Nanotechnology-inspired Grand Challenges in the United States

Mike Roco
NSF and NNI

Nanotechnology-inspired grand challenges

✓ S&T breakthroughs, the long-term vision-inspired research, and convergence processes create opportunities for progress

✓ Several U.S. priorities in 2016
  Nanotechnology Signature Initiatives
  Nanotechnology-inspired Brain-like Computing
  Brain Research
  National Strategic Computing Initiative
  Food-Energy-Water Systems
  National Network for Manufacturing Innovation
S&T breakthroughs underpin Grand Challenges
(examples of novel concepts targeted by NNI in 2000 “in 20-30 years”)

- **Library of Congress in a “one cubic cm” memory device:**
  target 30-40 atoms (2000); Realized 12-atom structure (IBM, 2012), DNA structure (Harvard, 2012; in “one cubic mm”). “**Millions times smaller**”

- **Exploit nano-photonics:** change direction and frequency of light (2004, then succession of solutions). “**New phenomena and devices**”

- **Molecular cancer detection and treatment** (first gold-shells, Rice, 2002 - 2016 many other solutions in progress) “**Not possible before**”

- **Quasi-frictionless nanocomponents:** quantum fluctuations between selected material surfaces (first Harvard, 2008). “**Almost frictionless**”

- **Magnetic computing** close to the lowest Landauer fundamental limit of energy dissipation under the laws of thermodynamics (STC Berkeley, 2016). “**Millions times less energy consumption**”
Vision-inspired discovery and inventions are essential for the future of innovation

Modified Stokes diagram

Relevance for the advancement of knowledge

High

Pure Basic Research (Bohr)

Use-inspired Basic Research (Pasteur)

Vision-inspired Basic Research
(added in CKTS, 2013)

Relevance for applications

Low use

Known use

New use

convergence stage / divergence stage / S&T breakthroughs

Empirical, less useful (Merlin)

Pure Applied Research (Edison)

Defining S&T convergence

Convergence is deep integration of knowledge, tools and other relevant areas of human activity that enable each other

- to allow society to answer questions, resolve problems and add-value that isolated capabilities cannot (is goal oriented),

- as well as to create new ideas, competencies, technologies, and products on that basis
  (divergence stage; see ~20 new NNI domains such as: plasmonics, metamaterials, modular DNA NT, nanofluidics, carbon electronics, nano-wood fibers, …)

- changing the system by using six convergence principles

(Ref 5: CKTS Report 2013)
Nanotechnology: from scientific curiosity to immersion in socioeconomic projects

30 year vision to establish nanotechnology:
In 3 stages changing focus and priorities

Three stages of convergence

I. Nanoscale Science, Engineering and Technology
   “Nanotechnology”
   Integrates disciplines and knowledge of matter from the nanoscale

II. Nano-Bio-Info-Cognitive Converging Technologies
    “NBIC”
    Integrates foundational, emerging technologies from basic elements using similar system architectures

III. Convergence of Knowledge, Technology and Society
     “CKTS”
     Integrates the essential platforms of human activity using six convergence principles
     (Ref 5: CKTS Report, 2013)
I. Nanotechnology Convergence leads to R&D programs in 27 agencies


www.nano.gov
National Nanotechnology Initiative, 2016

Nanotechnology Signature Initiatives

Sustainable Nanomanufacturing  www.nano.gov/NSINanomanufacturing

Nanoelectronics for 2020 and Beyond  www.nano.gov/NSINanoelectronics

Water Sustainability through Nanotechnology  www.nano.gov/node/1577

Nanotechnology Knowledge Infrastructure  www.nano.gov/NKIPortal

Nanotechnology for Sensors  www.nano.gov/SensorsNSIPortal

Other considered topics are related to: nanomodular systems, nanomedicine, nanocellulose, nanophotonics, nano for infrastructure, nano-city
United States - Korea collaboration in 2D materials after the 2015 Forum: NSF award supplements ("2-DARE", 2016)

- "Crystalline Atomically Thin Layers for Photonic Applications". Humberto Terrones (RPI) (NSF 1648899/ 1433311)
- "Functionalized Monolayer Heterostructures for Biosensors with Optical Readout". Alan T Johnson, U Penn (NSF 1648869/ 1542879)
- "Scalable Growth and Fabrication of Anti-Ambipolar Heterojunction Devices". Lincoln Lauhon, NWU U. (NSF – 1648954/ 1542879)
- "Few-Layer and Thin-Film Black Phosphorus for Photonic Applications". Fegnian Xia, Yale U. (NSF – 1644859/ 1542815)
- "Phosphorene, an Unexplored 2D High-mobility Semiconductor". Peide Ye, Purdue U. (NSF 1644785/ 1433459)
<table>
<thead>
<tr>
<th>NSF award</th>
<th>PI Last Name</th>
<th>Title</th>
<th>Institute</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>
<tr>
<td>NSF award</td>
<td>PI Last Name</td>
<td>Title</td>
<td>Institute</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------</td>
<td>----------------------------------------------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>1542883</td>
<td>Pop</td>
<td>Energy Efficient Electronics with Atomic Layers (E3AL)</td>
<td>Stanford U</td>
</tr>
<tr>
<td>1542741</td>
<td>Zhang</td>
<td>Valley Optoelectronics with Atomically Thin MX2</td>
<td>UC Berkeley</td>
</tr>
<tr>
<td>1542807</td>
<td>Kim</td>
<td>Quantum optoelectronics, magnetoelectronics and plasmonics in 2-dimension materials heterostructures</td>
<td>Harvard U</td>
</tr>
<tr>
<td>1542864</td>
<td>Salehi-Khojin</td>
<td>Thermal Transport in 2D Materials for Next Generation Nanoelectronics-From Fundamentals to Devices</td>
<td>U of Illinois Chicago</td>
</tr>
<tr>
<td>1542863</td>
<td>Menon</td>
<td>Excitonics and Polaritonics using 2D materials (ExPo2D)</td>
<td>CUNY City College</td>
</tr>
<tr>
<td>1542815</td>
<td>Xia</td>
<td>Few-layer and Thin-film Black Phosphorus for Photonic Applications</td>
<td>Yale U</td>
</tr>
<tr>
<td>1542707</td>
<td>Drndic</td>
<td>Two-dimensional nanopores with electro-optical control for next generation biotechnological applications</td>
<td>U of Pennsylvania</td>
</tr>
<tr>
<td>1542879</td>
<td>Johnson</td>
<td>Functionalized Monolayer Heterostructures for Biosensors with Optical Readout</td>
<td>U of Pennsylvania</td>
</tr>
<tr>
<td>1542747</td>
<td>Li</td>
<td>From Atoms to Devices: Pathways to Atomic Layer Optoelectronics via Multi-Scale Imaging and Spectroscopy</td>
<td>U of Texas Austin</td>
</tr>
<tr>
<td>1542798</td>
<td>Wu</td>
<td>Engineering novel topological interface states in 2D chalcogenide heterostructures</td>
<td>Rutgers U New Brunswick</td>
</tr>
</tbody>
</table>
National Science Foundation

National Nanotechnology Coordinated Infrastructure (NNCI)

http://www.nncli.net/; 2015-2025; Coordinating office at GA Tech

University of Washington with Oregon State University
Montana State University with Carlton College
University of Minnesota Twin Cities with North Dakota State University
Northwestern University with University of Chicago
Cornell University
University of Pennsylvania with Community College of Philadelphia
Virginia Polytechnic Institute and State University
North Carolina State University with Duke University and University of North Carolina-Chapel Hill

Stanford University
University of California, San Diego
Arizona State University with Maricopa County Community College District and Science Foundation Arizona

$81 Million
16 National Sites
5 Years of Funding

MC. Roco, Sept 26 2016
Water Sustainability through Nanotechnology
Nanoscale solutions for a global-scale challenge

**Research thrusts**

- **Increase water availability using NT**
  (ex: double the throughput systems within 5 years)

- **Improve the efficiency of water and use with NT**
  (Ex: Develop within 5 years nanotechnology-enabled coatings that reduce by 50% the amount of energy)

- **Enable the next-generation water monitoring systems with nanotechnology**
  (Ex: continuous, real-time measurement of water quality that are more sensitive, more reliable, easier to use sensors)
Water deficit worldwide

WATER STRESS BY COUNTRY

<table>
<thead>
<tr>
<th>Ratio of withdrawals to supply</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low stress (&lt; 10%)</td>
<td></td>
</tr>
<tr>
<td>Low to medium stress (10-20%)</td>
<td></td>
</tr>
<tr>
<td>Medium to high stress (20-40%)</td>
<td></td>
</tr>
<tr>
<td>High stress (40-80%)</td>
<td></td>
</tr>
<tr>
<td>Extremely high stress (&gt; 80%)</td>
<td></td>
</tr>
</tbody>
</table>

This map shows the average exposure of water users in each country to water stress, the ratio of total withdrawals to total renewable supply in a given area. A higher percentage means more water users are competing for limited supplies. Source: WRI Aqueduct, Gassert et al. 2013

“Brain like computing” (Nano-inspired Grand Challenge) combining National Nanotechnology Initiative (NNI), National Strategic Computing Initiative (NSCI) & BRAIN Initiative

- **Purpose:** “Create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain.”

Also: pattern recognition, human like simultaneous perception of information from various sources including the five senses,
Intelligent cognitive assistants (ICA)

May 2016 workshop goals (planned by NSF, SIA, SRC)

• Systems that are highly useful to humans, specifically on the topic of Harnessing Machine Intelligence to Augment Human Cognition and Human Problem-Solving Capabilities – e.g., research that drives towards “Intelligent Cognitive Assistants”

• Explore scenarios for developing the novel architectures, concepts and algorithms which will be required for “assistants” to energy-efficient perceive, compute, and interact, and in this way to provide actionable information and informed advice to their human users.

• Establish a long-term vision (10-20 years), from “knowledge and data” in 2015 to “intelligence and cognition” in 2030
Nanoelectronics Research Initiative
Funded Universities (SIA, NSF, NIST)

- UC Los Angeles
- UC Berkeley
- UC Irvine
- UC Riverside
- UC Santa Barbara
- U. Nebraska-Lincoln
- U. Wisconsin-Madison
- SUNY-Albany
- Purdue
- MIT
- Columbia
- Harvard
- GI
- U. Virginia
- NCSU
- Virginia Nanoelectronics Center (ViNC)

Partnerships NSF, NIST, SIA, SRC with > 30 Universities in 20 States (2014 - )

Awards made in 2011 for collaborative group research (NNI Signature Initiative)

- SPIN
- GRAPHENE
- TUNNEL FET
- SPIN LOGIC
- MC Roco, Sept 26 2016
Key components of the Nanotechnology Knowledge Infrastructure

- GitHub
- MaterialsHUB
- Summer School for Integrated Computational Materials Education
- The Materials Project
- KIM
- LAMMPS
- Interatomic Potentials Repository Project
- XSEDE
- caNanoLab
- NANO\textsc{m}ATERIAL\textsc{r}EGISTRY
- GoodNanoGuide

- Supported by NIH, NIOSH, NIST, NSF, ONR, DOE

http://nanoinformatics.org/2015/agenda/
Network for Computational Nanotechnology (NCN) nanoHUB.org

(a) - Red circles designate visitors viewing lectures, tutorials, or homework assignments. Yellow dots are users of simulation. Green dots indicate > 1,500 scientific publications citing nanoHUB;
(b) - nanoHUB usage in 2015
   172 countries
   Over 3,00 authors collaborating in research
   Over 13,000 users running interactive simulations
   Over 1.4 million visitors using lectures and tutorials
(c) - a typical nanoHUB interactive session
UC CEIN Predictive Toxicological Platforms (Andre Nel, 2016)

Nanomaterial libraries

Compositions
- metals, metal oxides, CNTs, graphene, silica, quantum dots, etc

Combinatorial properties
- size, shape, aspect ratio, dissolution, band gap, charge, functionalities, coatings etc

New Commercial nanoproducts
- profiled against a grid of library materials or data repository

High throughput screening
(adverse outcome pathway or AOP based)

Computational ranking/modeling/predictions

Cells, bacteria, yeasts, zebrafish embryos

In vivo hazard ranking and prediction testing

Tiered hazard/risk assessment and exposure-based decision analysis for:
- Safe implementation
- Regulatory decisions
- Reduced animal use
- Reduced Tier 3 testing
- Establishing exposure limits
- Structure-activity analysis
- Safer design

Tier 1
Compare
Rank
Prioritize

Tier 2
Select animal & organism testing
(short-terms protocols that reflect the In vitro AOP)

Rapid
High volume
Converging foundational technologies (NBIC) leads to

II. U.S. emerging S&T initiatives

Ref 9: Roco, “NBIC”, in Handbook of S&T Convergence, 2015
Networking and Information Technology R&D (NITRD) program with 12 research priorities

https://www.nitrd.gov/

- Big Data (BD)
- Cyber Physical Systems (CPS)
- Cyber Security and Information Assurance (CSIA)
- Health Information Technology Research and Development (Health IT R&D)
- Human Computer Interaction and Information Management (HCI&IM)
- High Confidence Software and Systems (HCSS)
- High End Computing (HEC)
- Large Scale Networking (LSN)
- Software Design and Productivity (SDP)
- Social, Econ., and Workforce Impl. of IT and IT Workforce Develop. (SEW)
- Video and Image Analytics (VIA)
- Wireless Spectrum Research and Development (WSRD)
Convergent Computing Trends

Desire for Convergence

Internet-Scale Computing

Computational Intensity

Data Intensity

Sophisticated data analysis
E.g., deep learning

Mixing simulation with real-world data

Real-time analysis of simulation results

Modeling & Simulation-Driven Science & Engineering

Desire for Convergence

Sophisticated data analysis
E.g., deep learning

Mixing simulation with real-world data

Real-time analysis of simulation results

Modeling & Simulation-Driven Science & Engineering
Aspirations for convergence

- "Big Data" Data Analytics
- Data Intensity
- State of the Art
- Goal of Initiative
- Large Scale Data Driven Modeling And Simulation
- Computational Intensity
- High-Performance Modeling And Simulation
National Strategic Computing Initiative NSCI

Objectives

1. Accelerate delivery of a capable exascale computing system (hardware, software) to deliver approximately 100X the performance of current 10PF systems across a range of applications

2. Increase coherence between technology base used for modeling and simulation and that used for data analytic computing.

3. Establish, over the next 15 years, a viable path forward for future HPC systems in the post Moore’s Law ...

4. Increase the capacity and capability of an enduring national HPC ecosystem, employing ... networking, workflow, downward scaling, foundational algorithms and software, and workforce development.

5. Develop an enduring public-private partnership to assure that the benefits .. are transferred to the U.S. commercial, government, and academic sectors
Rebooting the IT Revolution
2015 SIA & SRC workshop report sponsored by NSF, NIST and DARPA

**Recommendations (with research initiatives in 2016):**

- **Insight technologies ecosystem.** Insight computing requires research in machine learning, data analytics, neuromorphic computing, quantum communication, new approaches for user–machine interfaces, as well as increase computer capacity.

- Data-producing systems increasingly will involve small, low-power sensors and actuators embedded in the physical world—a network of sensor-enabled cyber-physical systems within IoT

- **Energy-efficient sensing and computing**

- **Real-time communication ecosystem**

- **Brain-Inspired Computing**

- **Multi-level and scalable security; cybersecurity in manufacturing**

- **Next-generation manufacturing paradigm**

MC. Roco, Sept 26 2016
Disruptive system architectures, circuit microarchitectures, and attendant interconnect technology aimed at achieving the highest level of computational energy efficiency for general purpose computing systems.

Revolutionary device concepts and associated circuits and architectures that will greatly extend the practical engineering limits of energy efficient computation.

Topics aligned with:
- Nanotechnology-inspired Grand Challenge for Future Computing, OSTP 2015
- National Strategic Computing Initiative (NSCI) (OSTP, 2015)
Quantum information systems

- US Interagency Program: **Quantum Information Systems**; in NSF six divisions from MPS, ENG and CISE contribute


- Research activities in industry (ex. at IBM Watson Lab. and government laboratories (ex. at Sandia National Laboratory)

- STC on **Integrated Quantum Materials**, Harvard U.; and STC on **Energy Efficient Electronics Science**, UC Berkeley

Note: “**Quantum Manifesto**” in EU, an initiative by European science, industry and policy communities, Oct. 2015 call, for a European strategy
• Federal agencies: NSF, NIH, DARPA, FDA
• Private partners: Allen Institute for Brain Science, Howard Hughes Medical Institute, Kavli Foundation
New Tools for Understanding the BRAIN

Optogenetic Manipulation

High Resolution Imaging

New concepts Computation

New system architectures

4D Analysis
Example of inter-field

Human / co-robot interaction (National Robotics Initiative)

- Cognition: Learning, Knowledge representation, Planning, Navigation
  - Networked Multi-Agent
- Intelligent Co-Robot
- Sensors & perception
- Human-robot interaction: physical & social, language & communication
- Manipulation: Haptics, Tactile
- Cognitive prosthetics
- Smart structures and environments

- Mobility: legged, wheeled, aquatic, aerial
- Exo-skeleton augmentation
- Soft structures
III. Convergence of Knowledge, Technology and Society

For societal benefit, human development

- Foundational tools – NBIC+
- Earth scale platform
- Human scale & quality of life
- Societal scale platform

System feedback

Innovation circuit

Human activity system
The conductor suggests societal governance of K&T converging platforms for societal benefit.

Ref: 5, “Convergence of knowledge, technology and society: Beyond NBIC”

Societal values and needs

Innovative & responsible governance- System behavior
Convergence of Knowledge and Technology (CKTS) leads to **U.S. global society-oriented initiatives**

- SunShot GC (DOE..)
- Climate Action Plan
- Global Change Research Program (GlobalChange.gov) (w/ program office)
- Asteroid GC (NASA..)
- Space Station (NASA..)
- Strategy for Arctic Region
- I-Corps
- Smart Communities
- Innovation
- Societal
- Earth
- Human
- NBIC+
- STEAM Education Initiative (NSF, DoEd)
- The National Network for Manufacturing Innovation (NNMI) (http://www.manufacturing.gov/nnmi) (with program office)

See Ref 9: “Principles and methods that facilitate convergence”, Handbook of S&T Convergence, 2015
The National Network for Manufacturing Innovation (NNMI) - 7 year plans -

Experiment in *ecosystem establishment* in “valley of death”
All the institutes will deal with nanotechnology to some extent
Current list - **10 institutes** (http://manufacturing.gov/):

- National Additive Manufacturing Innovation Institute (DoD/DOE) FY12
- Digital Manufacturing and Design Innovation (DoD) FY14
- Lightweight and Modern Metals Manufacturing (DoD) FY14
- Next Generation Power Electronics Manufacturing (DOE) FY14
- Clean Energy Manufacturing Innovation Institute for Composites Materials and Structures (DOE) FY15
- Photonics (DoD) FY15
- Hybrid Flexible Electronics (DoD) FY15
- Revolutionary Fibers and Textiles (DoD) FY16
- Two open competition centers (NIST) FY16-17
National Network of Manufacturing Institutes

- Network of institutes focused on reducing cost and risk of commercializing transformative new technologies to address relevant manufacturing challenges on production-level scale
- President has asked Congress to authorize one-time $1 billion investment—to be matched by private and other non-federal funds—to create initial network of up to 15 IMIs.
Other NSF specific initiative in 2016-

<table>
<thead>
<tr>
<th>Innovations at the Nexus of Food, Energy, and Water Systems</th>
<th>Understanding the Brain, as a part of BRAIN Initiative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk and Resilience</td>
<td>Broadening Participation</td>
</tr>
<tr>
<td>Clean Energy Technology</td>
<td></td>
</tr>
<tr>
<td>Cyber-Enabled Materials, Manufacturing, and Smart Systems</td>
<td>NSF INCLUDES: Inclusion across the Nation of Communities of Learners that have been Underrepresented for Diversity in Engineering and Science</td>
</tr>
<tr>
<td>- Advanced Manufacturing</td>
<td></td>
</tr>
<tr>
<td>Smart and Connected Communities</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Innovation Corps (I-Corps)</td>
</tr>
</tbody>
</table>

NSF INCLUDES: Inclusion across the Nation of Communities of Learners that have been Underrepresented for Diversity in Engineering and Science
Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP)

- Improves the resilience, interoperation, performance, and readiness of critical infrastructure
  - Advances knowledge of risk assessment and predictability
  - Supports novel tools, technologies, and engineered systems solutions for increased resilience

- CRISP initiative at NSF (ENG, CISE, and SBE)
  - Enhances understanding and design of interdependent critical infrastructure systems and processes that provide essential goods and services, both under normal conditions and despite disruptions and failures from any cause

MC. Roco, Sept 26 2016
Convergence-Divergence process (upstream): “Germination”
Germination of Research Ideas for Large Opportunities and Critical Societal Needs

To design learning frameworks, platforms, and/or environments to enable participants to conceive research ideas and questions with potentially transformative outcomes

NSF 16-028 Dear Colleague Letter for proposals

Proposers were asked to focus on the development of key skills and mindsets that will increase the capacity of participants to Identify big opportunities, Think creatively, Explore novel research formulations, Take intellectual risk Assess (a) Impact on participants (b) potential for scalability and adaptability
Convergence-Divergence process (downstream): Innovation Corps (I-Corps™)

- Provides experiential entrepreneurial education to capitalize on NSF investments in basic research

- Supports I-Corps™ Teams, Sites, and Nodes to build, utilize, and sustain a national innovation ecosystem

- Plans approximately 230 new I-Corps™ Teams, up to 71 active Sites, and up to 9 active Nodes in FY 2017

- Scaling via partnerships and networks: Federal agencies, states, private sector; and National Innovation Network

MC. Roco, Sept 26 2016
Smart and Connected Communities
(OSTP and NSF)

- Advances the integration of networked computing systems, physical devices, data sources, and infrastructure to allow communities to surmount deeply interlocking physical, social, economic, and infrastructural challenges

- FY 2016 DCL on Smart and Connected Communities
  - ENG, CISE, EHR, GEO, and SBE

- Dec. 2015 Workshop on Smart Cities, Arlington, VA

- Jan. 2016 Smart and Connected Communities: Planning Workshop, Seattle, WA

Searched by keywords in the title/abstract/claims (update Encyclopedia Nanoscience, Roco, 2016)

- Top 20 Journals' Nano Paper Percentage
- 3 Selected Journals' Nano Paper Percentage
- Title-claim Search's Nano Patent Percentage
- NSF Nano New Award Percentage

- NSE Awards started to use Combined Keywords from 2011
- For Top 20 journals, 3 selected journals, title-claim search of nano patents, Combined keywords are used since 2014.

- 2015 NSF grants ~ 14%
- 2015 Top 20 nano J. ~ 12%
- 2015 All journals ~ 5.2%
- 2015 USPTO patents ~ 2.5%

Est. Market / US GDP:
- 2014 ~ 2%
- 2016 ~ 3%
- 2022 ~ 10% (if 25% market growth rate)
Global revenue from nano-enabled products by sector

(Lux Research, updated in January 2016) (US / World ~ 32%)

<table>
<thead>
<tr>
<th>Sector</th>
<th>2012 (survey)</th>
<th>2013 (survey)</th>
<th>2014 (survey)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building materials</td>
<td>$28.837</td>
<td>$44.564</td>
<td>$66.891</td>
</tr>
<tr>
<td>Materials &amp; manufacturing</td>
<td>$457.936</td>
<td>$625.508</td>
<td>$826.704</td>
</tr>
<tr>
<td>Electronics &amp; IT</td>
<td>$265.306</td>
<td>$377.631</td>
<td>$527.137</td>
</tr>
<tr>
<td>Healthcare &amp; life sciences</td>
<td>$74.742</td>
<td>$103,350</td>
<td>$139,597</td>
</tr>
<tr>
<td>Energy &amp; Environment</td>
<td>$25,668</td>
<td>$38,478</td>
<td>$55,737</td>
</tr>
<tr>
<td><strong>Total (world)</strong></td>
<td><strong>$853</strong></td>
<td><strong>$1,190</strong></td>
<td><strong>$1,616</strong></td>
</tr>
<tr>
<td><strong>Annual Increase Rate (%)</strong></td>
<td></td>
<td><strong>40%</strong></td>
<td><strong>36%</strong></td>
</tr>
</tbody>
</table>

MC. Roco, Sept 26 2016
Nanotechnology-inspired Grand Challenges: Related publications

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


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

8. “Principles and methods that facilitate convergence” (Roco, Springer Reference, Handbook of Science and Technology Convergence, 2015)


(4 reports with R&D recommendations for 2020)