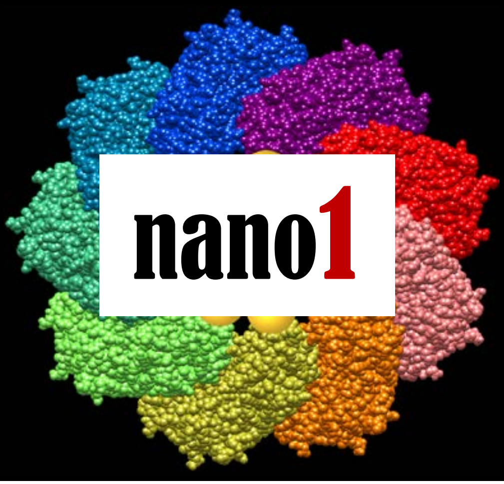
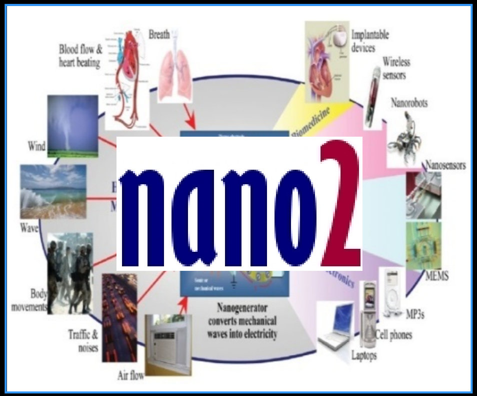
2000



2010



2020

2030

Nanotechnology Research Trends in the U.S.

Mihail C. Roco

National Science Foundation and National Nanotechnology Initiative

Korea-US Nano Forum, Seoul, September 29, 2014

Topics

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

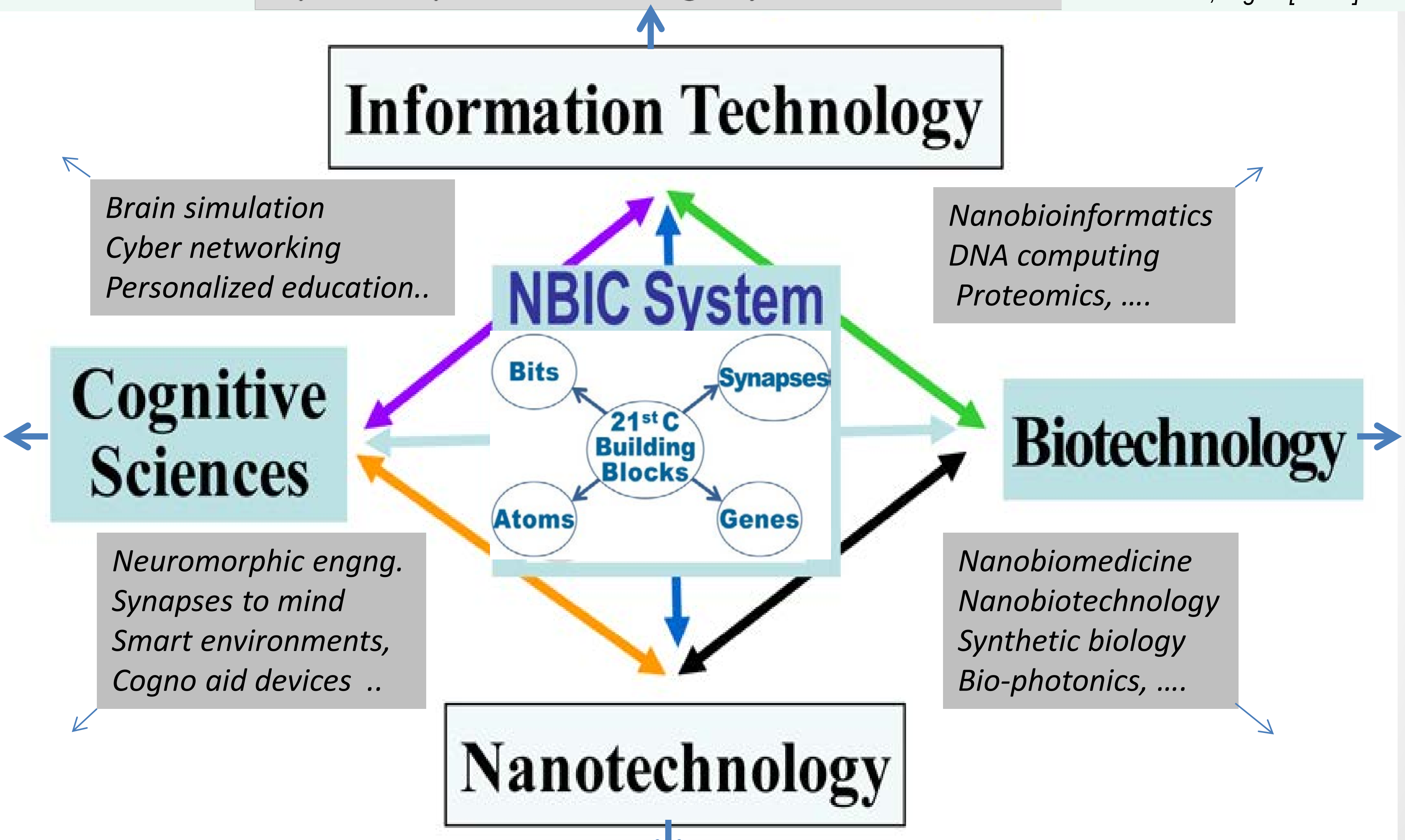
Current trends

- 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, .. .

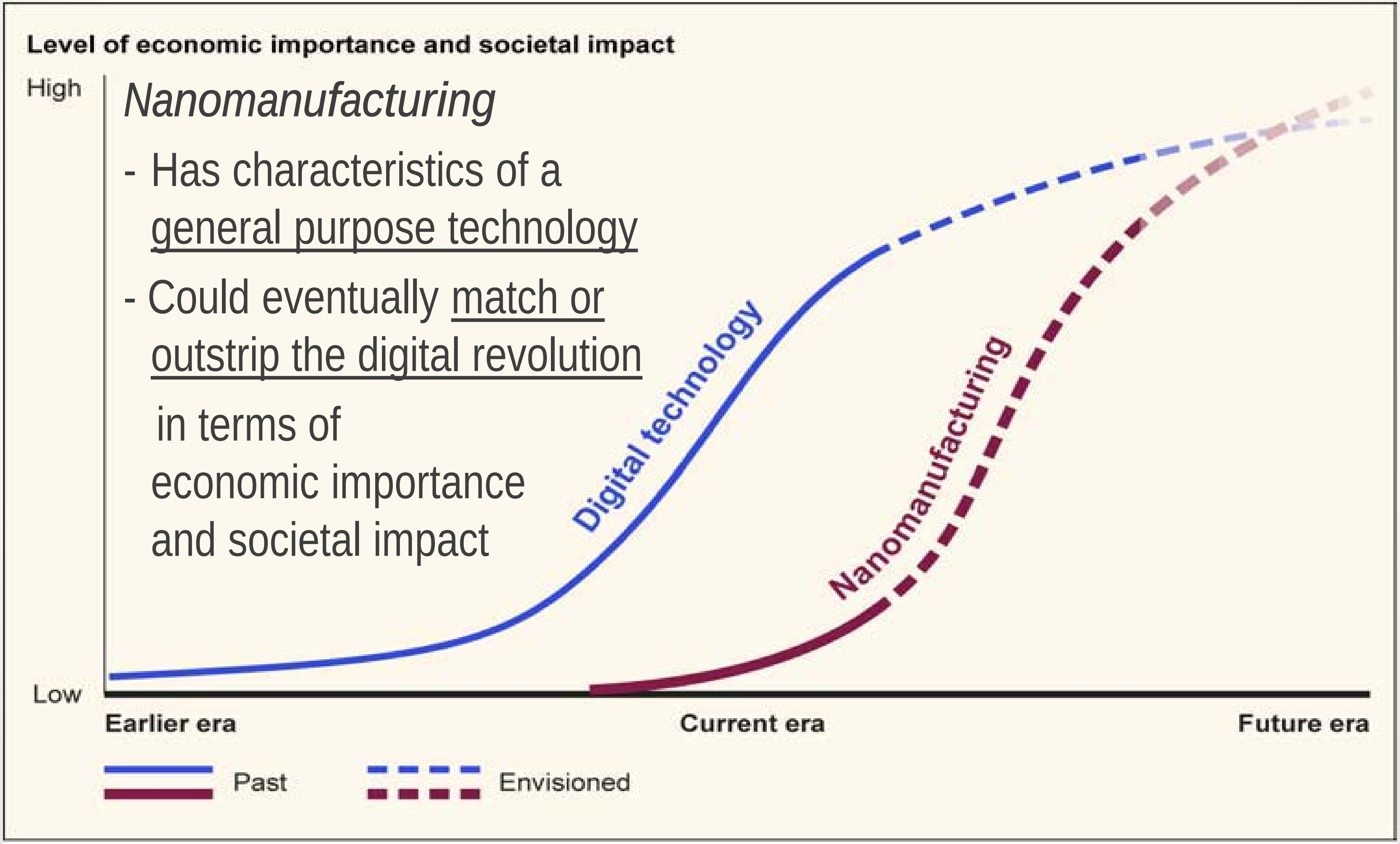
Roco and Bainbridge, 2013 , Fig 2 [Ref 1]



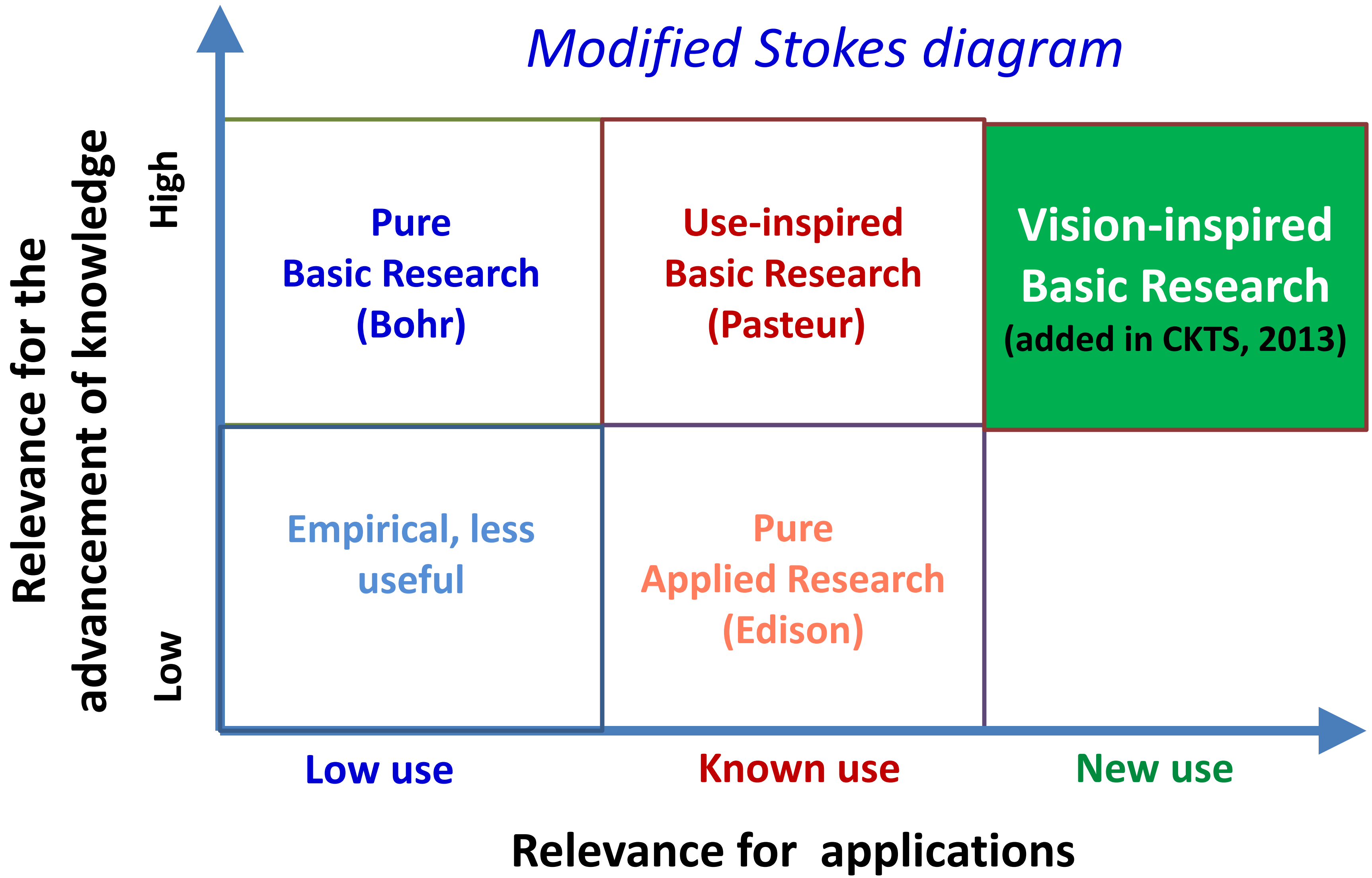
Nanotechnology Spin-offs : Nanophotonics, plasmonics, materials genome, mesoscale S&E, metamaterials, nanofluidics, carbon electronics, nanosustainability, wood fibers, DNA NT, ..

Conceptualization of "Nanomanufacturing" and "Digital Technology" megatrends

(**GAO-14-181SP Forum on Nanomanufacturing**, Report to Congress, 2014, Fig. 3)



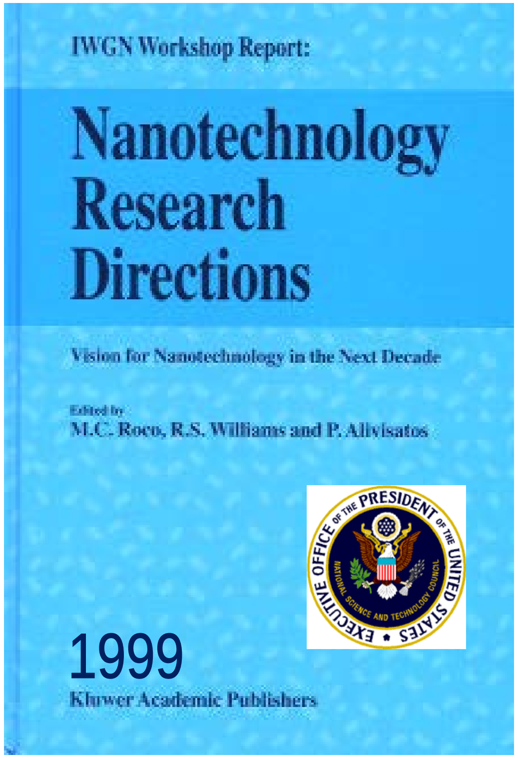
Vision inspired research is essential for the long-term view of nanotechnology



Roco and Bainbridge, 2013 , Fig 9 [1]

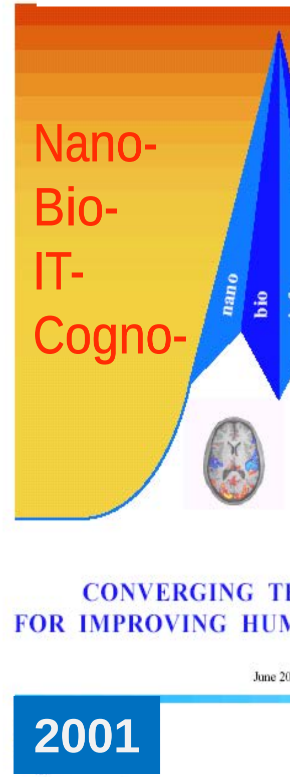
Nanotechnology: from scientific curiosity to immersion in socioeconomic projects

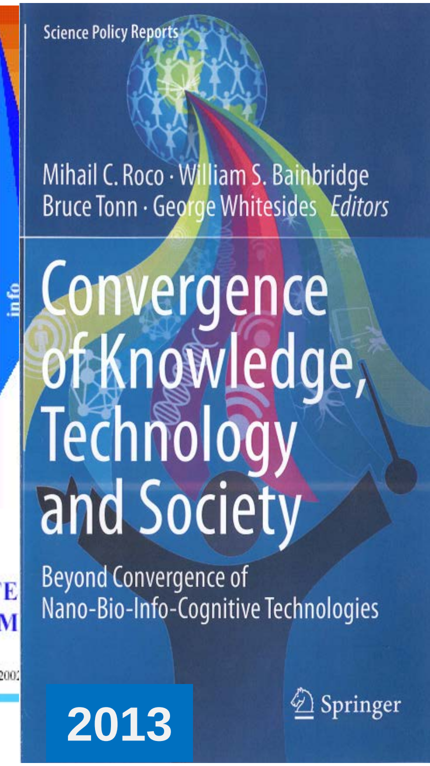
nano1 (2001-2010)



nano2 (2011-2020)

NBIC1&2 (2011-2030)





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)

FIVE GENERATIONS NANOPRODUCTS

2030

DIVERGENCE

New convergence platforms & economy immersion

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

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

5. NBIC Technologies Platforms

NS&E integration for general purpose technology

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

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

4. Molecular Nanosystems

3. Nanosystems

CONVERGENCE

Foundational interdisciplinary research at nanoscale

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

Create passive and active nanocomponents
by semi-empirical design

2. Active Nanostructures

1. Passive Nanostructures

2000

MC Roco, Sept 29 2014

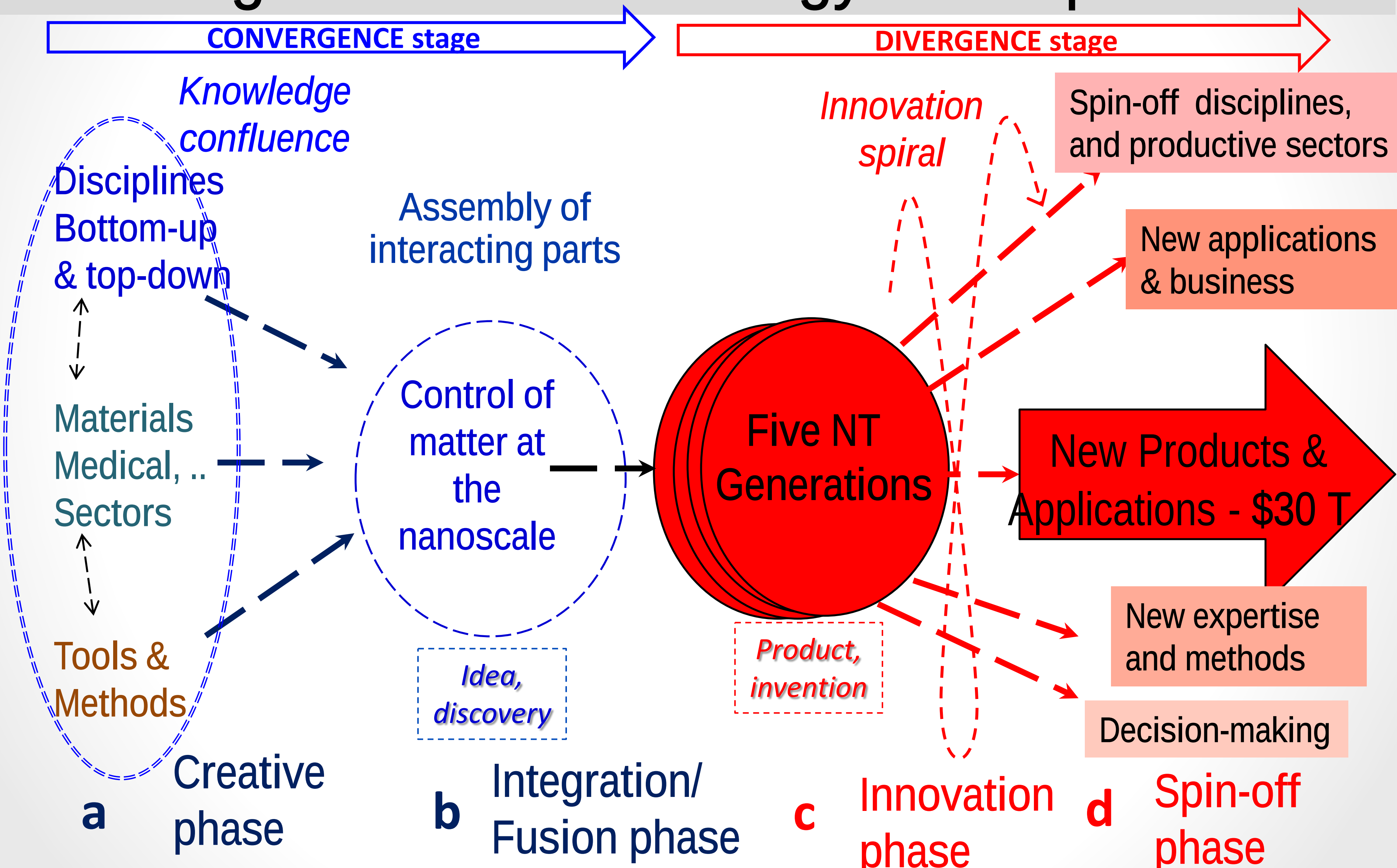
National Nanotechnology Initiative

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."

DOC/NIST
DOE
HHS/NIH
OSTP
OMB
NSF
DOD
HHS/FDA
NASA
HHS/CDC/ NIOSH
DOS
DOTr
DOT
IC/DNI
DOJ
DOC/EDA
DOC/BIS
DHS
CPSC
ITC
DOEd
DOL
DOI/ USGS
DOC/ USPTO
NRC
EPA
USDA/FS
USDA/NIFA
USDA/ARS

2000-2030 Convergence-Divergence Cycle for global nanotechnology development



Based on Roco and Bainbridge, 2013 ,Fig. 8 [1]

2010-2013 (data from Lux Research world industry survey, Jan 2014)

Global and US revenues from Nano-enabled products

(All budgets in $ billion)	2010	2011	2012	2013	2010-2013
Total world revenues	*339* *(10 yr ~ 25%)*	*514*	*731*	***1,014***	+ *676*
US	109.8 (10 yr ~ 24%)	170.0	235.6	**318.1**	+ 208
World annual increase	10 yr ~ 25%	52%	42%	39%	**44%**
US annual increase	10 yr ~ 24%	55%	39%	35%	**43%**
US / World	32.4% 10 yr ~ 35%	33%	32%	31%	**32%**

MC Roco, Sept 29 2014

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

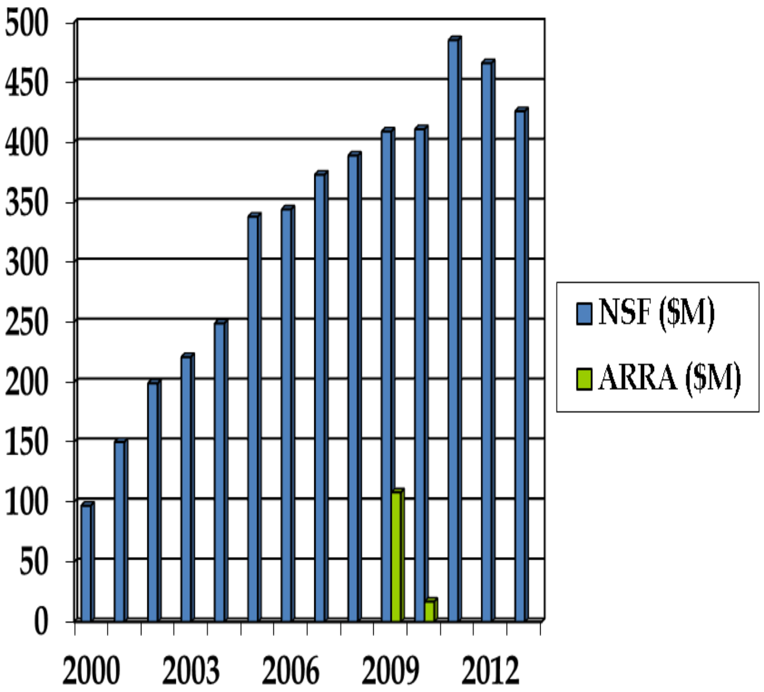
2001-
2014

NSF – discovery, innovation and education in Nanoscale Science and Engineering (NSE)

www.nsf.gov/nano , www.nano.gov

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)

Nanotechnology Signature Initiatives

National Nanotechnology Initiative (NNI), 2011-2014 (www.nano.gov)

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

  - Scalable Nanomanufacturing (NSF, 2011-2015)

  - 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

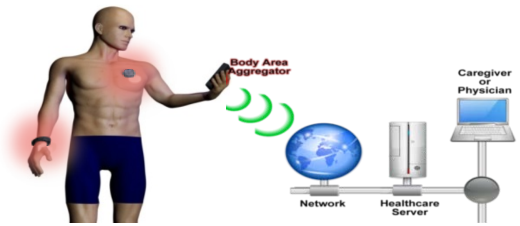
National Nanomanufacturing Network (2006-)
Its core: Four Nanomanufacturing NSECs

- Center for Hierarchical Manufacturing (CHM) *Video*
  - 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*

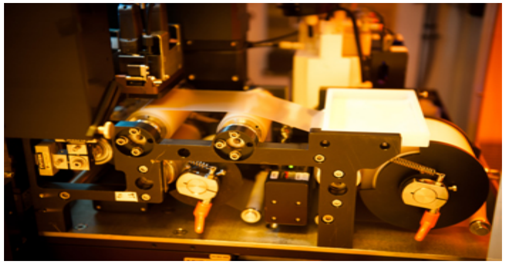
Nanosystems Engineering Research Centers

Three NSF awards of $55.5 million (2012-2017)

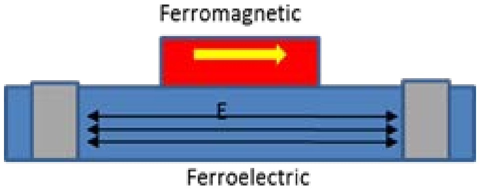
- **Advanced Self-Powered Systems of Integrated Sensors and Technology**, North Carolina State University: self-powered wearable systems that simultaneously monitor a person's environment and health



- **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.

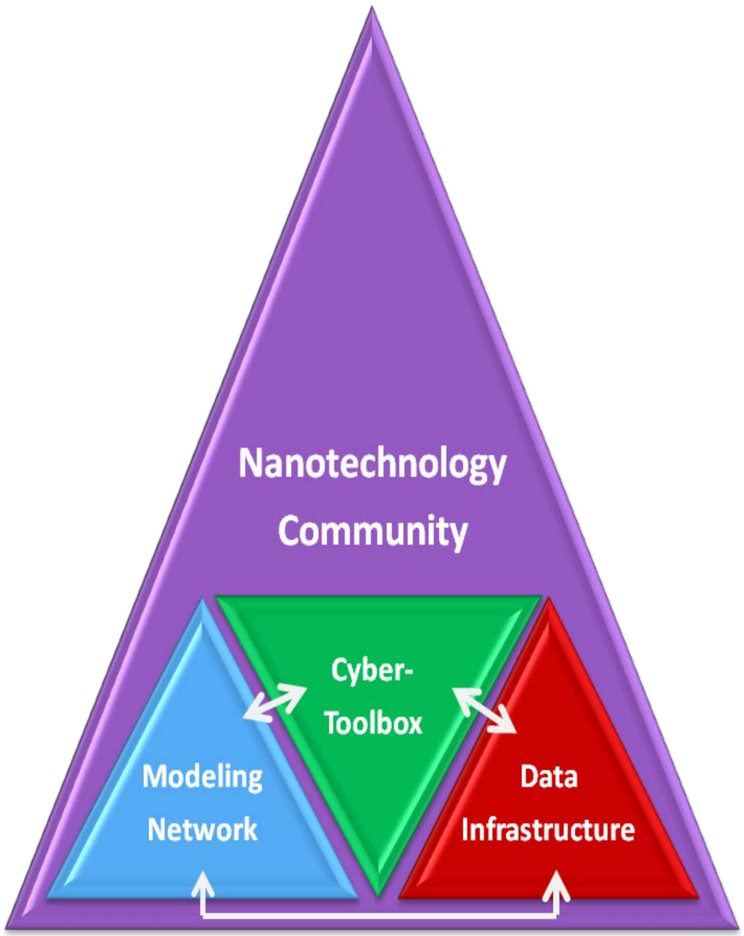


Opportunities to advance nano-informatics

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:

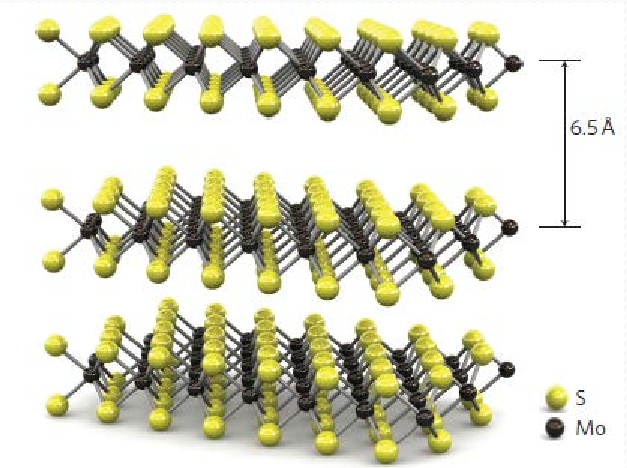
- for design,
- manufacturing,
- nano-EHS, ...



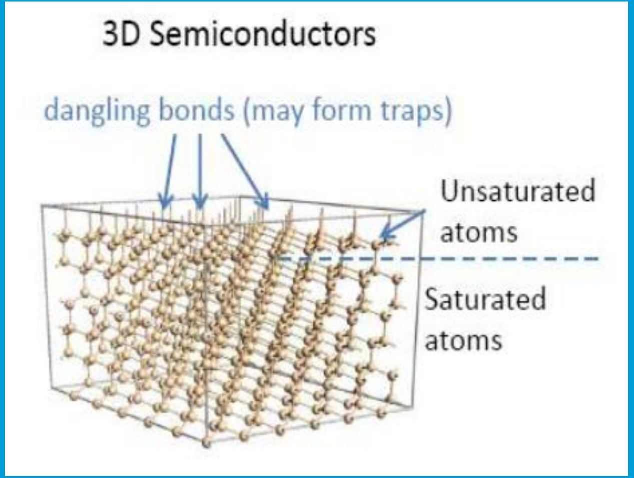
Nanocomposite 2D materials beyond graphene

- 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



Scaled 3D

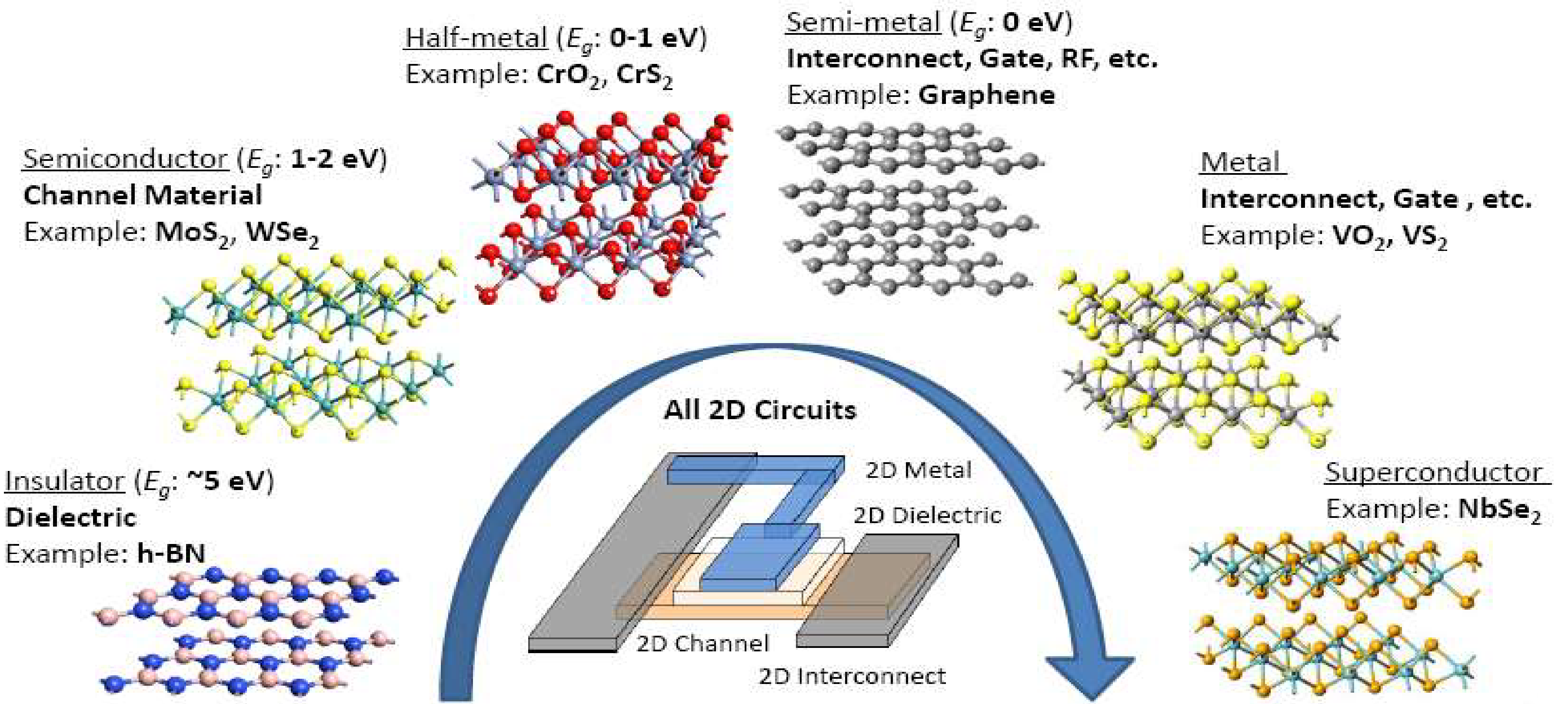


Modular Nanosystems

Example: using 2D electronic materials

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

Graphene Family (C, Si, BN)
MX_2 (TMD) Family (>88 members)



Courtesy Kaustav Banerji (UCSB)

2014 NSF Awards: Two-dimensional atomic tick materials

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

Convergence of Knowledge, Technology, and Society:

Beyond Convergence of Nano-Bio-Info-Cognitive Techologies

www.wtec.org/NBIC2-Report

Five convergence principles for progress applied in five human activity platforms.

Tissue Engineering meets 3-D Printing

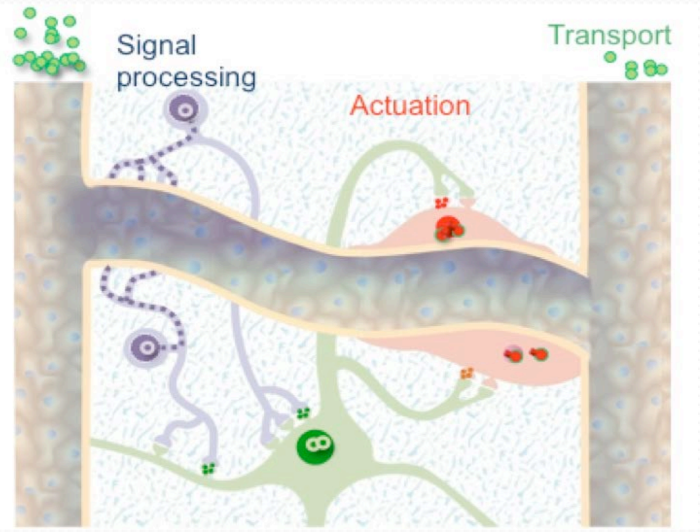
- 3D printing technology
- Tissue engineering
- Nanotechnology
- Additive manufacturing enables printing of scaffolds with nanoscale precision for tissue engineering

Coincidental convergence of four very different research directions

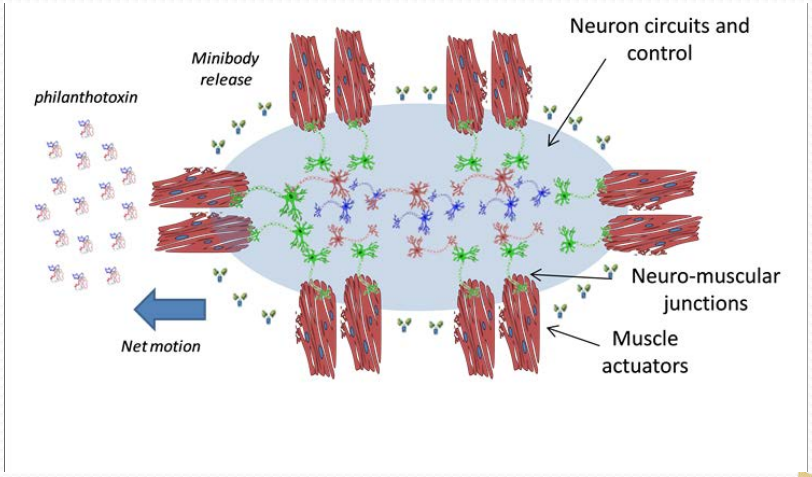
Novogen MMX Bipprinter
Credit: Organovo, Inc.

Emerging Behaviors in Integrated Cellular Systems (STC)

- building living, multi-cellular machines -



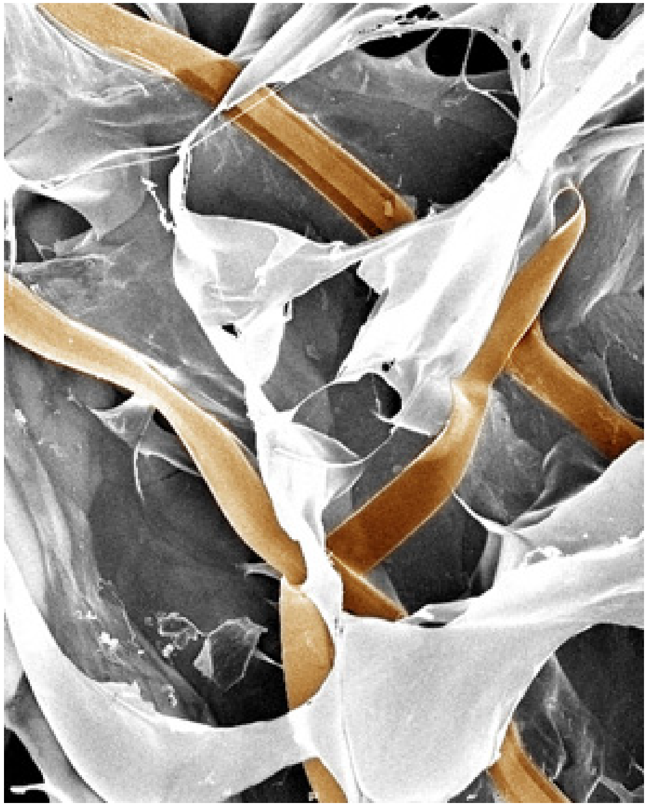
Develop experimental and computational tools for understanding, and controlling the complex functional behaviors of <u>interacting cell clusters or biological machines</u>



<u>Understand fundamental cellular behaviors</u> 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



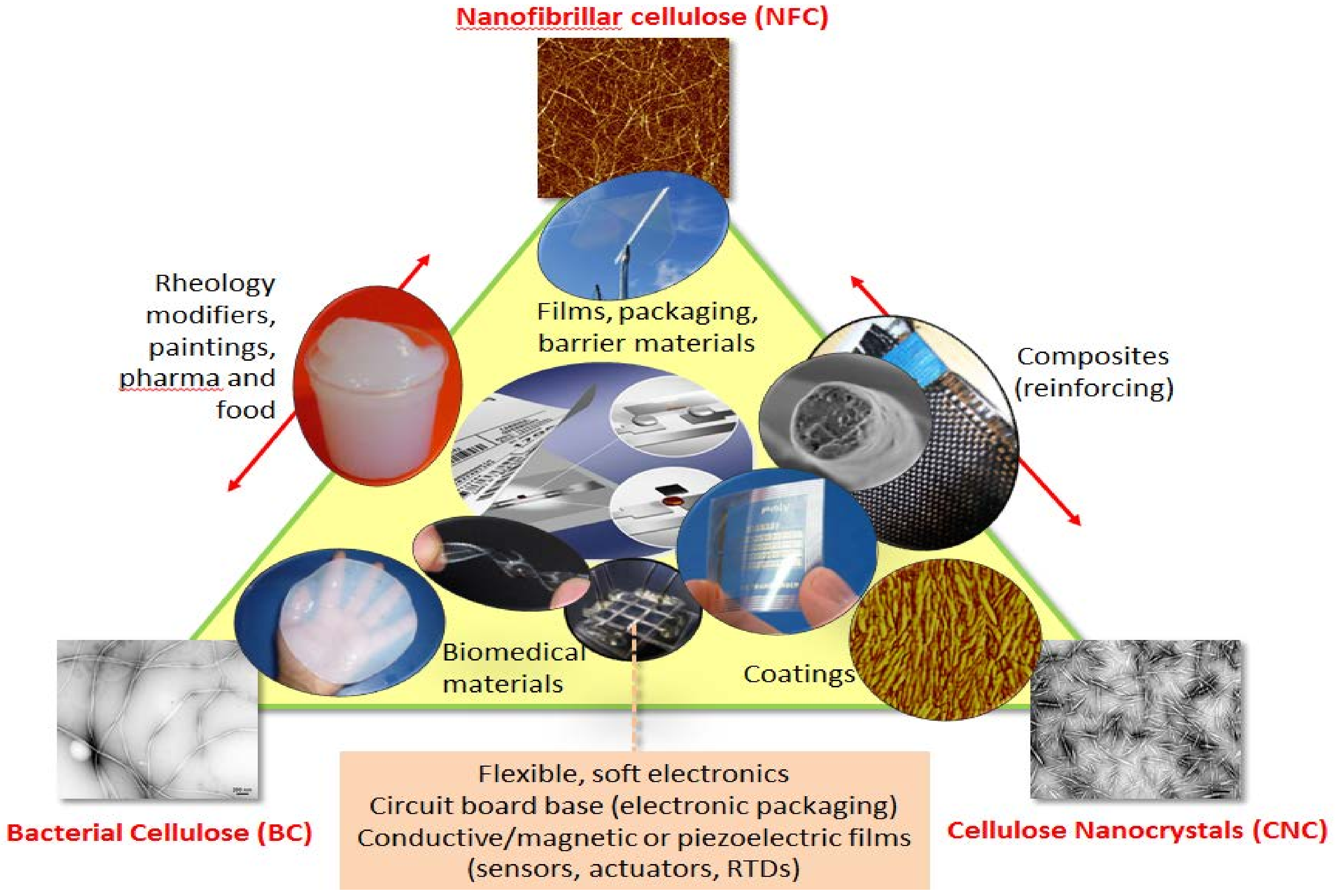
SEM images of a mesh nanoES/alginate scaffold, top (I) and side (II) views. The epoxy ribbons from nanoES are false-colored in brown for clarity

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)

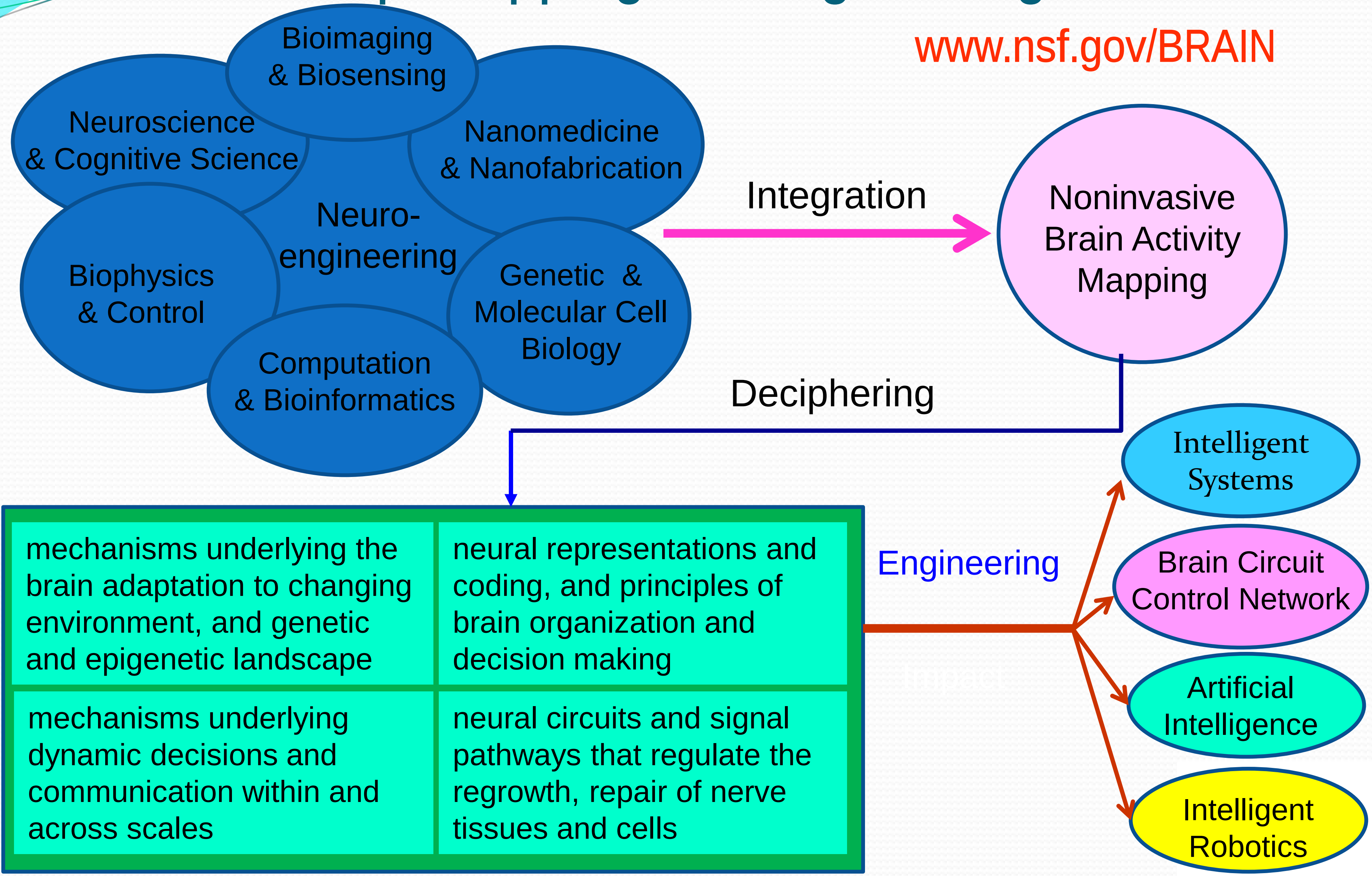
Cellulose nanomaterials



O.J. Rojas, NCSU, 2014

Understanding the brain

First step: Mapping and engineering the brain



nano2

Twelve global trends to 2020

www.wtec.org/nano2/

- Theory, modeling & simulation: x1000 faster, essential design
- “Direct” measurements – x6000 brighter, accelerate R&D & use
- A shift from “passive” to “active” nanostructures/nanosystems
- Nanosystems, some self powered, self repairing, dynamic
- Penetration of nanotechnology in industry - toward mass use; catalysts, electronics; innovation– platforms, consortia
- Nano-EHS – more predictive, integrated with nanobio & env.
- Personalized nanomedicine - from monitoring to treatment
- Photonics, electronics, magnetics – new capabilities, integrated
- Energy photosynthesis, storage use – solar economic by 2015
- Enabling and integrating with new areas – bio, info, cognition
- Earlier preparing nanotechnology workers – system integration
- Governance of nano for societal benefit - institutionalization

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)
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)
4. *NBIC1: "Converging technologies for improving human performance: nano-bio-info-cognition"* (Roco & Bainbridge, Springer, 468p, 2003)
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)