomic projects: 2000-2020” (Roco; CEP, 2011b)

7. “Mapping nanotechnology innovation and knowledge: global and longitudinal patent and literature” (Chen & Roco, Springer, 330p, 2009)

8. “Global nanotechnology development from 1991 to 2012” (JNR 2013c)