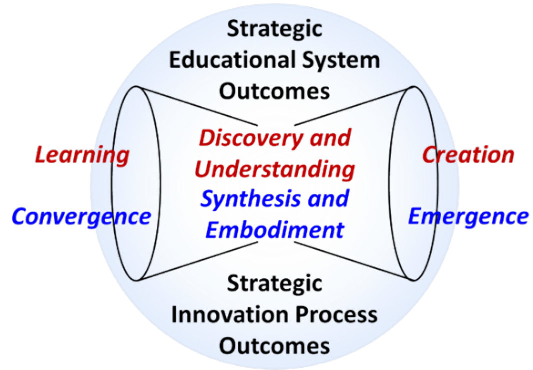
Global Perspectives in Convergence Education

November 2-3 2017
Washington DC
Workshop Report

Convened by:

The National Science Foundation
The Organization for Economic Cooperation and Development
The U.S. National Academies of Science, Engineering, and Medicine
The U.S. Department of State
The University of Southern California



Acknowledgements

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Sponsors

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This report describes discussions during the workshop and incorporates additional perspectives on convergence education provided by participants following the meeting. Any opinions, conclusions, or recommendations are those of workshop participants and do not necessarily reflect the views of the convening organizations or meeting sponsors.

Report located at: *www.nsf.gov/nano/ConvergenceEducation*

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Executive Summary

NSF defines convergence as the deep integration of knowledge, techniques, and expertise from multiple fields to form new and expanded frameworks for addressing scientific and societal challenges and opportunities. Convergence refers to not only the convergence of expertise across disciplines, but also the convergence of academic, government, and industry stakeholders to support scientific investigations and enable rapid translation of the resulting advances. With the continued growth in science and engineering knowledge, and the growing evolution toward deep interactions among and between the various academic disciplines, convergence is becoming a real challenge to the education communities.

This workshop, sponsored by the National Science Foundation (NSF), the Organization for Economic Co-operation and Development (OECD), the U.S. National Academy of Sciences, Engineering and Medicine (NASEM), and the University of Southern California (USC), addressed the outlook and needs across the stages of education; an integrated approach was necessary since the stages of education - from K-12 through adult continuing education – are highly interrelated. Given the already extensive number of years needed to complete formal education, and the ever growing extent of knowledge, it is important to make learning more effective to avoid growing the number of years needed for formal education. It will also be important to engage continuing education since an individual's time in the workforce, and the knowledge needed to be effective, will both be continuously growing. Finally, education has become more global than ever, so participants were invited from around the world to share experiences and lessons learned.

The workshop started with plenary sessions to set the stage and provide context on the current state of convergence and convergence education. This report includes a summary of those presentations with a bibliography of materials cited in each. The plenaries were followed by breakout sessions with both formal presentations and group discussion. Each breakout session emphasized developing prioritized, actionable recommendations to address the challenges of convergence education. These sessions were focused on:

- teaching convergence and responsible science via the concept of "grand challenges;"
- incorporating convergence into curricula and continuing education programs;
- developing mechanism(s) to keep abreast of the changing workforce education needs;
- identifying how best to "synchronize" or properly coordinate changes in educational institutions and society with changes in funding agencies;
- understanding the science of team science and its role in convergence education;
- elucidating new technologies for advancing convergence in education and training; and
- coordinating and fostering global convergence education via enhanced communication amongst national science funding agencies and multilateral fora to coordinate and foster global convergence education.

Recommendations for action items are incorporated in each of the breakout session section, and a second time, in a Key Findings (KF) section, which was parsed by education level or by overarching topic. At the closing session the various recommendations were discussed, but prioritization came from a subsequent e-mail request to the workshop participants. The top rated action item for each level/topic is:

Education Level
K-12
Observation: Teachers and other educators are struggling to implement convergence education and, in the U.S., the STEM education framework advanced in the Next Generation Science Standards (NGSS) which addresses convergence.
Action Item KF1a: Develop communities of practice that enable educators and community members to discuss challenges, share best practices, and implement changes in a structured, controlled fashion.

Community Colleges / Technical Colleges
Observation: Community Colleges / Technical Colleges are often models of industry-academe collaboration. But to be most effective at incorporating convergence into their curricula, they must sharpened their efforts.
Action Item KF2b: Work towards educating community college / technical college instructors in STEM fields to promote involvement in societal Grand Challenges and to share the potential benefits to their students, their institutions and their own professional development.

Undergraduate
Observation: One of the fastest ways for universities to bring out new knowledge to society is via the students and their entrance into workplaces.
Action Item KF3b: Develop a conceptual framework that would draw on the expertise from transdisciplinary fields to explore the details of a unified program center focused on addressing the challenge of convergence, learning, data analytics and workforce. The NSF Engineering Research Centers could provide a prime opportunity for such an effort. The NSF Research Experiences for Undergraduates (REU) awards also provide an untapped opportunity. They are currently managed within individual NSF directorates and few are focused on convergence.

Graduate
Observation: The 'Molecular Techniques in the Life Science' masters program, a collaboration among three Swedish universities, is an example where there is an explicit tie of convergence to pedagogical research. This linkage provides an opportunity to identify new convergence competencies for higher education programs.
Action Item KF4: Add a component of pedagogy evaluation / documentation to existing Center-scale convergence education programs.

Continuing Education
Observation: Many private industries, professional societies, and some pockets of academia are quite good at developing teams of collaborative researchers and providing training in communication, management, and leadership. Some of these have developed hubs for educating and training researchers on best practices.
Action Item KF5a: Develop mechanisms for dissemination of best practices; coupling this with funding agencies or other hubs for training could be transformative. Further, opportunities exist

to leverage resources such as the National Cancer Institute's Team Science Toolkit.

Overarching

Convergence Ecosystem

Observation: STEAM encompasses science communication, in all forms, as an effective vehicle for sharing the joy and wonder of engaging in discovery, and for communicating a compelling need for tinkering, critical thinking and the creative process throughout the formal and informal educational ecosystem, e.g., families, communities, etc.

Action Item KF9a: Focus on holistic convergence education, which creates future workers with enhanced technical and communication skills, instills context, i.e., a holistic awareness of and engagement with key stakeholders, and creates an understanding of their creations' potential implications.

Teaching Aides/Technology

Observation: Accessibility of digital teaching aides is constrained by cost and teacher familiarity.

Action Item KF12: Develop guidance on how to use most effectively the various teaching aides in a convergence environment, thereby minimizing the constraints. Identify lessons learned that could be shared.

Teaming

Observation: The role of team science competencies should be incorporated into educational and training strategies for convergence research.

Action Item KF14b: Provide faculty and senior researchers with training to prepare themselves to do collaborative science. Encourage researchers to include this training in their funding requests and urge funding agencies to pay special attention to these types of requests.

International Collaboration

Observation: The OECD can be an effective contributor toward understanding the implications of convergence education.

Recommendation KF19a: Prepare background information on convergence education to connect with ministers and policy-makers; identify the potential impact on socio-economics.

Funding

Observation: Partnerships among the many education stakeholders (parents, educators, science and engineering communities, government, industry, academe, and foundations) are needed to better identify the changing needs in student knowledge, including the creation of models to assess competency needs and personal learning graphs that address lifelong/life wide learning needs.

Action Item KF21a: Explore with industry and foundations the possibilities for government/academic/industry partnerships to develop new, affordable (including at the K-12 levels and in underserved populations) educational devices that could provide individualized instruction and would better enable convergence education.

Introduction

NSF defines convergence as the deep integration of knowledge, techniques, and expertise from multiple fields to form new and expanded frameworks for addressing scientific and societal challenges and opportunities.[1] Convergence refers to not only the convergence of expertise across disciplines, but also the convergence of academic, government, and industry stakeholders to support scientific investigations and to enable rapid translation of the resulting advances.[2] It has recently gained higher visibility through a number of events. In 2003 a book "Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology and Cognitive Science was published with eight contributions addressing education[3]. In 2013 a book "Convergence of Knowledge, Technology, and Society: Beyond Convergence of Nano-Bio-Info-Cognitive Technologies," summarizing the results from a series of international workshops, was published with Chapter 8 providing an extensive discussion on "Implications: People and Physical Infrastructure."[4] In 2014, the U.S. National Academies of Sciences, Engineering and Medicine (NASEM) released a report "Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering and Beyond."[5] This was followed in 2016 by a MIT study on "Convergence: The Future of Health."[6] Also in 2016 a Handbook of Science and Technology Convergence was published, including twelve contributions addressing education needs.[7] And in 2016, NSF identified "Growing Convergent Research at NSF" as one of its "Big Ideas."[8] In March of 2018 NSF released NSF 18-058, a Dear Colleague Letter: Growing Convergence Research.[9]

One goal of the sciences has always been convergence, but the limitations of the human mind and the complexity of the Universe have compelled the compartmentalization of learning, resulting in the present academic disciplines (mathematics, physics, chemistry, materials, biology, geology, astronomy, …). None-the-less, there have been prime examples of partial convergence in the past sixty years - materials science, information sciences, and nanoscale science and engineering.[10] Some seventy years ago there were no academic departments for these topics, nor funding agency programs. Today there are. Further, in that time frame, the Biological and Geological Sciences have evolved from a more taxonometric practice that had been compelled by complexity to an embodiment more fully based in chemistry, physics and engineering - convergence. The Social and Behavioral Sciences, another suite of complex systems, look to be beginning that same evolution.

To understand a complex entity requires both knowledge of the properties of its simpler components and the ability to synthesize and evolve those simpler properties into system behaviors. A couple of illustrations serve to make the case. Early physics deliberately chose simple systems to limit the complexity and to enable rigorous mathematical formulations. For instance, in earlier years, physics focused on single crystal materials to constrain the number of parameters and to enable solvable mathematics. But physics is now grappling with descriptions of the universe and biological systems, each with far greater complexity. The discipline of materials science and engineering started with separate efforts in metallurgy, ceramics, polymers, but is now dealing with metamaterials, where all of these efforts are intimately mixed together. Again, far greater complexity.

Understanding more complex systems requires far greater reliance on extensive data; that data is beginning to be collected, stored and analyzed. In 2011, the estimated size of the Library of Congress print collections was 10 Terabytes;[11] in 2013, 1200 petabytes were stored and processed on the Internet (Google, Amazon, Microsoft and Facebook). The U.S. NSF-funded Large Synoptic Survey Telescope (LSST) will generate 15 terabytes of data per night mapping the heavens; and NSF's NEON, Earth Cube, and Ocean Observatories will be additional large data providers. There are 1.5 Gigabytes of genomic data per diploid cell in the human body; with on average $3x10^{13}$ cells in a human body[12] and some 7B people populating the earth, that is $>3x10^{32}$ bytes of data (not counting the microbiome). There are several Brain Initiatives in progress around the world; there are an estimated quadrillion (10^{15}) synapses in each human brain.

Large data opportunities have been enabled by advances in State-of-Art (SoA) sensing (digital data acquisition, microsensors), processing (serial, parallel, neuromorphic, quantum), storing (volatile and nonvolatile RAM, and direct access) and communicating (electronic, photonic, quantum). For instance, in 1980, the VIC-20 personal computer had 3.5 KB of usable memory (RAM) and 3MHz clock speed; in 2016, the MacBook Pro SSD had 220GB of usable disk storage and 3GHz CPU clock speed. In the early 1980s, a vestigial internet had ~200 computers connected;[13] by 2015, the number of nodes was estimated at 15 billion.

The convergence of physics/engineering/biology is guiding new computer architecture. IBM introduced its TrueNorth neuromorphic CMOS chip in 2014 and Intel introduced its version, Loihi, in 2017. These chips have dramatically different architectures from past practice and reflect our growing appreciation of how the brain works. One of the expected consequences of neuromorphic computing is more efficient pattern recognition in large data sets.

The new technology sketched above will cause significant changes in education. Dr. Kaiser of MIT has a contribution "Imagining the Future of Technology Assisted Convergent Education – The Future of Convergence Education" in Appendix D3.

Convergence integrates knowledge, tools, and ways of thinking from life and health sciences, social sciences, the humanities and the arts, physical, mathematical, and computational sciences, engineering disciplines, and beyond to form a comprehensive framework for tackling scientific and societal challenges that exist at the interfaces of multiple fields. But it isn't just research discoveries that are motivating convergence. By merging these diverse areas of expertise in a network of partnerships, convergence stimulates transitions from basic science discovery to practical, innovative applications. As just one example of the on-going commercial impact of convergence, nanotechnology presently has a ~$1.5B annual U.S. Federal investment, with equivalent amounts being spent in other sectors of the world. A recent National Academies of Sciences, Engineering and Medicine (NASEM) report on the National Nanotechnology Initiative (NNI) cites ~$200B annual <u>growth</u> in nano-enabled commercial products in recent years.[14] Similar results can be expected from convergent-enabled biomedical technologies; this assertion is a premise of the MIT study, which states that more than $3 trillion per year—17.5 percent of U.S. gross domestic product — is spent in national healthcare expenditures.[6] These examples highlight the fact that there will be new products, and thereby workforce education needs, caused by convergence in science, engineering and technologies.

The OECD Working Party on Biotechnology, Nanotechnology and Converging Technologies (BNCT) has identified a number of convergence instances as part of a general development of the fields of biotechnology and nanotechnology over the last two decades; the BNCT found that the field of biotechnology broadened to include a growing area of topics, while the field of nanotechnology shifted from its original focus on metallurgy- and engineering-centric topics towards the biological sciences.[15]

The awareness that convergence will enable new technologies and require new workforce training is global. The BNCT assisted this workshop's steering committee in formulating the workshop. The workshop representation from international communities ensured the broadest utilization of lessons learned and resource development. In particular, Korea has a well-developed Convergence Education effort (Appendix D.2).

The workshop addressed the outlook and needs for all the stages of education (see Table 1); this integrated approach was necessary since the stages of education are all interrelated. Given the already extensive years needed for education, and the ever-growing extent of knowledge, it is important to make learning more effective to avoid growing the number of years needed for formal education. And it also will be important to engage continuing education, since an individual's time in the workforce, and the knowledge needed to be effective, will both be continuously growing.

Table 1: Stages of Education

1. Primary Grades: Kindergarten (K)-5
   Basic literacy and numeracy, as well as establishing foundations in science, mathematics, geography, history and other social sciences
2. Secondary Grades: 6-12
   Skills required in an increasingly complex society, including the dependence on science and technology
3. Community College (CC)/Technical College (TC): Grades 13-14
   Transfer education – Transfer to a four-year institution to pursue a BS/BA degree
   Career education – Associate Degree and directly enter the workforce
   Developmental – Remedial education for high school graduates
   Industry training – Company pays to provide specific training/courses for its employees.
4. Undergraduate (BS/BA): Grades 13-16
   Career education – Decision makers in business, government, finance, etc.
5. Graduate (Masters and Doctoral Degrees)
   Research toward the discovery of new knowledge/understanding
6. Continuing Education
   Rounding out the knowledge needed for career goals

The goal of an "up-to-date" STEM education is a moving target; the global investment in science and engineering research leads to the continual development of new information and knowledge. The scope of the problem was highlighted on a chart shown by Michael Richey in his plenary presentation (see Figure 1)

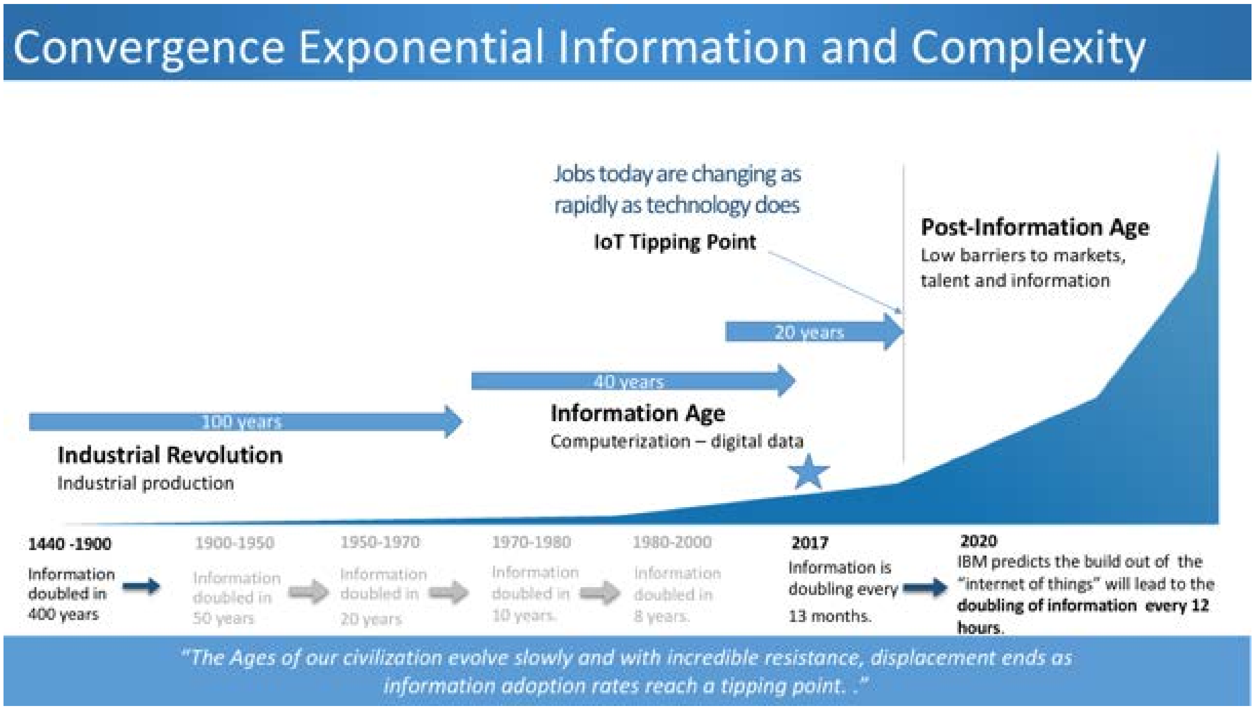

Figure 1: Timeline for Convergence Information and Complexity

According to Richey, it is of utmost importance to stay abreast of this development, in order to adequately prepare society for the disappearance of old jobs and the arrival of new ones.

The challenge to evolve science and engineering content in the various stages of education is not new; progress can be slow and hard to attain. However, one piece of evidence for success in this endeavor has been the incorporation of life sciences, earth and space sciences, engineering, technology, and applications with the physical sciences in the new U.S. K-12 "Next Generation Science Standards (NGSS)."[16] What makes the NGSS distinctive is the integration of crosscutting concepts and science and engineering practices with the core concepts. It's not so much the 'what is taught' (although that has been carefully honed down to truly core conceptual material), but 'how is it taught.' The approach to learning in the Next Gen Standards, as informed by the NASEM Framework,[17] is truly geared to produce convergent thinkers. On the other hand, the absence of meaningful computer science in either the U.S. Common Core (mathematics) or the NGSS standards is evidence of the difficulties in making changes to education.

Plenary Session Presentation Summaries

There is a Bibliography of the reference materials utilized in the following presentations at the end of the report.

Dr. C. Daniel Mote, president of the National Academy of Engineering and Regent's Professor, University of Maryland College Park, welcomed the workshop participants and highlighted the importance of convergence with an example of engineering a solution to bring water to a village, only to find the village women didn't use the local water taps because they valued the time spent together while traveling to the river.

Dr. Mihail C. Roco

Overview: Convergence Science for Societal Solutions and Education

Dr. Roco, drawing from his extensive experience in fostering convergence science and engineering, pointed out that convergence is a general strategy to holistically understand and transform a system to reach a common goal and is a core opportunity for progress. Supplementing his own work in convergence, he pointed to application domain driven reports with a strong focus on convergence.

He defined Convergence as deep integration of knowledge, tools, domains and modes of thinking driven by common goal, to form a new framework, paradigm or ecosystem from where emerge novel pathways, opportunities and frontiers. He cited an illustration with three stages of convergence -Nanoscale Science Engineering Technology, followed by convergence of foundational emerging technologies (Nano-, Bio-, Info-, and Cogno-), and then Convergence of Knowledge Technology and Society. The convergence process involves the escalating and transformative interaction of seemingly different disciplines, technologies, application domains and communities.

Convergence in science and technology is guided by *six principles* that enable or facilitate its effective implementation:

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

Convergence education methods include:

- Integration along disciplines, levels, borders and cultures
- "Trading Zones" among various areas of relevance
- Team Science with a system view
- Incentives for convergence of domains and modes of education in degree accreditation and academic promotion
- Improving interpersonal and intrapersonal training
- Revising organizational structure and regulations to allow convergence processes to be more effective
- Using higher level languages, such as art, mathematical and other abstractization tools
- Confluence of topics by bringing together societal challenges, feasibility (science and engineering), desirability (art and humanities) and viability (economics and management)

He identified the following *global action possibilities*:

- An international convergence network (Convergence of Knowledge and Technology for the Benefit of Society, CKTS)

- Government coordination for "science of convergence," "convergence technology platforms," and workforce preparation
- Manufacturing-, cognition-, biomedicine- and education- convergence are immediate opportunities for implementation with large return
- Create and expand cross-domain programs in universities and funding agencies
- Principles of convergence maybe applied to conflict resolution at personal to international level
- Approach the question of convergence education in international fora, such as the OECD

Dr. Susan Singer

Learning in a World of Convergence

Dr. Singer began her presentation by describing an experience in Zambia where, in a story similar to Dan Mote's, an effort to use genetically modified maize to help prevent loss of sight with young children required convergence of the technical, sociological and business communities. She then illustrated how convergence is beginning to appear in the several stages of education. Starting with K-12, the 2012 Framework for K-12 Science Education explicitly addresses convergence. At the Community College level, *Transform your ideas, Impact your World*, is a NSF Community College Innovation Challenge in its fourth year in FY2018 (https://www.nsf.gov/news/special_reports/communitycollege/ccic-about.jsp). The NSF Advanced Technological Education (ATE) National Convergence Technology Center (http://www.connectedtech.org/) focuses on engaging educators, students and businesses to meet workforce needs through the promotion and implementation of convergence technology degree and certificate programs in colleges across the nation. Dr. Singer noted that the general education requirements at most universities provide an untapped potential to develop key convergence competencies. At the postgraduate level, the NSF Research Traineeship (NRT), Graduate Opportunities Worldwide (GROW) and Graduate Research Internship Program (GRIP) programs all foster convergence. But the challenges/opportunities ahead of us include:

Developing a "convergence creole"
Developing intrapersonal and interpersonal skills
Learning any time, any where
Leveraging technology to enhance and understand convergence learning
Defining and measuring successful learning in a convergent world

Dr. Michael Richey

Convergence in Professional Education

Since his calendar permitted him to be present only part of Thursday, Dr. Richey also prepared some written insights to be shared with the workshop participants (see Appendix D1)

Dr. Richey spoke to the challenges with convergence in professional education. He pointed to the National Academy of Engineering (NAE) Grand Challenge of Advancing Personalized Learning and how the exponential growth in information now coming available (IBM predicts the build out of the "internet of things" will lead to doubling information every 12 hours, rather than the present timeframe of every year). As a case study, he discussed a partnership among EdX MIT, Boeing and MIT to develop a small private online certificate (SPOC) on "Architecture and Systems Engineering," with additional micro-certificates under development. The design principles are based on Siemens (Dr. Siemens is Professor and Executive Director of the Learning Innovation and Networked Knowledge (LINK) Research Lab at the University of Texas Arlington). Leveraging Big Data and Learning Analytics can be used to uncover expert cognitive systems, but the critical path will vary by learner, topic and expertise level.

Recommendations:

- Build a network of transdisciplinary complexity through leaders to address the significant challenges inherent in adaptive networked learning including learning science, network theory and research to practice.
- Explore the cognitive and sociocultural factors related to the new labor economy, evolving demographics and advancements in cyber-physical data rich complex learning ecosystems.
- Explore concepts and methods of this evolution through a complexity lens including the analytical, theoretical and methodological dimensions of data collection within a complex sociotechnical system.
- Co-operative research to characterizing the dynamics of networked information and its computational characterization: adaptive networks, network modeling and analysis; visualization of networks; agent-based modeling.
- Holistic-Transdisciplinary educational opportunities: Consider transdisciplinary teaming research models that expose student to collaborative research.
- Consider funding for alternative educational credentials; for example: low-cost high quality and relevant to workforce certificates and micro-masters.
- Explore alternative future and lifelong learning including the creation of lifelong personal learning profiles, mapping of competencies, and building education–workforce models to anticipate future labor market knowledge needs.

<u>Dr. Amy Jesson-Marshall</u>

AAC&U Perspective

Dr. Jesson-Marshall shared the findings of the American Association of Colleges (AAC&U) and Universities in supporting development of undergraduate competencies that are key to convergence, including teamwork, integrative thinking, intercultural knowledge and competence, global learning, and foundations and skills for life long learning. AAC&U has developed and validated assessments for key competencies that contribute to convergence education (https://www.aacu.org/value-rubrics).

<u>Dr. Steffi Friedrichs</u>

OECD Perspective

Dr. Friedrichs drew on her experience as Policy Analyst for the Organization for Economic Co-operation and Development (OECD) Working Party on Biotechnology, Nanotechnology and Converging Technologies (BNCT). She pointed out that the concept of the ‘convergence of sciences and technologies’ was decidedly different from that of ‘interdisciplinary science and technology.’ The latter maintains the organization of science and technology disciplines in siloes and merely emphasizes the requirement to increase the funding-, education- and research-activities at the interfaces between the siloes, while the former is a phenomenon arising from the loss of the traditional boundaries of classical science and technology fields.

It can be expected that convergence will lead to a “industry 4.0” (see Figure 2)

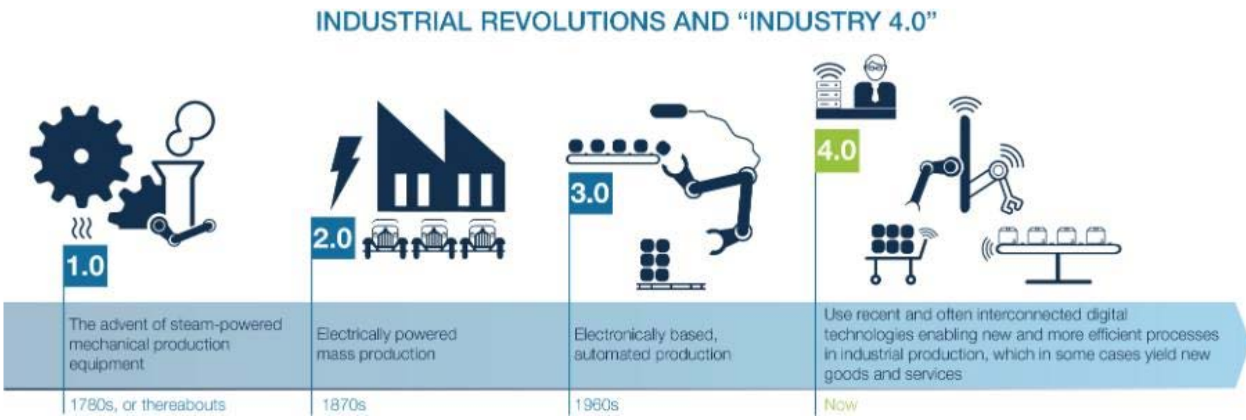

Figure 2. Eras in the history of industrial revolutions

Human Resource Challenges

- Companies - especially start-ups - need generalists, with converging technology (CT) programs perceived helpful
- Companies with in-house R&D prefer graduates from classical subjects
- High demand (and competition) for those people with the right high-tech skills
- Difficult to find quality manager and people with regulatory knowledge

Education Challenges

- How to match the rapid technology change with education/skills
- The pace and scope of technology drive labor market changes and leads to uncertainties
- Education policies need to tackle the problem of uneven job distribution
- Long term thinking (and constant attention) is essential for governments, businesses, educational institutions, etc.
- Effective systems for lifelong learning and workplace training
- Importance of interdisciplinary education and research will rise
- New jobs are likely to be increasingly skilled and need adaptability, problem solving and common sense
- Digital skills and skills that complement machines will grow in importance

<u>Dr. Richard Kitney</u>
Convergence Education in Synthetic Biology/Engineering Biology
Dr. Kitney spoke to the importance of convergence education using his extensive experience in synthetic biology/engineering biology. Synthetic biology seeks to exploit bio-based feedstocks toward new products, in contrast to the now prevalent use of oil-based feedstocks. To accomplish this vision, several Synthetic Biology Research Centres have been established in the U.K. with new undergraduate and graduate curricula. To accelerate innovation (which takes inventions into a commercial product), LEAP (Synthetic Biology Leadership Excellence Accelerator Program) was established utilizing a collaboration between Stanford University in the U.S. and Imperial College in the U.K. Lean LaunchPad (https://en.wikipedia.org/wiki/Lean_Launchpad) is an entrepreneurship methodology to test and develop business models based on querying and learning from customers. It is based on the scientific

method and combines experiential learning with the three building blocks of a successful lean startup. SynbiCITE (http://www.synbicite.com/) is able to offer all its partners the unique opportunity to participate in The Lean LaunchPad for Synthetic Biology.

Dr. Olof Emanuelsson

Three Universities, one MSc Program

Dr. Emanuelsson spoke to the *Molecular Techniques in Life Science* program which he directs at the KTH Royal Institute of Technology (technical) in Stockholm Sweden in conjunction with Karolinsk Institute (medical) and Stockholm University (natural science). As part of a government strategic program in molecular life science, a masters program was mandated in 2012. The first students in the program started in 2015, and to date, most students are international. The students get knowledge of different subject areas and their integration, getting the best from three universities with the goal of graduates that can a) navigate the modern life science landscape and b) contribute to the solution of pressing problems in health care. Lessons learned from the program include:

1) agreement between experts of the involved disciplines hasn't been a major problem, but is in itself insufficient for making the educational program work;
2) admission requirements are important to get right (due to the convergence of many fields of expertise); and
3) listening to the students has helped improve the program.

Dr. Y. Eugene Pak

Convergence Education: A Korean Perspective

Dr. Pak directs the Education Division at the Seoul National University's (SNU) Advanced Institute of Convergence Technology (AICT) which seeks to enable convergence technology by fusing different areas of science, engineering and art. He pointed to the 2016 success of AlphaGo (developed by Google DeepMind) in defeating the 18-time world champion Lee Sedol in the game of Go as a clear "wake up call" to the power of AI. He listed convergence education programs at nine major Korean Universities, with three Korean Ministries providing support. The Association for Convergence Education and Research (ACER) - a partnership of Research Institutes, Universities and Industries - started in 2016, with a kickoff meeting in October 2017. It expanded its domestic network in 2017 and looks to become global in 2019. The Pangyo Techno Valley was initiated to specifically foster convergence with ICT and software perspectives; it includes a test bed city for real world self-driving vehicles intermingled with ordinary cars. Three research platforms for convergence education are: 1) "BioCon Drug Discovery program, 2) the SNU graduate school of convergence science and technology (GSCST), and 3) the AICT XO Center for Wellness Program (XO connotes solving problems with convergence and creativity). (Appendix D2 has more details)

Lessons learned from these efforts:

- Reductionism versus problem solving (convergence) require different approaches
- A common goal (grand challenge) and money are needed to make convergence work
- A convergence leader is like a movie director or orchestra conductor
- Critical mass within physical proximity is important
- Elimination of departmental divisions
- It is sufficient for 10% of the students to be of the "convergence" type

- A good "convergence" student should be self-motivated and have a passion to succeed through convergence
- Big ego superstar professors are not helpful
- Evaluation criteria need include both technical excellence and teamwork
- The human factors are most important

Drs. Rebecca Keiser and Suzanne Iacono
Global Perspectives in Convergence Education at NSF
Drs. Keiser and Iacono spoke to the NSF mission and program with emphasis on the NSF 10 Big Ideas (which specifically includes growing convergence research). NSF has an international engagement which seeks to accelerate scientific advances, leverage NSF investments/resources, and advance workforce development goals. To support the usefulness of international collaborations, they showed a figure from the journal Nature that correlated more highly cited papers with those nations having more scientists coming in and going out.

Dr. Eleonore Pauwels
Artificial Intelligence and Converging Technologies: How to Prepare Students and Society for the Fourth Industrial Revolution?
Dr. Pauwels utilized the convergence of information technology and biotechnology to illustrate the challenges/opportunities, including the tensions between reductionism and complexity, and transparency and dual use. Using an Artificial Intelligence (AI) case study, she examined the challenges for addressing biases and ethics in AI. In a second case study, she cited the on-going convergence of genomics, AI, automation and cloud computing as opening opportunities for more prevalent biotechnology practices outside of the conventional laboratory structures. STEM and Education must be coaligned to make the 4th Industrial Revolution work for everyone. To the extent this can be successful, the consequences will include: the rise of bioinformation, precision medicine, a bio-citizens and entrepreneurs, and more anticipatory AI. As a result the education enterprise must pay attention to:
- Learning by doing
- Mentorship in technology and safety and ethics
- Problem solving, creativity and entrepreneurship

Breakout Sessions

Session 1.1 Teaching Convergence and Responsible Science via the Concept of "Grand Challenges"

Moderator: Dean Evasius, National Science Foundation
Rapporteur: Brian Gray, AAAS S&T Policy Fellow, NSF Office of Emerging Frontiers and Multidisciplinary Activities (EFMA)
Presenters: Dan Herr, Joint School of Nanoscience and Nanoengineering, North Carolina
Heidi Schweingruber, U.S. National Academies

1.1.1 Summary of Presentations
Dr. Daniel Herr
The Roles of Convergence and Responsible Research in Education
Dr. Herr presented on the roles of convergence and storytelling in the development of individual

interest in science and engineering, which built upon the findings of the December 2014 NSF *Nanoscale Science and Engineering Education (NSEE)— Next Steps* Workshop.[30] He shared a number of personal stories and anecdotes to highlight the roles of convergence and hands-on tinkering in his development as a researcher. In particular, he emphasized that for many researchers, there was a period of convergent, often informal, experiential learning, followed by a period of adversity or a catalytic moment that led to an intense phase of creativity, resilience and innovation.

Dr. Herr also presented on the evolution of emergent technologies as a ~30 year process and proceeding in distinct phases: an incubation phase (~20 years), during which ideas converge and coalesce; an innovation phase (~10 years), marked by a synthesis and a translation of ideas; and an emergent phase, in which new technologies or processes are launched or are adopted by industries and others.

In discussing how to identify the next emergent technologies, Dr. Herr advocated that 1) invested parties search everywhere for new ideas, focusing particularly on disruptive technologies; 2) researchers in convergence develop a shared language to exchange ideas; and 3) we utilize the idea of Grand Challenges as posited by organizations like the National Academies of Engineering and the National Science Foundation as signposts of where things may be emerging next.

Dr. Herr also touched briefly on the role of responsible research, concluding that the research community must strive to understand the impact of new technologies on the surrounding ecosystem, and if the consequences are negative, to take action to stop the research. Using a three-pronged approach is necessary: being transparent about the work and its implications, engaging with the broader community, and providing infrastructure for caregivers to engage with youth at much younger ages than we have been doing thus far, i.e., before age 5, in hands-on critical thinking, problem solving, creative and memory exercises, such as through puzzles, block play, drawing, image recognition and reading exercises. In fact, young children are natural convergent learners, and tend to perceive the natural world around them as a synthesis of convergent experiences. The disciplinary siloed educational experience appears to be a trained artifact and outcome of contemporary education, which now must be bridged to address 21st century societal needs and grand challenges. He called for greater alignment and leveraged engagement between informal experiential learning, provided by caregivers, and the disciplinary pedagogy provided by the more formal educational infrastructure.

He discussed that convergence was a necessary but not sufficient step in moving toward responsible research and effective education, and that several other elements were needed, e.g., including: community engaged learning, science communication, industry engaged learning, and math/critical thinking skills, coupled with effective and long-term mentoring approaches.

Dr. Heidi Schweingruber

Research-based insights for teaching convergence via Grand Challenges

Dr Schweinguber organized her presentation around a central question: what important principles should we consider in teaching convergence?

1. Three-dimensional learning is a framework that can be utilized for effective STEM education, including convergence. This type of learning focuses on ‘learning by doing’, and is borne out of the National Research Council’s *A Framework for K-12 Science Education*, and reflected in the Next Generation Science Standards currently adopted by some 20 states. The three dimensions include:

a) Science & engineering practices, developed from studies of scientists engaged in their work
b) Crosscutting concepts, which include overarching themes like patterns, cause-and-effect, models, mechanisms of action, etc.
c) Disciplinary Core Ideas, or discipline specific content

2. Effective and explicit integration of three-dimensional learning is important in order to facilitate educational impacts. Integration requires attending to a variety of elements; namely, we must attend to the disciplinary knowledge that students already possess (whilst building in opportunities to learn necessary knowledge), engage with the social aspects of learning, and support the overall development of student interest in learning.

This integration must be explicit. Often, integration is addressed by presenting a real world context for knowledge, but this alone is not sufficient. Instructors and mentors must draw attention to connections between knowledge areas, and help students utilize different forms of representation to understand concepts. Another key is to help students transfer concepts from one disciplinary realm to another, such as understanding the connection between discussions of ‘energy’ in physics, chemistry, and biology, among others.

Attending to students’ existing disciplinary knowledge is important, and two challenges were noted: 1) students may not recognize when to use their existing knowledge and 2) students may not revise their own understanding of knowledge with respect to experience. Both of these challenges take careful thought and planning to address.

Student interest is paramount in moving education forward - students are much more likely to engage with and develop a deeper understanding of knowledge they find intriguing. One caution here was that the Grand Challenges delineated by the National Academy of Engineering (NAE) and others represent areas where experts have interest, and this may not align with where students feel that their learning should focus. Emotions matter, and emotional investment of students can drive student engagement and learning.

To develop this connection, it’s important to utilize student experiences. Students have extraordinarily diverse experiences and have interacted with many people in a broad range of scenarios, so their interests are likely to reflect that. It’s important for educators to draw students into why Grand Challenges matter, and this might happen outside of the formal education sphere. Broadening participation was also a key discussion point; having diverse perspectives in the classroom represents a tremendous asset and research suggests that increased diversity of perspectives leads to greater creativity and innovation. Educators can support this in a number of ways:

- Allowing for “productive struggle” in which students can experience success

- Providing enough time for students to complete assigned activities as well as their own explorations
- Building in purposeful interactions with other students
- Emphasizing connections to both real-world applications and prior experience
- Developing an open learning environment with sustained inquiry experiences

1.1.2. Discussion

Central themes that emerged were:

- How best to integrate convergence (and more broadly, NGSS) into educational settings
    - It was widely acknowledged that this shift in teaching/education leads to discomfort for students and instructors
    - Contributors briefly shared some best practices among educators and noted a few models of effective professional development
    - A key recommendation was to develop a community of peers who can support one another and share their integration experiences
- Understanding the evidence on the effectiveness of these approaches in K-12 and higher education
- Recognition of the importance of informal education opportunities
- From an industrial viewpoint, being able to define a problem in the first place is a major issue – this is a skill that current and future leaders and practitioners will need
- Immersive experiences can be potentially transformative, especially in terms of exploring social issues in real settings
    - Several people cautioned that this approach could be exploitative by treating under-resourced communities as a learning laboratory instead of an actual community
    - It is important to include communities and families as equal contributors, especially in terms of identifying problems. Students can be best engaged when delineating issues they face in their own communities, instead of other communities
    - Building on the previous point, there was an admonishment to use students' own experiences to bridge to Grand Challenges instead of the other way around.
- Equity in education loomed large. Several speakers noted that the U.S. educational system excludes many perspectives and has historically suffered from a lack of equity.
    - There was consensus on this, i.e. the challenge of equity, being an unstated grand challenge and an example of an issue in convergence, with recognition that convergence education needs more than scientists and engineers represented; social scientists, policymakers, educators, and community members need to have active roles
    - Discussion of the role of community colleges/2 year institutions can play
    - There are challenges in the promotion and tenure processes in higher education that make it difficult to enact change on a broad scale
    - There was mention of developing communities of practice that can share best practices and highlight exemplars in this arena

1.1.3 Observations, Challenges, and Action Items

A. Educational Ecosystems

Convergence education's strategic goals should anticipate our strategic priorities, address emergent societal needs (and grand challenges),[18] and nurture unconventional perspectives and ideas. As an example, several of the nano-enabled high impact priorities identified in the February 2014 National Nanotechnology Initiative Strategic Plan[19,20] include: nanomanufacturing; nano-bio-info-cogno convergence and emergence; convergence of knowledge, technology, and society and new socioeconomic capabilities.[21] Figure 3 conveys a natural alignment between educational and innovation processes and a convergent infrastructure that uncovers 'new truths' and catalyzes breakthrough solutions to emergent societal needs and grand challenges. The innovation process attributes of convergence, synthesis and emergence nurture and support educational prototypes, e.g., "ugly ducklings." For example, the North Carolina A&T State University / University of North Carolina Greensboro (NCAT/UNCG) Joint School of Nanoscience and Nanoengineering offers team taught electives that bring together and dynamically engage faculty from different disciplines. It also plans to weave common thematic threads through its foundational disciplinary courses. These processes are well designed and positioned to address future needs, rather than to perpetuate entrenched processes.

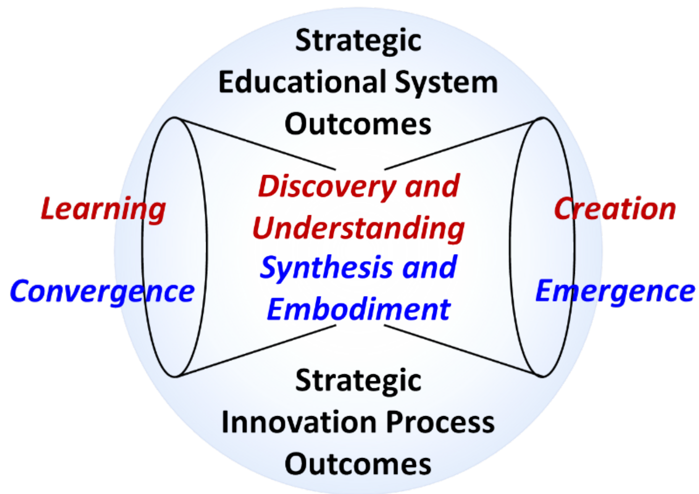

Figure 3. The alignment and parallel nature of innovation and education processes.

Observation 1: How can we (best) prepare future generations of convergence students for careers and leadership positions in such a challenging, dynamic, and uncertain and exciting environment? This question warrants a national discussion on formal and informal educational priorities that leverages ideas from many sectors. As a starting point for this conversation, entrepreneur and social critic Peter Theil suggests several clues as educational and entrepreneurial guideposts, which include: (1) every breakthrough discovery's catalytic moment in history only happens once, (2) there is no cookie-cutter formula that pioneers can follow, and (3) identify a new truth on which few people agree with you.[22]

Action Item #1: Design convergent educational ecosystems that catalyze innovation and breakthrough creations.[23,24]

Observation 2: Students need to be empowered to come up with their own questions based on issues faced in their own lives and communities, but students struggle to generate these questions in the first place.
Action Item 2: Fund research on how to ask big questions and how to create educational ecosystems that support inquiry and promote discovery and disruption.

Observation 3: Teachers and other educators struggle to implement convergence education and the framework advanced by NGSS.
Action Item 3: Develop communities of practice that enable educators and community members to discuss challenges, share best practices, and implement changes in a structured, controlled fashion

Observation 4: Students are motivated by issues they face in their own lives and communities, but sustained investment of time and effort is difficult for even the most passionate students. A convergence ecosystem will be needed to accelerate and adopt convergence education.
Action item 4: Identify and publicize prizes or awards that recognize excellence in convergence science and engineering.

Observation 5: Equity issues abound in many educational systems.
Action item 5*:* Encourage funding agencies to ensure that grants require inclusion efforts.

B. STEAM as a preferred approach to Convergent Education

Convergence education creates a natural environment that nurtures integrated STEAM learning, which includes science (S), technology (T), engineering(E), the arts (A) and mathematics (M). STEAM offers a transdisciplinary and platform-enhanced educational process that promotes disciplinary depth and breadth, as well as a common language, across all disciplines. It helps prepare students for careers that value creativity and innovation. It thrives on hands-on problem solving, critical thinking and communication skills. It also stimulates the discovery, understanding, application, integration, communication of future creations that will impact society, with benefits and risks, and address global challenges. While the STEAM educational paradigm helps to weave together adjacent sectors, e.g., information, energy, transportation, agriculture, healthcare and bio-technologies, it may not be sufficient to provide the holistic perspective that the future demands. Robust convergence education provides a platform, which catalyzes innovation, creativity and communication, and engages and stimulates conversations with other important disciplinary fields, such as the humanities and sociology.[22] Expert voices are needed more than ever in conversations of national and global importance. Scientists can help people understand the many ways that science shapes our lives and our understanding of the world—and, critically, their evidence-based findings and perspective can help in creating sound, scientifically informed public policy.[23]

Observation 6: Within this context STEAM encompasses science communication, in all forms, as an effective vehicle for sharing the joy and wonder of engaging in discovery, and for communicating a compelling need for tinkering, critical thinking and the creative process throughout the formal and informal educational ecosystem, e.g., families, communities, etc.
Action Item 6: Develop holistic convergence education, which creates future workers with enhanced technical and communication skills, instills context, i.e., a holistic awareness of and

engagement with key stakeholders, and creates an understanding of their creations' potential implications.

C. Transdisciplinary Education Ecosystems

Sometimes, terms like multidisciplinary, crossdisciplinary, interdisciplinary, and transdisciplinary are confounded, and tend to be used interchangeably. The pictographs in Figure 4 reflect the following working definitions for these relationships and approaches to problem-solving within the disciplinary hierarchy, which expand upon those proposed by Jensenius, Stember, and others:[25]

- Intradisciplinary - Perspectives and approaches to problem-solving that leverage the knowledge-base within a single discipline. This term also may represent the ultimate state of convergence when traditional disciplinary boundaries give way to a new and blended discipline.
- Multidisciplinary - Perspectives and approaches to problem-solving that leverage the knowledge-base from different disciplines.
- Crossdisciplinary - Perspectives and approaches to problem-solving that leverage another discipline's knowledge-base and coordinate the interface between different disciplines.
- Interdisciplinary - Perspectives and approaches to problem-solving that integrate and synthesize the knowledge-base and methods from different disciplines. For example, interdisciplinary curricula often weave common thematic threads through courses from different disciplines, e.g. applied math, physics, chemistry, and biology. This approach tends to create a common focus, while preserving disciplinary boundaries, with little attempt to establish a common language.[26] "A problem is more suitable for interdisciplinary study when a single discipline appears inadequate, the problem is on the fringe of two disciplines, conceptual integration of previous work is needed, and relevant disciplines appear ready and able to collaborate".[27]
- Transdisciplinary - Perspectives and approaches to problem-solving that create a deep convergence of intellectual frameworks beyond the disciplinary perspectives. A key attribute of transdisciplinary activities is the creation of a common language that enhances conversation among all key stakeholders.

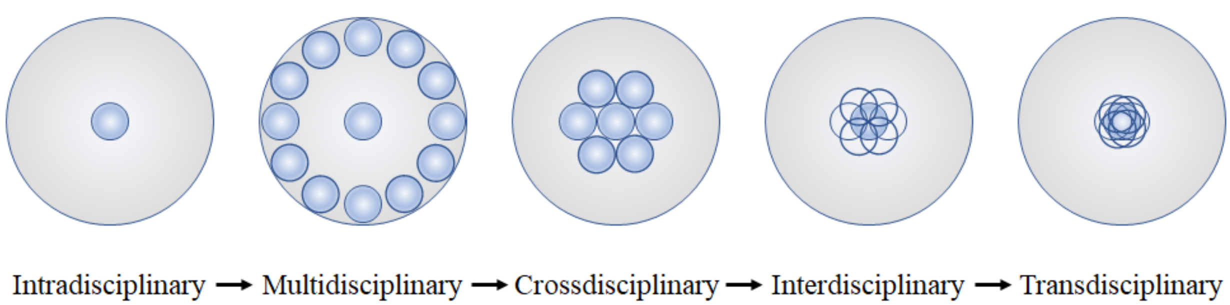

Figure 4. Pictorial summary of the convergent educational trend within the disciplinary hierarchy, including the transdisciplinary educational scenario that builds a common language across all disciplines.[28]

A well-designed educational ecosystem nurtures, leverages, and engages a diverse set of convergent and emergent ideas, inclusive relationships, interdependent networks, and creative hands-on opportunities throughout the formal and informal educational supply chain. Yet, as physicist, systems theorist, and philosopher Fritjof Capra asserts in his classic text, The Web of Life, "diversity is a strategic advantage only if there is a truly vibrant community, sustained by a web of relationships. If the community is fragmented into isolated groups and individuals, diversity can easily become a source of prejudice and friction. But if the community is aware of the interdependence of all its members, diversity will enrich all the relationships and thus enrich the community, as a whole, as well as each individual member. In such a community, information and ideas flow freely through the entire network, and the diversity of interpretations and learning styles-even the diversity of mistakes-will enrich the entire community. The more complex the network is, the more complex its pattern of interconnections, the more resilient it will be. However, if one tries to maximize any single variable instead of optimizing it, this will invariably lead to the destruction of the system as a whole".[29] "We are all interconnected. ... [An educational ecosystem] is not just about the structure and shape of things, but more importantly, it is about our relationships with those things."[30] Such an educational ecosystem thrives on a well networked infrastructure that reflects and engages the natural web of adaptive processes and mentoring relationships. Long term support for these processes and relationships enhances the strategic value of this living educational network for all key stakeholders.

Observation 7: Transdisciplinary environments can greatly enhance a student's educational experience, as they are particularly conducive to accelerating the convergence and synthesis of seemingly disparate ideas into new discoveries and foundational knowledge.
Action Item 7: Begin building a convergent educational infrastructure by weaving common transdisciplinary platforms and thematic threads through curricula. Ultimately, move towards a transdisciplinary educational ecosystem, as defined by the disciplinary hierarchy, shown above. Consider the implications for disciplinary centric versus a more convergent and integrated disciplinary educational infrastructure.

Observation 8: Convergent educational ecosystems, designed to catalyze innovations and breakthrough creations, will train a workforce that anticipates and addresses grand challenges and that provides transformative benefits to society. An educational infrastructure designed to achieve our strategic goals can: 1) Reduce overall educational costs and 2) better enable a skilled workforce to address academic, industrial, and societal challenges and to thrive on a dynamic landscape of emerging career opportunities.
Action item 8: Develop a best practice, evidence-based framework for exercising the emerging innovation process, i.e., a convergent incubation period, followed by a synthesis or 'ugly duckling' embodiment and an emergent innovation period, when addressing 'Grand Challenges' and exploring disruptive opportunities.

D. Success Factors in Convergence Education

Convergence serves as one of several critical success factors for catalyzing and sustaining the educational ecosystem; this point is made in the NSF Nanoscale Science and Engineering Education 'Next Steps' report[31] that provides the desired holistic educational experience. Many of the report's stakeholder sections share common attributes.[32] In fact, it was interesting to analyze selected key word and phrase frequencies in the Nanoscale Science and Engineering Education (NSEE)—the Next Steps' Workshop report.

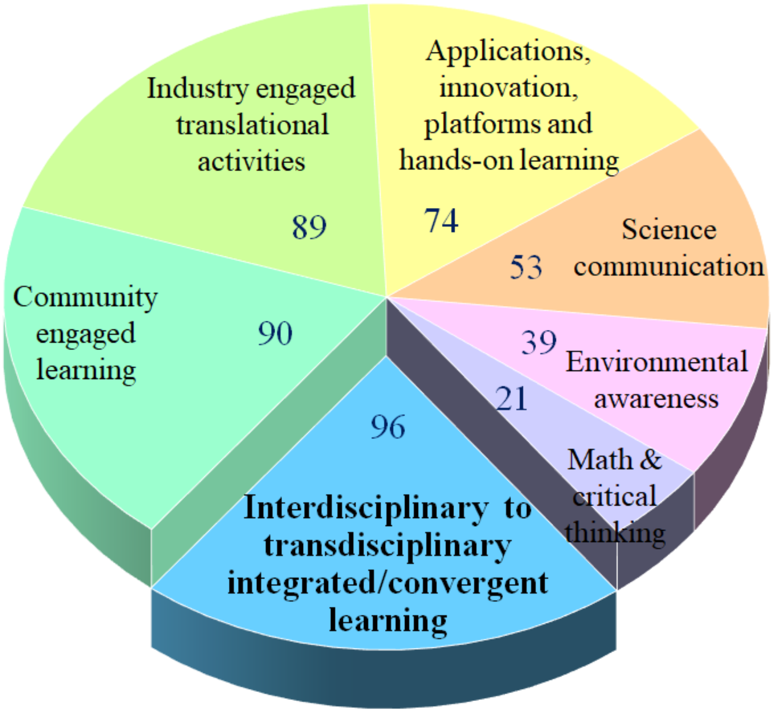

Figure 5. Common attributes of a robust and holistic educational ecosystem.

Figure 5 summarizes the meta-frequency analysis of the Workshop's recommendations, which reveals several shared themes that weave throughout each section of the report. It suggests that a successful educational ecosystem's set of attributes includes: community engaged learning; industrial engaged activities; applications, innovation platforms and hands-on learning; science communication; environmental awareness, as well as math and critical thinking skills; in addition to transdisciplinary and convergent learning environments.

Observation 9: Convergence serves as one of several critical success factors for catalyzing and sustaining the educational ecosystem
Action Item 9: Develop low cost ways to integrate the critical success attributes within and across the formal and informal educational infrastructure. For example, reestablish opportunities to enhance alignment and mutually-synergistic engagements between families and the formal educational infrastructure. Less formal educational settings may serve as one low cost path to nurture convergent experiences, transdisciplinary and hands-on learning, tinkering, innovation and discovery.

Session 1.2 Incorporation of Convergence into Curricula and Continuing Education Programs

Moderator: Y. Eugene Pak, Seoul National University
Rapporteur: Jennifer Brummet, Social Scientist, NSF BCS
Speakers: Jin-Taek Kim, Pohang University of Science and Technology
Fernando Quezada, Biotechnology Center of Excellence Corp
Jorge Huete-Perez, University of Central America

1.2.1. Presentation Summaries

Dr. Jin-Taek Kim

POSTECH CITE: Creative Convergence Education

Dr. Kim described his work in the Creative IT engineering program at POSTECH. The Creative IT program is for engineering students, and uses a convergence approach to teach entrepreneurial skills, creativity, and other skills that might be left out of more traditional engineering curricula. He discussed student-led research projects which can help provide “meaningful failure,” encourage a healthy research culture, and motivate students for strong academic achievement. The program has been around for 6 years, and has about 20 students each year. The students who enter this program as freshmen enter a completely different program and learn many skills.

Mr. Fernando Quezada

Convergence Education Initiatives in Mexico

Mr. Quezada discussed convergence education initiatives in Mexico. He discussed how Mexico is still laying the groundwork, and how there is very little cross-fertilization, very few industry-university links, and lack of technology transfer. He discussed how CONACYT (Consejo Nacional de Ciencia y Technologia) was created in 1970, and funded many projects and intiatives, including knowledge networks. Knowledge networks are competitively funded and include one on convergence of knowledge. The Network on Convergence of Knowledge is centered around the idea of convergence of knowledge for the benefit of society, and to “address the challenges of developing strategies for the design of processes for technological and knowledge convergence.” Traditionally, siloed research, publications, and other facets of academia haven’t rewarded transdisciplinary projects; how can we change processes to encourage innovation and transdisciplinary projects? The Network regularly meets to frame issues, develop curricula, discuss research initiatives, and publish findings. Continuing challenges include reaching policymakers, reaching industry, and working with a multitude of institutions with different agendas.

Fernando Quezada also highlighted that in developing countries there can be a need to concentrate resources and as such, convergence should be approached in different ways. For example, framing convergence from a point of view that highlights the added value of breaking the siloes and tacking issues that transcend individual disciplines to bring overall benefits to society.

Another barrier identified is the emphasis that has been placed at the institutional level on publications. If a researcher and a university’s success is measured largely by the quantity of publications produced, and traditionally staying within one’s silo is seen as the way for conducting research to achieve publications, then there is an opportunity to approach convergent research as a way to conduct more research that spans beyond the silos and can bring more success.

Dr. Jorge Huete-Perez

Strengthening research capacities in Nicaragua: A Convergence Research Approach

Dr. Huete-Perez discussed how to strengthen research capacities in Nicaragua, and how developing countries could benefit from a new, convergent scientific approach. Challenges for convergence research in Nicaragua include educational challenges (the traditional structure, lack of scientific talent), and the need to deal with specific challenges of development and postwar difficulties (corruption, extractivism, and migration). Additionally, Nicaragua is losing many young scientists to other countries. He provided one example of a convergent approach related to the Nicaragua Canal project that provided the framework for the convergence research approach. Challenges in Central America include that the current system favors independent researchers, science is housed in departments with a narrow focus, poor project management and allocation of specific resources, and that interdisciplinary research teams take a long time to organize.

Next, he discussed the University of Central America's interdisciplinary research initiatives. Challenges include departmental structure, lagging in science education, limited funding, and isolated research efforts. Opportunities include two research institutes linked to faculties (individual and institutional capacities), research for training new generation of scientists, basic institutional and specific grants, partnerships, collaboration, and high-quality research. Convergence can help shift some of the challenges into opportunities. There is a research agenda of big-picture questions, e.g., sustainable development, science education, and they are forming partnerships with industry, government, and communities. This agenda has established a way to organize and implement research efforts to confront local problems and respond to global problems. It recognizes that new trends in science and technology need to be applied to address the "local expression of global problems." Convergence research can help developing countries with limited research or resources by maximizing benefits.

1.2.2. Discussion

Fernando Quezada posed a question to the group about how might a convergence ecosystem contribute? Is convergence creating a new area? Is it a combination of existing areas? Is it providing added value? How does it touch upon the classroom? A point was made that we may not want only "jacks of all trades," so perhaps education should remain grounded in a specific discipline. Mexico itself may need to reach a critical mass before moving forward to convergence. Other points made were that smaller resources can mean that perhaps one person can look at something more broadly or be more informed by diverse topics. Convergence does not always mean bringing people together, but bringing ideas together. Having a problem to solve can make it easier to combine resources to address challenging societal problems.

There was a discussion about what happened in Korea to allow its convergence ecosystem to happen. How can we learn from the Korean experience, and what lessons have been learned from other countries? Korea is still generally a very traditional system, but they are trying to find ways to be leaders and not just "fast followers."

1.2.3. Observations, Challenges, and Action Items

Observation 1: There are a growing number of useful assets for convergence education, but they cannot be acquired without extensive work.
Action Item 1: There should be a centralized location to share resources, collected globally, about ongoing convergence education efforts.

Observation 2: The U.S. Next Generation Science Standards (NGSS) are currently being implemented in 19 states and the District of Columbia. There will be lessons learned worth sharing.
Action Item 2: The NGSS progress should be made readily available so other countries can follow these developments. Insights as to what works or not from countries with large scale emigration might be used to guide education efforts for migrants in those countries that are experiencing large immigration.

Observation 3: Creativity is an important aspect in the creation of innovative technologies.
Action Item 3: Universities should incorporate tools that foster creativity into their convergence curriculum. One such example is incorporating elements of the design thinking process into the classroom.

Observation 4: There are a number of ongoing, but rudimentary, efforts towards the incorporation of convergence into the education system.
Action Item 4. It would be worthwhile to encourage a study of a number of countries to understand how "convergence" factors are playing a role in their education structures. Countries from across the GDP spectrum should be included for contrast.

Observation 5: Since funding is usually constrained, it is often useful to leverage other Federal program activities as a potential source of supplemental funding
Action Item 5: As an example, continue to support existing convergent or interdisciplinary STEM funding initiatives. Further, many NSF directorates have STEM education in their programs; they could include the language of convergence within their solicitations.

Observation 6: There are many approaches to the incorporation of convergence into the education process. Look into the feasibility of developing, testing and disseminating workable approaches towards convergence education in the K-12 space as a way to prepare students for the future. A potentially interested partner may be magnet schools.
Action Item 6. Identify opportunities to pilot an effort toward convergence education in the K-12 space. Given their emphasis on STEM Education, magnet schools could be willing partners.

Session 2.1 Mechanism(s) to keep abreast of the changing workforce education needs as convergence in science, industry and economy continues its rapid market penetration

Moderator: William Bonvillian, MIT
Rapporteur: Bushra Akbar, Science Assistant, NSF DRL
Speaker: Margaret Hilton, National Academy of Science

2.1.1 Presentation Summary

Dr. Margaret Hilton

Keeping up with Changing Workforce Education Needs for Convergence

Dr. Hilton noted at the outset that she drew her observations primarily from findings in three National Academy of Sciences (NAS) reports: "Education for Life and Work," "Enhancing Team Science," and "Supporting Students' Science Success." She pointed out at the beginning that the growth of "team science" (collaborative, cross-disciplinary science) is illustrated by professional publications: over 90% of science and engineering publications are now co-authored, usually by 2-10 authors. This was a signal of the growing need for convergence in education. However, she noted that although colleges and universities are now starting to develop cross-disciplinary programs designed to prepare students for team science, and these programs target a variety of collaborative and other competencies, little empirical research is yet available on the extent to which participants learn the competencies targeted by these programs.

To frame the discussion, she indicated that the "Range of Competencies" includes:

- Knowledge (disciplinary grounding)
- Interpersonal competencies (coordination, teamwork)
- Intrapersonal competencies (critical thinking, reflective behavior)
- Values, attitudes and beliefs (positive view of convergence/team science)

The "Domains of Competencies," in turn, include:

- Cognitive: reasoning and memory, knowledge, creativity
- Intrapersonal: openness to others, conscientiousness, positive attitude
- Interpersonal: expressing ideas and interpreting and responding to others, teamwork, leadership
- These domains intertwine

A third aspect concerns "Deeper Learning and Transfer":

- Deeper learning is the process of learning for transfer—the ability to take what was learned in one situation and apply it to another situation
- The product of deeper learning is transferable knowledge, including content knowledge in a subject area, and procedural knowledge of how, why, and when to apply this knowledge to answer questions and solve problems in the subject area.
- The NAS study referred to transferable knowledge as "21st century competencies" to reflect that both skills and knowledge are included.

She noted that we must design instruction for "transfer." This means beginning with clearly-defined learning goals and a model of how learning is expected to develop. Next, we must use assessments to measure and support progress toward such goals. Further, we must provide multiple, varied representations of concepts and tasks. All of this must be in the context of encouraging questioning and discussion, engaging learners in challenging tasks, with support and guidance, teaching with carefully selected sets of examples and cases, and focusing on prime student motivation factors.

In turn, we can use formative assessment to provide feedback. Deeper learning of interpersonal competencies, in fact, requires improved assessments. Dr. Hilton concluded that this literature leads to the following recommendation: we must more clearly define and develop assessments of what the Academies reports have termed "21st century competencies" for workforce education, especially interpersonal and intrapersonal competencies.

This approach can be taken in two initial steps, she noted:

- Step 1 involves clarifying the dimensions of the competency to be measured.

- Step 2, once these are clarified, involves development of assessments. There are various assessment models available for this step; examples include:
    - Self-rating (prevalent but with well-documented limitations)
    - Others' ratings
    - Biographical data/personal essays
    - Interviews
    - Performance assessment
    - Behavioral measures
    - Situational judgment tests

Educational institutions traditionally assess and reward content knowledge (cognitive competencies). However, they don't evaluate interpersonal competencies. Higher education success, for example, is related to content knowledge (measured through GPAs, grades, and graduation). However, team and other interpersonal competencies may be important to later success in the workplace. Improved assessments would enable teaching interpersonal competencies for transfer and allow institutions to grade students on these competencies. Furthermore, awarding grades for teamwork and other interpersonal competencies would recognize and reward competencies needed for convergence and throughout the national economy.

Research in contexts in and outside of science has demonstrated that several types of team training improve team processes (i.e., interpersonal competencies) and outcomes. She cited the MIT Koch Institute's "Crossfire" program for interdisciplinary exchanges so that researchers working in one field can call on expertise in others, its "Engineering Genius Bar" system for information sharing across disciplines and across research efforts, and its "The Doctor is In" program that brings MDs from outside the Institute into the research design process, enabling access to additional disciplines and expertise.

In conclusion, she found that the research suggests that effective convergence in education, including workforce education, requires:

- Intertwined cognitive, intrapersonal, and interpersonal competencies (knowledge and skills).
- Instruction can be designed to teach transferable cognitive competencies, but improved assessments are needed to develop transferable interpersonal and intrapersonal competencies.
- Convergence teams require continuing cross disciplinary education and training.

2.1.2 Discussion

Workforce education, a growing need in the U.S. and other countries in light of declining employer support of training and continuing requirements, due to technological advance for workforce up-skilling, requires a new focus on a range of competencies. This includes a growing employer emphasis on interpersonal skills, including teamwork. The participants discussed the need for education for competencies as opposed to content; competency requires more of a convergence approach as a foundation for pursuing interdisciplinary efforts and for “team science.” In summary, workforce education in the future will require more of an inherently convergence approach.

Comments emphasized the need to focus on skills and knowledge that can lead to learning competencies, on the need to develop much better assessment of these competencies, and on the need for design principles, to structure learning around what can be assessed and can be taught. The transfer process was also emphasized as an important focus and goal. In general, comments pointed out that convergence requires teams, and therefore the inter- and intra-personal competencies need priority alongside traditional content focus.

There was extensive discussion of the importance of teambuilding as a workforce skill increasingly sought by employers. Elements discussed included the importance of creating trust and cohesion; behind these, the importance of shared understanding of goals was noted as a key contributing factor, which can be obtained through common team reflection together. In general, an approach of strategic “cross-training” for teaming skills was noted. In military settings, corresponding research efforts on how to achieve strong teaming has underscored the importance of such team training.

Rapidly changing teams also present challenges. Here, the importance of leaders sending signals supporting teaming, to support the culture of even a short-term organization, was felt to be significant.

In response to a question about strong examples of workforce education exemplifying the above points, a participant discussed the I-BEST (the Integrated Basic Education and Skills Training Program, https://www.sbctc.edu/colleges-staff/programs-services/i-best/) program for adult learning at Washington State as a quite constructive example. Used in Washington State’s community and technical colleges, I-BEST uses a team-teaching approach where students work with two teachers in the classroom: one provides job-training and the other teaches basic skills in reading, math or English language. Students see the connection between better jobs with technical skills, and the need to improve basic skills; one reinforces the other. The program reportedly significantly increases both skill acquisition and graduation rates for certificates and degrees. Students get the basic skill help they need while studying in the career field of their choice in a “learning-by-doing” approach. According to the commenter, I-BEST challenges the standard idea that students must move through a pre-arranged sequence of basic education or pre-college remedial courses before they can start working on certificates or degrees. The combined teaching method, with basic skills combined with a work setting, allows students to work on college-level studies without delays for remedial catch-up – the catch-up is part of the process. Other participants also noted this program as a workforce education success.

2.1.3 Observations, Challenges, and Action Items

Observation 1: Deeper learning of interpersonal competencies requires improved assessments.
Action Item 1: There should be investment in additional research, development and validation of new intra-inter-personal competency assessments that address the shortcomings of existing measures.

Observation 2: There are a number of team training efforts going on globally, but those efforts remain largely unassociated.
Action Item 2: Team-training researchers, universities, and science team leaders should partner to translate, extend and evaluate the promising organizational training strategies, creating continuing education opportunities for science teams.

Session 2.2 How best to "synchronize" or properly coordinate changes in educational institutions and society with changes in funding agencies?

Moderator: Richard Kitney, Imperial College London
Rapporteur: Ashley Gordon, University of Southern California
Speaker: Robert Chang, Northwestern University

2.2.1 Presentation Summary

Dr. Robert Chang

A Framework for Convergence Learning

1. Why emphasize K-12 education? Young kids are the most curious, willing to ask questions and daring to try something new. We have learned that it's ideal to introduce convergence culture at that age.

Although the U.S has the most highly sought-after STEM programs at the University level, most of the highly trained students in U.S. universities/colleges come from abroad. Why is that? Although NSF has been investing heavily in STEM education for many decades, the U.S. STEM education suffers a lack of integration (horizontal, vertical, and national) and is not as effective as it might be.

- *Horizontal* (between disciplines) – has been fragmented, missing the "Technology" and "Engineering", and lacking societal/economic relevance (inspiration & motivation)
- *Vertical* – "a mile wide and an inch deep" with little core mastery, there is no continuity between grade levels, and much of the material is outdated.
- *National* – logistics (in the U.S. there are 50 states and more than 50 sets of learning standards); counties implementing reforms can cause an equity problem (school funding being based on the wealth of the community the school is based in).

The NGSS is an attempt to remedy these problems. Other challenges include a lack of trained teachers (80% of teachers teaching outside major); textbooks are too expensive, go out-of-date quickly, and lack content aligned with new standards.

2. The U.S. needs a new paradigm that takes all of the above into account in developing a new educational system for a sustained national impact - an Integrated Systems Approach with:

- Vertical integration for smarter spending and better returns
- Horizontal integration to train systems-thinkers and collaborators
- Community integration for collective impact – regional and national
- Integration of learning settings to broaden access and support community-based learning

Systematically implementing these strategies nationwide would advance U.S. STEM by 2 years.

The establishment of community-based regional convergence educational programs could:

- Equalize access – including the use of digital/mobile delivery to reach the masses
- Extend learning beyond the classroom (in real space & online)

- Reinforce advanced concepts with interactive simulations, modeling, tools, and games
- Personalize content to support diverse learning styles & narrow achievement gaps

2.2.2 Discussion

What is the distribution of top-down versus decentralized educational models in the the world? The U.S. is pretty unique in how decentralized its educational system is. It has around 15,000 relatively independent school districts instead of a nationwide school district like in Mexico, France and the U.K.

The university system in the U.S. is very diverse in terms of standards and requirements and we don't have the pressures of something like the A-Levels to go to college. The U.S. system is better at not stifling individuals because there are many paths to college without the pressure of having to pass a test to go to college. The other countries with more rigorous requirements for college have better outcomes in terms of preparedness, but lack in creativity because of the pressure to pass the tests to get in to college.

How does one teach creativity? At some level it's not teaching, but allowing people to take risks. The U.S. system is relatively forgiving of failure; it gives people the freedom to be creative. When the consequences of failure are tremendously high, people are less likely to take chances. Korea, as a second example, is currently being very intentional about teaching creativity. In Korea, they move very fast on changing things in their curriculum. They've been focused on increasing technology to facilitate creativity. But they are finding mixed results because it's hard to measure creativity.

The funding streams for educational institutions in different countries are quite diverse. In the U.K., they use research funding agencies only for research. Anything focused on education is done with the Ministry of Education. There is some tension in the research community, in the U.K., over how the Ministry of Education decides what should be in the curriculum. The research community does provide a lot of input on what the Ministry of Education should be doing. It's similar in Mexico. The worst thing that happens is that it's extremely standardized and there's no room for modification. In such places, the private schools are where the flexibility comes in.

If one wishes to foster convergence education, it is important to convince the textbook and testing companies that convergence would be a lucrative change. Textbook companies, testing companies, and assessment companies all have monetary incentives and motivations that might have different goals and needs.

Is there a way for funding agencies to incentivize more community and industry funding to be directed toward schools? At the federal level, money might be distributed to schools based on the number of students in poverty. But there's just not enough funds to solve the "poverty" issues and there's a strong focus for these things to be locally decided. At local and regional levels, increasingly, industries are trying to interface with local colleges and universities. Is there a limitation to that approach? Is there a concern to having the convergence funding relying too much on industry's goals instead of general scientific research goals? The difficulty of industry injecting funds into education is that it's not always been a productive investment. For example, the Zuckerberg injection of money into the Newark school district caused structural issues and the funds were not used as effectively as they might have been.

2.2.3 Observations, Challenges, and Action Items

Observation 1: Frequently major change is facilitated through the use of pilot projects.
Action Item 1: Assist selected magnet schools in piloting efforts toward convergence education. Use those example schools to show how convergence would work in the real world.

Observation 2: In 1985 NSF gave MIT $20M to set up the first Bioprocessing Engineering Research Center. It had three conditions: 1) have an interdisciplinary focus, 2) involve undergraduate students, and 3) reach out to industry. This has been a highly successful program.
Action Item 2: The next generation of ERCs include Engineering Convergence Research Centers that have convergence education requirements. It could be listed as an option, a priority, or a mandate. Other NSF Center-scale solicitations might also formally incorporate convergence education requirements.

Observation 3: It would be worthwhile to encourage a study of a number of countries to understand how these factors are playing a role in their educations structures. Countries from across the GDP spectrum should be included for contrast.
Action Item 3: Organizations such as the OECD and the Global Research Council could institute such studies.

Observation 4: There is growing appreciation of the importance of convergence in education, but there is no central resource to provide ready access to pertinent materials.
Action Item 4: There should be a website (which infers an organization to keep it current) to share resources about ongoing convergence education efforts.

Observation 5: The U.S. NGSS is gaining momentum. Its implementation will provide successes/failures with value to others addressing similar goals.
Action Item 5: The NGSS development/progress should be made more available so other countries can follow these developments. Conversely, insights from lesser developed countries as to what works or not might be used to inform education of the migrant populations in the developed countries.

Session 3.1 New Technologies for Advancing Convergence in Education and Training

Moderator:	Dan Herr, Joint School of Nanoscience and Nanoengineering, North Carolina
Rapporteur:	Brian Gray, AAAS S&T Fellow, NSF Office of Emerging Frontiers and Multidisciplinary Activities
Speaker:	Kara Hall, National Cancer Institute, NIH

3.1.1 Presentation Summary

Dr. Kara Hall

Science of Team Science: Informing Convergence Education

Team Science is an approach to conducting research with two or more researchers in order to address scientific and societal issues. Team science takes place within complex social, organizational, political, and technological milieu that heavily influences how that work occurs.[33] Importantly, SciTS provide key insights into the formation and functioning of effective convergence research teams.

Dr. Hall described a continuum of disciplinary integration: disciplinary work within a single field, multidisciplinary work in which researchers from multiple fields work together in a sequential fashion, interdisciplinary work in which researchers from different disciplines work together jointly with little integration of the disciplines, and transdisciplinary work, or convergence, in which a shared conceptual framework is developed and utilized.

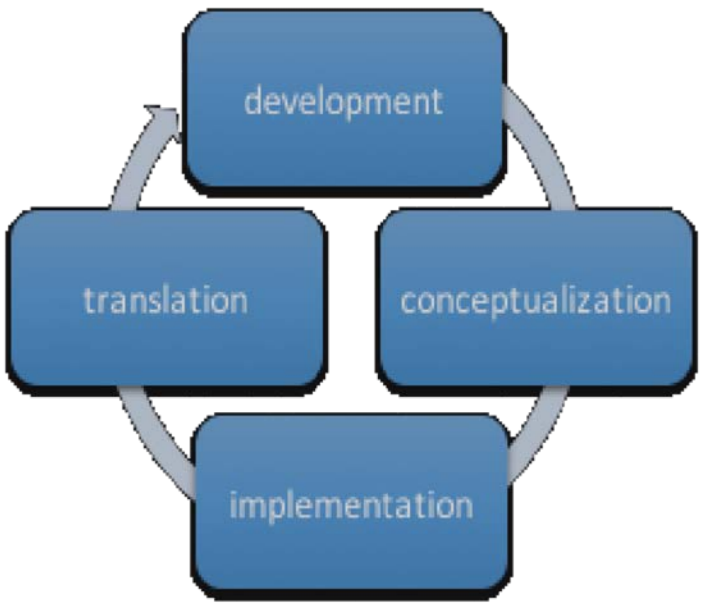

Figure 6. The four phases of convergence research[34]

Convergence research follows a four phase model, illustrated in Figure 6.

- In the *development* phase, researchers define the problem space; elucidate critical elements of the problem; identify key players and physical resources; and begin to develop a sense of psychological safety within the group. In short, the researchers are beginning to develop a shared mission and goals, develop critical awareness of the scope of the issues and the resources available to address them, and externalize group cognition (e.g. by putting things down on paper).
- In the *conceptualization* phase, the researchers develop shared mental models and associated questions, put forward a shared operational language, and establish a team ethic and work culture.
- In the *implementation* phase, the researchers determine who is responsible for completing particular tasks and develop an overall workflow. This is a phase of team learning, as well.

- In the *translation* phase, the researchers apply the findings from their work to advance progress in other areas, which feeds back into the development phase of a new convergence question.

The four-phase model emphasizes a culture of sharing and involves high level of interpersonal interaction; as such, a number of challenges may arise, exacerbated by the focus of convergence research on problems of great magnitude. These challenges may include:[35]

- *conceptual and scientific challenges* – convergence research is particularly prone to having a lack of clarity in terms of the research approach and a lack of role models; moreover, convergence research naturally stretches the intellectual and logistic capacities of individual researchers, being more complex in nature than disciplinary work.
- *cultural issues* – each discipline possesses its own values, language, and research traditions, and researchers within these fields operate within a comfort zone informed by these values and language.
- *incentives/recognition and academic norms* – the current model of academic incentives for promotion and tenure has not yet caught up to the new paradigm of convergence research; moreover, colleagues may not be familiar with convergence research, thereby representing a gap in informal incentives/recognition.
- *management* – Dr. Hall noted that “many scientists are comfortable with being a leader but not with being a manager”; management is a time-intensive, learned skill that involves high levels of introspection and compromise. As such, this expertise is a key challenge for scientific research teams, particularly as they move toward convergence: physical distance between researchers at different institutions can be difficult to overcome, and as the number of participating institutions increases, there often is a trend toward utilizing fewer coordination mechanisms – a counterintuitive approach that takes considerable foresight and effort to mitigate.

Dr. Hall then discussed the competencies critical for researchers in areas of convergence, focusing on those that allow for successful and effective outcomes.[36]

- *intrapersonal competencies* – being able to understand oneself and how one might contribute to a research challenge is important in developing a robust team of researchers who can work with one another; possessing an open mind and being willing to learn and ask questions is also key
- *disciplinary awareness and exchange* - knowing one’s own field well enough to contribute; this means also being very familiar with and able to evaluate the key assumptions inherent with a discipline. Finally, being able to share and communicate assumptions and knowledge is critical.
- *processes of integration* – key skills include a spirit of collaboration, the development of shared frameworks with other team members, and being able to grow/modify the nature of the collaboration (including who comprises the team) as the project progresses
- *teamwork/management & leadership* – salient points here include being able to build trust among team members and develop effective, open channels of communication in service of facilitating teamwork
- *competencies of function* – in contrast to disciplinary competencies, this involves being able to ensure that the proposed work gets done and that the knowledge that is generated

is disseminated in an effective fashion

Dr. Hall then shifted to how we might train researchers to be effective in convergence by understanding team science. In particular, understanding the needs of teams can help inform the research. In forming a team, researchers must consider the following:

- What kind of integrative approach is needed and why? There are many ways to form teams and to develop effective working relationships, so understanding the best approach for a particular team matters.
- Once a team is formed, the considerations shift a bit. Teams have unique dimensions, and knowing how to bring together disparate researchers to contribute effectively to the team is a critical skill. This skill typically involves high levels of preparation before any research is conducted.

There are many ways to integrate the principles of team science into education and training. In short, best practices focus on the development and application of strategies that integrate and promote cross-disciplinary perspectives and approaches. Developing a culture amenable to convergence is best achieved utilizing a two-pronged approach:

- In training current researchers, we need a top-down approach focused on ensuring that faculty and other researchers are comfortable operating in a convergence atmosphere. This may take many efforts: changing how promotion and tenure practices operate, providing support in learning how to communicate effectively, providing management training, etc.
- In training young researchers and students, the best strategy is likely to be a bottom-up approach that focuses on engaging students to learn and gain experience in convergence research incrementally and with increasing complexity.

3.1.2 Discussion

A senior researcher noted that he had struggled with managing a team recently, and asked for feedback. Two strands of thought percolated from the discussion:

a) Developing negotiation and management skills over a long period of time is helpful, and is needed in the educational realm. These skills are particularly important for convergence research because as the complexity of issues increases, the need for mediation also increases. Ensuring students have continual experience with incrementally more complex issues lays the groundwork for successful mediation, as they become senior researchers.
b) In the short term, utilizing frameworks and explicit agreements for the conduct of research within a team may prove useful.[37] These frameworks and agreements can take the form of 'prenuptial collaborative agreements,'[38] or touchstones with associated sets of expectations plans that all researchers agree upon prior to working together.

Issues of disparities in power among team members arose, especially in response to the concept of collaborative agreements. Several participants noted that there is often a highly unequal structure of power among even senior researchers, and this can be exacerbated with the addition of junior researchers and students. Further, this unequal power sharing might lead to an inability or unwillingness to recognize key contributors, especially if promotion and tenure schemes fail to adapt to changing research paradigms. Some suggestions for reconciling such inequities were to develop explicit outlines and recommendations for how convergence research these issues should proceed with teams of collaborators; in this case, a recent National Research Council report '10 Components to Plan for Team Science Success'[39] might be a useful tool.[40] For students and junior researchers, a 'welcome letter' outlining expectations[41] and operational procedures within a research team might be useful.

Developing a sense of true psychological safety within research teams is important, and discussion here centered on how to best do this while taking into consideration the often unequal distribution of power within a research setting. Shared opinions mostly focused on the idea that providing researchers with greater experience in handling uncertainty and decision-making (see above) will go a long way toward improving the situation.

There was a recognition that a major barrier to team-based research may be the static nature of promotion and tenure schema, and these will likely need to be reworked as the face of research continues to change.

Building on the theme of adapting promotion and tenure scheme (and incentives writ large), there was discussion of why researchers might be resistant to adopting convergence practices. In particular, many researchers view working as part of a team as less productive than working individually. Research on transdisciplinary science shows that there is an initial lag period, in terms of productivity when researchers work with one another, with productivity lower for the first four years or so; however, there is a huge acceleration of productivity after year four, and this increased level of productivity is sustained over the long term.[42] Building in an expectation of needing to navigate a growth period, then, would be useful for researchers entering the convergence sphere.

Team productivity became a central discussion point, with lots of perspectives about how differently structured teams might experience different levels of productivity (itemized below). This was viewed as particularly important given that 90% of all STEM research is now done in teams.[43]

a) One key point was that some funding agencies are now using evidence of successful team dynamics as part of the decision-making process. As one participant noted, "collaboration is where teams fail. If a team can't work together, then the intellectual merit of the project is moot."
b) Some general trends were noted: smaller teams tend to produce more disruptive work that define new fields or expose gaps in current fields, whereas larger teams tend to produce 'building blocks' critical to a field or discipline.
c) Academic teams with a 'flatter' structure tend to be more productive than those with a more defined hierarchy, within limits. Very large labs do not benefit from a flatter structure, and large labs need to balance managing people against reducing psychological safety by reinforcing authority.
d) Multi-national, multi-university, and multi-disciplinary teams generally outperform less complex teams. And as team science increases so does research impact, yet the productivity of a team may be reduced as more universities are involved due to insufficient use of coordination mechanisms.[44,45] Adequate resources and strategic management is critical for realizing the success of team science. For instance, dedicated resources are especially important for enhancing productivity, including funding, shared

websites and datasets, committed leadership, as well as staff who can devote time to a team science project (e.g., graduate students and postdocs with funding from a given project team).

e) This led into a brief discussion on what sorts of leadership traits would be most useful in scientific settings. Transformational leaders tend to do well, especially those focused on vision and engagement with their team and less on transactional issues. Again, mediation and communication skills were deemed paramount. However, Dr. Hall noted that there is little formal research on leadership within scientific teams and its effect on productivity.

3.1.3 Observations, Challenges, and Action Items

Observation 1: Key team science competencies should be matched to educational and training strategies for convergence research.
Action Item 1a: Strategically engage students to learn and gain experience in convergence incrementally and with increasing complexity as student progress through education levels (a 'bottom-up' approach)
Action Item 1b: Provide faculty and senior researchers with training to prepare themselves to do collaborative science. Encourage researchers to include this training in their funding requests and urge funding agencies to pay special attention to these types of requests

Observation 2: Research on team science, particularly in inter-, multi-, and transdisciplinary fields indicates variation across areas of science and context.
Action Item 2*:* Conduct more research within and across fields and contexts in order to codify and validate recommended strategies that match target areas.

Observation 3: Many private industries and some pockets of academia are quite good at developing teams of collaborative researchers and providing training in communication, management, and leadership. Some of these have developed hubs for educating and training researchers on best practices.
Action Item: Develop mechanisms for dissemination of best practices; coupling this with funding agencies or other hubs for training could be transformative. Opportunities exist to leverage resources such as the National Cancer Institute's Team Science Toolkit. [46,47] One specific suggestion was for funding agencies to include the '10 Component to Plan for Team Science Success' in grant applications, which focus on elucidating the key indicators of team configuration relevant to projects. Several participants noted that incorporating this into the funding process might speed adoption of best practices.

Session 3.2 New technologies for advancing convergence in education and training

Moderator: Kate Stoll, MIT Washington Office
Rapporteur: Ashley Gordon, University of Southern California
Speaker: Kurt Thoroughman, NSF Program Director, Science of Learning
Chris Kaiser, MacVicar Faculty Fellow, MIT

3.2.1 Presentation Summaries

Dr. Kurt Thoroughman
The NSF Science of Learning Program

The problem of convergence, we as societies created. We're the ones that decided the information was discrete. Even though we're now trying to break down information siloes, there is still some benefit from having some form of the silo. In the carrying out of the missions of each NSF directorate, there is collaboration between the directorates. Also, individual core programs live within each directorate, which are natural homes for interdisciplinary projects; they can develop basic theoretical insights and fundamental knowledge about learning.

NSF also uses special program solicitations. These solicitations allow for larger duration, broader collaboration. They're tailored and have limited opportunity. Many directorates might participate in a single solicitation. Solicitations that could be relevant to convergence would include: *Cyber-learning for Work at the Human-Technology Frontier* and *Integrative Strategies for Understanding Neural and Cognitive Systems.* These bigger solicitations work because the directorates and individual programs connect and collaborate to make them happen.

In the past NSF, funded Science of Learning Centers (SLC); the Social, Behavioral and Economic Science (SBE), Biological Sciences (BIO), Computer, Information Science and Engineering (CISE), Office of International Science and Engineering (OISE), Education and Human Resources (EHR), Engineering (ENG), and Mathematical and Physical Sciences (MPS) Directorates were all involved in the development of SLCs. Presently, the NSF's Division of Behavioral and Cognitive Sciences (in the Social, Behavioral and Economic Sciences Directorate) has a program on Science of Learning (PD 16-004Y), which provides an opportunity for continued growth to the communities that address learning.

NSF has identified Ten Big Ideas to drive NSF's long-term research agenda. Two are particularly relevant for this workshop:

1. *Work at the Human-Technology Frontier: Shaping the Future* – Understand how constantly evolving technologies are actively shaping our lives and how we in turn can shape those technologies, especially in the world of work.
2. *Growing Convergent Research at NSF* – Integrate knowledge, tools, techniques, and modes of thinking from widely diverse fields to address pressing societal problems and profound research questions.

Dr. Chris Kaiser

Six Insights from Developing Digital Education Tools at MIT

The main value to MIT of Massive Open On-line Courses (MOOCs) and other digital educational tools is their portability. They enable educational advances developed at MIT to be readily shared with other institutions.

The problem with the flipped classroom model is that we don't yet have something good with which to replace the classroom time. The lecture hall experience is meaningful in its own right, so that's why MOOCs haven't taken over the whole learning process.

Introduction of MOOCs through MITx/EdX opened the possibility to be free of the constraints of Lecture/Problem Set/Exam format. It forces you to examine the basic functions of what you actually want to achieve. MOOCs have devalued content delivery and have raised the ante on teaching things like creativity, and creative problem solving. Information Technology (IT) has shifted the emphasis of how a lot of our classes have been taught.

The new education technology offered by MITx/EdX created new career paths for young people interested in careers in education. It has been hard to position students who wished to teach because they couldn't compete against the experience of established teachers.

Digital simulators are a mechanism to give students practice in the design and interpretation of experiments. Simulators also have the capacity to generate large amounts of data which can compel the use of statistical tools to extract meaning from the data.

Engaging, realistic assessments can be a compelling means to provide useful feedback and to show students what is important. We found it crucial to match the mode of learning to the mode of assessment. For instance, if a simulator is used to teach, it is important to use a simulator for assessment.

In many respects, Ed Tech companies are better suited than educational institutions to develop education software platforms. The optimum partnership seems to be – Ed Tech for platform; Ed Institution for content

3.2.2 Discussion
There are a couple of different perspectives to convergence education: 1) technology can improve technical know-how of convergence education, 2) but how do we address the societal concerns and do we need technology to do that?

Some problem-solving platforms can be used in a highly collaborative way across universities. These technologies should not replace campuses, but should enhance them. A common theme is that we're looking for these technologies to be helpers, enablers, enrichers – support rather than replace. The technology should be adaptive and not prescriptive. With the continuing proliferation of new education technologies, if we're going to move forward, we have to take a convergent approach to educating for convergence.

We may have to figure out how to leap forward with new technology, past the current bottlenecks on access (i.e. how mobile computing allowed countries in Africa to bypass the problem the U.S. has with increasing broadband access). But the technological disparities are growing instead of shrinking. It would be useful to undertake a study to figure out why there is such a huge disparity in making these tools more useful in different countries. Higher Education at the Margins[48] - as an example - provides higher education in refugee camps and creates facilitators in their own communities; maybe this can be a model for new programs or initiatives.

A potential priority is to have people who have some kind of a sense of where the world is going with regard to this technology. If they could figure out what qualities schools should instill in young people to help them function in this world, it would be very useful. There is value in learning from the students how to teach them better. The students will show you what the world looks like from the perspective of a non-expert. It's different from an expert view. It's not always a good way to learn from the expert view.

There would be value in starting a national conversation about the skills the students will need by 2026 and beyond. What are we funding today that will enable that in the future? We have to clarify what are the pertinent topics.

In education innovations, there are so many groups that create nodes, then there come networks, but there's not often times where you see networks connecting to networks. There might be some benefit from connecting global networks. Are there any programs that support that? Several levels within NSF have a good framework to think about upcoming opportunities. There might be a white paper stage that is asking communities for input on what would be opportune.

3.2.3 Observations, Challenges, and Action Item

Observation 1: Teachers need to know better how to get students prepared, this includes both the use of new education technologies as an education resource, as well as the skill sets a student needs to function in the coming society.
Action Item 1a: Start a conversation about the skills the students will need by 2026 and beyond, including those efforts that are being funding today.
Action Item 1b: Develop and disseminate expert guidance on how to implement these technologies in the many communities that are included in the various nations around the world.

Observation 2: 'Higher Education at the Margins' provides higher education in refugee camps and create facilitators in their own communities; efforts such as this might be a model for new programs or initiatives.
Action Item 2a: Do a landscape analysis that will identify the players who are getting educational technologies to low resource communities, such as the Higher Education at the Margins program, and what they are already doing to get these technologies universally adopted. How are they being used? How can they be improved?
Action Item 2b: Undertake a study to figure out why there is such a huge disparity in making these tools more useful in different communities/countries.

Session 3.3 Communication Among National Science Funding Agencies and Multilateral Fora to Coordinate and Foster Global Convergence Education

Moderator: Lisa Friedersdorf, Director, National Nanotechnology Coordination Office
Rapporteur: Sarah Flores, Science Education Analyst, NSF EHR DGE
Speakers: Finbarr (Barry) Sloane, NSF EHR

3.3.1 Presentation Summary

Drs. Finbarr Sloane and Anthony Kelly
Capacity for Convergence Science in STEM Education Research
One of the present NSF programs is "Smart and Connected Communities." Its projects are expected to pursue research and capacity-building activities that integrate multiple disciplinary perspectives and undertake meaningful community engagement. For education, the program expected novel computing technologies related to education and learning (including cyber-learning) and advances in theories of learning. Disappointingly, very few of the received proposals centrally engaged STEM Education and none were funded by EHR. As we move

forward. There is a clear need for STEM education research addressing community-centered convergence science and to link STEM Education Research to:

- Cyber-physical systems
- Novel uses of data science and data modeling
- Emerging methods of experimental design
- Transportation systems
- City planning and services

3.3.2 Discussion

The current K-12 and Higher Education enterprises are missing key elements to produce the kinds of educators, and conditions needed for the kind of approaches and outcomes desired through convergence education:

- It is unclear how the current community, as is, can plug into the convergence education effort; there would need to be changes, and looking into the near future, there will be a limited change in K-12 education in the U.S.
- There is no ownership in Higher Education that produces the teachers that are needed to teach the type of education that convergence requires. The teacher community is grossly underprepared to teach convergence to take on this challenge.
- Because scientists are experts in a subject area, it cannot be assumed that they have expertise in learning and pedagogy. There is not a close connection with the people who are studying learning.

Gaps and questions identified towards achieving convergence education:

- How do we overlay a science of learning and science of education?
- How do we prepare those who go into the sciences so they can learn in convergent environments?
- What does it mean, in practice, to build convergent scientists?
- What is the baseline knowledge for teachers who are teaching convergence sciences? This is nuanced when there are multiple audiences (K-12, Undergraduate, Graduate)
- Are there best practices in assessment of outcomes? How do we know interventions are working? There will be a need to identify a set of indicators – STEM learning while in school and the retention post school.
- One needs a certain amount of competency before entering the convergent space – when and how do we know that competency is sufficiently built?
- How do we engineer situations for people to come and work together?
- How do you identify when a new field grows outside of its ‘home’ field?
- Changing the culture around pursuing non-academic careers: what are the different career tracks in the life sciences. Academics should not see alternative career tracks as less than the academic track.

Challenges to a Global Approach:

- Best-practices and evidence-based approaches for global convergence education will be hard to apply given that early education is so different from country to country. To this problem, one could “draw a line,” which indicates what the kids should learn and retain toward choosing a career. Then we need to push them into the convergence arena later. After learning foundational knowledge in a STEM field, a student can approach STEM education within a convergent education context

- Foster and leverage – how do we take some of these local best practices, and move them forward?
- Are science funding agencies set-up to have any influence on education? In the U.S., the NSF has demonstrated investments in this arena, but this is not the case equally around the globe. The frame of our meeting/task, in asking if there is an opportunity to coordinate through national science funding agencies does not apply globally. For example, in Chile science funding resides within the ministry of education, but that is not the case in other countries.
- How do we strengthen training and competency-development of research scientists across the globe? There is an opportunity to frame this approach with the mobility that international collaboration provides.

3.3.3 Observations, Challenges, and Action Items

Consider solutions that:

- Identify funding for alternative models for graduate education.
- Identify lessons learned from existing interdisciplinary and convergent NSF STEM education programs and approaches
- Prepare background information to connect with ministers/policy-maker: identify socio-economic impacts as this will help with engaging these stakeholders and garnering their support.
- Enable a much more focused discussion to move forward: perhaps around a specific topic, in a subfield, e.g., biotech.
- Identify ways to infuse convergence approaches into post-graduation/education: Allowing people to become experts in an area, and then showing them pathways for entering the convergence space from their specific field, and developing practices for incorporating convergence education after students complete studies in their specific fields.
- Build more partners: Need to identify other fora where the education and the science of education is the focus of those groups.
- Engage Private funding players: look to philanthropic, and industry partners to forge more public-private partnerships. Look to conveners and connectors to pursue this work, such as professional societies.
- Bring together National Science and Education Agencies, and multilateral partners: for example, the OECD, Inter-Academy Partnership, Academy of Science for the Developing World, Global Research Council, World Economic Forum, Industry Associations, AAAS, UNESCO, African Academy of Sciences, and others.
- Rethink ways in which we provide opportunities for doctoral students to have learning experiences. Let the people who want to do so, follow the tradition of working on a thesis. But we currently have a singular competency model for the learning experience that is not readily amenable to alternative approaches.

Observation 1: The Bioinformatics program currently in place at three Swedish Universities is an example where there could be a tie to pedagogical research. For example, identify the new competencies this program produces to understand new, convergence competencies for higher education programs.
Action Item 1: Add a component of pedagogy evaluation, as well as documentation to existing convergence education programs, to quantify impact and better understand the success and challenges of approaches.

Observation 2: The Global Research Council serves as a global network and forum. Funding agencies around the world meet through this Council annually. There are 5 regional meetings that take place annual. The meeting planned for this year will focus on merit review and another on science diplomacy. There is an opportunity to elevate the discussion on convergence education in this setting and to engage funding agencies from around the globe
Recommendation 2: Suggest to the GRC that convergence education be the focus of a future meeting.

Observation 3: The OECD can be an effective partner toward understanding the implications of convergence education
Recommendation 3a: Prepare background information on convergence education to connect with ministers and policy-makers; identify the potential impact on socio-economics.
Recommendation 3b: Identify ways to infuse convergence approaches into post-graduate education; develop practices for providing convergence education after students complete studies in their specific fields.
Recommendation 3c: There is a need to share best practices and lessons learned in teaching convergence. Note: best practices and lessons learned are not the same as a comprehensive body of knowledge based on evidence; there should also be an effort to develop that body of knowledge.

Key Findings (KF)

Selected observations/action items, already identified in the breakout sessions and in the general discussions, are parsed below according to an education level where appropriate, or as an overarching issue in curricula, technology/teaching aides, teaming, international collaboration, and funding.

K-12 Education Level

Observation KF1: Teachers and other educators are struggling to implement convergence education and, in the U.S., the STEM education framework advanced in the Next Generation Science Standards (NGSS) which addresses convergence.
Action Item KF1a: Develop communities of practice that enable educators and community members to discuss challenges, share best practices, and implement changes in a structured, controlled fashion.
Action Item KF1b: Assist magnet schools in efforts toward convergence adoption.
Action Item KF1c: The NGSS progress should be made readily available so other countries can follow these developments.
Action Item KF1d: Insights as to what works, or not, from countries with large scale emigration might be used to inform education efforts for immigrants in the more developed countries.

CC/TC Education Level

Observation KF2. Community Colleges / Technical Colleges are often models of industry-academe collaboration. But to be most effective at incorporating convergence into their curricula, they must be sharpened their efforts.
Action Item KF2a: Identify ways or strategies for active recruitment and inclusion of community colleges/technical colleges in the societal Grand Challenge approach to education, thereby exposing students to the utility of convergence.
Action Item KF2b: Work towards educating community college / technical college instructors in STEM fields to promote involvement in these societal Grand Challenges and to share the potential benefits with their students, their institutions and their own professional development.

Undergraduate Education Level

Observation KF3: One of the fastest ways for universities to bring out new knowledge to society goes via the students and their entrance into workplaces.
Action Item KF3a: The research funding organizations should set solicitation requirements for larger research programs to address convergence in higher education.
Action Item KF3b: Develop a conceptual framework that would draw on the expertise from transdisciplinary fields to explore the details of a unified program center focused on addressing the challenge of convergence, learning, data analytics and workforce. The NSF Engineering Research Centers could provide a prime opportunity for such an effort. The NSF Research Experiences for Undergraduates (REU) awards also provide an untapped opportunity. They are currently managed within the directorates and there are few focused on convergence.
Action Item KF3c: There is need to share best practices and lessons learned in teaching convergence.

Graduate Education Level

Observation KF4: The 'Molecular Techniques in the Life Science' masters program, a collaboration among three Swedish Universities, is an example where there is an explicit tie to pedagogical research. This linkage provides an opportunity to identify new convergence competencies for higher education programs.
Action Item KF4: Add a component of pedagogy evaluation / documentation to existing Center-scale convergence education programs.

Continuing Education Level

Observation KF5: Many private industries, professional societies, and some pockets of academia are quite good at developing teams of collaborative researchers and providing training in communication, management, and leadership. Some of these have developed hubs for educating and training researchers on best practices.
Action Item KF5a: Develop mechanisms for dissemination of best practices; coupling this with funding agencies or other hubs for training could be transformative. Opportunities exist to leverage resources such as the National Cancer Institute's Team Science Toolkit.
Action Item KF5b: Identify how to utilize best Professional Society education activities for convergence education.

Overarching Issues

<u>Convergence Ecosystem</u>

Observation KF6: Creativity is an important aspect in the creation of innovative technologies.
Action Item KF6: Education at all levels should incorporate tools that foster creativity in their convergence curriculum.

Observation KF7*:* A number of grand challenges have been identified (Smalley's Humanity's Top 10 Problems for the next 50 Years (2003), the NAE Grand Challenges for Engineering (2008), U.K. Institution of Engineering and Technology's Six Global Grand Challenges Themes (2013), Societal Challenges in the EU Horizon 2020 (2014), and NSF Big Ideas (2016)). Convergent educational ecosystems, designed to catalyze innovations and breakthrough creations, will train a workforce that anticipates and addresses grand challenges and that provides transformative benefits to society.
Recommendation KF7a: Build on the general public interest in Grand Challenge efforts, especially at the primary/secondary school levels where the next generation of scientist/engineers is being formed, by developing a convergence education curriculum that will better enable those solutions. This is also an opportunity to develop citizen science among younger students.
Action item KF7b: Develop a best practices, evidence-based framework for exercising the emerging innovation process, i.e., a convergent incubation period, followed by a synthesis or 'ugly duckling' embodiment and an emergent innovation period.

Observation KF8: A convergence ecosystem will be necessary to accelerate convergence education. Prizes/awards can incentivize the process. Students are motivated by issues they face in their own lives and communities, but sustained investment of time and energy is difficult for even the most passionate students

Action Item KF8: Identify and publicize prizes/awards that recognize excellence in convergence science/engineering, e.g., the U.S. National Academy of Science's Sackler Prize for Convergence Research. More importantly, encourage other groups to establish such awards.

Observation KF9: STEAM encompasses science communication, in all forms, as an effective vehicle for sharing the joy and wonder of engaging in discovery, and for communicating a compelling need for tinkering, critical thinking and the creative process throughout the formal and informal educational ecosystem, e.g., families, communities, etc.
Action Item KF9a: Develop holistic convergence education, which creates future workers with enhanced technical and communication skills, instills context, i.e., a holistic awareness of and engagement with key stakeholders, and creates an understanding of their creations' potential implications.
Action Item KF9b: Develop low cost ways to integrate the critical success attributes within and across the formal and informal educational infrastructure. For example, reestablish opportunities to enhance alignment and mutually-synergistic engagements between families and the formal educational infrastructure. Less formal educational settings may serve as one low cost path to nurture convergent experiences, transdisciplinary and hands-on learning, tinkering, innovation and discovery.
Action Item KF9c: There should be a centralized location to share the growing resources about ongoing convergence education efforts. This implies a mechanism/organization with the continuing responsibility to keep the site up-to-date and attractive.

Observation KF10: Transdisciplinary environments can greatly enhance a student's educational experience, as they are particularly conducive to accelerating the convergence and synthesis of seemingly disparate ideas into new discoveries and foundational knowledge. The Next Generation Science Standards (NGSS) for K-12 and the Vision and Change in Undergraduate Biology efforts provide good starting points.
Action Item KF10a: Co-develop a conceptual framework that would draw on the expertise from transdisciplinary fields to explore the details of a unified program center focused on addressing the challenge of convergence, learning, data analytics and workforce.
Action Item KF10b: Begin building a convergent educational infrastructure by weaving common transdisciplinary platforms and thematic threads through curricula at all levels of education.

Observation KF11: Teachers need to know better how to get students prepared, what are the skill sets a student needs to function in the coming society. The NRC *Education for Work and Life* Report provide a good start on developing transferable skills through STEM education
Action Item KF11a: Start a conversation about the skills the students will need by 2026 and beyond, including those efforts that are being funding today.

Teaching Aides/Technology

Observation KF12. Accessibility of digital teaching aides is constrained by cost and teacher familiarity.

Action Item KF12: Develop guidance on how to use most effectively the various teaching aides in a convergence environment, thereby minimizing the constraints. Identify lessons learned that could be shared.

Teaming

Observation KF13: Research on team science, particularly in inter-, multi-, and transdisciplinary fields, indicates variations across areas of science and context.
Action Item KF13*:* Conduct more research within and across fields and contexts in order to codify and validate recommended strategies that match target areas..

Observation KF14: The role of team science competencies should be incorporated into educational and training strategies for convergence research.
Action Item KF14a: Strategically engage students to learn and gain experience in convergence incrementally and with increasing complexity as student progress through education levels (a 'bottom-up' approach).
Action Item KF14b: Provide faculty and senior researchers with training to prepare themselves to do collaborative science. Encourage researchers to include this training in their funding requests and urge funding agencies to pay special attention to these types of requests.

Observation KF15: To provide improved understanding of interpersonal competencies, and their role in convergence education, improved assessments will be needed.
Action Item KF15: There should be investment in additional research, development and validation of new intra-inter-personal competency assessments that address the shortcomings of existing measures.

International Collaboration

Observation KF16. There are wide variants in the different country experiences toward convergence education.
Action Item KF16a: There would be value in a study of efforts toward convergence around the world, sampling a variety of countries (U.S., Europe, Asia, Latin America, Africa), and identifying the roles of the various stakeholders, such as National and Local Departments of Education, National Research Agencies, Industry, Textbook/Assessment companies, Professional Societies, Foundations, Benefactors and Industry.
Action Item KF16b: Approach the ~180 Academies of Science around the globe and/or the OECD participant countries to provide information on convergence education teaching principles, best practices and key competencies. Also, the Global Research Council (a virtual organization comprised of the heads of science and engineering funding agencies from around the world) has two studies every year. Convergence Education could be chosen as one of those topics in the future.

Observation KF17. Developing countries have special needs toward convergence education, some of them with parallels for the migrant populations growing in many more-developed countries. Toward broadening participation, while recognizing the migrant populations establish new cultures in their new country, lessons learned form developing country education efforts may help address the education needs associated with migrant populations, and vice versa.

Action Item KF17: Institute a collaborative program between developed and developing countries toward convergence education.

Observation KF18: 'Higher Education at the Margins' provides higher education in refugee camps and create facilitators in their own communities; efforts such as this might be a model for new programs or initiatives.
Action Item KF18: Do a landscape analysis that will identify the players who are getting educational technologies to low resource communities, such as the Higher Education at the Margins program, and what they are already doing to get these technologies universally adopted. How are they being used? How can they be improved?

Observation KF19: The OECD can be an effective contributor toward understanding the implications of convergence education.
Recommendation KF19a: Prepare background information on convergence education to connect with ministers and policy-makers; identify the potential impact on socio-economics.
Recommendation KF19b: Identify ways to infuse convergence approaches into post graduation education; develop practices for providing convergence education after students complete studies in their specific fields.
Recommendation KF19c: There is a need to share best practices and lessons learned in teaching convergence. But best practices and lessons learned are not the same as a comprehensive body of knowledge based on evidence; there should also be an effort to develop that body of knowledge.

Funding

Observation KF20. Budget constraints limit the flexibility of Federal Funding initiatives, so identifying unconventional sources of funding is needed to provide supplemental funding to address the challenges/opportunities associated with convergence.
Action Item KF20: The various National Funding Agencies should explore how specific budget line item programs might be expanded to address convergence challenges, for instance, in the U.S. the Research Traineeship, Advanced Technical Education (post secondary), Small Business Innovative Research / Small Business Technology Transfer, and Established Program to Stimulate Competitive Research programs could be engaged.

Observation KF21: Partnerships among the many education stakeholders (parents, educators, science and engineering communities, government, industry, academe, and foundations) are needed to better identify the changing needs in student knowledge, including the creation of models to assess competency needs and personal learning graphs that address lifelong/life wide learning needs.
Action Item KF21a: Explore with industry and foundations the possibilities for government/academic/industry partnerships to develop new, affordable (including at the K-12 levels and in underserved populations) educational devices that could provide individualized instruction and would better enable convergence education.
Action Item KF21b: NSF's Engineering Directorate is exploring both a new generation of Engineering Research Centers with convergence as one of the specific goals. Workshop participants strongly support the inclusion of convergence in this program and encourage equivalent efforts in other countries.

Action Item KF21c: Define the role of social networks and social capital as research threads within a future NSF engineering research center.

Appendix A: Agenda

"Global Perspectives in Convergence Education"
NSF / OECD / U.S. National Academies / U. Southern California Workshop

2-3 November 2017
National Academies of Sciences Building
2101 Constitution Ave, NW Washington DC, United States

Workshop Agenda

Day one (November 2nd)

7:30 – 8:30 Registration and Socialization

8:30 – 10:00 Plenary session 1
Moderator: Jim Murday, University of Southern California
- 8:30 Welcome — C. Daniel Mote, Jr. President, U.S. National Academy of Engn; Steffi Friedrichs, OECD, and Yousaf Butt, U.S. Dept. of State
- 8:45 Charge to participants — Jim Murday, University of Southern California
- 8:50 Overview: Convergence science for societal progress and education. Mike Roco, NSF
- 9:10 Advances in education programs: US perspectives
  - 9:10 Learning in an world of convergence, Susan Singer, Rollins College
  - 9:25 Convergence in professional education, Michael Richey, The Boeing Company
  - 9:40 AAC&U Perspective, Amy Jessen-Marshall, Assoc. of American Colleges and Universities
  - 9:55 Q&A

10:10 – 10:40 Break

10:40 – 12:00 Plenary session (continued)
Moderator: Mihail C. Roco, National Science Foundation
- 10:40 Overview, OECD Perspective — Steffi Friedrichs, OECD
- 11:00 International Perspectives on Convergence in Education
  - 11:00 Richard Kitney, Imperial College of London, UK
  - 11:15 Olof Emanuelsson, Royal Institute of Technology, Sweden
  - 11:30 Y. Eugene Pak, Seoul National University, South Korea
  - 11:45 Q&A

12:00 – 1:00 pm Working Lunch: "NSF Big Ideas"
- 12:30 Suzanne Iacono, NSF Office of Integrating Activities
- 12:45 Rebecca Keiser, NSF Office of International Science and Engineering

1:00 – 2:55 Early Afternoon breakout sessions
- 1.1 Teaching convergence & responsible science via the concept of "grand challenges"
  - Moderator: Dean Evasius, Division of Graduate Education, NSF
  - Rapporteur: Brian Gray, AAAS S&T Policy Fellow, NSF EFMA
  - Speaker: Dan Herr, Joint School of Nanoscience and Nanoengineering; Heidi Schweingruber, National Academy of Sciences

1.2 Incorporation of convergence into curricula and continuing education programs being developed in various countries; and responsible science implications.
Moderator: Y. Eugene Pak, Seoul National Univ., South Korea
Rapporteur: Jennifer Brummet, Science Assistant, NSF BCS
Speakers: Jin-Taek Kim, Pohang University of Science and Technology
Fernando Quezada, Biotechnology Center of Excellence Corp
Jorge Huete-Perez, University of Central America

2:55 – 3:35 Break

3:35 – 5:30 Mid Afternoon breakout sessions

2.1 Mechanism(s) to keep abreast of the changing workforce education needs as convergence in science, industry and economy continues its rapid market penetration.
Moderator: William Bonvillian, MIT
Rapporteur: Bushra Akbar, Science Assistant, NSF DRL
Speaker: Margaret Hilton, Board on Science Education, National Academy of Sciences

2.2 How best to "synchronize" or properly coordinate changes in educational institutions and society with changes in funding agencies?
Moderator: Richard Kitney, Imperial College London
Rapporteur: Ashley Gordon, USC Research Advancement
Speaker: Robert Chang, Northwestern University

5:30 – 6:30 Plenary session (2)
Moderator: Katherine Bowman, NAS
Reports from the working groups to a plenary session (15 minutes from each breakout session)

6:30 - 8:00 Reception in the Grand Hall

Day 2 (November 3rd)

8:00 – 8:30 Registration and Socialization

8:30 – 9:00 Plenary Session
Moderator: Yousaf Butt, Department of State
8:35 – 8:55 Eleonore Pauwels, S&T Innovation Program, Woodrow Wilson Center for Scholars

9:00 – 11:15 Morning breakout sessions

3.1 Science of team science and its role in convergence education, including broadening participation
Moderator: Dan Herr. Joint School of Nanoscience and Nanoengineering
Rapporteur: Brian Gray, AAAS S&T Policy Fellow, NSF
Speakers: Kara Hall, Behavioral Research Program, NCI, NIH

3.2 New technologies for advancing convergence in education and training
Moderator: Kate Stoll, MIT Washington Office
Rapporteur: Ashley Gordon, USC Research Advancement
Speaker: Chris Kaiser, MacVicar Faculty Fellow, MIT
Kurt Thoroughman, NSF Program Director, Science of Learning

3.3 Communication amongst national science funding agencies and multilateral fora to coordinate and foster global convergence education
Moderator: Lisa Friedersdorf, National Nanotechnology Coordination Office

Rapporteur: Sarah Flores, Science Education Analyst, NSF DGE
Speaker: Finbarr (Barry) Sloane, Education and Human Resources, NSF

11:15 – 12:00 Plenary session 3
Moderator: Anders Jornesten, Sweden
Reports from the working groups to a plenary session (15 minutes from each breakout session)

12 to 12:30pm Pick up working lunch

12:30 – 3:00pm Plenary session 4
Moderators: Jim Murday and Steffi Friedrichs

- Discussion of priorities
- Discussion of preparation of the report
- Wrap-up

Appendix B: Biosketches of the Speakers (in alphabetical order)

Yousaf Butt is a Foreign Affairs Officer in the U.S. Department of State. He was a research professor and scientist-in-residence at the James Martin Center for Nonproliferation Studies at the Monterey Institute for International Studies. Previously, Butt was a scientific consultant to the Federation of American Scientists and a physicist in the High-Energy Astrophysics Division at the Harvard-Smithsonian Center for Astrophysics. He was on the instrument operations team responsible for the main focal plane instrument aboard NASA's orbiting Chandra X-ray Observatory from 1999-2004. He has also been a fellow in the Committee on International Security and Arms Control at the National Academy of Sciences and a research fellow in the Global Security Program at the Union of Concerned Scientists.

R.P.H. (Bob) Chang is a recognized innovator in materials research, interdisciplinary science education and international networking. Chang earned his B.S. in Physics and a Ph.D. in Astrophysics at MIT and Princeton respectively. He spent 15 years performing basic research at Bell Labs (Murray Hill). During the past 30 years at Northwestern University, he has directed several NSF Centers and Programs in materials research and education. His current research interests include nanostructured materials, nanophotonics, and advanced solar cell development. His groundbreaking education projects include the first NSF Research Experience for Teachers Program, the inquiry-and-design based Materials World Modules program for middle and high school students, and the nation's first nanotechnology education center, the NSF-NCLT. He was honored in 2005 with the NSF Director's Distinguished Teaching Scholar Award for his contributions to materials research and education. He is the General Secretary and Founding President of the International Union of Materials Research Societies (IUMRS) with adhering bodies on five continents. Working with his IUMRS colleagues, he has helped with the launching of the Global Materials Network for young researchers in 2012, in Singapore.

Olof Emanuelsson is associate professor in bioinformatics at KTH Royal Institute of Technology (Stockholm, Sweden). He is the program director and academic responsible for the newly instated MSc program Molecular Techniques in Life Science, a joint program between three universities in Stockholm. He studied molecular technology engineering at Uppsala University, went on to do a PhD at Stockholm University and was a postdoctoral fellow at Yale University. His research focus is on developing methods for analyzing large-scale molecular biology data sets, applied to such diverse areas as spruce reproduction and the role of inflammation in cardiovascular disease.

Steffi Friedrichs is policy analyst for biotechnology, nanotechnology and converging technologies for the organization for Economic Cooperation and development. She started her scientific career with an undergraduate degree in 'Diplom-Chemie' at the Technical University of Braunschweig (Germany), before taking a DPhil at the University of Oxford (UK), specializing in single-walled carbon nanotubes (both synthesis and toxicology). She subsequently held a Fellowship at Oxford University and a Lectureship in Nanotechnology at Cambridge University, where she developed and coordinated a Master's Programme in Micro- & Nanotechnology Enterprise. In 2006, Dr Friedrichs chaired the UK Committee for the Recognition of Nano-science and -technology Educational Programmes (Institute of Nanotechnology), and is member of the Board of Editors for the journal NanoEducation.

Kara L. Hall is a Health Scientist, the Director of the Science of Team Science (SciTS) Team, and Director of the Theories Initiative in the Health Behaviors Research Branch (HBRB) at the National Cancer Institute (NCI). Dr. Hall's research has focused in the areas of health behavior intervention and theory and the science of team science. While at NCI Dr. Hall has also led initiatives to advance dissemination and implementation research; promoting the use, testing, and development of health behavior theory; and champion systems science approaches, research methods, and intervention development. Notably, Dr. Hall helped launch the SciTS field by co-chairing the 2006 conference The Science of Team Science: Assessing the Value of Transdisciplinary Research and co-editing the 2008 American Journal of Preventive Medicine Special Supplement on SciTS. Dr. Hall provides continued leadership for the SciTS field through roles such as leading the Annual International Science of Team Science (2010-17) and serving as a member of The National Academies Committee on the Science of Team Science (2012-15). The resulting NRC report, *Enhancing the Effectiveness of Team Science*, was the third most downloaded National Academies Press report in 2015.

Dan Herr serves as professor and Nanoscience department chair at the University of North Carolina's Joint School of Nanoscience and Engineering (JSNN). He leads a highly collaborative and transdisciplinary team that explores and addresses emerging and convergent nanoscale research opportunities, with a focus on functional nanomaterials, nanobioelectronics, computational nanotechnology, nanobiology/medicine, nanometrology, functional self-assembled nanomaterials and biomimetic systems. Dr. Herr also is passionate about communicating the joy of science and STEAM opportunities to the community and to the next generations of scientists, engineers, and other creative people. His current research interests include useful sustainable and nanoenhanced agriculture, self-assembled and biomimetic nanosystems, nanobioelectronics, composite nanomaterials, and nanoenergy.

Margaret Hilton is a senior program officer of the Board on Science Education of the National Academies, where she has directed studies on the assessment of intrapersonal and interpersonal competencies, the effectiveness of team science, 21st century skills, and high school science laboratories. She also participated in studies on discipline-based education research and using computer games and simulations to support learning. Prior to joining the National Academies staff, she was a policy analyst at the Congressional Office of Technology Assessment, where she directed studies of workforce training, work reorganization, and international competitiveness. She has a B.A. in geography from the University of Michigan, an M.A. in regional planning from the University of North Carolina at Chapel Hill, and an M.A. in education and human development from George Washington University.

Jorge A. Huete-Pérez is the Senior Vice President of the University of Central America (UCA, Nicaragua). He has received numerous scholarships, fellowships and awards from diverse organizations including the WHO, McArthur Foundation, and Rockefeller Foundation. He also won a Pew Latin American Fellowship for postdoctoral research in molecular parasitology at the University of California. In 1998 he founded the Molecular Biology Center (MBC) at the University of Central America (UCA), the first molecular biology research and training laboratory in Nicaragua. Dr. Huete-Pérez was a postdoctoral fellow at Harvard University (2001), and a Research Fellow at the Sandler Molecular Parasitology Center of U.C. San Francisco (2004). His laboratory collaborates with New England Biolabs, a successful biotech company in the U.S. He is a consultant to numerous governmental and non-governmental organizations, and has been an outspoken advocate for improving science education and the appropriate use of biotechnology for development. In 2009 Dr. Huete-Pérez became the Founding President of the Academy of Sciences of Nicaragua, serving in that post for two terms.

Suzanne Iacono joined NSF in 1998 from Boston University where she served on the faculty of the School of Management. Since joining NSF, Iacono has been a program director, senior science advisor and the deputy assistant director for the Directorate for Computer and Information Science and Engineering. Before that, she served as a visiting scholar at the Sloan School, Massachusetts Institute of Technology and as a research associate at the Public Policy Research Office, University of California, Irvine. She received her doctorate from the Department of Management Information Systems, University of Arizona and her master's and bachelor's degrees in social ecology from the University of California, Irvine.

Amy Jessen-Marshall is Vice President, Office of Integrative Liberal Learning and the Global Commons, AAC&U. She has analyzed what works in supporting educators in supporting integrative (convergence) learning across many domains for students over a 10-year period. She also addresses what is known about what this learning looks like and how it can be measured and assessed using the integrative learning, collaborative learning, and teamwork learning rubrics that the AAC&U has developed and worked with, in partnership, with a broad range of public and private colleges and universities across the nation. Previously she served as Dean of the Faculty, Vice President for Academic Affairs and Professor of Biology at Sweet Briar College in Virginia, as well as Provost and Dean of University Programs at Otterbein University in Westerville Ohio.

Chris Kaiser joined the MIT faculty in 1991, after earning his A.B. in biochemistry from Harvard University and his Ph.D. in biology from MIT. In 1999 Kaiser was named a MacVicar Fellow, an MIT honor reflecting outstanding undergraduate teaching, mentoring and educational innovation. At MIT, Kaiser has served on task forces and advisory committees including the Task Force on the Undergraduate Educational Commons; the Institute-wide Planning Task Force’s revenue enhancement working group; the Benefits Advisory Group; the SHASS Reorganization Committee; the SMART MIT Advisory Committee; and the Pre-Med Advisory Council; and as MIT provost from 2012 to 2013.

Rebecca Spyke Keiser has been the Head Office of International Science and Engineering at The National Science Foundation since April 2015. Dr. Keiser is a Special Advisor for NASA's Innovation and Public-Private Partnerships. She held several positions with NASA, including Associate Deputy Administrator for strategy and policy, Associate Deputy Administrator for policy integration, Executive Officer to the Deputy Administrator, and Chief of Staff for the Exploration Systems Mission Directorate. She also served as Assistant to the director for international relations at the White House Office of Science and Technology Policy (OSTP), where she provided policy guidance to the President's science advisor.

Anthony E. Kelly serves as a Senior Advisor in the Directorate for Education and Human Resources at the US National Science Foundation. He is also a Professor of Educational Psychology and an Associate Dean for Research at the College of Education and Human Development at George Mason University in Virginia. His interests are in STEM education, research methodology and education science policy.

Jin-Taek Kim serves as professor of Creative IT Engineering at POSTECH in KOREA. He received a Doctorate in media aesthetics / philosophy from University of Paris 1 (Pantheon Sorbonne), France. He is interested in body, image, new media art, transhumanism, and creative convergence education. He has been studying and teaching about the convergence domain of humanities and technology. Especially nowadays, he is creating philosophical concepts about 'Value Design' and researching its specific creative projects and works. In 2015 he was a consultant of Asia Pacific Organization to the UNESCO WHC (World Heritage City) and in 2017 he served as a co-chair of the HCI K Society and a consultant of LG Edge Technology Forum. In addition, since last year, he has been working as a host of a TV program which discovers and introduces future jobs.

Richard Ian Kitney is Professor of Biomedical Systems Engineering and Co-Director and Co-Founder of the Imperial College Centre for Synthetic Biology and Innovation. He is a Fellow of The Royal Academy of Engineering and Chaired the Academy's Inquiry into Synthetic Biology - and is a member of the U.K.'s Ministerial Leadership Council for Synthetic Biology. Kitney (with Professor Paul Freemont) has been responsible for developing the Imperial College Synthetic Biology Hub. In 2013 they won the competition to establish the U.K.'s national industrial translation centre for synthetic biology - SynbiCITE. Kitney has published over 300 papers in the fields of synthetic biology, mathematical modelling, biomedical information systems, and medical imaging and has worked extensively in and with industry. He was an author of both of the U.K. Government's Roadmaps for synthetic biology. Kitney was made a Fellow of the World Technology Network (1999) and an Academician of the International Academy of Biomedical Engineering (2003). He is also a Fellow of AIMBE, the America Academy of Biomedical Engineering. In 2006 he was made an Honorary Fellow of both The Royal College of Physicians and The Royal College of Surgeons. In March 2016 Kitney was made a Fellow of The Royal Society of Edinburgh.

C. Daniel Mote, Jr. is president of the National Academy of Engineering and Regents' Professor on leave from the University of Maryland, College Park. Dr. Mote is a native Californian who earned his B.S., M.S., and Ph.D. degrees at the University of California, Berkeley in mechanical engineering between 1959 and 1963. After a postdoctoral year in England and three years as an assistant professor at the Carnegie Institute of Technology in Pittsburgh, he returned to Berkeley to join the faculty in mechanical engineering for the next 31 years. In 1998 Dr. Mote was recruited to the presidency of the University of Maryland, College Park, a position he held until 2010 when he was appointed Regents' Professor. The NAE elected him to membership in 1988 and to the positions of Councilor (2002–2008), Treasurer (2009–2013), and President for a six–year term beginning July 1, 2013. He has served on the NRC Governing Board Executive Committee since 2009.

James S. Murday received a B.S. in Physics from Case Institute of Technology in 1964, and a Ph.D. in Solid State Physics from Cornell in 1970. Prior to joining the University of Southern California's Research Advancement Office in Washington DC as Director of Physical Sciences in fall 2006, he was at the Naval Research Laboratory (NRL) where he served as bench scientist from 1970 - 1974, led the Surface Chemistry effort from 1975-1987, and was Superintendent of the Chemistry Division from 1988 to 2006. Additional responsibilities include: from January 2003 to July 2004, he served as Chief Scientist, Office of Naval Research; from January 2001 to

April 2003 he served as Director, National Nanotechnology Coordination Office; and from January 2001 to November 2006 he served as Executive Secretary to the U.S. National Science and Technology Council's Subcommittee on Nanometer Science Engineering and Technology (NSET).

Y. Eugene Pak is Director of Education Division at the Seoul National University's Advanced Institute of Convergence Technology (AICT). Primary responsibility of the Education Division is to transfer research knowledge to the industry workers as well as to the general public including secondary school and college students. Prior to joining the AICT in 2009, he was Vice President of Corporate Technology Office at Samsung Electronics and Director of Microelectromechanical Systems Lab at the Samsung Advanced Institute of Technology. He received his M.S. and Ph.D. degrees in Mechanical Engineering from Stanford University, and B.S. degree in Mechanical Engineering from SUNY at Buffalo.

Eleonore Pauwels is an international science policy expert, who specializes in the governance of emerging technologies, including genomics, digital and bio-engineering, participatory health design, and citizen science. At the Wilson Center, she is the Director of Biology Collectives, and Senior Program Associate within the Science and Technology Innovation Program. With funding from the Robert Wood Johnson Foundation, Eleonore directs the Citizen Health Innovators Project. In this context, her research focuses on developing regulatory and governance mechanisms for the fast-growing ecosystem of health innovators, built around maker spaces and community bio labs, to support responsible innovation in distributed networks. This is part of her larger effort to design actionable ethics and governance strategies to enable responsible and fair citizen participation in new health and genomics technologies. She is particularly interested in the perils and promises of personal genomics, and how to harness this trove of data and techniques to truly, ethically empower citizens in different societal contexts and cultures.

Fernando Quezada is Executive Director of the Biotechnology Center of Excellence Corp., a U.S.-based private, non-profit organization. His professional assignments have included project evaluation for the Ministry of the Economy of Chile, the U.S.-Mexico Foundation for Science, the Puerto Rico Science, Technology and Research Trust, and the U.S.-Israel Science and Technology Foundation. He coordinated a study for the German Agency GIZ on The Knowledge Economy in Central America. Appointed to Chile's National Commission for the Development of Biotechnology by the President of Chile, and received the 2015 Foreign Minister's Commendation from the Foreign Minister of Japan for his work in the area of science and technology cooperation. He has served as consultant to the United Nations Industrial Development Organization, the United Nations Economic Commission for Latin America and the Caribbean and the Board on Science and Technology in International Development of the National Academy of Sciences. He studied at UCLA and Massachusetts Institute of Technology and has taught at the Federal University of Para and the University of São Paulo in Brazil, the Monterrey Institute of Technology in Mexico, and Lesley University in Cambridge, Massachusetts. Currently serves on the Board of LASPAU, a higher education development program affiliated with Harvard University and on the Board of Trustees at Framingham State University in Massachusetts. His publications focus on biotechnology commercialization, technology-based innovation and public policy.

Michael Richey is a Boeing Associate Technical Fellow currently assigned to support educational technology and innovation research at The Boeing Company. Michael is responsible for leading a team conducting engineering education research projects that focus on improving the learning experience for students, incumbent engineers and technicians. His research encompasses, Sociotechnical Systems, Learning Curves, and Engineering Education Research. The online educational programs and research focus on practical understanding of human learning and the design of technology-enhanced learning environments and promoting global excellence in engineering and learning technology to develop future generations of entrepreneurially-minded engineers. Michael has served on various advisory groups including, the editorial board of the Journal of Engineering Education, Boeing Higher Education Integration Board, American Society for Engineering Education Project Board and the National Science Foundation I-UCRC Industry University Collaborative Research Center Advisory Board. Michael has authored or co-authored over 40 publications in leading journals including Science Magazine, The Journal of Engineering Education and INCOSE addressing topics in large scale system integration, learning sciences and systems engineering. Michael often represents Boeing internationally and domestically as a speaker - presenter and has authored multiple patents on Computer-Aided Design and Computer-Aided Manufacturing, with multiple disclosures focused on system engineering and elegant design. He is currently the Principle Investigator for the Boeing Internet of Learning Consortium, the Technical focal for the Boeing ASEE and manages the Boeing Santa Fee Institute Applied Complexity Network and edX Corporate Advisory Board relationship.

Mihail C. Roco is the founding chair of the U.S. National Science and Technology Council's subcommittee on Nanoscale Science, Engineering and Technology (NSET) and the Senior Advisor for Science and Engineering at the National Science Foundation (NSF). Prior to joining NSF, he was a professor of mechanical engineering at the University of Kentucky (1981-1995) and held professorships at the California Institute of Technology (1988-89), Tohoku University (1989), Johns Hopkins University (1993-1995), and Delft University of Technology (1997-98). He is Member of European Academy of Sciences and Arts, Correspondent Member of the Swiss Academy of Engineering Sciences, Honorary Member of the Romanian Academy, a Fellow of the ASME, a Fellow of the Institute of Physics, and a Fellow of the AIChE.

Heidi Schweingruber is the director of the Board on Science Education at the National Research Council (NRC). In that role she oversees the board's portfolio which includes work in K-12, higher education and informal education settings. She co-directed the study that resulted in the report *A Framework for K-12 Science Education* (2011) which is the first step in revising national standards for K-12 science education. She served as study director for a review of NASA's pre-college education programs completed in 2008 and co-directed the study that produced the 2007 report *Taking Science to School: Learning and Teaching Science in Grades K-8*. She served as an editor on the NRC report *Mathematics Learning in Early Childhood: Paths to Excellence and Equity (2009)*. She co- authored two award-winning books for practitioners that translate findings of NRC reports for a broader audience: *Ready, Set, Science! Putting Research to Work in K-8 Science Classrooms (2008)* and *Surrounded by Science (2010)*. Prior to joining the NRC, Heidi worked as a senior research associate at the Institute of Education Sciences in the U.S. Department of Education where she administered the preschool curriculum evaluation program and a grant program in mathematics education. Previously, she was the director of research for the Rice University School Mathematics Project an outreach program in K-12 mathematics education, and taught in the psychology and education departments at Rice University. Heidi holds a Ph.D. in psychology (developmental) and anthropology, and a certificate in culture and cognition from the University of Michigan.

Susan Singer led the Discipline-based Education Research study at NASEM, directed the Division of Undergraduate Education at NSF which supports convergence education, and authored a recent chapter on convergence education. She will add to the panel by providing an overview of the many different efforts underway to advance convergence education that are often disconnected from each other and will illustrate how enhancements in digital learning can support lifelong education in convergence. Susan is the Vice President for Academic Affairs and Provost at Rollins College where a new, integrated general education program to support convergence learning has been implemented and is being assessed with the support of the Mellon Foundation.

Finbarr (Barry) Sloane, a native of Ireland, received his Ph.D. in Measurement, Evaluation, and Statistical Analysis from the University of Chicago with specialization in Mathematics Education and Multilevel Modeling. Prior to joining the faculty at ASU he was a program director at the National Science Foundation's Division of Research, Evaluation, and Communication. There he oversaw a national effort to conduct research on the scaling of educational interventions in STEM disciplines. While at the NSF he provided institutional direction to Trends in International Mathematics and Science Study (TIMSS), the Board on International Comparative Studies in Education (BICSE), and has presented to the National Research Council of National Academies of Science. His research has appeared in Educational Researcher, Reading Research Quarterly, and Theory into Practice. He serves on the editorial boards of a number of journals including: Irish Educational Studies, Mathematical Thinking and Learning, and Reading Research Quarterly; he is treasurer and secretary for the International Society of the Learning Sciences; he sits on the board of trustees for the AMB Foundation (a small foundation dedicated to support of Native Peoples of the Americas).

Kurt Thoroughman is on assignment from the Department of Biomedical Engineering at Washington University in St. Louis. There he founded research reverse engineering the human brain, using robotics, virtual reality, psychology, biomechanics and bioelectrics, and computation. His research team discovered ways that learning itself can be shaped by recent experience. This work has its roots in neuroscience but has impact across scientific disciplines and clinical practice. Dr. Thoroughman has also built, led, and researched to improve higher education. He co-founded the Cognitive, Computational, and Systems Neuroscience pathway and served as its IGERT PI. He directed undergraduate studies in his department and his School of Engineering. He built new initiatives across the School; grew connections and programs across the University and in St. Louis; and currently researches and develops holistic learning and diversification of educational systems.

Appendix C: List of Attendees

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Appendix D: Selected Convergence Education Contributions

1. Dr. Michael Richey, Boeing – Selected Research Experiences with UTA, IU and Microsoft
2. Dr. Eugene Pak, Seoul National University – Korea's Convergence Education Program
3. Dr. Chris Kaiser, MIT - Imagining the Future of Technology Assisted Convergent Education - The Future of Convergence Education
4. Dr. Rebeca De Gortari, Universidad Nacional Autónoma de México – Mexico's Convergence of Knowledge Network
5. Dr. Robert Chang, Northwestern – Materials World Modules

1. Selected Research Experiences on Convergence
Dr. Michael Richey, Boeing

In order to promote generative workshop discussions on convergence, I've highlighted selected research questions below, from our research with UT-A (Siemens, Joksiomovic, Kovanovic, Gasevic and Dawson), IU (Borner), and Microsoft (Rubin and Roy). We understand the NSF's Engineering Directorate is exploring a new generation Engineering Research Center with convergence as a framework. The Directorates for Education and Human Resources (EHR) and Computer and Information Science and Engineering (CISE) DCL letter results (see below) will provide detail research goals that fall under this broad convergence theme.

On a convergent partnership: Learning needs are evolving rapidly to respond to changes in society, technology, and business. In higher education, this impact is being felt through alternative learning models, notably a rise in focus on competencies and alternative credentialing (Chronicle, Selingo, 2016). An expectation of future and lifelong learning (a 40-year relationship instead of a 4 year relationship as is the current norm). Massive open online courses (MOOCs) address part of this emerging challenge, but report low completion rates and limited engagement (Chuang and Ho, 2016). By contrast, the first cohort in the Microsoft professional Program in Data Science on edX had a 29% completion rate over 9 courses representing a comprehensive skills map (Rubin, 2017). The first cohort of the Boeing MIT edX and NASA System Engineering Small Private Online Certificate (SPOC) completion rate was over 1500, a 94% completion rate (Richey, 2017). The higher completion rates were driven by greater social support and guidance for individual learners, a feature that underpins the development of Advancing Personalized Learning.

- How can we partner to create the data structures that enable higher education and industry to better serve America's knowledge needs through the creation of models to assess competency needs, personal learning graphs that address lifelong/life wide learning needs?
- Recommendation: Define the role of innovative and learning data structures as a research thread within a future NSF engineering research center.

Convergent research for Social Networks and Social capital: Organizations are inherently relational. In the jargon of complex systems, institutions are complex adaptive systems composed of a network of employees bound together by contracts, who perform tasks by negotiating both internal relationships within firms, but also by observing, managing, and responding to constantly shifting external environments" (Richey et al., 2014). One of the missing components of the cultural change equation is understanding the linkages between actors (Central, Peripheral and Isolated actors) including the "supergroups" that emerge and move potential to action within the network. Key to understanding this flow of human and network capital is measuring the quality social ties, i.e., making emergent actor expertise explicit as innovation resides within densely connected trusting, social-work related networks. Social Network Analysis consist of instrumenting a set of nodes, actors, including the ties that connect the nodes (simmelian) and social; relationships (ego – homophile).

- Can we identify the organizational, institutional policy, technological, and cultural performance factors that lock innovation and alternative pathways out of our formal educational system.

- How do we turn this intuitive understanding of how things work into a dynamic model which is sufficiently explanatory to guide us toward improvement?
- Recommendation: Define the role of social networks and social capital as a research thread within a future NSF engineering research center.

Convergent research for online and blended data analytics: The prospect of big data as a new model for research (Hey, Tansley, and Tolle, 2009) is being realized in education with the development of the learning analytics field. When applied in education, big data promises to drive better learning, more competition between institutions, and a strategic priority for national governments (Siemens, Dawson, Lynch 2013; Madhavan and Richey, 2016). When moving from a classroom to workforce systems level, learning analytics can contribute to the development of adaptive and personalized learning environment with the intent to improve the quality of learning, the successful performance of low income and minority students, as well as reducing costs (SRI, 2016). One focus of convergence could explore using process mining methods, network analysis, and co-evolution of competencies with labor market capabilities to research the following:

- Co-create and Co-pilot adaptive models of content development and instruction for universities to integrate with learning needs of corporations (NASA, Boeing, Microsoft examples above) - i.e. rapid online course development based on predictive models of anticipated future needs for competencies, including: Advanced Manufacturing, Robotics, Additive Manufacturing, Professional Skills, Cyber Security, Data Analytics, Information Technologies, Program Management etc.
- Recommendation: Define NSF academic – Industry co-funded partnerships as a research thread within a future NSF engineering research center. Leverage the NSF research expertise to assist industry with on line design principles and development – analyses of co-created online learning certificates for students and industry professionals.
- Specific research focused on active learner environments that directly address a recent NSF DCL Principles for the Design of Digital Science, Technology, Engineering, and Mathematics (STEM) Learning Environments and the NAE Grand Challenge – Advance Personalized Learning:
- What advances in learning environment design are required to support multi-modal learning for individual or team-based learning? What new research or data analytic methods may help overcome any barriers?
- What innovative approaches to research methods, statistical techniques and modeling formalisms are necessary to capture, characterize and support causal claims about individual or team-based learning, especially for complex, multi-source streaming data?
- How can learning environments collect data to systematically inform our understanding of learners' current state of knowledge, their achievements in challenging STEM content, their motivations for learning and perseverance, or the formation of effective teams that are both diverse and inclusive? (Mine the evolutionary processes of individual competencies as well as their spread through social structures).
- How can advances from data science inform innovative formative, continuous, or summative assessments that provide rich diagnostic information on learning? How doe we move away from a test and rank model to an engage until mastery model?
- How can educational digital resources (e.g., videos, animations, images, or audio files) be analyzed and exploited to support significant progress in student learning, assessment, or

program evaluation? How can instructors, mentors and learners modify and exploit these resources?
- How can learning environments be designed to scale successful efforts across: (a) different content areas, (b) diverse student populations, (c) different contexts, or (d) variable time spans?
- How can learning environments capitalize on teacher or learner "presence" via virtual or immersive technologies such as augmented or virtual reality?
- Recommendation: Define the role of innovative and learning ecosystems as a research thread within a future Academia, Industry, NAE, NAS, NSF, DOD MURIs, a Department of Education IES program engineering research center.

On Social Networks and Social capital: The underlining research should converge on what structure - system supports environments where learning by doing takes place and where social – cultural engagement happens both inside and outside of an online environment blurring boundaries of culture and learning including:

- Explore learning as a social and interactive process for idea generation and knowledge building (Bereiter, Siemens, Pentland).
- Instrument online learning environments that measure social network, including leveraging social capital (simmelian ties) within networks support the goal oriented behaviors of social agents? (Contagion phenomena)
- Explore instrument the convergent and emergent nature of learning within online environments; how do social agents receive or acquire knowledge; the information is leveraged against a schema, processes and acted on.
    - Within the social network, how do agents access information, what is the level of fidelity, how do they direct their acts toward
    - What are the commonalities among adaptive agents? Can we leverage data to distill these behaviors into prototypical adaptive behaviors; can we leverage this insight to shift lifelong learning strategies? Can we identify the level of sophistication and enabling conditions?

The rhetoric of a knowledge economy has been ongoing for over four decades (Drucker, 1968). In spite of this acknowledgement that the future of society and humanity rests in the generation of knowledge organizations, universities do not yet have a convergent model to address the need for ongoing and lifelong learning and corporations have not developed sophisticated and granular models to track and even predict knowledge capabilities. These limitations are pronounced in the engineering and technology fields. As you've already stated, "The diffusion of new technology is therefore dependent on a solid research basis in all higher education." The construct of a convergent government, academic and industry model that integrates digital and social learning profiles, relevant competency mapping, and emerging labor market skillset prediction from industry holds the potential to rapidly reduce the time and cost it takes to train engineers and technicians as well as contributing to a new business model for universities to realign their missions to better serve the needs of the modern economy.

Recommendation: Co-develop a conceptual framework that would draw on the expertise from transdisciplinary fields to explore the details of a unified program center focused on addressing the challenge of convergence, learning, data analytics and workforce.

2. **Korea's Convergence Education Programs**
Dr. Y. Eugene Pak, SNU Korea

Government's Efforts:
Having achieved a prominent economic status with a successful fast-follower approach, Korea is now facing a qualitative change as a first mover who must pioneer a new area on its own for continued economic growth. To this end, Korea is gearing up for the upcoming 4th Industrial Revolution which is strongly based on the convergence of various technologies led by the ICT technology. As it integrates cyber and physical spaces by breaking its boundaries, the science and technology policy of South Korea has been to encourage 'Creative Education for Convergence' to expedite the merging of various academic disciplines, technologies, and industries. The term 'Talent for Convergent Capability' defines a person who has the insight of humanities, scientific creativity, and the ability to conceive original values with an interdisciplinary approach (Global Human Resource Forum, Seoul, 2016). People with the convergence talent have a deep understanding of their specialty, complex problem-solving skills, ability to create new values, and a global leadership. Since 2007, the Korean government has been investing in interdisciplinary education and research for convergence. In 2016, the government of South Korea invested $670M USD focusing on the STEAM[1] programs to cultivate talents with a convergence capability and an additional $2,200M USD on convergence-based R&Ds.

It is believed that the core of convergence is based on building a robust and well-connected network so that the experts of diverse background can come together for interdisciplinary research. Moreover, the aim is to establish a discussion platform that can tackle Grand Challenges in an economically feasible way while putting the highest level of social resources in action. Due to such consideration, the Association for Convergence Education & Research (ACER) was founded in October 2017 with the participation of 126 academic institutions, national laboratories, and corporations. Thereby, ACER acting as the hub, intend to build a culture of integrated fusion research. One of the primary roles of ACER is to operate a cooperation network connecting institutions to openly collaborate on strategic planning as well as to exchange skills and expertise. Vitalizing the open access of information by providing the right infrastructure is paramount in enabling researchers, students and corporations to reach out for valuable contents while keeping people and ideas as fluid as possible. Moreover, ACER is expected to grow at the national level as a Convergence Policy Advisory Committee supporting the groundwork for unearthing the future issues and fostering convergence research even further. Stimulating convergence research will create values for breakthroughs, overcome limitations of current technologies, and lead to discovery of unexplored fields. It is anticipated that these convergence efforts will motivate the technology sector to expand its boundary towards the humanities and social science sphere.

[1] Science, Technology, Engineering, (Liberal) Art, and Mathematics

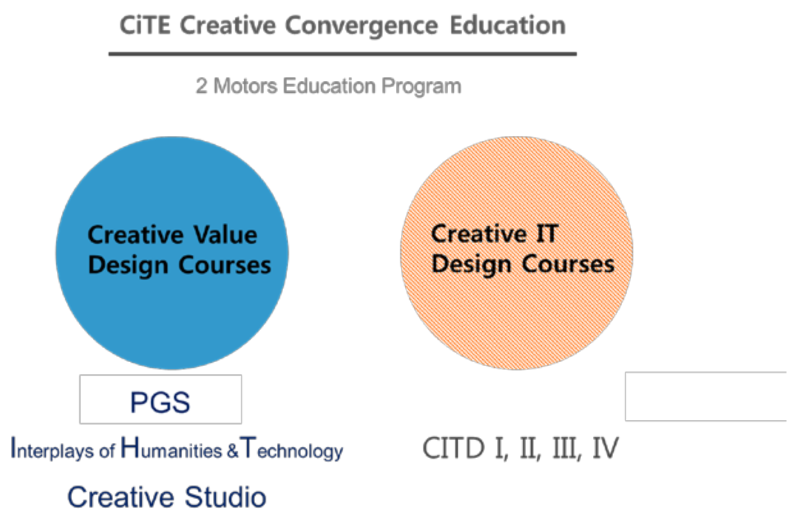
Undergraduate Convergence Education:

- Department of Creative IT Engineering (CiTE)

Pohang University of Science and Technology (POSTECH)

POSTECH was established in 1986 in Pohang, Korea by POSCO, one of the world's leading steel companies, for the purpose of providing advanced education for budding engineers and laying the groundwork for future technological development. In 2011, the Department of Creative IT Engineering (CiTE) was established to become one of the world's top IT convergence education institutes that nurture creative talents who will lead future IT industry as part of the IT Consilience Creative Program supported by the Ministry of Science, ICT and Future Planning. This program embodies POSTECH's new educational philosophy: First, the students must be freely allowed to have multidisciplinary exploration; second, the students must be trained to solve specific and realistic problems with creativity; and third, they must be made to practice skills based on their self-initiated willingness and competence.

CiTE program has two education motors running. One is Creative Value Design and the other is Creative IT Design. The main themes of the Creative Value Design program are Self-Initiated Growth, Interplays of Humanities and Technology, and Creative Studio.

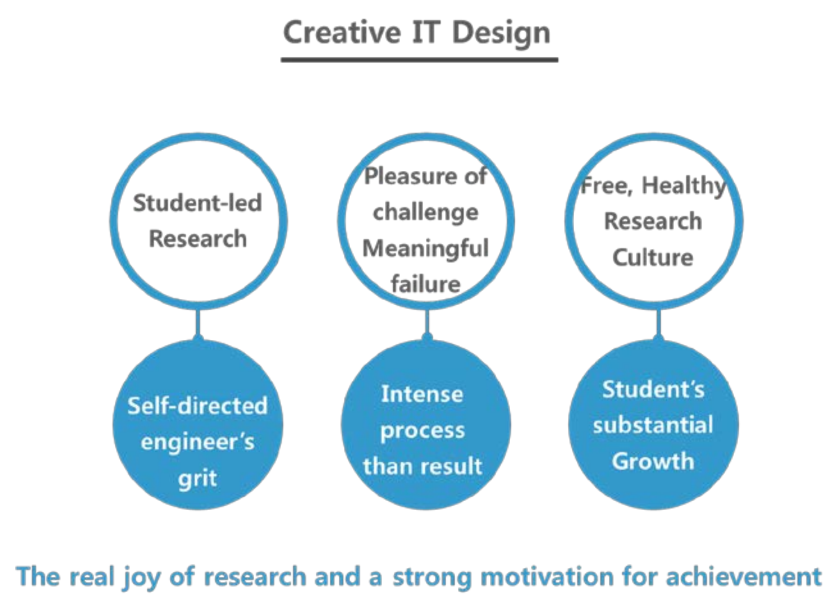


The Self-Initiated Growth theme is to help students to draw up one's dream and strategically design future growth in a big picture. For ten weeks, they try to observe themselves by writing a self-growth declaration, and learn about the feeling of success or failure by writing a bucket list of what they intend to do while in college. This is followed by in-depth individual interviews with professors and mentors outside the university to become aware of the realistic challenges in realizing one's dream.

Through the Interplays of Humanities and Technology theme, the students break away from a narrow and short-sighted worldview of practical engineering and are trained to understand humans and the world more holistically, and are encouraged to practice intuitive insights through philosophical introspection. The Creative Studio theme has a course in which the students suggest solutions to the specific real-world problems by designing multidisciplinary solutions encompassing the liberal arts point of view.

The Creative Studio theme is taught by professors who examine scientific technologies from the perspective of humanities. Each of the studio subjects have different approaches to problems and cover different topics, but they all solve problems creatively based on design thinking. Students recognize that they can create new values in human society when their engineering knowledge converges with insights from humanities. Since it is a new multidisciplinary project-based class, professors and students are encouraged to put in much effort in communicating with each other so that creative ideas can come alive and detailed solutions can be generated.

Another motor of CiTE education is the Creative IT Design program, which converges various IT-based knowledge so that free engineering imagination can be inspired. The Creative IT Design classes are designed to innovatively change the unproductive traditional educational process by instilling the research fun into students and enabling them to discover the joy of pursuing self-initiated research and exploration.



As an example, say that a student in CiTE program wants to realize a swimming underwater robot as an undergraduate research project. He or she faces various challenges throughout the semester such as finding what technologies are needed, in what mechanisms they are realized, and how they must be made. In a traditional mechanical engineering, computer engineering or IT-focused department, a customized class is not offered to carry out such research project. In CiTE program, professors spend as much time as possible to help and listen to their students, find and study research papers and data with them. Through this collaboration, professors also find and learn the knowledge they have not known which is naturally shared with the students. In some cases, the professors ask researchers and research professors of the department for help or even other professors in POSTECH so that students can get individual support. This is what professors and students carry out continuously during a Creative IT Design course.

CiTE students who entered as freshmen in 2012 have experienced a completely different educational program, sometimes facing frustration and feeling lost. But it can be confidently said that they have grown to be excellent human resources by gaining strength from their steadfast achievements and even from failures. All professors and students are glad to say that the path they have walked has been the right one despite the unexpected struggles and hardships, which eventually led to their personal and professional growth.

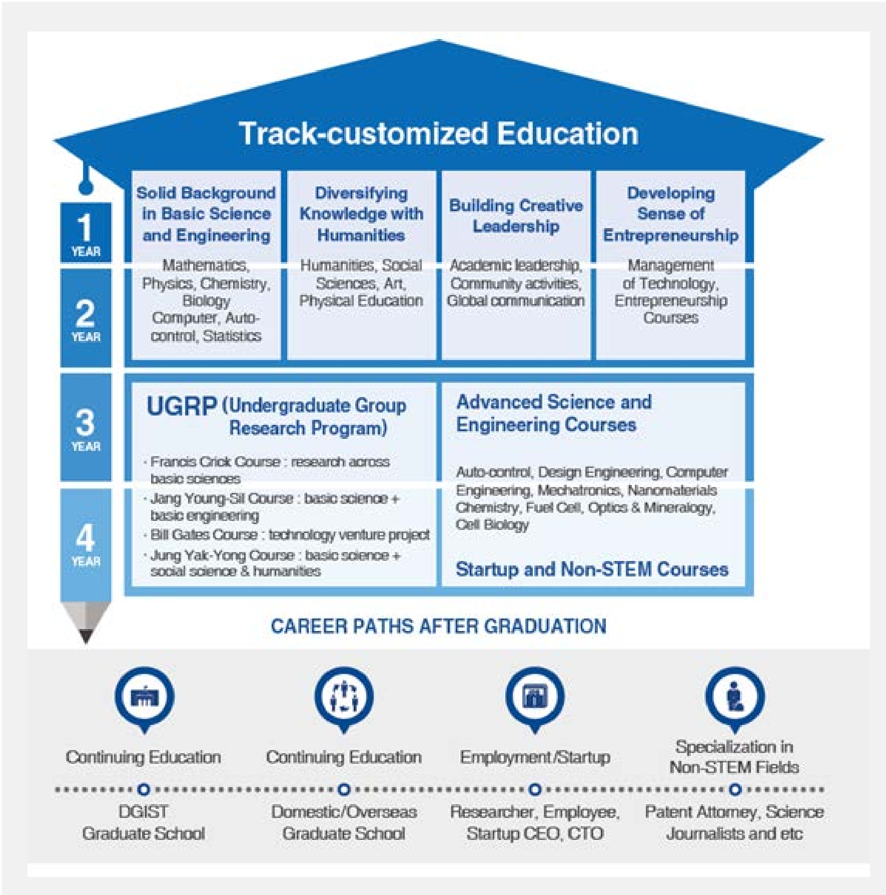
- College of Transdisciplinary Studies

Daegu Gyeongbuk Institute of Science & Technology (DGIST)

DGIST is a national science & technology institute first established as a research institute by the Korean government in 2004. The College of Transdisciplinary Studies (CTS), launched in 2014, is the undergraduate school at DGIST. The College of Transdisciplinary Studies is categorically a unique educational experience in Korea (or quite possibly unique even in the world), which employs an entirely non-departmental, that is, truly transdisciplinary undergraduate education system. CTS offers student-focused education within the world-class research university in which the faculty are exclusively committed to undergraduate education and their students. Even the campus architecture supports this special transdisciplinary approach wherein the main building for CTS, the Consilience Hall, is an elongated structure literally spanning all five graduate departments at DGIST, allowing easy access to all academic facilities for CTS students and faculty. In this sense, form has very deliberately been designed to follow function.

CTS admits about 200 undergraduate students every year, many of whom are from leading science high schools nationwide. The undergraduate student body forms a single unity without any departmental walls. Students study the basic sciences and engineering subjects such as mathematics, physics, chemistry, biology and computer sciences together with carefully selected liberal arts courses, along with physical fitness and music training during their first two years. From their 3rd and 4th years, more advanced science and engineering courses are provided under the close cooperation with the faculty members from the graduate programs.

In addition, junior and senior students conduct research in groups of 3~5 students supervised by 1~2 advisors through the Undergraduate Group Research Program (UGRP). The UGRP research topics can be suggested not only by the faculty members and researchers but also by the students themselves. UGRP topics are categorized in four groups: the Francis Crick course for biological sciences, the Jang Young-Sil Course for science and engineering, the Bill Gates Course for technology venture projects, and the Jung Yak-Yong Course for basic sciences and humanities.



Undergraduate Curriculum of CTS

CLE Educational Principles	Convergence Education	Leadership Education	Entrepreneurship Education
Three Innovative Education System	Transdisciplinary Curriculum within the Single Unified school	Teaching Faculty Dedicated to Undergraduate Education	Faculty-developed Electronic Textbooks

<u>Graduate Convergence Education:</u>

- Graduate School of Convergence Science and Technology (GSCST)

Seoul National University

Seoul National University (SNU) has been recognized as a prestigious institution in Korea since its foundation in 1946, and it has grown into one of the world's leading research universities. The local Gyeonggi Province recognized the potential synergy between SNU's prominence and Gyeonggi Province's cluster strategy and established a research and educational institution devoted to the development and application of convergence technologies, the first of its kind in Korea. The research arm was named the Advanced Institutes of Convergence Technology (AICT), and the education arm was named the Graduate School of Convergence Science and

Technology (GSCST). They are co-located in the Gwanggyo Techno Valley in Suwon 30 km away from the main SNU Seoul campus.

GSCST has the mission of fostering creativity as well as field expertise in the new convergence technologies such as NT, IT, BT, and CT, thereby promoting the creation and the development of new industries. To this end, the GSCST has established the graduate convergence research program consisting of Nano Science and Technology, Digital Contents and Information Studies, Intelligent Systems, Biomedical Radiation Sciences, and Molecular Medicine and Biopharmaceutical Sciences.

GSCST has been accumulating an extensive experience in convergence education and convergence research since its opening in 2009, and some of the important advantages and difficulties have been identified. As expected, GSCST's broad spectrum of research topics turned out to be a good stimulus for promoting new and convergent research topics. Easy access to the experts in near or far disciplines have been helpful, and arguably the daily interactions and casual discussions have been the most important for keeping eyes and minds open for convergence research. Also, the program has attracted students with diverse backgrounds, allowing students to see different approaches on similar research topics. This has particularly been beneficial for the platform-based research such as robotics which requires students from diverse disciplines who would have been difficult to recruit in a traditionally-disciplined engineering department. Natural convergence of talents paid off handsomely when the GSCST robotics team won the 12th place in DARPA Robotics Challenge in 2015. Occasionally, the student diversity forced their advisors to learn new disciplines, naturally promoting convergence. Because of the program's convergence-oriented goals, GSCST has been encouraging its members to freely choose and alter their research topics. Having a flexibility has greatly lowered the barrier for investigating new directions.

The graduate program requires all student to take the Interdisciplinary Project Design course. This class is to promote teamwork and collaboration among the graduate students. Students from different research disciplines are encouraged to identify a common problem or a research topic that can be investigated and studied together as a group. Once the topic has been identified, a technology roadmap is made and technology sensing is carried out to gather necessary technologies to arrive at a convergence solution. A rapid prototyping is then performed to demonstrate the solution. The course provides support through other students' and faculty members' feedbacks to arrive at an optimal solution.

As for the future improvements, two of the most important ones were recognized. First, convergence among weakly related disciplines has been challenging. An expert from nanomaterials and an expert from human-computer interaction can discuss their research topics, but they would rarely come up with a common research topic that they could collaborate on. Without a strong connection, it has been difficult to apply a systematic approach, and the convergence efforts can ended up being opportunistic. Secondly, convergence and innovation indeed requires enough time and resource, as well as a new evaluation and faculty tenure review system that should encourage teamwork and convergence rather than academic accomplishments in a narrowly focused area. Fortunately, the situation has greatly improved over the years with enough convergence research funding and the promotions of young faculty members, allowing them to freely explore and establish new convergence research topics.

<u>Convergence Education for the General Public</u>

- Advanced Institute of Convergence Technology (AICT)

Seoul National University[2]

AICT was established in 2008 as an independent nonprofit research organization whose infrastructure was built by the local Gyeonggi Province while research and management functions are being carried out by SNU. In addition to its main mission to conduct convergence research for the discovery and creation of key technologies to improve future economy, one of the AICT's important agenda is to educate the general public including, industry engineers, government personnel, and students ranging from primary school to college. To this end, AICT has developed a variety of programs and is currently running the following educational and public relations programs.

World Class Convergence Program

This 6-month-long executive program aims to help CEOs and CTOs of SMEs to become world-class corporate leaders so that they can make a leap forward in leading the company through the use of convergence technologies and technology management methodologies. The program offers exposure to state-of-the-art technology trends, technology management tools, and problem-based learning sessions to address the real-world issues in effectively growing an enterprise.

Short Course on Convergence Science and Technology

This 2-day short course is aimed at educating the workers of the government and public agencies. It is designed to enrich their science and technology convergence awareness and to provide information on domestic and overseas convergence activities so that they can contribute effectively to the current issue resolution and policy making.

Cultural Concert for Convergence

This open concert is designed to educate the public about convergence in the areas of science, technology, and humanities by inviting publicly well-known speakers to give a series of lectures. The lectures are preceded by cultural events such as musical concerts or performing arts. This program is particularly popular among the local high school students who can get personal exposures to the lecturers of national fame.

Internship Program for College Students

Six-month-long internship program is offered throughout the year to students who have finished first year or beyond in college. Selected students acquire hands-on research and on-the-job training experiences. A popular activity among the students is the brown-bag seminar where

[2] Pak YE and Rhee W (2015) Convergence Science and Technology at Seoul National University. Handbook of Science and Technology Convergence (eds. Bainbridge WS, Roco MC), Springer International Publishing, Switzerland.

professors and researchers from AICT and GSCST give interesting and informative talks on the topics of their convergence research.

Youth Convergence Science Camp
Targeting primary through high school students in Gyeonggi Province, this 2-day sleepover camp is designed to promote creativity in the youth and to rear them as global leaders by providing them with early opportunities to experience convergence research activities. This program includes series of lectures and hands-on laboratory experience so that the students can gain better understanding of the topics and methods of convergence science and technology.

Concluding Remarks
Korea is investing heavily on the convergence research and education. The success of these efforts will depend on the central government's leadership in addressing the Grand Challenges, including the long-term vision, workable strategies, and funding plans. Parallel efforts should be made by the local governments responding with matching investments in providing appropriate environment and infrastructure conducive for creative convergence activities along with the funding for convergence research. The local governments' technology cluster strategy was proven to be effective for bringing many technologies and businesses together in one location and creating synergy through convergence. Lastly, the academic and research institutions should in time produce tangible results, which can be achieved through diversity and flexibility that encourage convergence and innovation. Furthermore, the institutions are responsible for delivering education and training not only for the skilled workers and professionals but also for the general public. Overall, the diversity and openness are important components for science and technology convergence, and in addition the humanities, arts, and social sciences should play essential roles for a broader success.

3. **Imagining the future of technology assisted convergent education - The Future of Convergence Education**

Dr. Chris Kaiser, MIT

Overview

The concept of convergence has already shown great success as an organizing principle for directing attention and resources towards exciting research spanning disciplines in the life sciences, physical sciences, and engineering. But the idea of convergence serves as an equally powerful framework for innovation and transformation in STEM education in both the graduate and undergraduate programs. Here we would like to focus attention on key areas for which a transformation based on convergence thinking may have maximum impact in recruiting promising young scientists, improving quantitative and hands-on education, democratizing access to STEM fields, and leading the way in the broad transformation of education in the information age.

Using Convergence as an attractor for young scientific and engineering talent

Plutarch's aphorism "*Education is not the filling of a pail, but the lighting of a fire*" is surely still true today although there is vastly more information that might be poured into the pail than in Plutarch's time. One of the most fundamental and important ways that education can advance convergence of life sciences and physical sciences is to recruit the next generation of leaders to advance this new frontier.

An instructive historical example of how new ideas can be used for recruitment is Erwin Schrödinger's book, "*What is Life*". This brief book, published in 1945, is an informal and imaginative take on genetics as viewed from the perspective of quantum physics and is credited with recruiting many physicists to the emerging field of what is now called molecular biology. A focal point of the book is the question of what is the physical substance that makes up genes. In a memorable passage Schrödinger argues that distinct human traits, which must be the result of specific molecular variants of gene structure, can be seen to be faithfully passed from one generation to the next over hundreds of years. He observes that classical molecules do not have this thermodynamic stability proposes that new physics may be required to explain the incredible stability of the genetic material and that using physics to study of genes was an open new frontier in understanding the fundamental principles of the natural world. Indeed, many of the young scientists who led the birth of the field of molecular biology were students of quantum physics interested in such a challenge.

Schrödinger's book still stands as an example of how to connect powerfully with the imagination of young scientists and engineers. Following his example, curricula and materials for convergence courses should be explicitly designed to inspire and lead in the following ways:

Fundamental and challenging problems should be highlighted. Ambitious young people seek ways to leave their mark on the world. Correspondingly, educators and mentors can attract the brightest young scientists and engineers to work on problems that can be framed as grand challenges. Just as with Schrödinger's challenge to physicists, many research problems that are ripe for convergence solutions research can be framed as grand challenges; such as – "How is cognition encoded in the neural circuitry of the brain? – and – "How can the emergent properties of complex cell biological systems be explained from the behaviour of individual molecules?"

The connection to important applications should be clear. Young people often look for professional pathways that will allow them to work on problems that will lead to applications that will make the world a better place. Convergence approaches to biomedicine have many important applications is the most important medical challenges that can be highlighted, such as cancer, brain disease, emerging viral diseases, and combating the rise of antibiotic resistance.

Point the way to new frontiers where young people can make their mark. Career decisions often track towards opportunities to be part of some new enterprise. This explains why young people are often attracted to new experimental paradigms. The convergence approach by its nature is rich in opportunities to establish innovative and distinctive new research programs. Education in convergence can play an important part in advancing and attracting young people to the field by deliberately pointing the way to these new opportunities.

Convergence thinking in the effective deployment of digital educational technology
We are long overdue for a sea-change in the way that we teach biology. The general outline for what needs to be accomplished can be found is in multiple reports (a good example is the NSF and AAAS report: "Vision and Change in Undergraduate Biology Education") which reinforce the idea that biology education should be more quantitative, have more hands-on experiences, and have more interdisciplinary connections. These imperatives are well aligned with the objectives of convergence education in biology, and is there is an opportunity and a mandate for those who are designing convergence courses and curricula to lead the way in delivering on new and visionary ways to teach biology.

One of the most significant ways that biological research is becoming more quantitative is through the use of statistical and probabilistic algorithms to extract meaningful biological information from very large (and often noisy) data sets. Nowhere in the curriculum is the need for hands-on experiences in quantitative biology more urgent in providing students real world experiences in biological data analytics. However, it has not been feasible to simply retrofit existing biology laboratory classes with a "big data" component. The problem being that student labs are not able to generate large data sets that would be worthwhile analyzing; labs are usually not equipped with the necessary equipment for high throughput data generation and in any case students don't have the laboratory skills or the time to produce large quantities of reliable data. The confluence of data analytics and molecular life sciences is a hotbed of activity on the convergence landscape and research labs working in convergence areas are well positioned to supply teaching labs with the basis to teach biological data analytics. A fruitful way to generate realistic large data sets – such as genome-wide expression profiling or genome wide association studies in human populations – would be to develop Monte Carlo simulators that could provide synthetic data the existing research data analytics platforms. Such simulated data can readily be made to appear to be highly realistic, even with synthetic noise added, and such simulations are already routinely used to perform statistical power calculations.

A second major benefit of developing digital educational tools is that they are readily transferrable. A simulator for data analytics would not only enhance quantitative biology education at home but could easily be shared with other institutions and could even be used to organize collaborative inter-institutional educational experiences.

Convergence leading the way in the coming transformation of education in the information age
One of the most profound changes in academic scholarship is the ubiquity and easy accessibility of high quality information connected to all STEM fields. Today's students have at their fingertips all of the course content in STEM fields many times over. Despite this, delivery of fact-laden narrowly disciplinarily focused course content, in classroom lectures, streaming online video and in textbooks has not changed much in thirty years. The time is ripe to embrace the accessibility of information and to orient teaching away from content delivery and towards arming students with a tool-kit that will empower them most efficiently seek content for themselves. Convergence education, which has as its essence building modes thinking that cross disciplinary boundaries is a natural platform to lead in this transformation.

A STEM curriculum at all but a very few institutions in higher education is organized in a hierarchical fashion where advanced subjects only offered to students who have fulfilled the necessary prerequisites. It is only at the most introductory level that subjects designed for students outside the field may be found; for example, classes often nicknamed "Physics for poets" may be offered for humanities students to fulfil a distribution requirement in the natural sciences. Rarely, seen are classes designed to take advantage of the fact that any advanced student who is doing well in a STEM major will have mastered problem-solving ability, experimental design, numeracy, and data analysis and would thus benefit from a much more advanced cross disciplinary subject matter.

But there is a pressing need for this type of training for advanced convergence students working at the confluence of disciplines. Imagine an engineering student developing a rapid assay for body fat composition. In order to think about how best to deploy such an assay that student may need to know enough about human genetics to know what a reasonable sample size for a genome wide association screen without knowing all of the details of such a screen that might be taught in an advanced human genetics course. Alternatively, a biology student contemplating a high throughput cell- microscopy assay might need to understand enough about computational optics to know what image capture rate would be feasible without necessarily knowing how algorithms for rapid feature recognition actually work.

Such advanced cross disciplinary education is not well supported by the current system in which the curriculum is organized around academic departments which usually have a mandate to educate only their own majors except at an introductory level. The advent of educational programs designed ton the principle of convergence should provide new incentives for experiments in cross-disciplinary education. Such experiments will give us a vision for how STEM education will advance into the information age and should be greatly encouraged.

4. The Knowledge Convergence Network - Mexico
Dr. Rebeca de Gortari, UNAM

The Knowledge Convergence Network for the benefit of society is interested in analyzing and studying the interaction between fields of knowledge related to biotechnology, nanotechnology, ICT and the digitalization of industry, advanced manufacturing and the aerospace industry. In this sense, the Network will focus its efforts on contributing to the creation of Science, Technology and Innovation (STI) policies oriented towards the convergence of said fields of knowledge through the proposal of reference frameworks and, if possible, success stories and good practices where convergence of knowledge turns out to be a key element of the results obtained. That is why it has proposed a set of recommendations aimed at tracing the transition of some of the elements of science and technology policy in Mexico to convergence, from the transformation of the relationship between science and industry towards a collaborative scheme at various levels, the modification of the perspective of linking, seeking the integration of more actors and a new governance of science and technology.

The agenda seeks to meet several objectives, be part of the analysis of industrial sectors, referring to the most relevant sectors of the national economy where convergence has greater conditions to develop, as would be the case of health, and middle and high manufacturing. Sectors that are increasingly subject to processes of high complexity that modify labor competencies, industrial relations and production systems, and subject to the effects of the Internet revolution in manufacturing, industry 4.0. In this regard, different funding programs are also analyzed in order to identify the extent to which they are adequate to promote innovation and the possibilities of promoting scientific and technological convergence, where a different design is proposed in the use and structuring of budgetary and financial instruments.

Another axis is Consejo Nacional de Ciencia y Technolgia (CONACYT, Mexico's equivalent of NSF) programs, such as mixed funds, as instruments for promoting applied research that have contributed to the improvement of graduate programs and the formation of resources and the creation and strengthening of research groups with the purpose of making proposals that can be aligned to promote the convergence of knowledge, have a multidisciplinary nature and, as far as possible, overcome the disciplinary logic. Among these, the the border programs of science and national problems stand out, which address fields of knowledge in biotechnology, nanotechnology, ICT (Information and Communications Technology) and digitalization of industry, advanced manufacturing and aerospace. However, the development of research in these fields, according to the criteria of public policy, usually travels through disciplinary matrices and, in that same perspective, they align the agents of the innovation system.

A highlight are the programs of networks and consortiums as new forms of organization of thematic consortiums for applied research and technological development, as possible spaces of convergence. A key aspect of convergence is the need to reorient and coordinate in the scientific, technological and productive spheres the type of training required by these new environments, with the purpose of instilling the notion of technological and scientific convergence that requires new knowledge and skills. Where physical and information infrastructures are also combined, as well as institutional and educational infrastructures for the training of new generations of scientists and engineers. In this sense, the postgraduate programs of the national census of Conacyt were considered. The evolution of postgraduate studies has been directed to increase their number and decentralization to the interior of the country and more recently to postgraduate studies with industry. However, most are still disconnected from the needs of the industrial and regional context at a social and economic level; there are few inter-institutional programs that complement scientific and technological capabilities; multidisciplinary postgraduate programs are insufficient, to the extent that most are disciplinary and maintain little communication with other scientific areas, which largely obeys the National System of Researchers that continues to be proposed under a disciplinary logic. However, postgraduate studies with industry have begun to move from the development of competencies for research with a high specialization towards the development of cognitive and instrumental skills and competencies, to favor the training of high level professionals capable of identifying, defining and solve problems as well as generate opportunities for innovation in a multidisciplinary scheme. Thus, fields are already supported in the interface between disciplines, and mainstreaming is observed above all through ICTs, in the same way as in inter-institutional alliances with specific industrial sectors. Others have arisen in response to the demand for services such as security and transmission of information, and certain sectors such as electronic, automotive ICT regionally.

The third axis is the regional and local aspect, which highlights the need to boost the governance of state innovation ecosystems with social impact, through the design of initiatives that articulate scientific and technological developments and shared goals of the productive, social and scientific innovation actors. There are differences between regions focused on sectors such as ICT, aerospace, nano and bio more related to the revolution 4.0 compared to other more traditional and where modernization is sought. Among the proposals are the generation of policies that promote the formation of human resources under a multidisciplinary and interdisciplinary approach and promote projects that must be resolved by multidisciplinary research teams.

The fourth axis is aimed at promoting the intensification and strengthening of dialogue and alliances between the different intermediate bodies both public and Higher Education Institutions (HEIs) and public research centers, and associations that group them as the Asociacion Nacional de Universidades e Instituciones de Educacion Superior (ANUIES) and Federation de Instituciones Mexicanas Particulares de Educacion Superior (FIMPES), the Red Nacional de Consejos y Orgnismos Estatates de Ciencia y Technolgia (REDNACECYT), and the Consultative Forum of science and technology, as well as private as the sectorial and business chambers, together with the new actors such as ECATis (Center for Technological Care of the Industry), the National Laboratories, and the Conacyt Chairs that participate in the dynamics of science, technology and innovation and in the political dialogue with the entities that define the national agenda are some proposals for the dissemination of convergence and its implications as well as its inclusion in public policies.

Finally, an element and no less important is the evaluation of CONACYT programs and projects that must meet different objectives and where the evaluating committees do not always have the necessary training and therefore do not understand the scope of multidisciplinary projects. and interinstitutional, for this reason it is necessary to emphasize the interaction between social and cognitive factors, and the use of new logical and reference frameworks against parameters such as publications, patents and congresses. Thus, several proposals are made, mainly aimed at training and training the evaluators with new metrics, this notwithstanding the need to propose new logical and reference frameworks in the multi-institutional and interdisciplinary programs. It should be noted that in several axes, it was possible to observe the participation of multidisciplinary research teams, as well as diverse modalities of scientific-technological convergence, in the same way as in the training of human resources, on which, however, there is no inventory to know its content in terms of the knowledge provided, as well as the spectrum of possibilities of application and / or diversification of the results. That`s why the new types of scientific and educational infrastructure will play a critical role in the success of the convergence of knowledge and technologies. New educational paradigms are required to prepare the next generation of scientists and engineers to work with convergent knowledge and technologies. This requires, at the same time, new R & D strategies to go beyond multidisciplinary research and support the type of transdisciplinary research needed by the convergence processes.[3,4] As an example, it stands out on one side, the national consortium of research in translational medicine and innovation , where the academic multidisciplinary groups, business and government sectors are meeting and which have started collaboration so that the results of research work addressed from the convergence point towards the clinical, instrumentation, biomedical or treatment application and contribute in the intervention, prevention and treatment of the diseases that afflict the Mexican population. On the other is the project about to be approved by the National Autonomous University of Mexico (UNAM) for the creation of a National School of Higher Studies in Juriquilla Queretaro, taking advantage of the infrastructure of a set of multidisciplinary institutes, centers, laboratories and postgraduate programs, promoting new plans and study programs such as bachelor's degrees in genomic sciences, in renewable energies, neurosciences among others, integrating knowledge and practical and collaborative learning research activities.

[3] Hacklin, Battistini and von Krogh, 2013
[4] Roco et al., 2013

5. **Materials World Modules**
Dr. Robert Chang, Northwestern

Materials World Modules

Meeting the Next Generation Standards through Scientific Inquiry & Engineering Design

Imagine…

What if students could study nanotechnology from the 6th grade on? What if right in their classrooms, they could design and test high-efficiency solar cells, environmental photocatalysts, and drugs for targeting cancer? What if they could learn to innovate, collaborate, communicate and apply systems thinking at age 12, and use the same advanced visualization and modeling tools as professional scientists and engineers? What if schools had an easy, affordable way to update their STEM curricula to meet the latest standards?

What is MWM?

The ***Materials World Modules (MWM)*** is a highly successful national program for integrated STEM learning established at Northwestern University in 1993 with funding from the National Science Foundation.

Sixteen classroom modules describe how materials and their properties can solve global problems and transform our everyday lives. Module topics cut across science disciplines and link them to engineering, math, and technology applications.

Published MWM Modules:

Biodegradable Materials
Biosensors
Concrete
Ceramics
Composite Materials
Food Packaging
Polymers
Smart Sensors
Sports Materials
Introduction to the Nanoscale
Drug Delivery at the Nanoscale
Dye-Sensitized Solar Cells
Environmental Catalysis
Nanopatterning
Nanotechnology
Manipulation of Light at the Nanoscale

Scientific inquiry and engineering design activities let students perform the work of scientists, engineers and entrepreneurs. Each module begins with a 'hook" activity followed by inquiry activities that culminate in an engineering design challenge. Students work on teams to design engineering solutions and communicate their benefits.

MWM and the New STEM Curriculum

• • •

Next Generation Science Standards: MWM emphasizes cross-cutting concepts, real-world relevance and a close integration of content learning and hands-on practice. The iterative process of scientific inquiry and engineering design demonstrates relevance and deepens student content knowledge.

National Math Standards: Students apply mathematical ways of thinking to real-world issues and challenges and use mathematics to analyze, understand, and make decisions based on empirical situations.

Vertical Integration – Ensuring Progression Across Grade Levels: MWM introduces fundamental concepts early on and reinforces them over time to create strong and coherent learning trajectories. Many teachers use MWM as a "DNA spiral" to provide continuity across grade levels and connect STEM disciplines.

Reinforce Science Literacy and Communication Skills: Inquiry activities require students to follow written procedures, make, test, and refine predictions based on activities, short summaries, and experiments. They must also support their claims with data and scientific findings.

Co-authored by teachers and university researchers, modules are continuously updated with the latest interdisciplinary research concepts and technology applications from the nation's top university laboratories. Each module includes student and teacher manuals, assessment questions, and a kit of classroom supplies (above.) Our nanotechnology modules also include interactive online tools that help students visualize and explore the nanoscale inside or outside class.

Flexibility for crowded curricula. Each module, from hook activity to design project, can be taught in just 10 class periods. Modules can be inserted into any math, science, or technology course, or combined to create semester-long courses on a variety of topics. Content is scalable from 6-12 grade.

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