Knowledge and technology in a convergence spiral

Mihail C. Roco
National Science Foundation and National Nanotechnology Initiative

University of Miami, February 20, 2018
Evolution in nature, science, technology, society is

- **Turbulent**
- **Coherent**
- **Emergent**

Examples of ecosystems too complex for simple methods

**Convergence is a general strategy** to holistically understand and transform a system for reaching a common goal **(Roco 2002)**
Convergence is a core opportunity for progress, a general-purpose paradigm in problem solving.

Making the case

✓ Defining the convergence spiral in knowledge, technology and innovation

✓ Basic Concepts theory, principles and methods

✓ Applications and trends convergence for general purpose technologies, production, research & education, governance
Earlier studies on technology convergence
Seven reports on convergence

Coevolution of Human Potential and Converging New Technologies

(M.C. Roco and C. Montemagno)
Convergence: timely, broad opportunity after 2000

- Material unity at the nanoscale and technology integration from the nanoscale, “science beyond the Renaissance ideal”

- Powerful transforming tools (nano-bio-info-cogno-AI system) and technology platforms developing concurrently at the confluence of disciplines, integrated from the nanoscale

- Towards an “universal domain of exchange” for ideas, etc.

- Improvement of human potential becomes possible

- New social relations (adapting organizations and business)

- New opportunities for innovation; for anticipatory, holistic and adaptive governance measures (‘Learning before doing’)

- Needs for increasingly interacting and more crowded world

Refs: 1,2, and 5
Twelve challenging ideas from 2001 NBIC Report that are reality or in development in 2018

- 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

Ref. 5: NBIC Report, 2003
Convergence of Knowledge, Technology, and Society:
Beyond Convergence of Nano-Bio-Info-Cognitive Technologies
Recent Convergence Reports

- **2013**
  - International benchmarking

- **2014**
  - Life, physical and engng. sciences convergence

- **2016**
  - Convergence of health
  - Convergence principles and methods

- **2017**
  - Convergence engineering centers
Defining convergence
1. Defining S&T convergence

Convergence is:

- the deep integration of knowledge, tools, domains, modes of thinking, from a unifying concept for reaching a common goal

- to form new frameworks, paradigms or ecosystems
  – that allows to answer questions, resolve problems and build things that isolated capabilities cannot (*convergence stage for creating new ecosystem*),

- from where emerge novel pathways, opportunities & frontiers for problem solving and progress
  – in competencies, knowledge, technologies, and applications (*divergence stage from the new ecosystem*)

Convergence science – Creating/ changing an ecosystem for a goal based on **10 theories, 6 convergence principles, and specific methods** (Ref 7-10)
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)
3. Convergence of Knowledge, Technology and Society

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

Ref: 6: “Convergence of knowledge, technology and society: Beyond NBIC” 2013
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. Fundamental integration principles
8. Progress asymptote
9. Exogenous revolution
10. Response to social problems

Ref 7: Science and technology convergence, J Nanopart Res (2016) 18:211
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 learning and 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

Ref 7: Science and technology convergence, J Nanopart Res (2016) 18:211
A. Interdependence principle
in nature, technology and society

The interdependence:
- determines coherence of processes in the system:
  structuring, transformation, convection, diffusion
- new interdependencies determines system changes:
  changing the links, nodes, and overall system in time
- requires system view w. team approach: team science

Examples
- Communication across cells in a tissue or organism (ecosystem)
- Changing the manufacturing / enterprise: from vertical and large to more distributed and specialized because of the connectivity
- Societal polycentric system
- Circular solutions in science and economy
The innovation spiral is pulled by the added-value goal, through interactions 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)
Examples of spiral patterns in the convergence-divergence cycle

- **In nature**: Various shapes of tornados

- **In thinking**: Combining computational, directional reasoning ("left brain") and interferential, lateral creativity ("right brain") leads to a spiral pattern

- **In general**: DNA spiral, bio-evolutionary spiral; innovation evolutionary spiral, stellar spirals . . .: fractals of a higher order principle?

Ref 10: Handbook of science and technology convergence (Springer, 2016)
Innovation index in a convergence process

\[ I \sim k(S,E) \frac{S^2 O}{T^3} \]  

- **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)

(Ref 6: CKTS Report 2013)
Example convergence-divergence opportunities: cellular phone

_Coincidental convergence:_

- **Creative phase:** Confluence energy, environment, cognition, security, electronics, personalized learning, healthcare.

- **Integration phase:** Including high-frequency communications and packet switching protocols; data storage, touch screens, antennas, and cognitive science and human–computer interface technologies.

- **Innovation phase:** Smart phone and its platform, form groups.

- **Outcomes, spin-off phase:** Social networks, controlling swarms, inexpensive miniaturized satellites, healthcare and many other examples affecting virtually every aspect of our society.

MC. Roco, Feb 20 2018
“Endless Column”, sculpture by C. Brancusi (1937)

Convergence-divergence elements
C. System-logic Deduction in learning, decision making and problem solving

Results are better if larger system with faster information circulation

- Multi-disciplinary input (bottom-up)
- Convergent-divergent Cycle input (evolutive)
- Peer lateral input
- Long-range input
- System-logic deduction
- Societal-scale platform
- Earth-scale platform
- Human-scale platform
- Foundational tools (NBIC)

MC Roco, Feb 20 2018
D. Example unifying cross-domain languages

Universal laws for system architectures

(Ref. 8, 2015, based on concepts suggested by Turing; Doyle and Csete)
E. Confluence of resources leading to system changes (the S-curve)

(Ex: GAO-14-181SP Forum on Nanomanufacturing, Report to Congress, 2014)
F. Vision inspired discovery and inventions are essential for the future of innovation

Modified Stokes diagram

<table>
<thead>
<tr>
<th>Pure Basic Research (Bohr)</th>
<th>Use-inspired Basic Research (Pasteur)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empirical, less useful (Merlin)</td>
<td>Pure Applied Research (Edison)</td>
</tr>
</tbody>
</table>

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

Relevance for applications

Ref 5: “Convergence of Knowledge, Technology and Society: Beyond NBIC” (Springer, 2013)

MC. Roco, Feb 20 2018
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?

Convergence is both:

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

Using integrative approaches in convergence aims at:

a general strategy for creating value-added (cost benefit; ex gene sequencing) and changing the system (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

(Ref 6: CKTS, Springer, 2013)
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)
Perceptions

“Convergence” is not

- Not “just multidisciplinary research” - Convergence is a goal-driven process of a system that may include various disciplines, sectors and players creating new entities, and then spinning off in to new capabilities and applications.

- Not “just coincidental links” - convergence is an interactive, purpose driven process, with node contributions. Ex: Links alone may lead to “information silos” or “eco chambers”.

- Not “top-down governing” - but governance is dominated by horizontal links and self-organization principles.

- Not “just a large number of contributors” - but how they collectively interact and contribute to the goal.

MC Roco, Feb 20 2018
Three hierarchical stages of S, T & I Convergence

I  Nanotechnology
II  Foundational NBICA
III  Society ecosystem
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-AI Converging Technologies
   “NBICA”
   Integrates foundational and emerging technologies
   from key basic elements using similar system
   architectures and dynamic networking

III. Convergence of Knowledge, Technology and Society
    “CKTS”
    Integrates the essential platforms of human activity
    using six convergence principles
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
I. 2000-2030 Convergence-Divergence cycle for global nanotechnology development

(Based on Roco and Bainbridge, 2013, Ref. 7, Fig. 8)
1. Nanotechnology programs: S&T divergence

Control of matter at the nanoscale

U.S. National Nanotechnology Initiative, 2000-2030
Nanotechnology papers in all SCI extended journals in the Words of Science, in 2000-2016, by five regions.

2000 - 2016 worldwide annual growth rate ~ 15%

“Title-abstract” search by keywords (International perspective on nanotechnology papers, patents and NSF awards (2000-2016), J. Nanoparticle Research, Nov 28017)
Twelve global nano trends to 2020
10 year perspective, 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, APM
- **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 **integrated** capabilities
- **Energy** photosynthesis, storage use – solar economic
- Enabling and **integrating with new areas** – bio, info, cognition
- **Earlier** preparing nanotechnology workers – system integration
- Governance of nano for societal benefit - **institutionalization**
II. Nano-Bio-Info-Cognitive Converging Technologies

**NBIC 2001:** NSF Workshop “Converging Technologies for Improving Human Performance: *Nano-Bio-Information-Cognitive*”

**NBICA 2015:** added “*systems Artificial Intelligence*” as a foundational emerging field affecting human performance

Synergistic combination of 5 foundational emerging fields from their basic elements (*atoms, bits, genes, neurons, logic step*) up and using similar system architecture concepts, for common core goals such as learning, productivity & aging
II. Emergence & divergence of foundational NBIC

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

II. U.S. emerging S&T initiatives

National Information Technology R&D
(nitrd.gov) (with coordinating office)

National Nanotechnology Initiative
(nano.gov) (with coordinating office)

Materials Genome | Photonics | NNI Grand Challenges

Biological centered
Biomedical / Health focus
Precision Med

Architecture, Life, Human-technology

BRAIN Initiative
(whitehouse.gov/share/brain-initiative)

National Robotics Initiative

Artificial Intelligence

Big Data
National Strategic Computing Initiative

OSTP

Brain-like Computing: Smart systems

Ref 10: “NBIC”, in Handbook of S&T Convergence, 2016

M.C. Roco, Feb 20 2018
Ex II. Examples of NBIC domains (2005-2017) 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)
Ex. II: Nanotechnology-inspired Grand Challenge

“Brain like computing”

combining National Nanotechnology Initiative (NNI), National Strategic Computing Initiative (NSCI) & BRAIN Initiative

• Nanotechnology-Inspired Grand Challenge for Future Computing (DOD, DARPA, DOE, IARPA, NSF), announced by OSTP in Oct 2015: http://www.nano.gov/futurecomputing

• 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.”
Ex II: Intelligent cognitive assistants
2016 workshop (sponsored by NSF, SIA, SRC)

Systems harnessing new machine intelligence and problem-solving capabilities to work collaboratively and enhance human cognitive and physical abilities - by assisting in working, learning, interacting with new cyber-physical systems, transport, healthcare, and other daily activities.

Ref: Intelligent Cognitive Assistants (ICA) report, 2016; and ICA2-2018
The report is available on: www.nsf.gov/nano and www.semiconductors.org/issues/research/research/
About 5% of total NSF new awards since 2009
III. Convergence of Knowledge, Technology, and Society

For societal benefit, human development

Innovative & responsible governance - System behavior

System feedback

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” 2013
An integrated vision for the future society
(including UN Millennium Development Goals; advanced by S&T)

(Sustainability, Resilient Infrastructure)

(Human Development)

(Productivity, Wellness, Healthcare, Education Access)

(MC Roco, Feb 20 2018)

(Ref 5: Convergence of Knowledge, Technology and Society, 2013)
Convergence of Knowledge and Technology (CKTS) leads to

III. U.S. global society-oriented initiatives

- SunShot GC (DOE..)
- Climate Action Plan
- Strategy for Arctic Region
- Global Change Research Program (Global Change.gov) (with coord office)
- Asteroid GC (NASA..)
- Space Station (NASA..)
- Smart and Connected Communities
- I-Corps
- Innovation
- Infrastructure
- Aging Population
- STEAM Education Initiative (NSF, DoEd)
- Societal
- Earth
- Human
- NBICA
- Productivity, Sustainability, Equality, Safe

Advanced manufacturing:
National Network for Manufacturing Innovation (NNMI)
(http://www.manufacturing.gov/nnmi) (with program office)

(Ref 8: “Principles and methods that facilitate convergence”)
A network of 14 translational manufacturing institutes

https://www.manufacturingusa.com/institutes
Ex III: 14 Manufacturing USA Institutes

Deloitte report (2017): The Power of Connections is a Key Advantage

Addressing the “valley of death”
~ 1,200 core organizations in an inter-industry Network comprised of > 9,000 organization networked/coordinated

Organizations in the outer “fans” - take advantage of the convening of Institutes
Organizations in the center of the network - help steer the direction of the network.
**Ex III: 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**
Several opportunities of implementation of convergence

- Production processes
- Biomedicine, science and engineering
- Individualized learning
- Research and Education
- Intelligent cognitive assistants
- Citizen science
- Governance (local, national, global)
- Sustainability/global change (at NSF)
- Smart communities
Convergence in advanced production

• The increased interactions - determines a change to "cloud" production (distributed growth with the Internet of Things)

• Exchanges of models between various domains – leads to "trading zones" production

• Penetration of foundational technologies – leads to NBICA manufacturing (nano-, bio-, digital-, cognitive-, and combined 2-4 technologies, including Modular production)

• “Smart” production (incl. Artificial intelligence)
Convergence in advanced production

- Converging “supply chains” from concept to internet, production and use – leads to “cyber-physical-social” production
- Integration of design methods, manufacturing and service lead to several fast growing areas, such as: IT equipment convergence, sensors-computer-medical devices convergence
- Considering the overall effects of production over life time of events leads to: life-cycle design, benign by design, ethical governance.

MC Roco, Feb 20 2018
Examples of BNCT activities (2017-2018):

- Harnessing Converging Technologies for the Next Production Revolution
- Gene Editing in an International Context: Scientific, Economic and Social Issues across Sectors
Convergence is the deep integration of knowledge, techniques, and expertise to form new and expanded frameworks for addressing scientific and societal challenges and opportunities, with two primary characteristics:

1. **Deep integration across disciplines**, from which new frameworks, paradigms or disciplines can form from sustained interactions across multiple communities.

2. **Driven by a specific and compelling challenge or opportunity**, whether it arises from deep scientific questions or pressing societal needs.

Ex: Upstream: **Germination**; Downstream: **Innovation Corps**

www.nsf.gov/od/oia/convergence/index.jsp
NSF Overview

- 2014-2016 topic funded by NSF mostly on hills (using full text proposals)
- 2017 Convergence awards in the valleys
Examples for: Convergence methods in research

• Higher-level abstraction, unifying multidomain perspective and methods of investigation

• Funding the gaps between fields (such as using private foundations flexible funding, SGER, etc.)

• Bring together academic (high-level deliberations, depths in selected areas) with industry (sense of urgency and integration because of external factors) perspectives

• Big 10 Ideas – accelerating research through convergence
2016 NSF 10 Big Idea  \textit{(a. research)}

- Understanding the Rules of Life: Predicting Phenotype
- Shaping the New Human-Technology Frontier
- Windows on the Universe: Era of Multi-messenger Astrophysics
- Navigating the New Arctic
- Data science
- The Quantum Leap
2016 NSF 10 Big Idea

- INCLUDES: Enhancing Science & Engineering through Diversity
- Mid-scale Research Infrastructure

- NSF 2050: The Integrative Foundational Fund
- Growing Convergent Research at NSF
Examples for:
Convergence methods in education

• Trading zones among various areas of relevance

• Confluence of topics: bringing together
  - Feasibility topics (science and engineering),
  - Desirability topics (art and humanistics) with
  - Viability topics (economics and management)

• Using higher level languages (such as music, mathematics, virtual reality connecting fields, value and intellectual driven fields, etc.).
Ex: Schematic highlighting six axes of integration required for convergence of knowledge & technology to further education

(CKTS 2013, Courtesy R. Chang)
Example in Education:

National Convergence Technology Center illustrated for Collin County Community College, CA
www.connectedtech.org

The National Convergence Technology Center (CTC) leads the Convergence College Network (CCN), a group of 50+ community colleges and universities from across the country that shares resources and best practices at both regularly scheduled meetings and special one-off webinars.
Several trends
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
Opportunity: National convergence knowledge and technology office

- decisions to be taken by considering all the factors in a systematic way; bring more coherence and information flow
- not only connection, but approach how to do it considering creativity/invention/innovation path, longer-range connections and potential for the future

Goal: increase added-value by improving the innovation spiral, synergism among programs, vision driven projects, with limited additional cost
Would you formulate a new concept / tool for identifying / creating a field of science & technology?

What:
- Identify or formulate a S&T trend and propose a macro-level & longer-term (across domains, disruptive, anticipatory..) solution
- Imagine the future with convergence

Examples:
- Brain like computing
- Intelligent cognitive assistants
- Microbiome

“Endless Column”, sculpture by C. Brancusi (1937) suggesting the convergence-divergence process in 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 committee on Converging Technologies (2014-)
Related publications

1. “Coherence and Divergence of Megatrends in Science and Engineering” (Roco, JNR, 2002)
4. NANO 2020: “Nanotechnology research directions for societal needs in 2020” (Roco, Mirkin & Hersam, Springer, 690p, 2011a)
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. “Science and technology convergence, with emphasis for nanotechnology-inspired convergence” (Bainbridge & Roco, JNR, 2016)
10. HSTC: “Handbook of Science and Technology Convergence” (Bainbridge & Roco, 2016)