Nanotechnology Path to Sustainable Society

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National Science Foundation and National Nanotechnology Initiative

SUN-SNO-GUIDENANO Sustainable Nanotechnology Conference
Venice, March 9, 2015
Topics

• Sustainable society

• Long-view of nanotechnology affirmation
  US & international perspective

• Paths to sustainable society
  Nano – a general-purpose technology
Sustainable society

Social (population growth and needs, governance, enduring democracy),

economic (knowledge, technology, materials, water, energy, food, climate), and

environment (clean, renewable, biodiverse)

sustainability in planetary boundaries
Nanotechnology Governance

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

Four key functions:

Visionary

Transformative

Responsible

Benefit society

Sustain

Risk

Inclusive

Risk Governance

MC Roco, March 9 2015
The functions of good governance are applied to several governance levels:

- **International**
  - Ex.: Int. dialogue
  - Ex.: (in US) NT Law and WH NNI priority
  - Building capacity in national R&D, organizations, policies
  - Establish programs organizations and regulations
  - Adapt existing regulations, organizations

- **Societal**
  - Ex.: Treating new nanostructures as new chemical; Fundamental research/communication for new knowledge

- **Technological system**
  - Ex.: Specific legislation for hybrid nano-bio systems

- **System component**

MC Roco, March 9 2015
The functions of good governance are applied to FIVE GENERATIONS OF NANOTECHNOLOGY.

1st: Passive nanostructures (1st generation products)
   a. Dispersed and contact nanostructures. Ex: aerosols, colloids
   b. Products incorporating nanostructures. Ex: coatings; nanoparticle reinforced composites; nanostructured metals, polymers, ceramics

2nd: Active nanostructures
   a. Bio-active, health effects. Ex: targeted drugs, biodevices
   b. Physico-chemical active. Ex: 3D transistors, amplifiers, actuators, adaptive structures

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

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

5th: Converging technologies

Risk Governance Frame 1

Frame 1
Illustration of new challenges for integrated architectures

ITRS Report, 2015

Source: Georgia Tech PRC, http://www.prc.gatech.edu/overview/images/etpc.jpg
Illustration of new challenges: Emerging Behaviors in Integrated Cellular Systems and their Boundaries

Controlling the complex functional behaviors of interacting cell clusters, and their interaction with the surroundings

Understand cellular behaviors guided by integrated biological, biochemical, and physical processes, and their interaction with the surrounding systems

NSF STC: MIT (Kamm); GA Tech, Illinois, Morehouse, UC Merced, City College
What is Sustainable Development?

• **Bruntland Commission (1987)**
  Development that would meet the needs of the present without compromising the ability of future generations to meet their own needs

• **Herman Daly**
  – Non-renewable resources should not be depleted at rates higher than the development rate of renewable resources
  – Renewable resources should not be exploited at a rate higher than their regeneration level
  – The absorption and regeneration capacity of the natural environment should not be exceeded
Sustainable nanotechnology solutions for clean environment; energy, water, food, mineral resources supplies; green manufacturing, habitat, transportation, climate change, biodiversity

Current critical planetary boundaries are
- biodiversity
- nitrogen cycle
- climate change

(Rockström et al. 2009)
Sustainability has emerged as the key driver for addressing global problems facing the world, including:

– Energy and Water
– Agriculture, Food and Natural Resources
– Human Health and Well-Being
– Urban and rural communities
– Materials and Manufacturing
– Environment and Climate Change
– Societal Engagement and Public Benefits
Possible targets for nanotechnology and convergent technologies

- **Infinitely Recyclable, Re-usable, and Renewable Industrial Ecosystems (IR$^3$)**
  - Reduce demand for virgin materials, reduce carbon emissions

- **Community, buildings and household self-sufficiency**
  - Focus on low-income communities and households
Long view

• Since 2000, nanotechnology is an essential megatrend in S&E, the most exploratory field as a general foundation as compared to IT and BIO

• Nanotechnology today 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, and respective education & physical infrastructure are established
Nanotechnology: from scientific curiosity to immersion in socioeconomic projects

**nano1** (2001-2010)

IWGN Workshop Report:

Nanotechnology Research Directions

Vision for Nanotechnology in the Next Decade

Edited by: M.C. Roco, R.S. Williams and P. Alivisatos

1999

Kluwer Academic Publishers

**nano2** (2011-2020)

Science Policy Reports

Mihail C. Roco - Chad A. Mirkin
Mark C. Hersam

Nanotechnology Research Directions for Societal Needs in 2020

Retrospective and Outlook

2010

Springer

**NBIC1 & 2** (2011-2030)

Nano-Bio-IT-Cogno-

Convergence of Knowledge, Technology and Society

Beyond Convergence of Nano-Bio-Infra-Cognitive Technologies

2001

2013

Springer

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)
Converging foundational technologies - NBIC

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

Roco and Bainbridge, 2013, Fig 2 [Ref 1]

Nanotechnology Spin-offs: Nanophotonics, plasmonics, materials genome, mesoscale S&E, metamaterials, nanofluidics, carbon electronics, nanosustainability, wood fibers, DNA NT, ...

Brain simulation
Cyber networking
Personalized education...

Nanobiotechnology
Synapses to mind
Smart environments,
Cogno aid devices...

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

Brain simulation
Cyber networking
Personalized education...

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

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

Converging foundational technologies - NBIC

Information Technology

NBIC System

Biotechnology

Nanotechnology

Cognitive Sciences

21st C Building Blocks

Bits

Synapses

Atoms

Genes

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

Roco and Bainbridge, 2013, Fig 2 [Ref 1]
Conceptualization of “Nanomanufacturing” and “Digital Technology” megatrends: S-curves (GAO-14-181SP Forum on Nanomanufacturing, Report to Congress, 2014)

Nanomanufacturing
- Has characteristics of a general purpose technology
- Could eventually match or outstrip the digital revolution in terms of economic importance and societal impact

~ 2010
2014
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 applications:
- Low use
- Known use
- New use

Relevance for the advancement of knowledge:
- Low
- High

Roco and Bainbridge, 2013, Fig 9 [1]
Implementing the 30 year vision in U.S.

NNI in three administrations: Clinton, Bush and Obama

President Clinton announces NNI in January 2000

NSF vision report March 1999


President Obama

WH approves 15 yr view by PCAST 2014
Three overarching goals for nanotechnology development

- Increase productivity (in industry, agriculture, transportation, ..)
- Quality of life (health, culture, security, aging, ..)
- Societal sustainability (physical Surroundings, resources, biodiversity, economic, social, cultural, ..)
National Nanotechnology Initiative, 2000
(Vision: control of matter at nanoscale will bring a revolution in technology; see www.nano.gov)

PCAST Report on NNI, 2014:
Recommends New Grand Challenges
Over 80 countries with nanotechnology R&D

2013 industry survey (Lux Res.): global revenues $1 trillion
Global Nanotechnology future

Breakthroughs in novel system architectures and nano-bio-info-cognitive convergence are expanding and leading to emergence of novel technology platforms

S – development curve for foundational nanoscale science and technology

- amplified return on investment/ multiple branches
- revenue growth ~ 43% per year in 2011-2014
- nanotech products est. to reach >10% GDP in most developed countries by 2030
**2000-2030 Convergence-Divergence Cycle for global nanotechnology development**

**Knowledge confluence**

Disciplines
- Bottom-up & top-down
- Materials
  - Medical, ..
- Sectors
- Tools & Methods

**Assembly of interacting parts**

Control of matter at the nanoscale

**Creative phase**

**Integration/Fusion phase**

**Innovation phase**

**Spin-off phase**

**Innovation spiral**

Spin-off disciplines, and productive sectors

New applications & business

New Products & Applications - $30 T

Based on Roco and Bainbridge, 2013, Fig. 8 [1]
CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES

1. Passive Nanostructures
   ~ 2001 ← nano1 component basics → ~ 2010
   Create passive and active nanocomponents by semi-empirical design

2. Active Nanostructures
   2000

3. Systems of Nanosystems
   ~ 2011 ← nano2 system integration → ~ 2020
   NS&E integration for general purpose technology
   Create nanosystems by science-based design/processes/technology integration

4. Molecular Nanosystems

5. NBIC Techn. Platforms

6. Nanosystem Conv. Networks

New convergence platforms & economy immersion
~ 2021 ← nano3 technology divergence → ~ 2030
Create spin-off nano-platforms in industry, medicine and services;

2030

FIVE GENERATIONS NANOPRODUCTS

MC Roco, March 9, 2015

(Refs. 2-5)
Examples for Nano 1 (2001-2010)

- New individual phenomena, processes, structures

- Semi-empirical synthesis of nanocomponents (particle, quantum dots, tubes, coatings,..) over all the periodic table

- Nanocomponents have extended semiconductor’s Moore’s law since 2000
Examples for Nano 2 (2011-2020)

• Direct measurements & simulations (at femtosecond, N \( \uparrow \) interacting atoms) for domains of biological and engineering relevance

• Science based integrated nanosystems by design

IBM: 12-atom structure (2012)

UIUC: Nanofluidics system (2011)

NCSU: Nanosystem for health and environmental monitoring (2014)

Atomic and femtosecond resolutions. A. Zewail, Caltech
Examples for Nano 3 (2021-2030)

• **New system architectures**: guided self-assembling structures, evolutionary architectures, biomimetics--based, biorobotics-based, neuromorphic, adiabatic switching and reversible logic for IT, … to be invented.

• **Nano-Bio-Info-Cognition technology platforms**

• **Service and molecular medicine** individualized

• Genetic – neurotechnologies – robotics - .. to improve human potential

• High productivity - high return **new industry sectors**
Perception

“Nanotechnology” is not:

• Not “a buzz word” – corresponds to the transition in nature and technology from individual atomic properties to their collective effects enabling diversity on the Earth

• Not “a pollutant technology” – aims at non-covalent assembling, low (p,T) & pollution, “how molecules like”

• Not “a mature field” – going beyond the 1st generation of passive nanoparticles toward complex nanosystems

• Not “limited to unsolicited research” – it needs new tools, infrastructure, unifying concepts in education, focus R&D efforts on emerging and bottleneck research
### 2000-2010 (data from Nano2 Report, NSF/WTEC)

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

<table>
<thead>
<tr>
<th>Year</th>
<th>World (US)</th>
<th>People - primary workforce</th>
<th>SCI papers</th>
<th>Patents applications</th>
<th>Final Products Market</th>
<th>R&amp;D Funding public + private</th>
<th>Venture Capital</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2000</strong></td>
<td>~ 60,000 (25,000)</td>
<td>18,085 (5,342)</td>
<td>1,197 (405)</td>
<td>~ $30 B ($13 B)</td>
<td>~ $1.2 B ($0.37 B)</td>
<td>~ $0.21 B ($0.17 B)</td>
<td></td>
</tr>
<tr>
<td><strong>2010</strong></td>
<td>~ 600,000 (220,000)</td>
<td>78,842 (17,978)</td>
<td>~ 20,000 (5,000)</td>
<td>~ $300 B ($110 B)</td>
<td>~ $18 B ($4.1 B)</td>
<td>~ $1.3 B ($1.0 B)</td>
<td></td>
</tr>
<tr>
<td><strong>2000 - 2010</strong></td>
<td>~ 25% (~23%)</td>
<td>~ 16% (~13%)</td>
<td>~ 33% (~28%)</td>
<td>~ 25% (~24%)</td>
<td>~ 31% (~27%)</td>
<td>~ 30% (~35%)</td>
<td></td>
</tr>
<tr>
<td><strong>2015</strong></td>
<td>~ 2,000,000 (800,000)</td>
<td>~ $1,000B ($400B)</td>
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<tr>
<td><strong>2020</strong></td>
<td>~ 6,000,000 (2,000,000)</td>
<td>~ $3,000B ($1,000B)</td>
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### Evolving Topics

Research frontiers change from passive nanostructures in 2000-2005, to active nanostructures after 2006, and to nanosystems after 2010

(updated Nano2 Report, 2010, p. XXXIII (Ref. 3))
### Global and US revenues from Nano-enabled products

(All budgets in $ billion)

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2010-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total world revenues</strong></td>
<td>339</td>
<td>514</td>
<td>731</td>
<td>1,014</td>
<td>+ 676</td>
</tr>
<tr>
<td><em>(10 yr ~ 25%)</em></td>
<td></td>
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<tr>
<td><strong>US revenues</strong></td>
<td>109.8</td>
<td>170.0</td>
<td>235.6</td>
<td>318.1</td>
<td>+ 208</td>
</tr>
<tr>
<td><em>(10 yr ~ 24%)</em></td>
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<tr>
<td><strong>World annual increase</strong></td>
<td>10 yr ~ 25%</td>
<td>52%</td>
<td>42%</td>
<td>39%</td>
<td>44%</td>
</tr>
<tr>
<td><strong>US annual increase</strong></td>
<td>10 yr ~ 24%</td>
<td>55%</td>
<td>39%</td>
<td>35%</td>
<td>43%</td>
</tr>
<tr>
<td><strong>US / World</strong></td>
<td>32.4%</td>
<td>33%</td>
<td>32%</td>
<td>31%</td>
<td>32%</td>
</tr>
<tr>
<td><em>(10 yr ~ 35%)</em></td>
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Total nano product revenues annual growth **> 40% in 2010-2013. “S – curve”**
Nanotechnology publications in the WoS: 1990 - 2014

“Title-abstract” search for nanotechnology by keywords for six regions (update of NANO2, Fig 1 (Ref. 3) using the method described in (Ref. 7))

2000 - 2014
Worldwide annual growth rate ~ 16%

U.S./World ~ 29.5% in 2001-2005

U.S./World ~ 19% in 2014

Rapid, uneven growth per countries

MC Roco, March 9 2015
Five countries’ contributions to Top 3 Journals (Nature, Science, PNAS) in 2014, by individual journals

Different countries’ contributions in top 3 journals’ nanotechnology paper publications: Science, Nature, and PNAS (title-abstract search)

U.S. leads with about 66% (at least one author from US)
Number of nanotechnology patent applications per year published annually (1991-2014)

“Title-abstract” search for nanotechnology by keywords (Chen and Roco 2013, based on [4])

<table>
<thead>
<tr>
<th>Year</th>
<th>All applications</th>
<th>Non-overlapping Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>224</td>
<td>224</td>
</tr>
<tr>
<td>2001</td>
<td>2,163</td>
<td>2095</td>
</tr>
<tr>
<td>2014</td>
<td>21,678</td>
<td>20,062</td>
</tr>
</tbody>
</table>

Longitudinal evolution of the total number of nanotechnology patent applications in the 15 repositories per year (“title-abstract search by keywords” 1991–2014). Data was obtained from UA's NSE database (crawled from Espacenet).

USA in 2000
15 repositories ~ 35%
USPTO ~ 70%

- 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 (updated keywords used for all 2014 data, and 2011-2014 for NSF grants)

- 2014 NSF grants ~ 14%
- 2014 Top 20 nano J. ~ 12%
- 2014 All journals ~ 5.5%
- 2013 USPTO patents ~ 2.1%

## Nanotechnology penetration in economy
*(Nano 2020, Lux Research)*

### U.S. 2000 - 2010 - Est. in 2020

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
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<tbody>
<tr>
<td><strong>Catalysts</strong></td>
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<tr>
<td><strong>Coatings</strong></td>
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<tr>
<td><strong>Insulation</strong></td>
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<td><strong>Filtration</strong></td>
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<tr>
<td><strong>Transportation</strong></td>
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<tr>
<td><strong>Robotics</strong></td>
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<td><strong>Mobile electronics</strong></td>
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<tr>
<td><strong>Displays</strong></td>
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<tr>
<td><strong>Packaging (electronics)</strong></td>
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<tr>
<td><strong>Thermal management</strong></td>
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<tr>
<td><strong>Batteries</strong></td>
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<td><strong>Supercapacitors</strong></td>
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<td><strong>Paint</strong></td>
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<tr>
<td><strong>Diagnostic and monitoring sensors</strong></td>
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<tr>
<td><strong>Cosmetics</strong></td>
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<tr>
<td><strong>Food products and packaging</strong></td>
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<td><strong>Personal care products</strong></td>
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<td><strong>Sunscreen</strong></td>
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<tr>
<td><strong>Packaging (medical)</strong></td>
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<td><strong>Surgical tools</strong></td>
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<tr>
<td><strong>Implantable medical devices</strong></td>
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<tr>
<td><strong>Contrast agents (medical)</strong></td>
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<tr>
<td><strong>Lab supplies</strong></td>
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<tr>
<td><strong>Fuel cells</strong></td>
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<td><strong>Hydrolysis</strong></td>
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<td><strong>Solar cells</strong></td>
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<td><strong>Grid storage</strong></td>
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<td><strong>Water treatment and purification</strong></td>
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<td><strong>Air purification</strong></td>
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<tr>
<td><strong>Environmental monitoring</strong></td>
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<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2010</th>
<th>Est. in 2020</th>
</tr>
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<tbody>
<tr>
<td><strong>Semiconductor industry</strong></td>
<td>0</td>
<td>60%</td>
<td>100%</td>
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<tr>
<td><strong>New nanostructured catalysts</strong></td>
<td>0</td>
<td>~35%</td>
<td>~50%</td>
</tr>
<tr>
<td><strong>Pharmaceuticals</strong></td>
<td>0</td>
<td>~15%</td>
<td>~50%</td>
</tr>
<tr>
<td><strong>Wood</strong></td>
<td>0</td>
<td>0</td>
<td>~20%</td>
</tr>
</tbody>
</table>
Nanotechnology-enabled products by sectors in 2014

**Materials and manufacturing:** Fiber reinforced plastics, nanoparticle catalysts, coatings, insulation, filtration, transportation (cars, trucks, trains, planes, ships), robotics (actuators and sensors)

**Electronics and IT:** Semiconductors, mobile electronics and displays, packaging, thermal management, batteries, supercapacitors, paint

**Health care and life sciences:** Diagnostic and monitoring sensors (cancer), cosmetics, food products and packaging, personal care products, sunscreen, packaging, surgical tools, implantable medical devices, filtration, treatments (cancer radiation therapies) and medications formulations, contrast agents, quantum dots in lab supplies like fluorescent antibodies

**Energy and environment:** Fuel cells, hydrolysis, catalysts, solar cells, insulation, filtration, supercapacitors, grid storage, monitoring equipment (sensors), water treatment and purification

*(from industry sources, Lux Research)*
FY 2015 Budget Request - $412 million

Interval FYs 2000-2013: U.S. average - $23.5 / capita

- 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
WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

- Estimation made in 2000 after international study in > 20 countries
- THE ESTIMATIONS ARE IN AGREEMENT WITH SURVEYS UNTIL 2010; then, LUX surveys larger in 2012 (world $731B, US $235B; ~40% annual increase)

Rudimentary                                                                 Complex
Passive nanostructures                                                     Nanosystems by design
Active nanostructures

Final products incorporating nanotechnology in the world

Two orders of magnitude in 20 yr.

World annual rate of increase ~ 25%; Double each ~ 3 years

~ $40B  ~ $120B  ~ $250B  ~ $91B, U.S.  $1T by 2015  $3T by 2020

Ref: Roco and Bainbridge, “Societal Implications..” 2001; and NANO2, Fig 3 [3]
Corporate entry into nanotechnology
Leading countries, 2011-2014*

*Corporate entry in the nanotechnology domain through patent applications (1990-Spring 2014) or publications (1990-2014), by corporate organizations.
Source: P. Shapira, J. Youtie, and Y. Li (Georgia Institute of Technology and Center for Nanotechnology in Society CNS-ASU), analysis of records (January 2015) in the EPO Worldwide Patent Statistical Database (PATSTAT) and Thomson Reuters Web of Science. PATSTAT data was provided by L. Kay (CNS-UCSB).
Notes: Analysis of corporate organizations (N=12,495). Organizations matched where possible to reduce most apparent duplicated variations of corporate names. Universities and non-profits excluded. OECD = 34 member countries as of January 2015. Europe = 25 European countries that are OECD members.
Paths to sustainable nanotechnology

- Nanotechnology (less material, energy, water and waste) immersion in socio-economic projects

- Transformative and responsible S&T governance: sustainable nanotechnology development and societal sustainability (economic, social, cultural, for communities) using nanotechnology

- Convergence with other fields to create new S&T platforms

- Establish sustainability research & educ. programs
Leave molecules and nanostructure to do what they do well preference to non-covalent bonds (lower energy, pressure, temperature)

Ex: Bioinspired Random Fractal Structures
Cellulose Nanomaterials

Nanofibrillar cellulose (NFC)

Rheology modifiers, paintings, pharma and food

Films, packaging, barrier materials

Composites (reinforcing)

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
nanocomposite 2D materials beyond graphene – for sustainable & safe manufacturing

- Various 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
12-atom and DNA data memory systems

2000: NNI goal for ~2025 that all information from Library of Congress in a device of size of sugar cube 1cm cube (Pres. Clinton) – was then labeled as too ambitious.

Jan 2012: 12 atom structure, store it in 1cm cube (Science, 2012) IBM

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

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

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

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

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

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

- **Superconductor**
  - Example: NbSe₂

All 2D Circuits

2D Metal
2D Dielectric

2D Channel
2D Interconnect

Courtesy Kaustav Banerji (UCSB)
Nanomodular 2D/3D structures for devices

In-Plane 2D Devices

Stacked 2D Devices

NANO - MATERIALS/SYSTEMS/DEVICES BY DESIGN
Courtesy P. Ajayan (Rice U.)
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

Open-access network  
[www.nanomanufacturing.org beta.internano.org](http://www.nanomanufacturing.org beta.internano.org)

MC Roco, March 9 2015
Additive selfassembling on roll-to-roll process
(U. Mass. – Amherst, J. Watkins)

Additive-driven self assembly yields well ordered periodic assemblies of nanoparticle polymer hybrids (left) while R2R nanoimprint lithography produces sub-100 nm device patterns 70 nm grating pattern shown (right).
Manufacturing of 3-D nanostructures using directed nanoparticle assembly process. (A and B) NPs suspended in aqueous solution are (A) assembled and (B) fused in the patterned via geometries under an applied AC electric field. (C) Removal of the patterned insulator film after the assembly process produces arrays of 3-D nanostructures on the surface. (D) Scanning electron microscopy (SEM) image of gold nanopillar arrays. Economic approach.
Nanoscale Offset Printing System
2014 spin-off of Northeastern University

NanoOPS will enable diverse manufacturing of nano-enabled products and devices. It eliminates some of the high-cost barriers to businesses seeking to fabricate devices and systems with nanomaterials.
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.
The Field Effect Transistor (FET), sparked the information technology revolution decades ago. Opportunities outside the “FET box” to reduce energy dissipation in logic are vast and suitable to be addressed by U-G-I partnerships:

- **Abrupt Switching** (i.e. improve Conventional Logic)
- **Adiabatic Switching**
- **Reversible Logic**
- **Quantum Computing**, in which adiabatic switching and reversible logic circuits are implemented in quantum systems.
Programs on sustainable and safe nanomanufacturing

- **Sustainable Nanomanufacturing** a part of **NNI** and in support of **Advanced Manufacturing** (NSF, NASA, DOE, DOD, NIST, USDA ..)

- **Nanotechnology Signature Initiative** :

  [www.nano.gov/NSINanomanufacturing](http://www.nano.gov/NSINanomanufacturing)

    - Scalable Nanomanufacturing (NSF 2011-2015)

    - NSF National Nanomanufacturing Network (NSF 2005-2016), [http://www.internano.org/content/newsletter-bounces@nanomanufacturing.org](http://www.internano.org/content/newsletter-bounces@nanomanufacturing.org)
Sustainable development: advances last ten years (1)

- Local initiatives are blossoming around the world; Non-profits specialize in helping communities achieve sustainability (e.g., ICLEI);
  Companies are increasingly implementing and promoting their sustainable practices
- Standards (e.g., ISO – 14000 series), certifications (e.g., LEED for buildings), and labeling (e.g., Energy Star) are proliferating
- Incipient programs to address long-term challenges
Sustainable development advances in the last ten years (2)

- Nanotechnology has provided solutions for about half of the new projects on energy conversion, energy storage, and carbon encapsulation in the last decade.
- Entirely new families have been discovered of nanostructured and porous materials with very high surface areas, including metal organic frameworks, covalent organic frameworks, and zeolite imidazolate frameworks, for improved hydrogen storage and CO₂ separations.
- A broad range of polymeric and inorganic nanofibers for environmental separations (membrane for water and air filtration) and catalytic treatment have been synthesized.
- Testing the promise of nanomanufacturing for sustainability.
Not fully realized objectives after ten years

- General methods for “materials by design” and composite materials (because the direct TMS and measuring techniques methods were not ready)

- **Sustainable development projects**: energy received momentum only after 5 years, nanotechnology for water filtration and desalination only limited; delay on nanotechnology for climate research (because of insufficient support from beneficiary stakeholders?)

- **Public awareness remains low**, at about 30%. Challenge for public participation
Convergence of Knowledge, Technology, and Society:
Beyond Convergence of Nano-Bio-Info-Cognitive Technologies

www.wtec.org/NBIC2-Report

Five convergence principles for progress applied in five human activity platforms.
Gene sequencing cost after adoption of methods from nanoelectronics

(after NIH/NHGRI, K.A. Wetterstrand, 2013)
Tissue Engineering and NT meets 3-D Printing

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

Convergence of four very different research directions
Example of convergent approach in nano-EHS
(risk estimation, CEINT, Duke University)

- Measurement in prescribed system
- Quantifies a meaningful process for exposure, hazard or both

Nanoparticle Properties
System Properties
Social Properties

Functional Assays

Exposure
Hazard

Biouptake / System Transfer

RISK
Adaptive and integrative risk governance model
(Renn 2015, p. 280, in Convergence of S&T)
Relationship between stakeholder participation and risk categories in risk governance
(Renn 2015, p. 280 in Convergence of S&T)

- **Simple**: Find the most cost-effective way to make the risk acceptable or tolerable.
- **Complexity**: Use experts to find valid, reliable and relevant knowledge about the risk.
- **Uncertainty**: Involve all affected stakeholders to collectively decide the best way forward.
- **Ambiguity**: Include all actors so as to expose, accept, discuss and resolve differences.

As the level of knowledge changes, so also will the type of participation need to change.
World acceptance of nanotechnology

Recognized as an international scientific and technology revolution by industry, economists, politicians, and philosophers (multidisciplinary community of 2M, publ. companies 12K, ~ all universities)

In all large research institutions

Small is not dangerous, it is at the foundation of life!

“We saw the future yesterday”
Several priorities

• **Integration of knowledge at the nanoscale and of nanocomponents in nanosystems.** Ex: Nanomodular systems; Nanoengineering; NBIC systems with emerging nano-bio behavior (hybrid, robot, synthetic)

• **Nanotechnology for increased productivity and sustainability.** Ex: Reducing energy dissipation in nanoelectronics by >100; Water resources; Wood, agriculture and food systems

• **Institutionalize nanotechnology:** Ex: Create standing organizations and programs for sustained support of future nanotechnology efforts
Related publications

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

2. **NANO1**: “Nanotechnology research directions: Vision for the next decade” (Roco, Williams & Alivisatos, Springer, 316p, 2000)

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)

9. “Long View of Nanotechnology Development: the NNI at 10 Years” (JNR, 2011d)