



Science, technology and innovation in a convergence spiral

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National Science Foundation and National Nanotechnology Initiative

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Convergence is a core opportunity for progress

Making the case

- ✓ Defining convergence in science, technology and innovation
- ✓ Convergence principles applied to three general purpose technologies (nanotechnology, NBIC emerging technologies, CKTS ecosystems)
- ✓ Several trends

Defining convergence

CONVERGENCE OF KNOWLEDGE, TECHNOLOGY, AND SOCIETY:

Beyond Convergence of Nano-Bio-Info-Cognitive Technologies

Springer 2013; www.wtec.org/NBIC2-Report; M. Roco et al.



INTERNATIONAL BENCHMARKING and APPLICATIONS

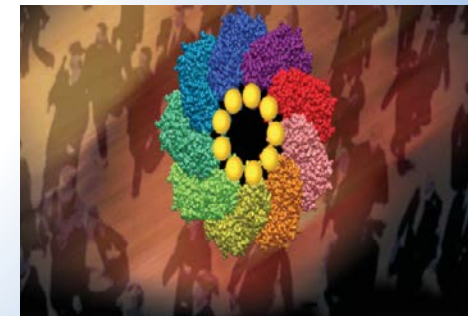


1. Defining convergence

(Ref 6: "Convergence of Knowledge, Technology and Society", Springer, 2013)

Convergence is deep integration of knowledge, tools and all relevant areas of human activity

- into a unified ecosystem - that allows to answer questions, resolve problems and build things that isolated capabilities cannot (*a goal oriented stage*),
- as well as that creates new pathways and opportunities - competencies, knowledge, technologies, applications (*divergence stage*)



Convergence science – Creating / changing a unified ecosystem based on *10 theories* and *6 convergence principles*



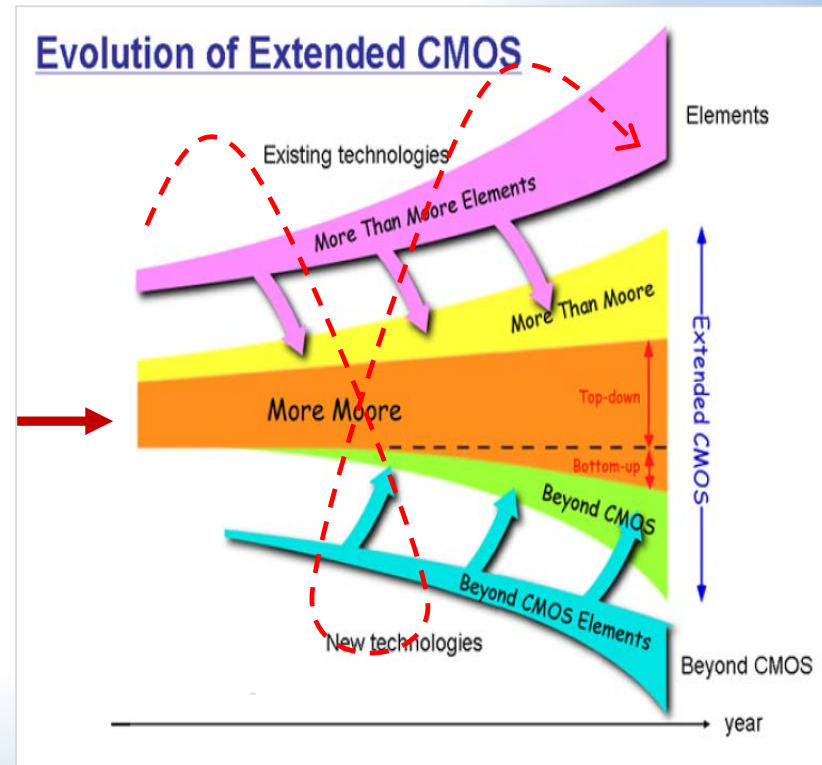
2. The convergence process

(Ref 6: CKTS, Springer, 2013)

Convergence process is the escalating and transformative interaction of seemingly different disciplines, technologies, and communities

(it is a dynamic process)

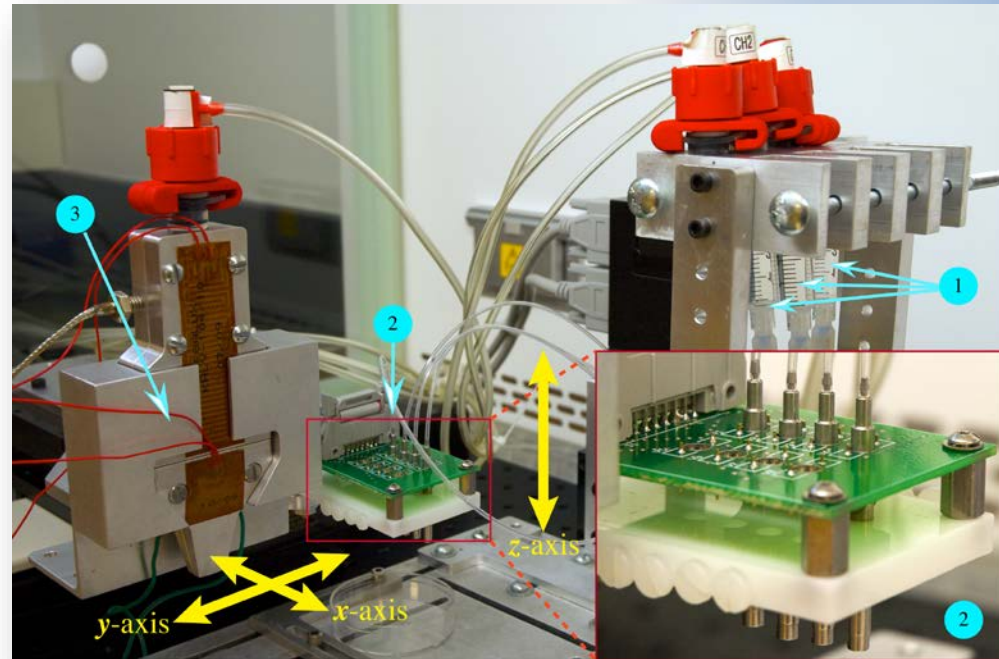
- to achieve their mutual compatibility, synergism and integration,
- and through this process to create *added-value* and *branch out* for shared goals *(driven by the convergence driver)*



Convergence effect: Outcomes not possible before by convergence of three research directions

Tissue Engineering and Nanotechnology meet 3-D Printing (example of convergence)

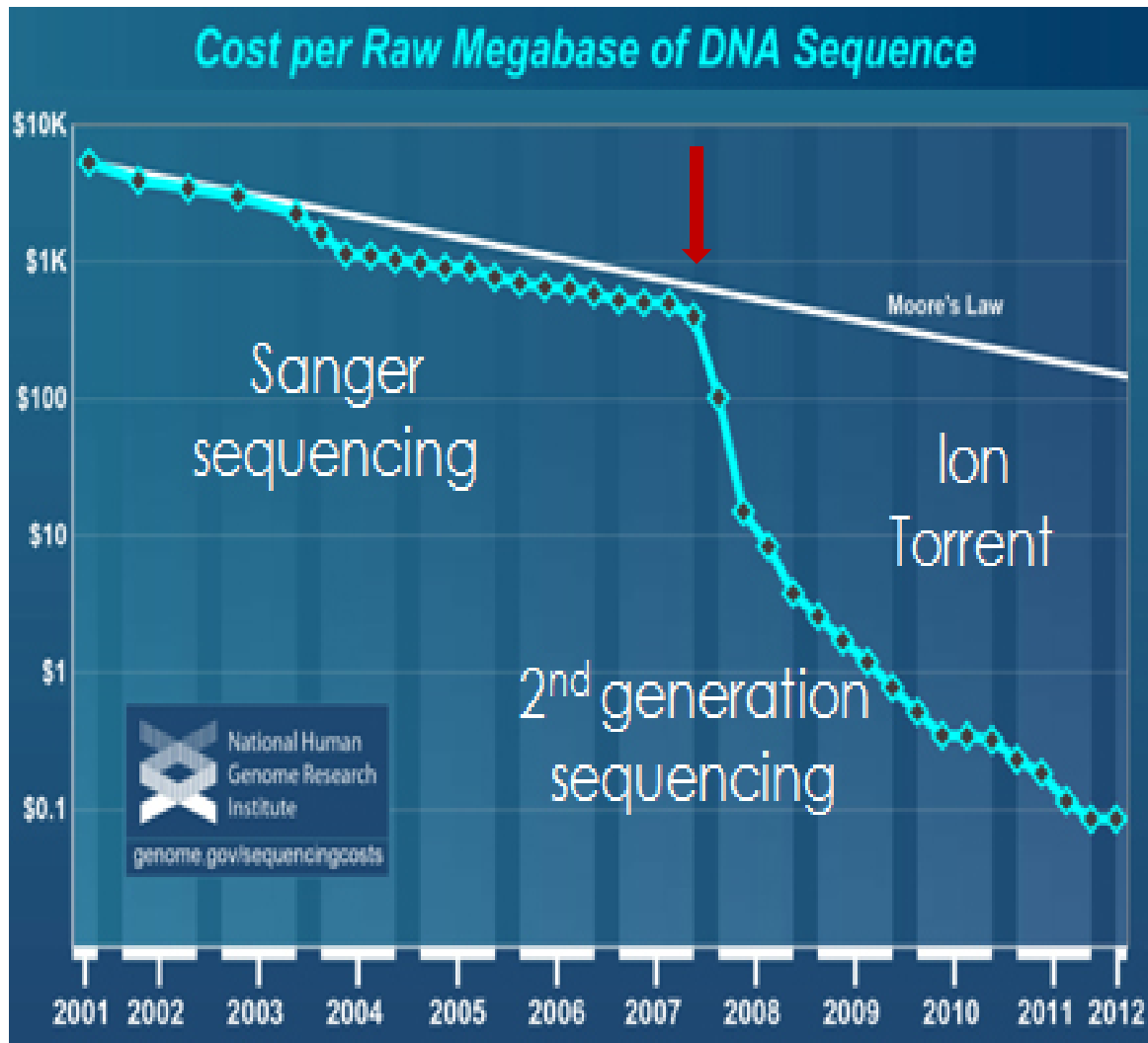
- (i) 3D printing technology
 - (ii) Tissue engineering
 - (iii) Nanotechnology
- for additive manufacturing
of scaffolds with
nanoscale precision



Doi, RPI

Convergence effect: *Gene sequencing cost benefit after integration of biomed and nanoelectronics methods*

(after NIH/NHGRI, K.A. Wetterstrand, 2013)

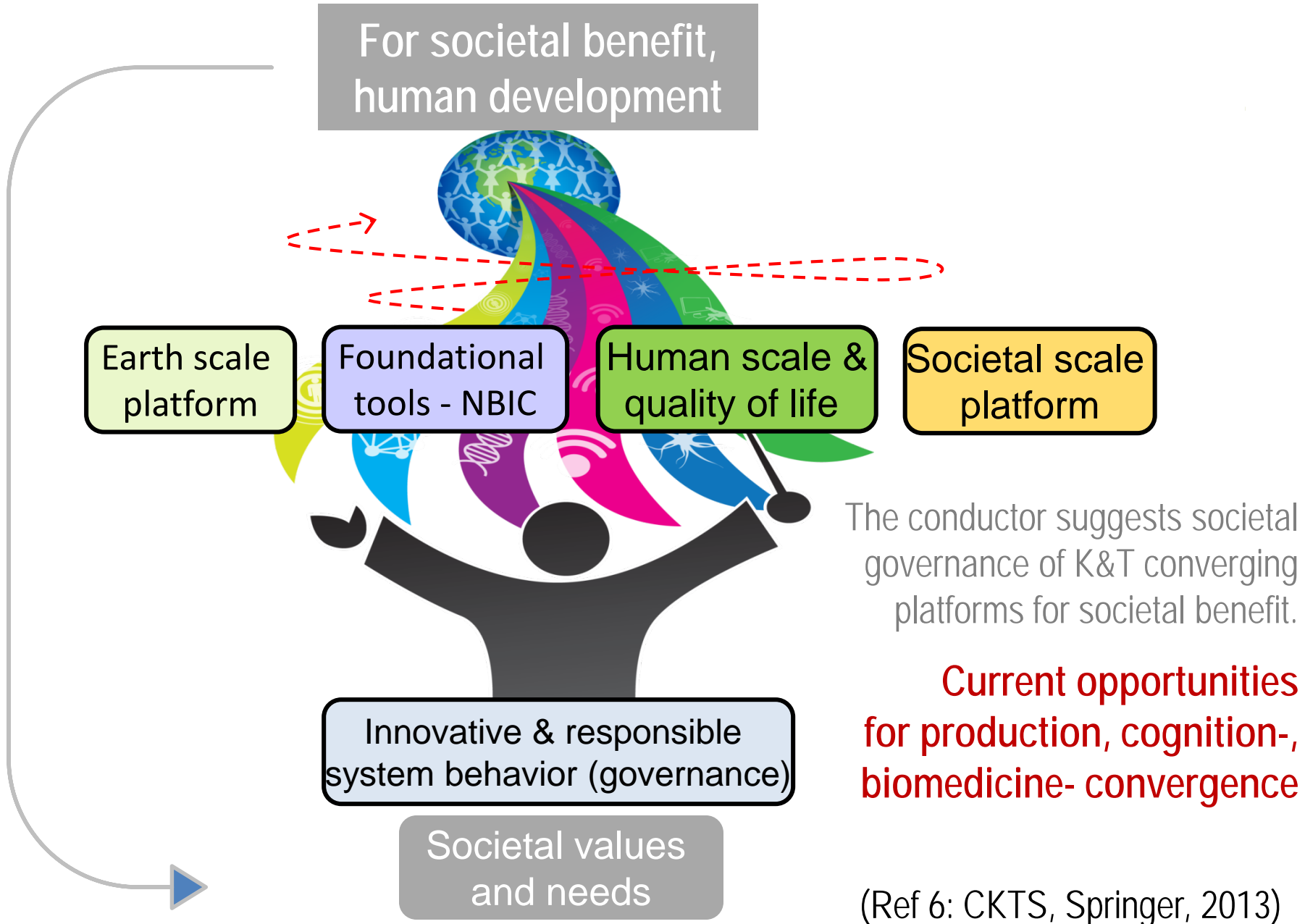


2001: Begins \$3B research program for ~3B DNA letters

2016: Whole genome sequencing much faster with less than \$1,000 (Veritas Genetics, Oxford Nanopore, portable devices,....)

(convergence inspired bio-nano research)

3. Convergence of five human activity platforms



4. Convergence is realized in conjunction with ten theories

1. Unity of nature
2. Human interaction ecosystem
3. Systems adaptive complexity
4. Economic growth
5. Specialization network
6. Reverse salient
7. Fund. integration principles
8. Progress asymptote
9. Exogenous revolution
10. Response to social problems

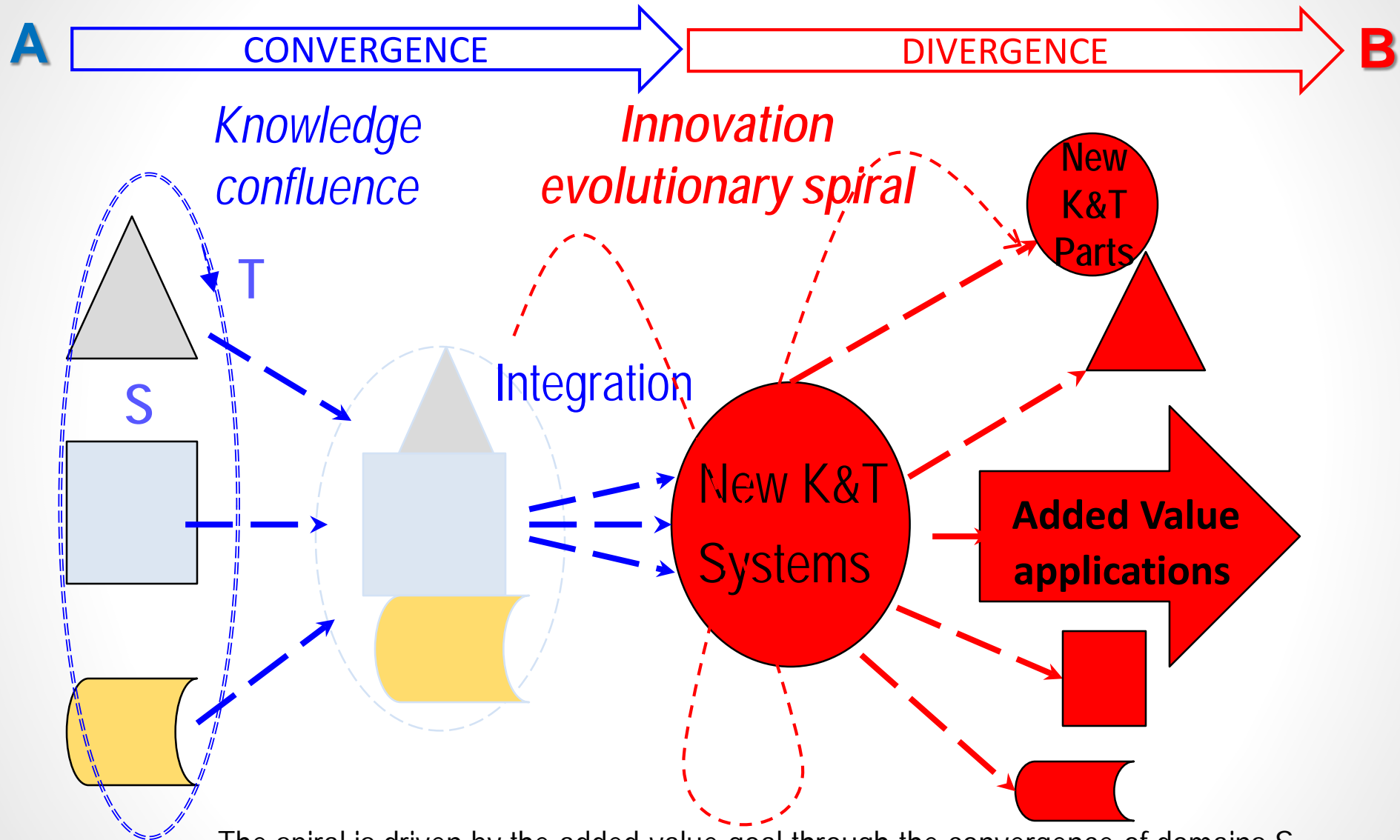
***CONVERGENCE
THEORY SPIRAL***

5. *Convergence of knowledge, technology and society is guided by six general principles*

- A. The interdependence in nature and society
- B. Evolutionary processes of convergence and divergence
- C. System-logic deduction in decisions
- D. Higher-level cross-domain languages
- E. Confluence of resources leading to system changes (S curve)
- F. Vision-inspired basic research for long-term challenges

PRINCIPLES FOR CONVERGENCE

Evolutionary processes of convergence and divergence in S&T



The spiral is driven by the added-value goal through the convergence of domains S, in the external context ENV (imagine a “tornado” or “hurricane” with surrounding air flow and Earth rotation). After Refs. 1 (Roco 2002) and 6 (CKTS Report 2013)

Innovation index in a convergence process

$$I \sim k_{(S,E)} S^2 O / T^3 \quad (1)$$

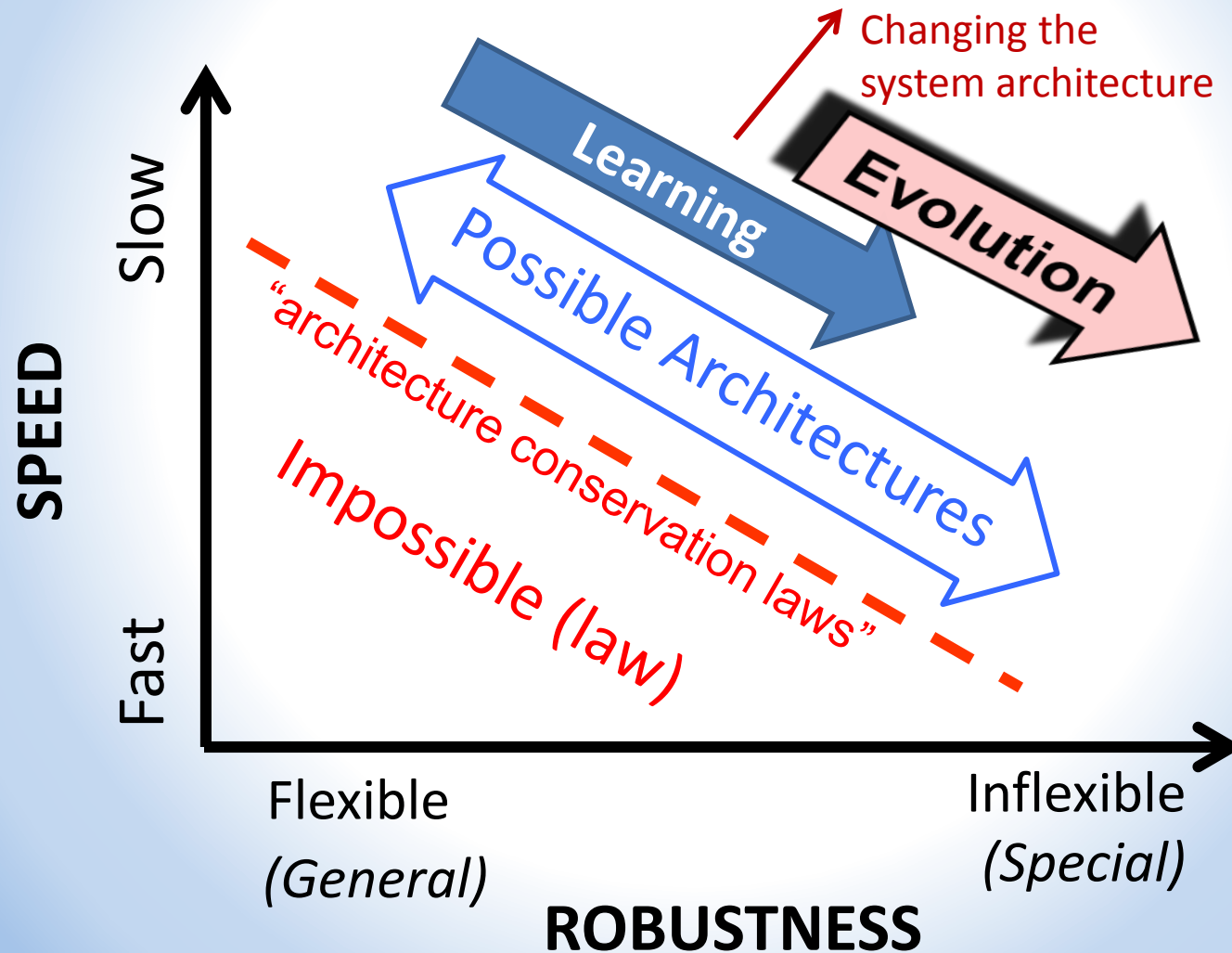
- I** - potential increase of outcomes as a function of the process characteristics (innovation index describing augmentation of the effects or convergence intensity)
- T** - time scale for the convergence–divergence cycle (~ information exchange)
- S** – the size of the convergence domain from where information is collected (the domain circumscribed by the innovation spiral, or the number of disciplines or application areas intersected by the circumferential spiral, in the activity system)
- O** - outcome ratio between the output and input; O/T – divergence angle (diffusion coefficient)
- k** - coefficient of proportionality (a function of convergence domain S and external context E)

Particular cases of (1) are: (a) **“Metcalf’s Law”** (the value of a network scales as the square of the number of nodes (S^2) in network; Shapiro and Varian 1999); (b) **“Moore’s law”** in the semiconductor industry (The proportionality with the (O/TT) agrees with the exponential growth of technological developments); (c) **The rate of technology diffusion** (The remaining $(1/T)$ term)

Example higher level multi-domain languages

Universal laws for system architectures

(Ref. 8, 2015, based on concepts suggested by Turing; Doyle and Csete)



Conceptualization of “Nanomanufacturing” and “Digital Technology” megatrends (S-curves)

(GAO-14-181SP Forum on Nanomanufacturing, Report to Congress, 2014)

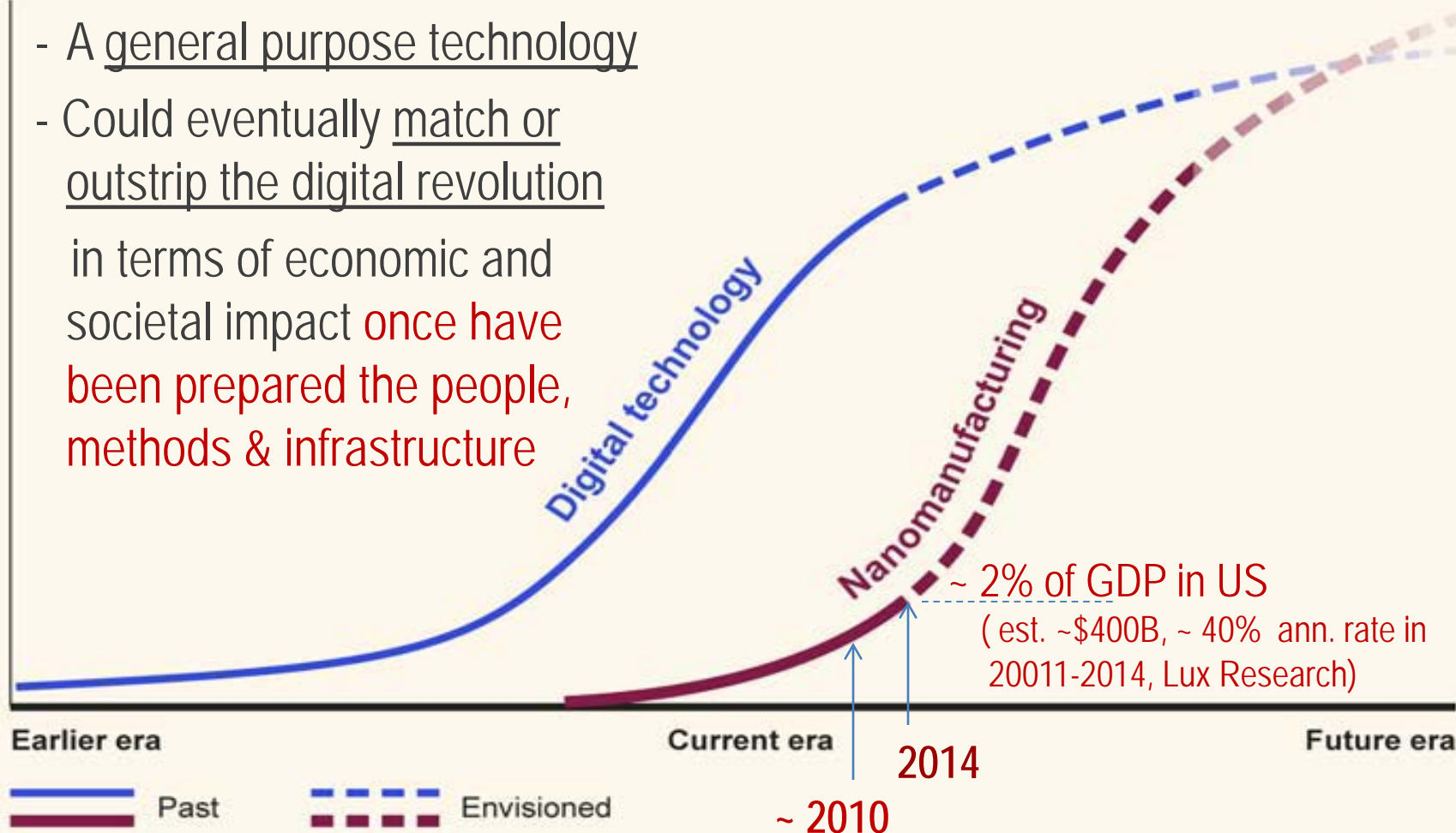
Level of economic importance and societal impact

High

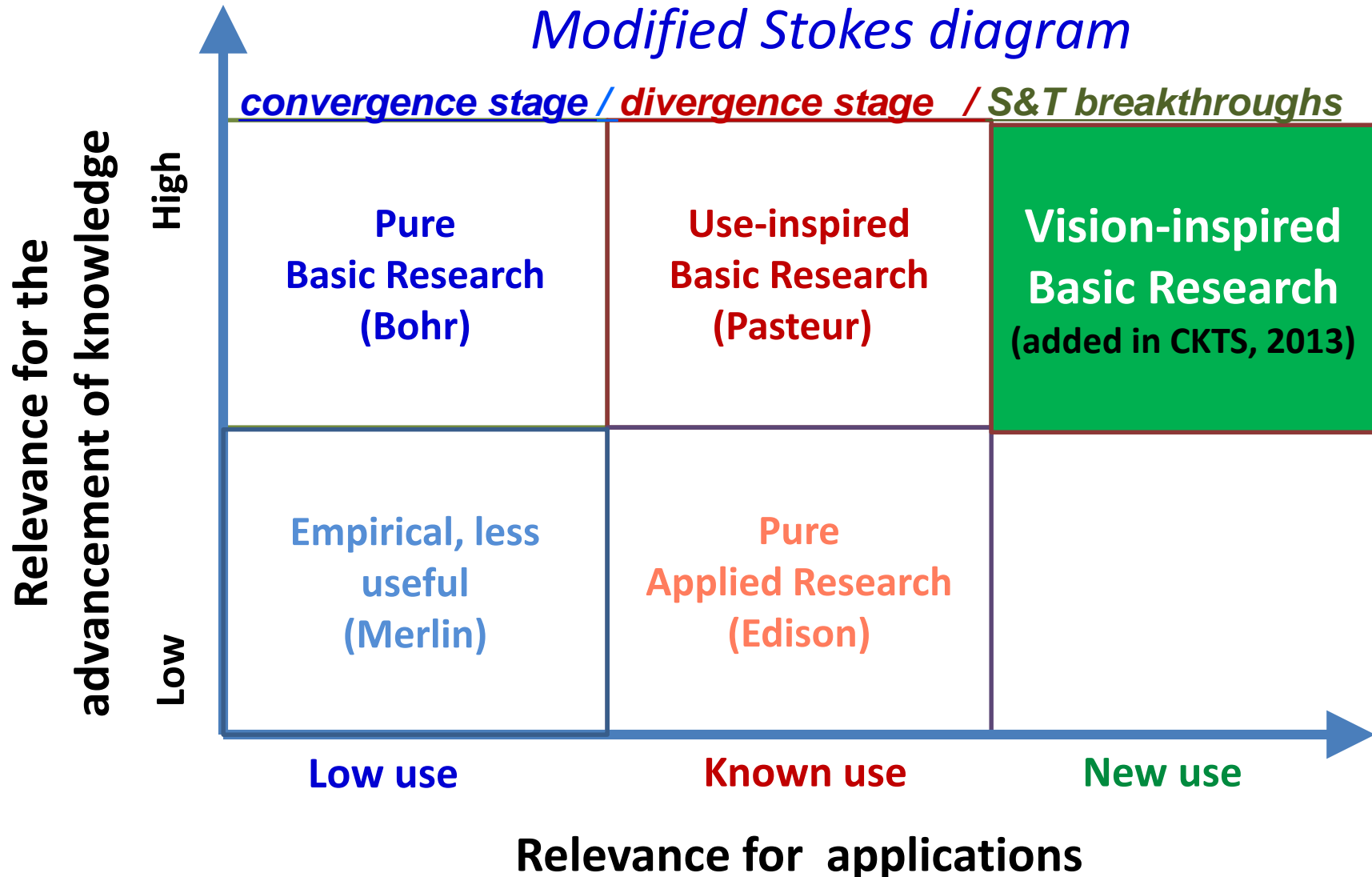
- A general purpose technology
- Could eventually match or outstrip the digital revolution

in terms of economic and societal impact **once have been prepared the people, methods & infrastructure**

Low



Vision inspired discovery and inventions are essential for the future of innovation



Vision-inspired S&T breakthroughs underpinning GCs

(examples of new 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); 12-atom structure (IMB, 2012), DNA structure (Harvard, 2012; on 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 to many 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*"

6. Why convergence is important?

(Ref 6: CKTS, Springer, 2013)

Convergence is both:

- a fundamental principle of nature
- opportunity for S&T progress in knowledge society

Using integrative approaches in convergence aims at:
value-added (cost benefit; ex gene sequencing)
and changing the systems (things not possible before)

"It must be remembered that there is nothing more difficult to plan, more doubtful of success, nor more dangerous to manage, than the creation of a new system. " Machiavelli 1513

Three implemented stages of STI Convergence

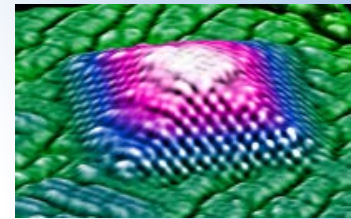


Three stages of convergence

(Ref 6: CKTS, Springer, 2013)

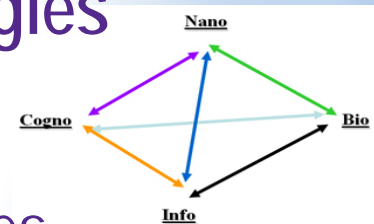
I. Nanoscale Science, Engineering and Technology “Nanotechnology”

Integrates disciplines and knowledge of matter from the nanoscale



II. Nano-Bio-Info-Cognitive Converging Technologies “NBIC”

Integrates foundational and 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 five convergence principles



Supporting studies for three stages of convergence: Nanotechnology, NBIC, CKTS

I. Nanotechnology: “Nanotechnology Research Directions: Vision for the next Decade” (1999) ; Nano 2020 (2011)

Lead to NNI and R&D programs in over 80 countries

II. NBIC: “Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology and Cognitive Sciences” (2001 - 2003)

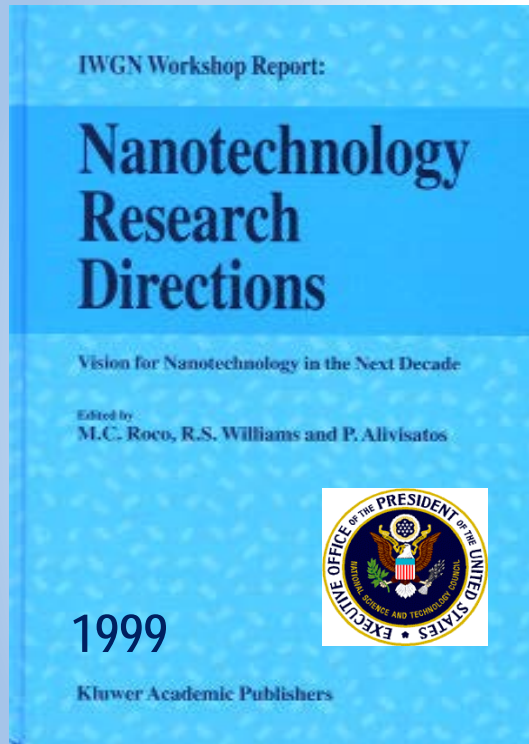
Lead to visionary ideas, establishing international community and programs in several countries

III. CKTS: “Converging Knowledge, Technology and Society: Beyond NBIC” (2013)

Lead to methods to facilitate convergence and progress

Nanotechnology: from scientific curiosity to immersion in NBIC & CKTS socioeconomic projects

nano1 (2001-2010)



nano2 (2011-2020)



NBIC1 & 2 (2011-2030)



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

Reports available on: www.wtec.org/nano2/ and www.wtec.org/NBIC2-report/ (Refs. 3-6)

Benchmark with experts in over 20 countries

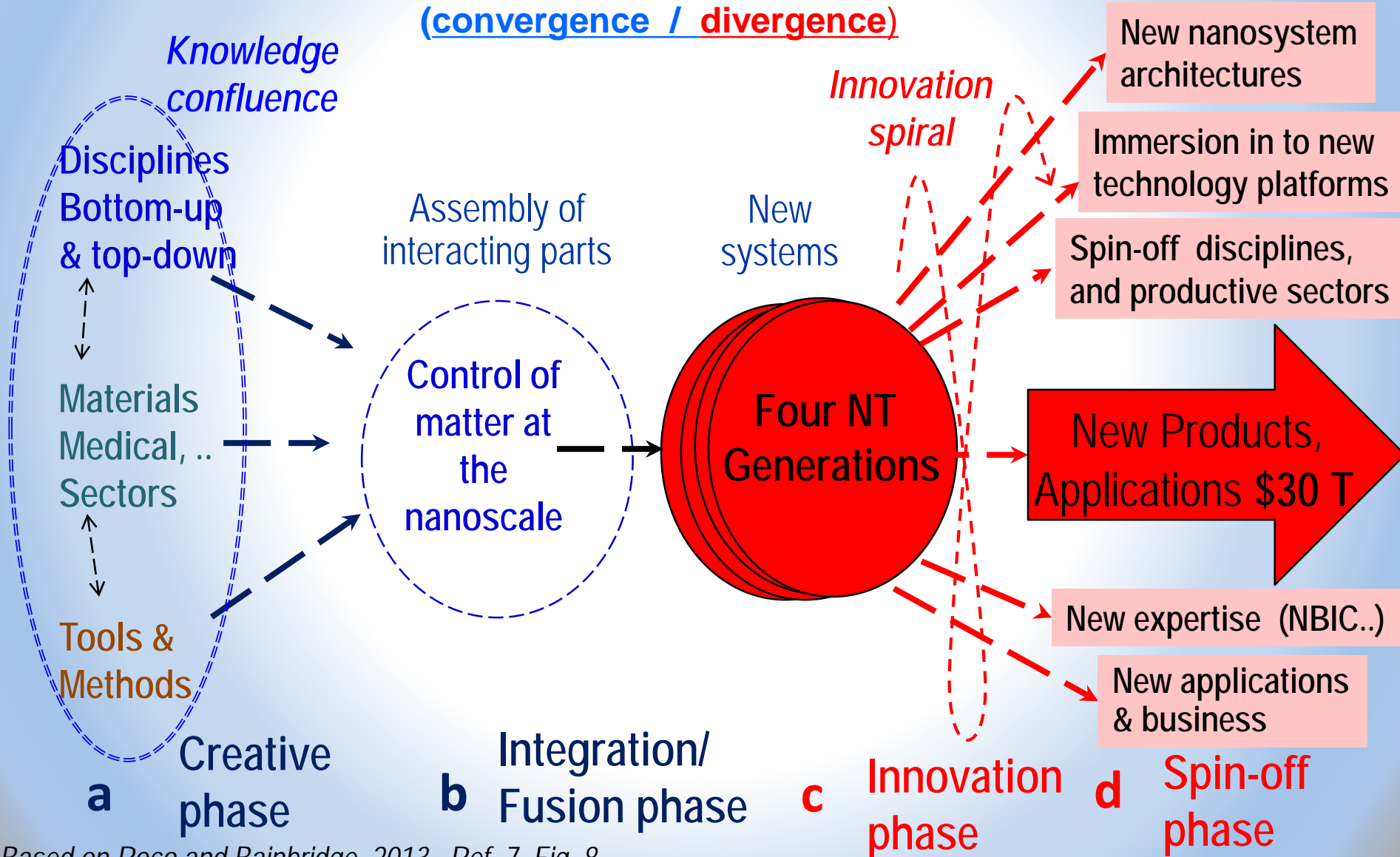
"Nanostructure Science and Technology"

Book Springer, 1999

I. Nanotechnology

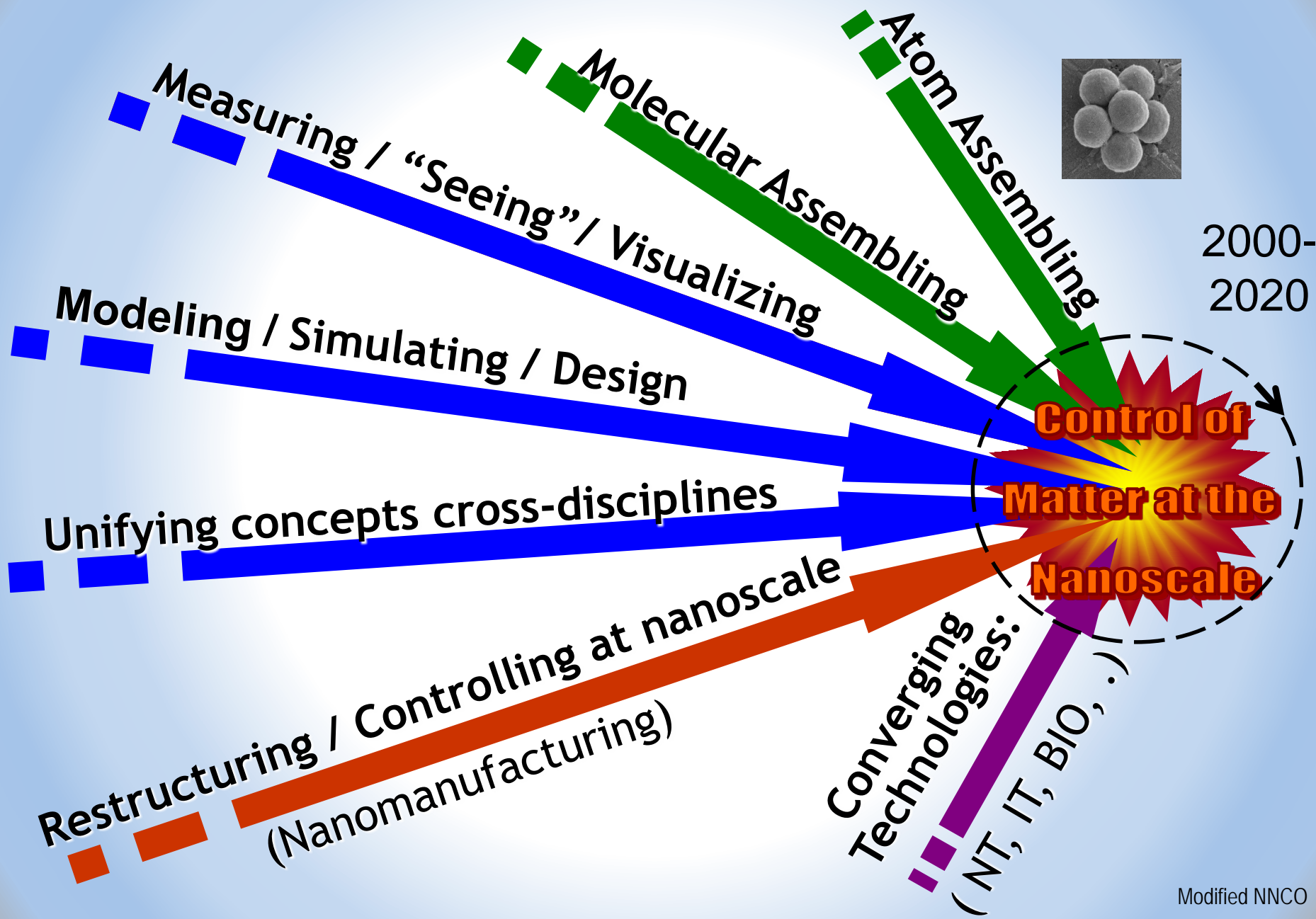
is the control and restructuring of matter at dimensions of roughly 1 to 100 nanometers (from about 1 atom to about 100 molecular diameters), where new phenomena enable new applications

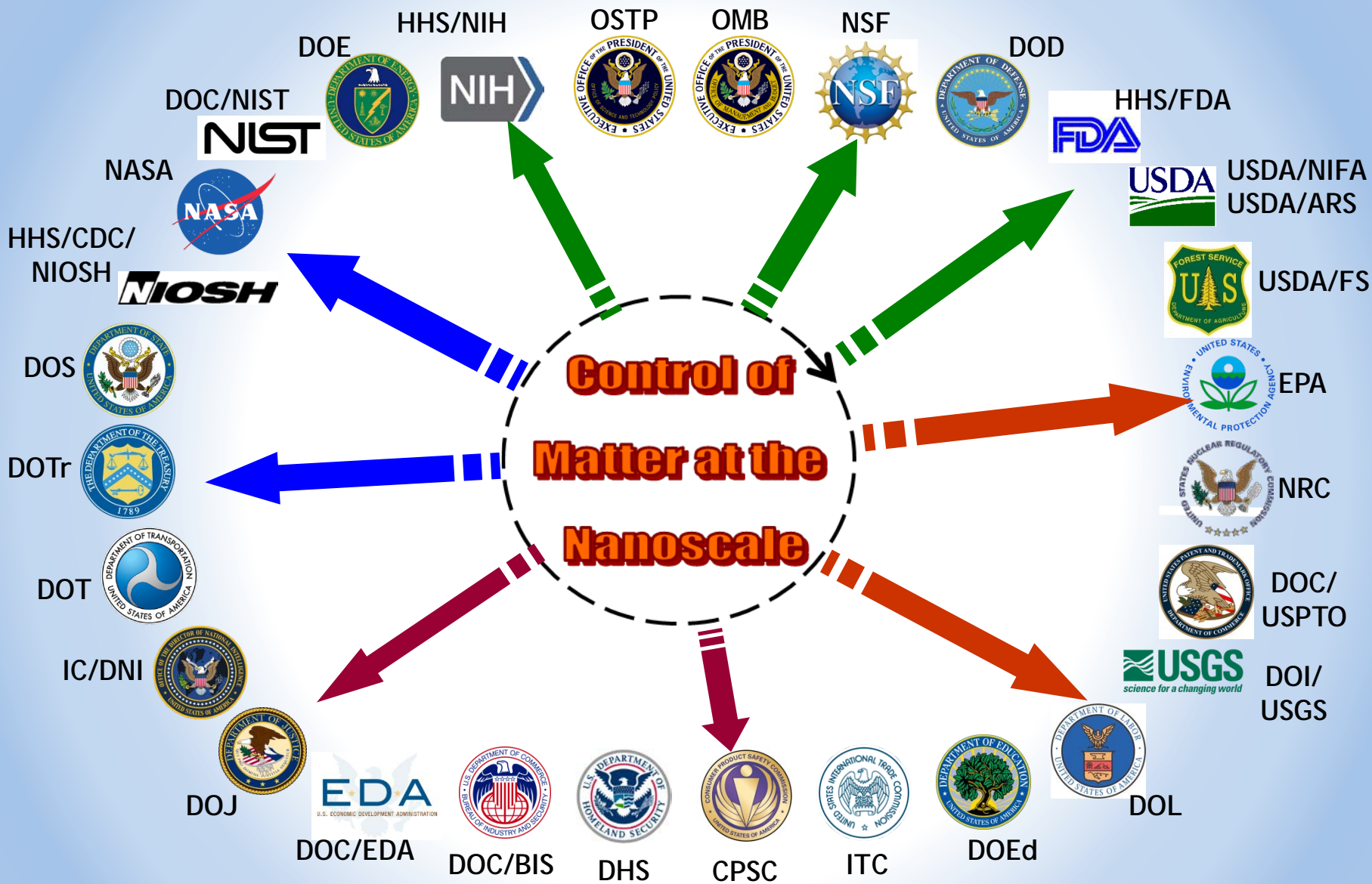
2000-2030 Convergence-Divergence cycle for global nanotechnology development



Based on Roco and Bainbridge, 2013, Ref. 7, Fig. 8

Nanotechnology convergence: concurrence of capabilities





STI Divergence: U.S. National Nanotechnology Initiative, 2000-2030

II. Nano-Bio-Info-Cogno Convergence

NBIC (Convergent new technologies) refers to the synergistic combination of emerging technologies with four major “NBIC” (nano-bio-info-cogno) most transformative provinces of S&T each of which is currently progressing at a rapid rate

- *Cognitive technologies* are based on computer science, psychology, neuroscience, philosophy, anthropology, economics, sociology
- NBIC convergence arising when *accelerated improvement of human potential* become possible

Defining Nano-Bio-Info-Cognitive Converging Technologies

(December 2001)



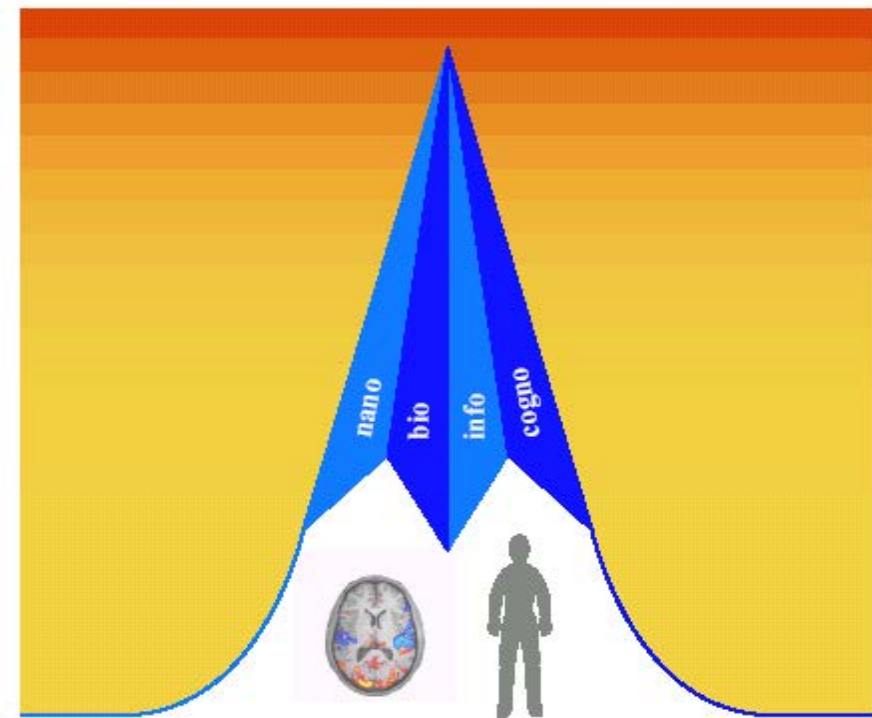
Workshop (NSF, 2001): "Converging Technologies for Improving Human Performance: Nano-Bio-Information-Cognitive"

NBIC: Synergistic combination of four foundational emerging fields from their basic elements (atoms, bits, genes, and neurons) up and using similar system architecture concepts, for common core goals such as learning, productivity & aging

On this basis: 20 visionary scenarios for 20 years ahead

Six volumes on convergence

2003, 2006 and 2007 Springer; 2004 NYAS;
NSF 2004 (Organizations and Business); 2013



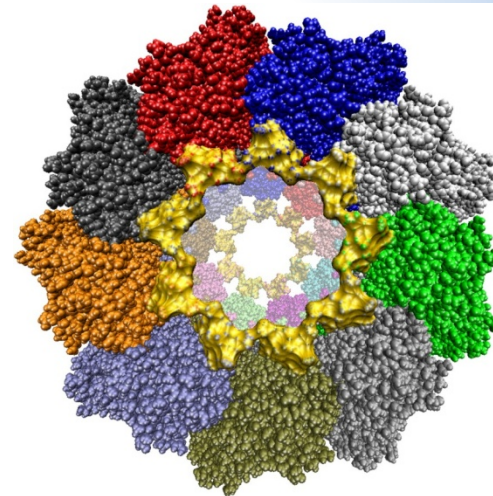
**CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE**

June 2002



**Workshop, Dec. 2001
In Springer, 2003**

Coevolution of Human Potential and Converging New Technologies (Feb. 2003 and Feb. 2004 meetings)



In: *Annals of the New York
Academy of Sciences*,
Vol. 1013, 2004

(M.C. Roco and C. Montemagno)

**MANAGING NANO-BIO-INFO-COGNO
INNOVATIONS**

CONVERGING TECHNOLOGIES IN SOCIETY

MIHAIL C. ROCO AND WILLIAM SIMS BAINBRIDGE (Eds.)



 Springer

November 2006

Progress in Convergence
Technologies for Human Wellbeing

EDITORS

William Sims Bainbridge

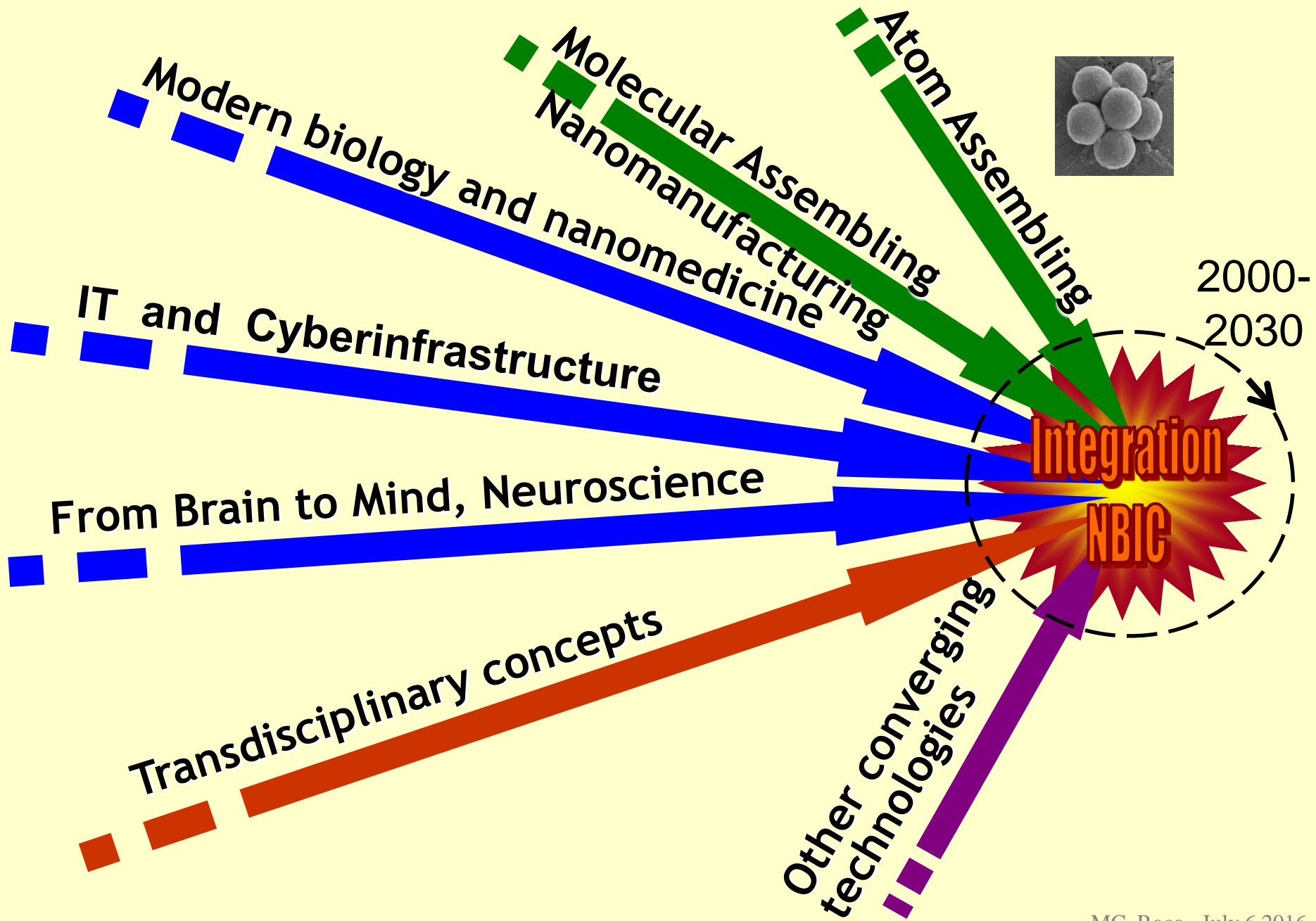
Mihail C. Roco

NYAS

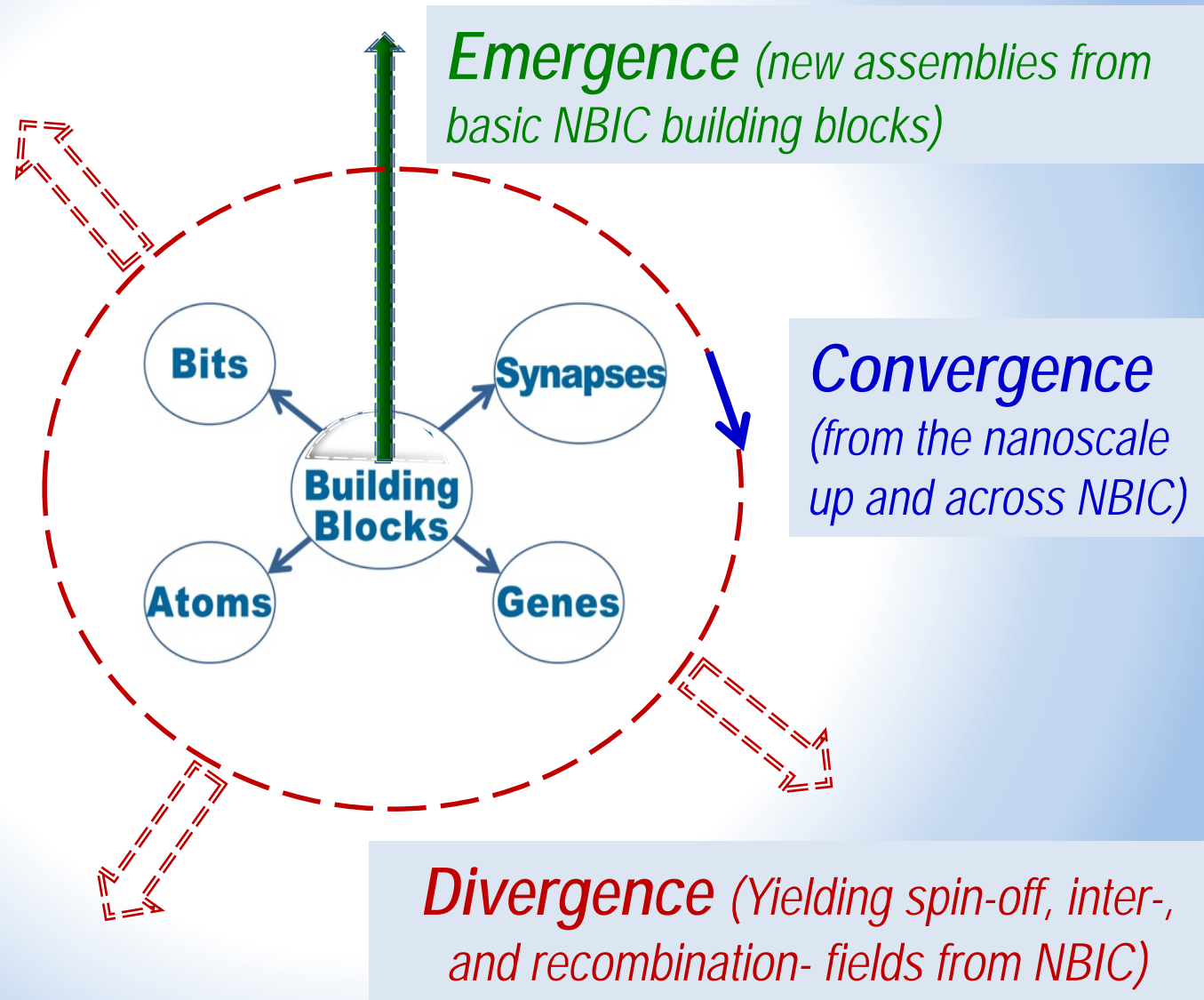
December 2006

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES VOLUME 1093

NBIC: concurrence of capabilities



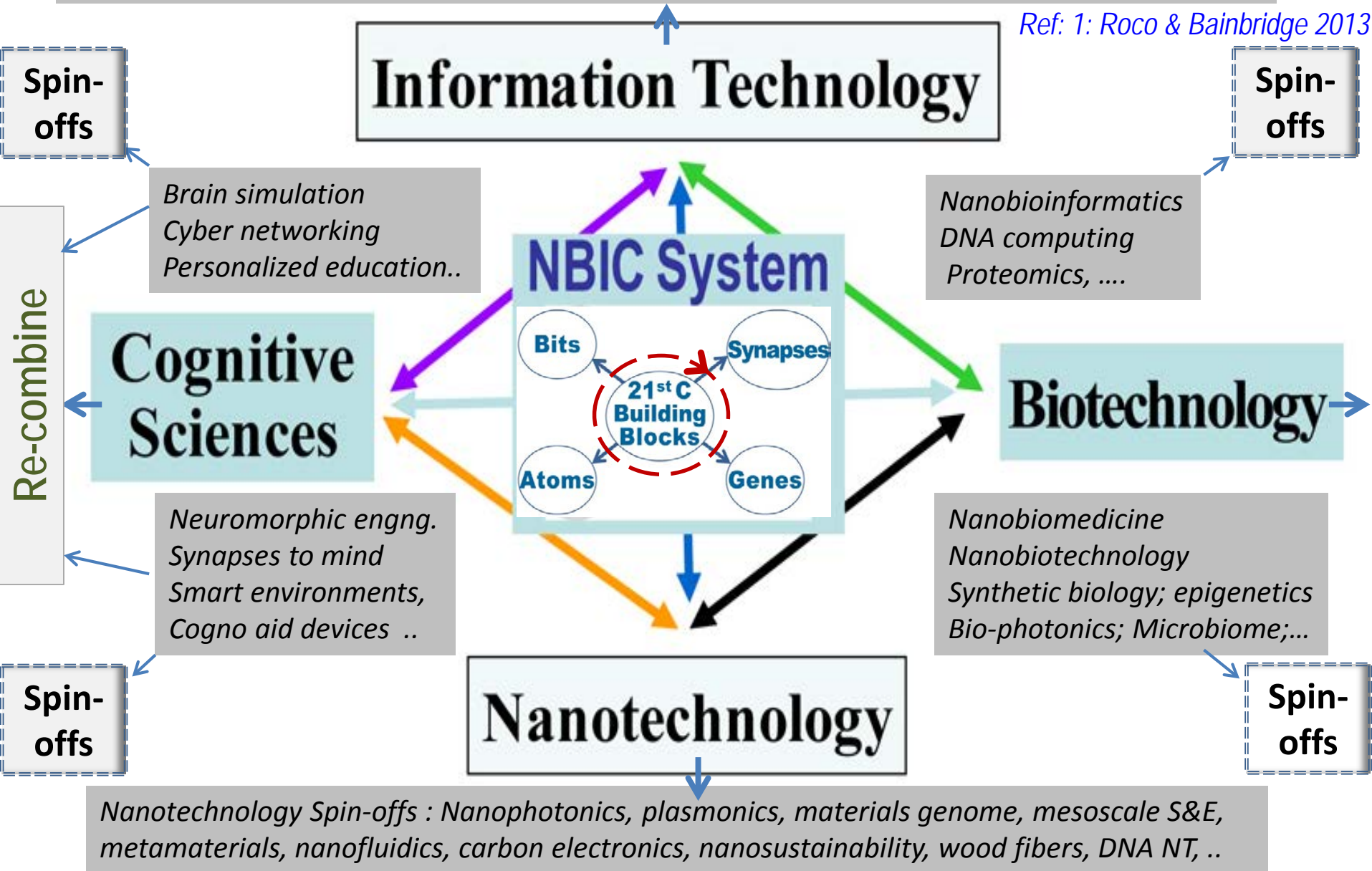
Emergence, convergence, and divergence of NBIC



Emergence & divergence of foundational N B I C

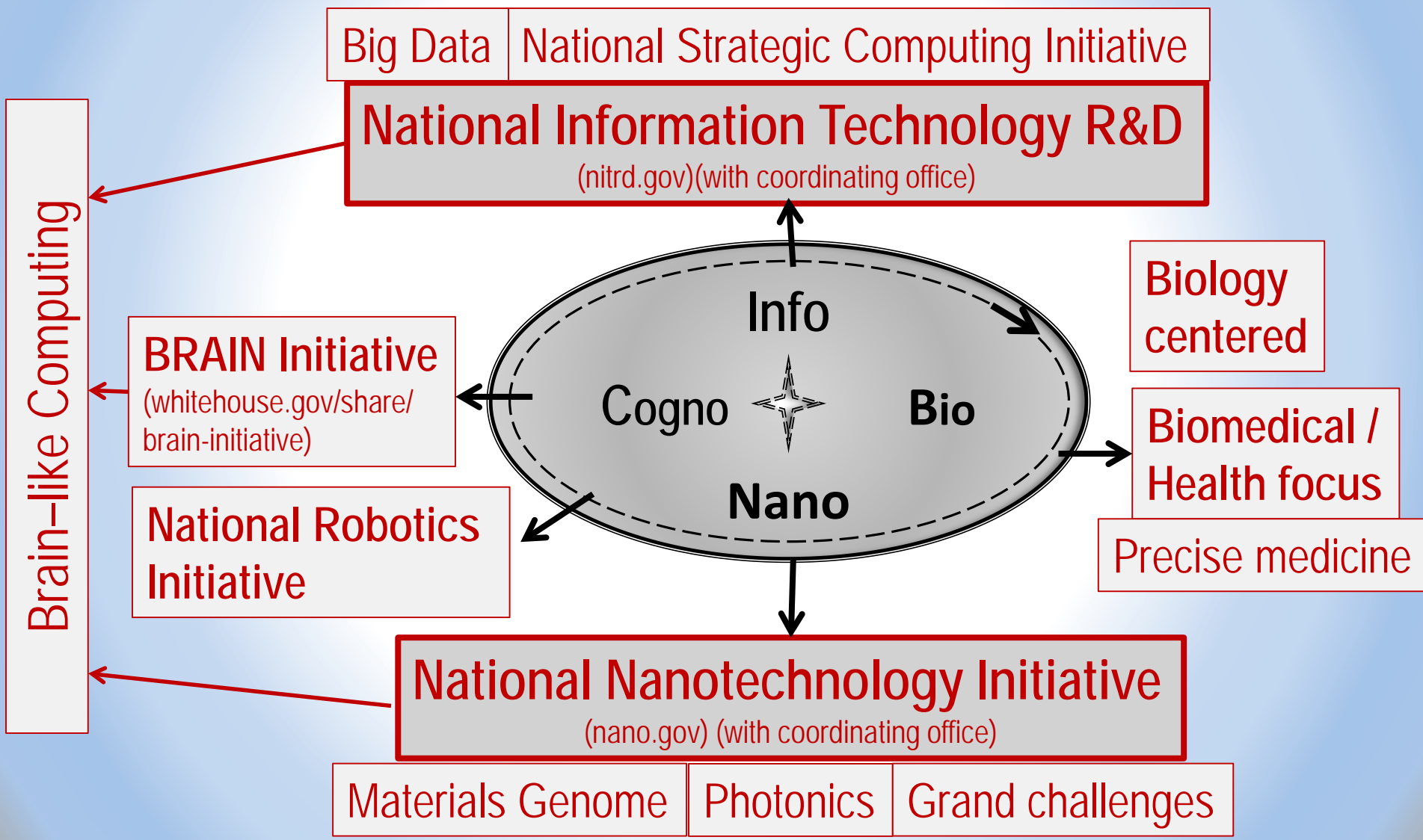
Information Technology Spin-offs: Large databases, cyber-physical-social infrastructure, Internet of Things, connected sensorial systems, topical computer-aided design, cyber networks, ...

Ref: 1: Roco & Bainbridge 2013





Converging foundational technologies (NBIC) leads to *U.S. emerging S&T initiatives*





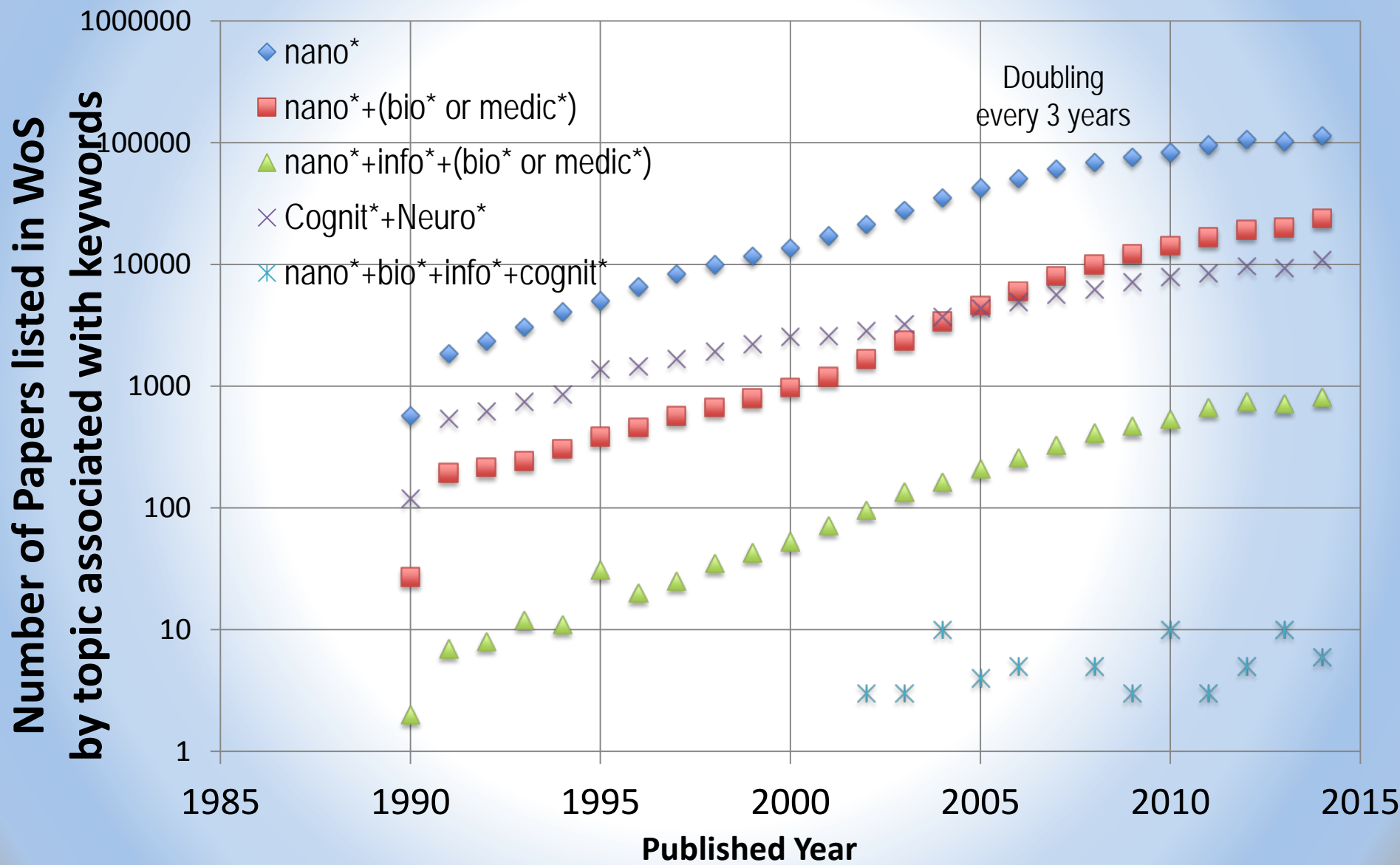
U.S.: Seed R&D programs 2002-2004 had a lasting impact

- Converging S&E components in: **Nanoscale Science and Engineering, ITR, Biocomplexity, Sensors** (all 2002-)
- DARPA **nano-bio-info-cognitive** research focus (2002 -)
- Improving human performance in **NSF Human and Social Dynamics** (2003-)
- NSF **SBIR** focus on **converging technologies** (2003-2004)
- NSF-NIH on computer **simulation of the brain** (2004-)
- NSF centers for “**science of learning**” (2004 -) from brain R&D)
- NASA **improving human performance** for space exploration, and nano-bio-info programs (2004 -)
- About ten **NSF and NASA** centers on domains of NBIC (2004 -)

Examples of NBIC domains (2005-2016) with U.S. National Science Foundation awards

- **Quantum information science** (IT; Nano and subatomic physics; System approach for dynamic/ probabilistic processes, entanglement and measurement)
- **Eco-bio-complexity** (Bio; Nano; System approach for understanding how macroscopic ecological patterns and processes are maintained based on molecular mechanisms, evolutionary mechanisms; interface between ecology and economics; epidemiological dynamics)
- **Neuromorphic engineering** (Nano, Bio, IT, neurosc.)
- **Cyber-physical systems** (IT, NT, BIO, others)
- **Synthetic biology** (Bio, Nano, IT, neuroscience)
- **Brain-like computing** (neuroscience, IT, NT, Bio, psychology)

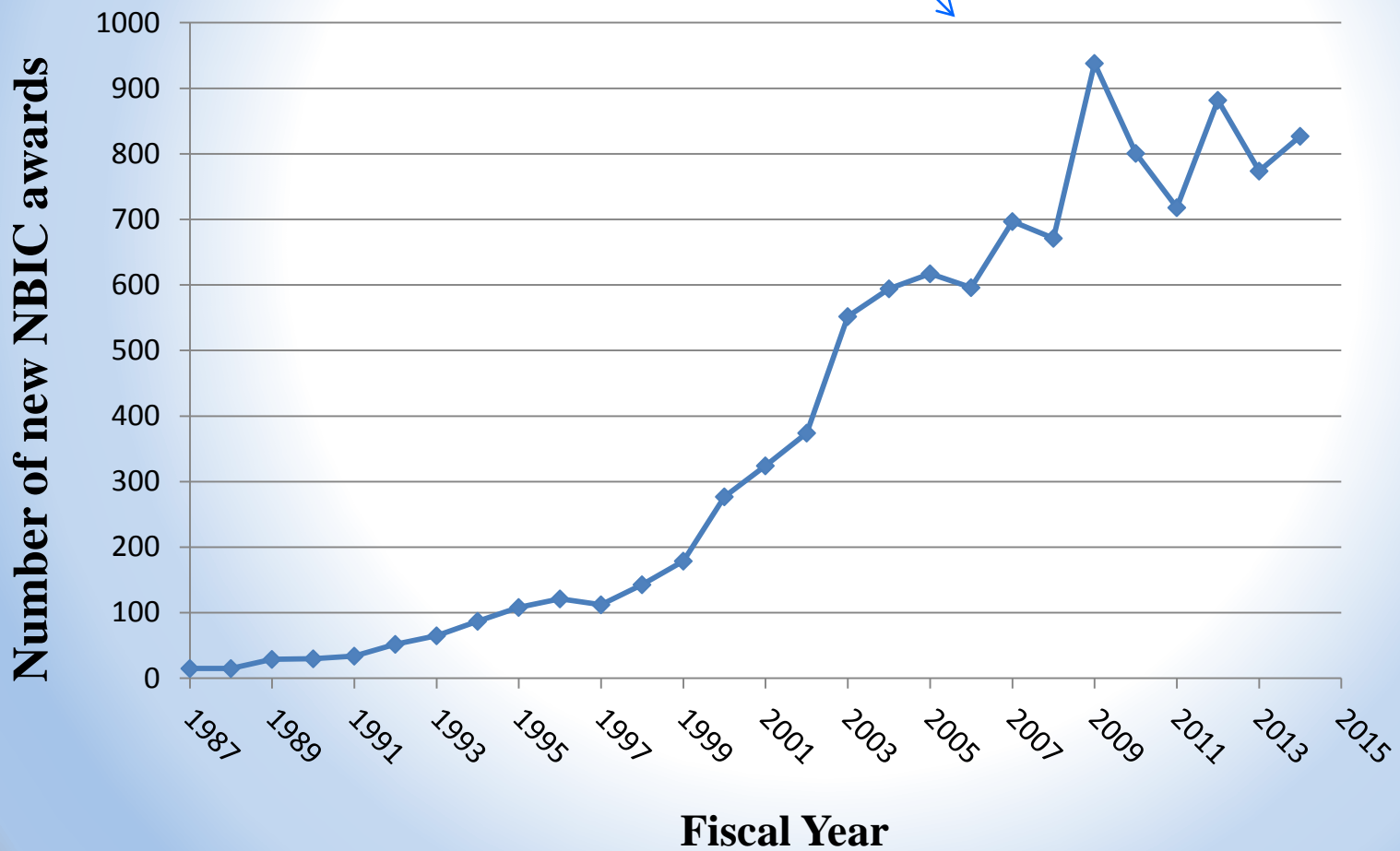
Thomson Reuters Web Of Science (WoS) Papers on Foundational Tools NBIC (1990 - 2015)



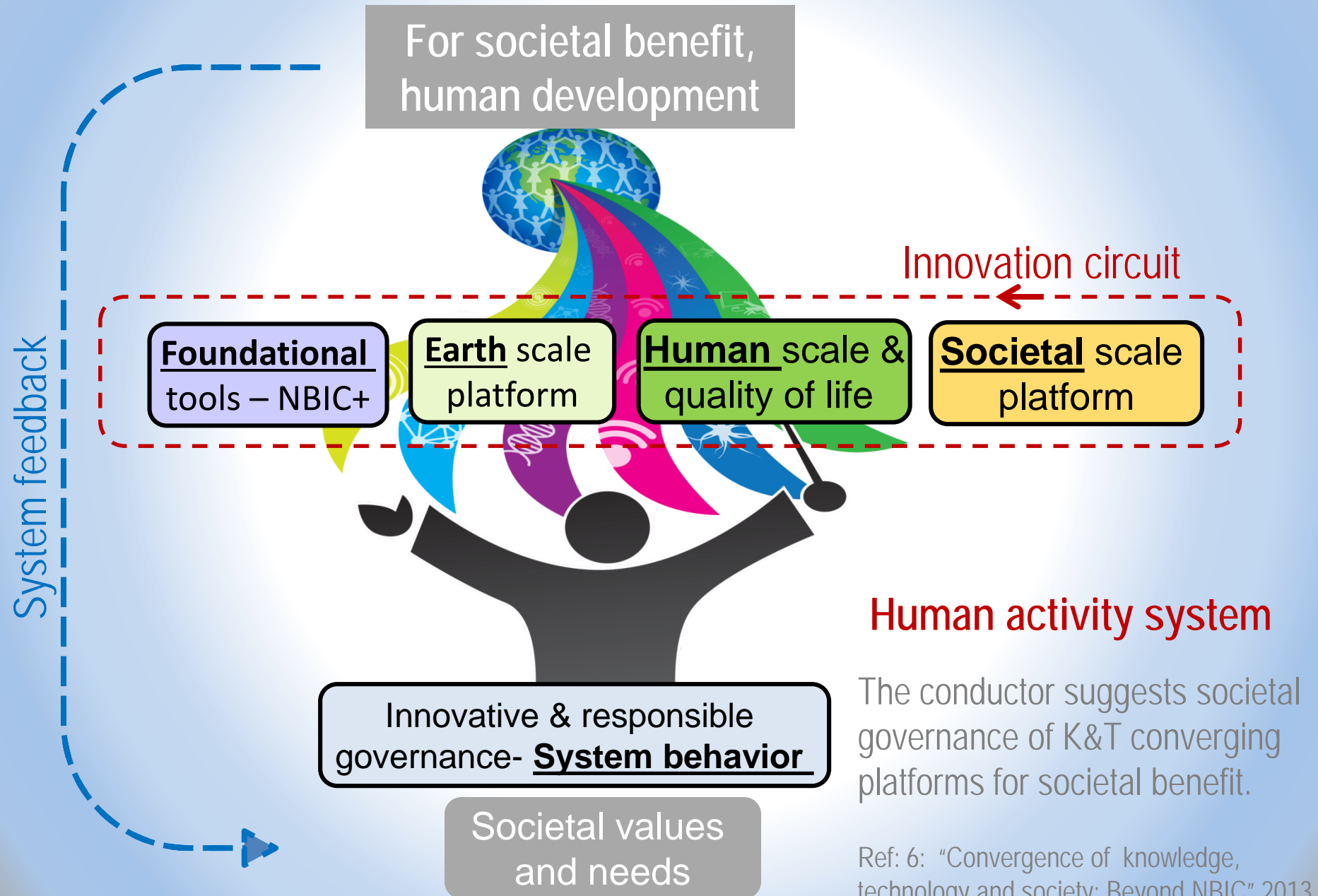
Number of NBIC Awards at NSF (1987-2015)

Search by combined keywords

About 5% of total NSF new awards since 2009



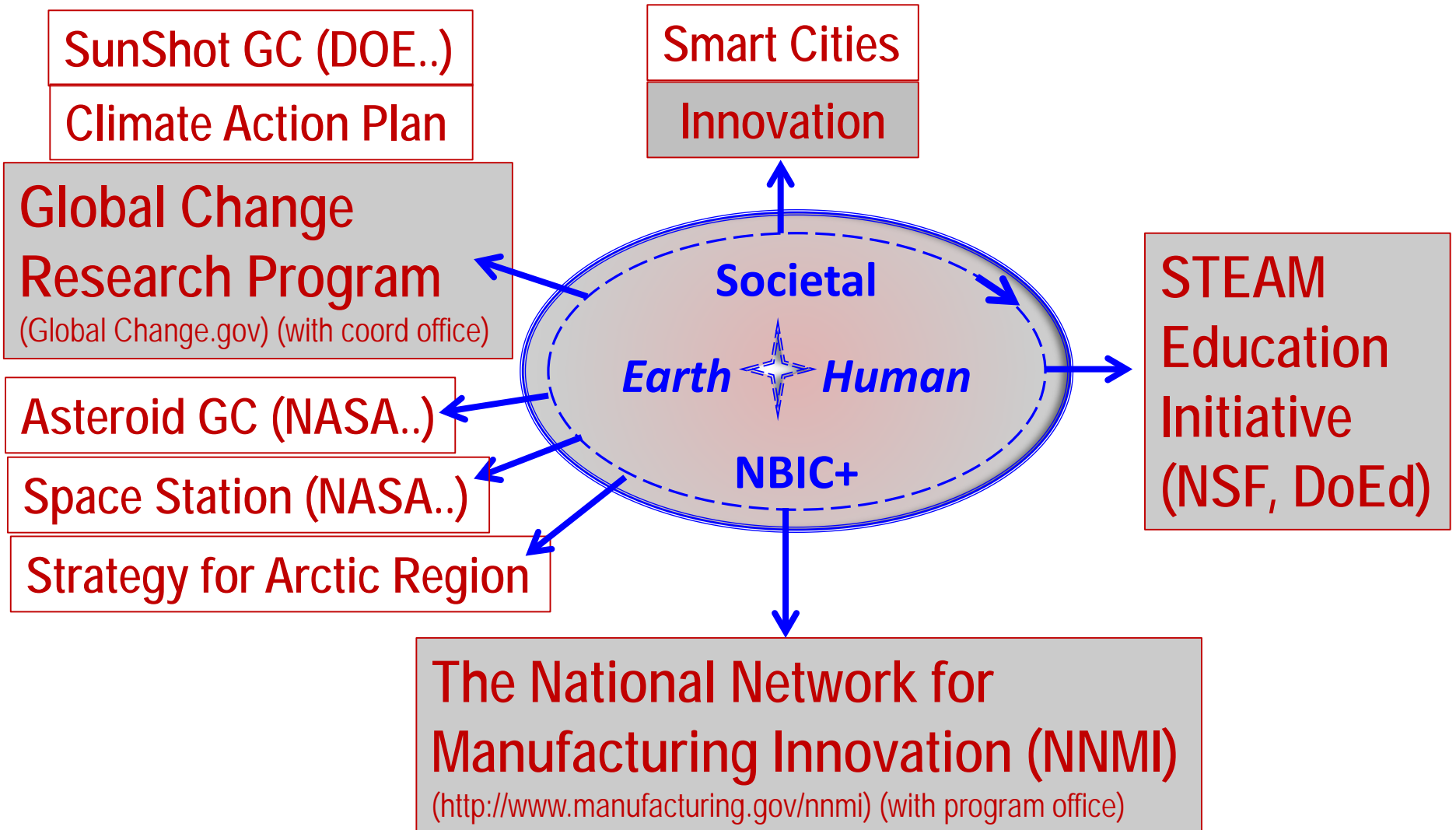
III. Convergence of Knowledge, Technology and Society



Ref: 6: "Convergence of knowledge, technology and society: Beyond NBIC" 2013



Convergence of Knowledge and Technology (CKTS) leads to *U.S. global society-oriented initiatives*



(Ref 8: "Principles and methods that facilitate convergence")

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

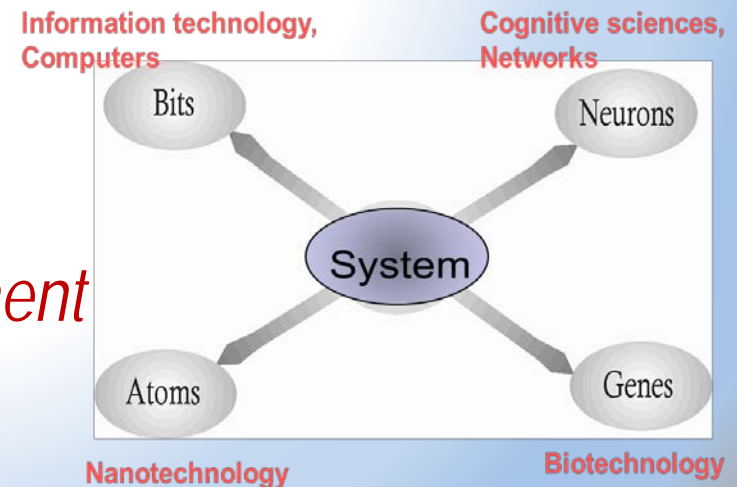
Current list - **8 institutes** (<http://manufacturing.gov/>):

- 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

Several trends

Twelve challenging ideas from 2001 NBIC Report that are reality or in development in 2015

- Hierarchically interconnected world – *a reality in 2015*
- Non intrusive brain-to-brain communication – *accepted*
- Computer Personal advisor – as laptop or cell – *at beginning*
- Brain machine and brain robotics systems – *in development*
- From physics/chemistry to mind and education – *in BRAIN R&D*
- Centers of leaning: for brain to education methods – *in function*
- Regenerative medicine, Gene editing, 3-D print parts - *accepted*
- Nano-info-biomedical developments
- Proteases activated by brain - *done*
- Education earlier for NBIC - *modules*
- Intelligent environments – *in development*
- ELSI community – *organized in 2013*



Digital Society

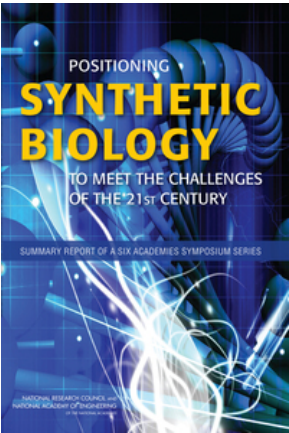
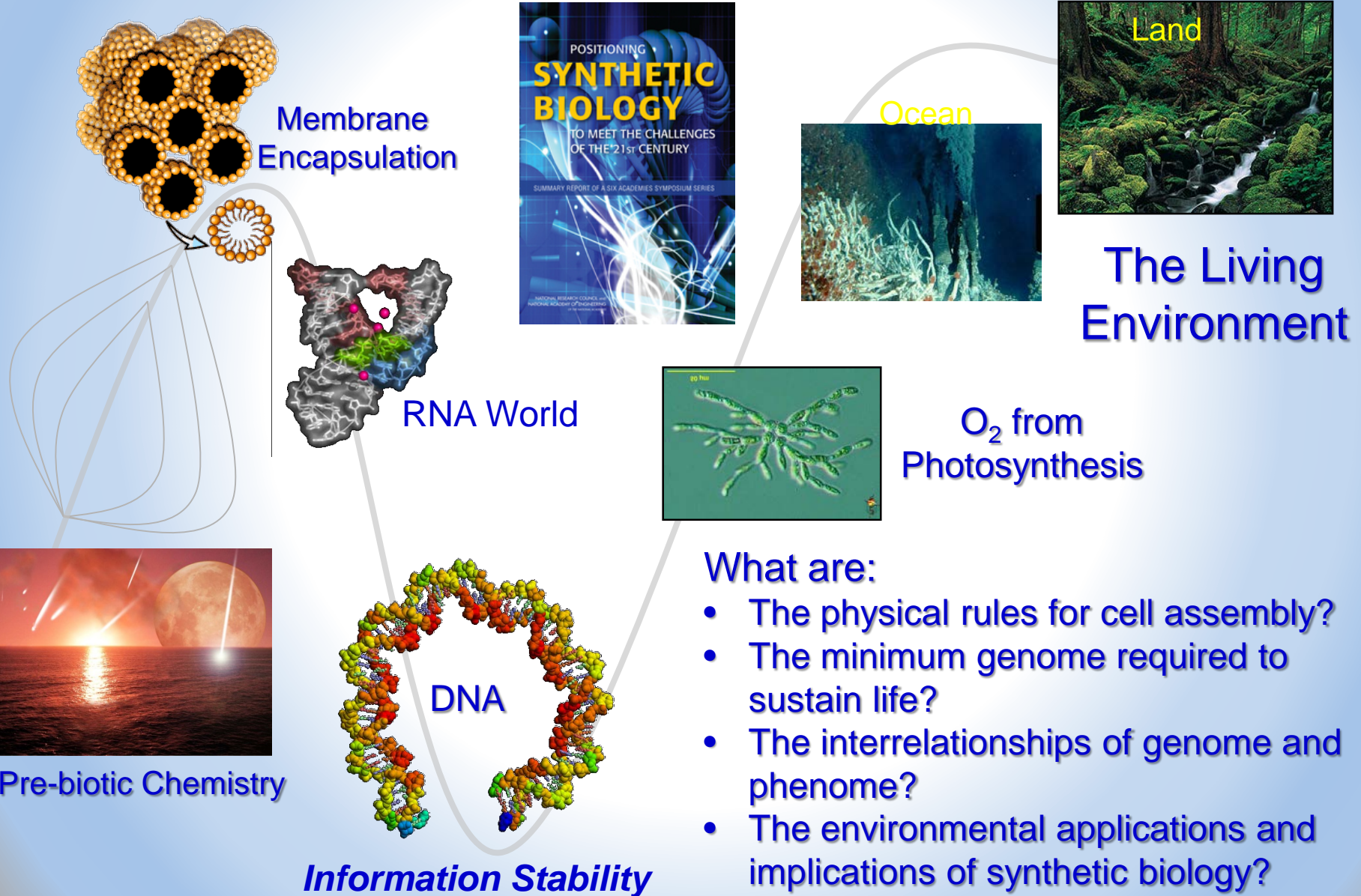
- **Digital society is enabled** by the progress in computing and databases, and has immediate relevance to digital manufacturing, cyber-physical-social systems, large databases, and Internet of Things. Digital relationships and networking are expected to change the respective ecosystems for production, learning, trading and other areas.
- Convergence within government has a focus on coordination and collaboration across boundaries to create “**virtual agencies.**”
- Digital resources develop through a sequence of technical, economic, legal, and social steps. **Convergence of curation** aims bringing common nomenclature, standards and easier communication

Convergence in advanced PRODUCTION

- Increased system interactions – supports **cloud production**, leads to **“trading zones” production**
- Penetration of foundational technologies – leads to **NBIC production** (nano-, bio-, digital-, cognitive-, and combined 2 to 4 technologies), including – **composable and modular production**
- Converging “supply chains” from concept to internet, production and use – lead to **“cyber-physical-social” production, life-cycle design and benign by design**
- Leads to **new emerging fast-growing areas**

What are the indispensable requirements for Life?

- Convergence of Chemistry, Synthetic Biology, Nanotechnology, Philosophy, ... -



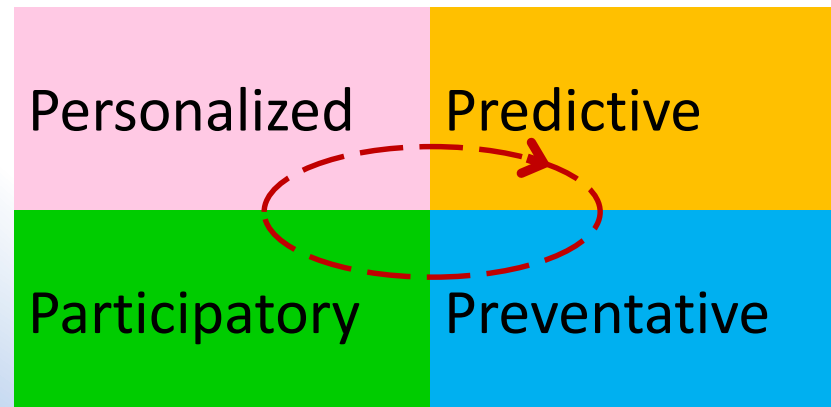
- What are:
- The physical rules for cell assembly?
 - The minimum genome required to sustain life?
 - The interrelationships of genome and phenome?
 - The environmental applications and implications of synthetic biology?

Information Stability



Human Health and Physical Potential Goals Enabled by Convergence

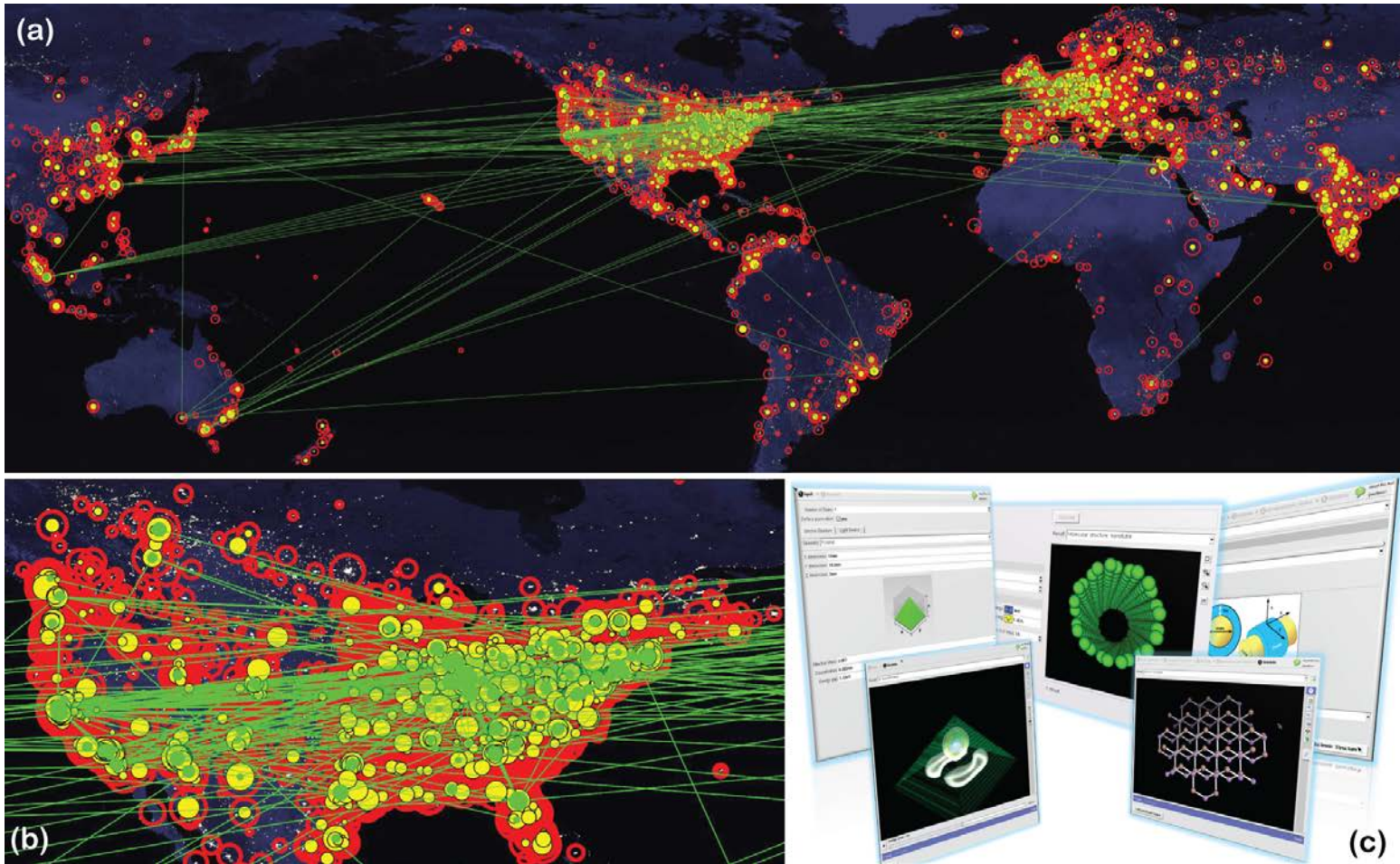
- Advance cancer detection and treatment w/ reduced side effects
- Health data analysis and delivery for real-time health monitoring
- Regenerative medicine and advanced prosthetics
- Next generation vaccines
- **Wellness-focused: distributed P4 medicine**



Needed infrastructure for convergence

- Centers for the science and methods for convergence
- Technology platforms for addressing societal grand challenges, including distributed NBIC manufacturing and global virtual factories, cognitive technologies and brain mapping
- Universal convergence databases
- Organizations to monitor and support increase in human potential, societal sustainability, and responsible governance
- Government support and coordination of convergence in STI investment planning and policies, decision-making

Example: Network for Computational Nanotechnology



nanoHUB usage in 2015: 172 countries

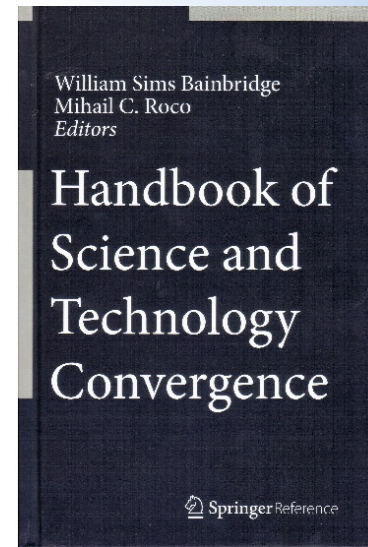
Over 3,00 authors collaborating

Over 13,000 users running interactive simulations

Over 1.4 million visitors using lectures and tutorials

Several current U.S. activities

- NSF lead reports (2001-2016)
- US agency funding: NSF, DARPA, EPA, NIH, AFOSR, others
- Academy study: Convergence - Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond (2014)
- *MIT-Harvard convergence for health (Biomed&S&E; 2016)*
- *NSF priority areas: human-technology frontiers, microbiome, quantum computing systems, citizens science, longitudinal "science of education", convergence in governance of S&T*



Global Action Possibilities

- An international convergence CKTS network
- **Government coordination** for supporting: *“science of convergence”* & *“convergence technology platforms”*
- Manufacturing, cognition-, biomedicine- convergence
- Cross-domain programs in universities & funding agencies
- Principles of convergence **for conflict resolution**
- **OECD new committee on convergence** created in 2014

Related publications

1. *"Coherence and Divergence of Megatrends in Science and Engineering"* (Roco, JNR, 2002)
2. *"Nanotechnology: Convergence with Modern Biology and Medicine"*, (Roco, *Current Opinion in Biotechnology*, 2003)
3. ***NANO1: "Nanotechnology research directions: Vision for the next decade"*** (Roco, Williams & Alivisatos, WH, 1999, also Springer, 316p, 2000)
4. ***NANO 2020: "Nanotechnology research directions for societal needs in 2020"*** (Roco, Mirkin & Hersam, Springer, 690p, 2011a)
5. ***NBIC: "Converging technologies for improving human performance: nano-bio-info-cognition"*** (Roco & Bainbridge, Springer, 468p, 2003)
6. ***CKTS: "Convergence of knowledge, technology and society: Beyond NBIC"*** (Roco, Bainbridge, Tonn & Whitesides; Springer, 604p, 2013b)
7. *The new world of discovery, invention, and innovation: convergence of knowledge, technology and society* (Roco & Bainbridge, JNR 2013a, 15)
8. *"Principles and methods that facilitate convergence"* (Roco, Springer Reference, *Handbook of Science and Technology Convergence*, 2015)
9. ***HSTC: "Handbook of Science and Technology Convergence"*** (Bainbridge & Roco, 2016)