The National Academies of
SCIENCES · ENGINEERING · MEDICINE

Integration of Education in the Sciences, Engineering, and Medicine with the Arts and Humanities at the Undergraduate and Graduate Levels

Program Book

July 27-28, 2016
NAS 120
2101 Constitution Avenue
Washington, DC

INTEGRATION OF EDUCATION IN THE SCIENCES, ENGINEERING, AND MEDICINE WITH THE ARTS AND HUMANITIES AT THE UNDERGRADUATE AND GRADUATE LEVELS

Agenda for the First Committee Meeting

NAS Building Room 120

2101 Constitution Avenue NW, Washington, D.C.

July 27-July 28, 2016

Wednesday, July 27, 2016

2:00 p.m. – 3:00 p.m. Closed Session

3:00 p.m.-7:30 p.m. Open Session and Reception

3:00 p.m.-3:45 p.m.

- Committee hears from project sponsors

3:45 p.m.-4:00 p.m. Coffee Break

4:00 p.m.-5:30 p.m. Committee discusses the goals of the study and broader questions, such as:

- What evidence exists on the impact of educational experiences that integrate the arts, humanities, and STEM?
- What kinds of integrated programs exist and which disciplines and sub-disciplines from the humanities, arts, and STEM are most typically integrated?
- How are the arts, humanities, and STEM distinct from each other? Are they really so different?
- Are there skills and competencies that are distinctly developed through the study of the arts, vs. the humanities, vs. STEM?

5:30 p.m.-6:00 p.m. Committee hears input from audience members and guests

6:00 p.m.-7:30 p.m. Reception in the Great Hall

Thursday, July 28, 2016

9:00 a.m.-10:00 a.m. Closed Session

10:00 a.m. -2:00 p.m. Open Session

10:00 a.m.-10:45 a.m.

- 15-minute presentation by Robert Root-Bernstein (Professor of Physiology Michigan State University) on *"A Review of Studies Demonstrating the Effectiveness of Integrating Arts, Music, Performing, Crafts and Design into Science, Technology, Engineering, Mathematics and Medical Education"* followed by discussion

10:45 a.m.-11:00 a.m. Coffee Break

11:00 a.m.-12:00 p.m.

- Panel discussion with William "Bro" Adams (Chairman of the National Endowment for the Humanities) and Richard Miller (President of Olin College of Engineering)

12:00 p.m. -1:00 p.m. Lunch

1:00 p.m.-2:00 p.m.

- Committee hears additional input from audience members and guests

2:00 p.m. -4:00 p.m. Closed Session

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Committee on Integration of Education in the Sciences, Engineering, and Medicine with the Arts and Humanities at the Undergraduate and Graduate Levels

Membership

David J. Skorton (NAM), Committee Chair
Secretary
The Smithsonian Institution

Susan Albertine
Vice President of the Office of Diversity, Equity, and Student Success
Association of American Colleges & Universities

Norman Augustine (NAS/NAE)
Retired Chairman and CEO
Lockheed Martin Corporation

Laurie Baefsky
Executive Director
ArtsEngine and the Alliance for the Arts in Research Universities (a2ru)

Paul Bevilaqua (NAE)
Retired Manager of Advanced Development Programs
Lockheed Martin Aeronautics Company

Kristin Boudreau
Professor and Department Head of Humanities and Arts
The Worcester Polytechnic Institute

Norman Bradburn
Senior Fellow
National Opinion Research Center
University of Chicago

Al Bunshaft
Senior Vice President
Dassault Systèmes' Americas Corporation

Gail Burd
Vice Provost for Academic Affairs
University of Arizona

Edward Derrick
Director Center of Science, Policy & Society Programs (CSPSP)
American Association for the Advancement of Science

E. Thomas Ewing
History Professor and Associate Dean of Graduate Studies, Research, and Diversity
The College of Liberal Arts and Human Sciences of Virginia Tech

J. Benjamin Hurlbut
Assistant Professor of Biology and Society in the School of Life Sciences
Arizona State University

Pamela Jennings
Director of the Center for Design Innovation
University of North Carolina in Winston-Salem

Youngmoo Kim
Director of the Expressive and Creative Interaction Technologies (ExCITe) Center and Associate Professor of Electrical and Computer Engineering
Drexel University

Tom Nelson Laird
Associate Professor in the Higher Education and Student Affairs Programs
Indiana University

Robert Martello
Professor of the History of Science and Technology
Olin College of Engineering

Gunalan Nadarajan
Dean and Professor at the Penny W. Stamps School of Art and Design at the University of Michigan

Lynn Pasquerella
President
Association of American Colleges and Universities

Suzanna Rose
Senior Associate Dean for the Sciences and Professor of Psychology & Women's Studies in the College of Arts & Sciences
Florida International University

Bonnie Thornton Dill
Dean and Professor of Women's Studies
University of Maryland, College of Arts and Humanities

Laura Vosejpka
Professor of Physical Science
Mid Michigan Community College

Lisa M. Wong
Musician, Pediatrician, and Past President
The Longwood Symphony Orchestra

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Irene Ngun
Research Associate
Board on Higher Education and Workforce

Committee Member Biographies

Chair

David J. Skorton (NAM) is the 13th Secretary of the Smithsonian. He assumed his position July 1, 2015. As Secretary, Skorton oversees 19 museums and galleries, 20 libraries, the National Zoo and numerous research centers, including the Smithsonian Astrophysical Observatory, the Smithsonian Tropical Research Institute and the Smithsonian Environmental Research Center. He is responsible for an annual budget of $1.3 billion, 6,500 employees and 6,300 volunteers. The Smithsonian's federal appropriation for fiscal year 2015 is $819.5 million, which accounts for 62 percent of the Institution's funding. The Smithsonian generates additional funding from private contributions and business revenues.

Skorton, 65, a board-certified cardiologist, previously was the president of Cornell University, a position he held from July 2006. He was also a professor in the Departments of Medicine and Pediatrics at Weill Cornell Medical College in New York City and in Cornell's Department of Biomedical Engineering at the College of Engineering. His research focus is congenital heart disease and cardiac imaging and image processing. Skorton is the first physician to lead the Smithsonian.

An ardent and nationally recognized supporter of the arts and humanities, Skorton has made the advancement of the arts a priority at the Smithsonian.

Members

Susan Albertine is Vice President of the Office of Diversity, Equity, and Student Success, at the Association of American Colleges & Universities. She provides leadership for the overall program of LEAP partner state initiatives, for programs and activities related to college readiness and student success, and for the Making Excellence Inclusive initiative. She serves as liaison to project contacts in the field, including policy, campus, business, P16, and community leaders. The office is responsible for AAC&U's Network for Academic Renewal meetings and for the Institute on High-Impact Practices and Student Success. Albertine received her BA in English from Cornell University, her MA in English from SUNY Cortland, and her Ph.D. in English from the University of Chicago. She was active in AAC&U before becoming vice president, serving as co-leader of the Educated Citizen and Public Health initiative, a collaborative project co-sponsored by AAC&U, the Association for Prevention Teaching and Research, the Council of Colleges of Arts and Sciences, the Association of Schools of Public Health, and other organizations, with support from the Centers for Disease Control and Prevention. She was dean of the School of Culture and Society and professor of English at the College of New Jersey from 2002 to 2008.

Previously, she served as vice provost for undergraduate studies, Temple University, and assistant to the provost, University of Pennsylvania. She has held faculty positions at the University of North Florida, St. Olaf College, and Susquehanna University, where she was chair of the Department of English. Her scholarship in American literature of the late 19th century led to research and an array of publications on women's work in print culture and on businesswomen's careers (in fiction and history) during the growth phase of industrialization in the U.S. A former public school teacher, Albertine has been nationally active to advance pre-school through college alignment, working with the Education Trust and the American Diploma Project. Her board service has included the Camden Academy Charter High School in Camden, New Jersey; the Advisory Board for the Delaware Study of Instructional Costs and Productivity—Faculty Study, University of Delaware; the Art Sanctuary, an African-American arts and letters organization based in Philadelphia; the Council of Colleges of Arts and Sciences. Albertine is a member of the Advisory Board, National Center for the First-Year Experience and Students in Transition.

Norman Augustine (NAS/NAE) is retired chairman and CEO of Lockheed Martin Corporation. Augustine was raised in Colorado and attended Princeton University where he graduated with a BSE in Aeronautical Engineering, magna cum laude, and an MSE. He was elected to Phi Beta Kappa, Tau Beta Pi and Sigma Xi.

In 1958 he joined the Douglas Aircraft Company in California where he worked as a Research Engineer, Program Manager and Chief Engineer. Beginning in 1965, he served in the Office of the Secretary of Defense as Assistant Director of Defense Research and Engineering. He joined LTV Missiles and Space Company in 1970, serving as Vice President, Advanced Programs and Marketing. In 1973 he returned to the government as Assistant Secretary of the Army and in 1975 became Under Secretary of the Army, and later Acting Secretary of the Army. Joining Martin Marietta Corporation in 1977 as Vice President of Technical Operations, he was elected as CEO in 1987 and chairman in 1988, having previously been President and COO. He served as president of Lockheed Martin Corporation upon the formation of that company in 1995, and became CEO later that year. He retired as chairman and CEO of Lockheed Martin in August 1997, at which time he became a Lecturer with the Rank of Professor on the faculty of Princeton University where he served until July 1999.

Augustine served on the President’s Council of Advisors on Science and Technology under Democratic and Republican presidents and led the 1990 Advisory Committee on the Future of the U.S. Space Program and the 2005 National Academies commission that produced the landmark report, Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future.

Augustine has been presented the National Medal of Technology by the President of the United States and received the Joint Chiefs of Staff Distinguished Public Service Award. He has five times received the Department of Defense's highest civilian decoration, the Distinguished Service Medal. He is co-author of The Defense Revolution and Shakespeare In Charge and author of Augustine's Laws and Augustine’s Travels. He holds 23 honorary degrees and was selected by Who’s Who in America and the Library of Congress as one of “Fifty Great Americans” on the occasion of Who’s Who’s fiftieth anniversary. He has traveled in over 100 countries and stood on both the North and South Poles of the earth.

Laurie Baefsky is Executive Director for ArtsEngine and the Alliance for the Arts in Research Universities (a2ru). She has served in this position since August 2014. Housed at The University of Michigan, a2ru is a partnership of over thirty institutions committed to ensuring the greatest possible institutional support for interdisciplinary research, curricula, programs and creative practice between the arts and other disciplines. Laurie has developed, led and taught within other interdisciplinary arts education initiatives for over 20 years. From 2007-2011 she established the USU ArtsBridge program at Utah State University, connecting university students with area schools and community organizations through arts-based interdisciplinary service-learning initiatives. During this time she also directed professional development efforts for northern Utah schools for the Beverley Taylor Sorenson Arts Learning Program. Prior to joining ArtsEngine / a2ru she served as grants manager for the Utah Division of Arts and Museums in Salt Lake City, where she oversaw the annual distribution of $1.3 million in state and federal funding for individuals, organizations, communities and educators. A skilled grant writer herself, her efforts have resulted in over $4.5 million in arts funding through grants from federal, state and private sources. Also an active performer and arts educator, Laurie has appeared on flute and piccolo with the Minnesota Orchestra, Utah Symphony, New World Symphony, and as a tenured member of the Virginia Symphony. As a chamber artist, her performance venues have ranged from Symphony Space and Chamber Music Society of Lincoln Center, NYC to northeastern Morocco and Umbria, Italy.

Paul Bevilaqua (NAE) is Retired Manager of Advanced Development Programs at Lockheed Martin Aeronautics Company. Paul Bevilaqua has spent much of his career developing Vertical Take Off and Landing aircraft. He joined Lockheed Martin as Chief Aeronautical Scientist and became Chief Engineer of the Skunk Works, where he played a leading role in creating the Joint Strike Fighter. He invented the dual cycle propulsion system that made it possible to build a stealthy supersonic VSTOL Strike Fighter, and suggested that conventional and Naval variants of this aircraft could be developed to create a common, affordable aircraft for all three services.He subsequently led the engineering team that demonstrated the feasibility of building this aircraft. Prior to joining Lockheed Martin, he was Manager of Advanced Programs at Rockwell International's Navy aircraft plant, where he led the design of VSTOL interceptor and transport aircraft. He began his career as an Air Force officer at Wright Patterson AFB, where he developed a lift system for an Air Force VSTOL Search and Rescue Aircraft. He received degrees in Aeronautical Engineering from the University of Notre Dame and Purdue University. He is a Fellow of the American Institute of Aeronautics and Astronautics and a member of the National Academy of Engineering. He is also the recipient of a USAF Scientific Achievement Award, AIAA and SAE Aircraft Design Awards, AIAA and AHS VSTOL Awards, and Lockheed Martin AeroStar and Nova Awards.

Kristin Boudreau is Professor and Department Head of Humanities and Arts at the Worcester Polytechnic Institute. Boudreau's research interests involve the ways literature reflects on and intervenes in cultural transformations. Professor Boudreau has written about the literature of slavery, the labor movement, capital cases, and modernization. After teaching in English departments for 17 years, she came to WPI in 2009 to chair the Department of Humanities and Arts, where she has taught HUA writing courses, Inquiry Seminars, and literature courses, has co-taught the Great Problems Seminar "Feed the World," and has advised and co-advised IQPs.

Like many faculty in the Humanities and Arts Department, Boudreau enjoys not only digging into her disciplinary research (19th-century American literature) but also stretching to join that disciplinary perspective to the topics of science and technology that are so important to WPI's students and faculty. Long interested in the literature of the nineteenth century and African American and working-class history and culture, she is now collaborating with colleagues in the Gordon Library and the Departments of Computer Science and Social Science and Policy Studies to bring these interests into conversation with the engineering challenge of restoring clean water to developing communities. Her team's goal is to design a series of classroom simulations that can approximate projects where actual projects are unfeasible. With students and colleagues she has developed an interdisciplinary role-playing simulation, "Worcester 1899: The Sanitary Engineering Challenge," and is working on another simulation based in contemporary rural Ghana. These simulations approach the engineering challenge of ensuring clean water while providing a rich cultural context that attends to historical particulars while also teaching a variety of disciplinary approaches.

Norman Bradburn is a Senior Fellow at NORC at the University of Chicago. He also serves as the Tiffany and Margaret Blake Distinguished Service Professor Emeritus in the faculties of the University of Chicago's Irving B. Harris Graduate School of Public Policy Studies, Department of Psychology, Booth School of Business and the College. He is a former provost of the University (1984-1989), chairman of the Department of Behavioral Sciences (1973-1979), and associate dean of the Division of the Social Sciences (1971-1973). From 2000-2004 he was the assistant director for social, behavioral, and economic sciences at the National Science Foundation. Associated with NORC since 1961, he has been its Director and President of its Board of Trustees. Bradburn has been at the forefront in developing theory and practice in the field of sample survey research in the cultural sector. He co-directs the American Academy of Arts and Sciences' Humanities Indicators project and Principal Investigator of the CPC's Cultural Infrastructure project. For the Humanities

Indicators project he oversees the collation and analysis of data, the creation of reliable benchmarks to guide future analysis of the humanities, and the development of a consistent and sustainable means of updating the data. For the Cultural Infrastructure project he oversees the systematic measurement of recent building projects and their consequences, modeling levels of creativity and sustainability of individual arts organizations before and after building projects, and the overall cultural vibrancy and vitality of their cities or regions as a result. Bradburn is a fellow of the American Statistical Association, a fellow of the American Association for the Advancement of Science and an elected member of the International Institute of Statistics. He was elected to the American Academy of Arts and Sciences in 1994. In 1996 he was named the first Wildenmann Guest Professor at the Zentrum for Umfragen, Methoden und Analyse in Mannheim, Germany. In 2004 he was given the Statistics Canada/American Statistical Association Waksberg Award in recognition of outstanding contributions to the theory and practice of survey methodology.

Al Bunshaft is the Senior Vice President of Dassault Systèmes' Americas Corporation where he spearheads key strategic initiatives and corporate leadership programs. He was a key architect in Dassault Systèmes' acquisition of IBM's PLM business and led the selection, design, construction and opening of the company's North American headquarters, an award-winning campus recognized for sustainable innovation and located in Boston's technology belt. Prior to joining Dassault Systèmes, Bunshaft served as global vice president of IBM PLM where he helped major manufacturing companies transition from physical to digital design practices and played a key role in the first digitally-designed automobile. He is a leading voice in corporate citizenship and science, technology, engineering and mathematics (STEM) initiatives, such as Teachers at Dassault Systèmes and "Day of Service at Dassault Systèmes." He is a member of the STEM subcommittee of the Clinton Global Initiative, a board member of the Massachusetts High Technology Council, and an advisory board member at the University at Albany, State University of New York's Department of Information and Computer Science. He received his Bachelor of Science in Computer Science and Mathematics from the school and has a Master of Science in Computer Engineering from Rensselaer Polytechnic Institute (RPI).

Gail Burd is the Vice Provost for Academic Affairs of the University of Arizona. Burd was appointed the Vice Provost for Academic Affairs in August 2008. In this role, Dr. Burd works closely with campus leaders to coordinate programs that will advance the academic mission of the University and help colleges and departments develop and assess their academic degree programs. Dr. Burd is also a Distinguished Professor in Molecular and Cellular Biology, Cell Biology and Anatomy, and the Committee on Neuroscience with a research program focused on development and neural plasticity in the vertebrate olfactory system. In prior administrative roles at the University of Arizona, Dr. Burd served as the Associate Dean for Academic Affairs in the College of Science, the Interim Department Head of Molecular and Cellular Biology, and the Associate Department Head of Molecular and Cellular Biology. A fellow of the American Association for the Advancement of Science, she has chaired several committees for national professional organizations, served on numerous government panels for the National Institutes of Health and the National Science Foundation, and received awards for her undergraduate teaching.

Edward Derrick became director of the AAAS Center of Science, Policy & Society Programs (CSPSP) in July 2011 after serving as deputy director then acting director of the AAAS Science and Policy Programs. The Center of Science, Policy & Society Programs bridges the science and engineering community on one side, and policymakers and the interested public on the other. The programs address an array of topics in science and society, including the interplay of science with religion, law and human rights; they also connect scientists and policymakers through programs in science and government, including the S&T Policy Fellowship program; and help improve the conduct of research through peer review and discussion of standards of responsible conduct. As chief program director, Derrick oversees the programs, which combined have a staff of about 35 and an annual budget of over $20 million, and serves as a member of senior management at AAAS. Ed first joined AAAS in 1998 as a member of the AAAS Research Competitiveness Program (RCP).

RCP provides review and guidance to the science and innovation community. He became director of the program in January 2004, with responsibility for the development of new business and oversight of all aspects of the design and execution of projects. Ed has participated directly in over 50 RCP projects, having led committees to assist state and institutional planning for research, to review research centers and institutions and to advise state and international funds on major investments. He holds the Ph.D. from the University of Texas at Austin, with a dissertation in theoretical particle physics, and the B.S. from the Massachusetts Institute of Technology, with an undergraduate thesis in biophysics. Between degrees, he worked for Ontario Hydro in the Nuclear Studies and Safety Division. Prior to joining AAAS, he spent two years as an Alexander von Humboldt Fellow in Germany.

E. Thomas Ewing is History Professor and Associate Dean of Graduate Studies, Research, and Diversity at the College of Liberal Arts and Human Sciences of Virginia Tech. is education included a BA from Williams College and a PhD in history from the University of Michigan. He teaches courses in Russian, European, Middle Eastern, and world history, gender / women's history, and historical methods. His publications include, as author, Separate Schools: Gender, Policy, and Practice in the Postwar Soviet Union (2010) and The Teachers of Stalinism. Policy, Practice, and Power in Soviet Schools in the 1930s (2002); as editor, Revolution and Pedagogy. Transnational Perspectives on the Social Foundations of Education (2005); and as co-editor, with David Hicks, Education and the Great Depression. Lessons from a Global History (2006). His articles on Stalinist education have been published in Gender & History, American Educational Research Journal, Women's History Review, History of Education Quarterly, Russian Review, and The Journal of Women's History. He has received funding from the National Endowment for the Humanities, the Spencer Foundation, and the National Council for Eurasian and East European Research.

J. Benjamin Hurlbut is Assistant Professor of Biology and Society in the School of Life Sciences at Arizona State University. Dr. Hurlbut is trained in science and technology studies with a focus on the history of the modern biomedical and life sciences. His research lies at the intersection of STS, bioethics and political theory. He studies the changing relationships between science, politics and law in the governance of biomedical research and innovation in the 20th and 21st centuries. Focusing on controversy around morally and technically complex problems in areas like human embryo research, genomics, and synthetic biology, he examines the interplay of science and technology with shifting notions of democracy, of religious and moral pluralism, and of public reason. He holds an A.B. from Stanford University, and a Ph.D. in the History of Science from Harvard University. He was a postdoctoral fellow in the Program on Science, Technology and Society at the John F. Kennedy School of Government at Harvard.

Pamela Jennings is the Director of the Center for Design Innovation at the University of North Carolina in Winston-Salem. She is also the CEO and President of CONSTRUKTS, Inc. a start-up company that has been supported by the National Science Foundation Small Business Innovation Research program (SBIR) and Highway1 Hardware Start-up incubator. Prior to her appointment at the Center for Design Innovation, Pamela directed the Shapiro Center for Research and Collaboration at the School of the Art Institute of Chicago a faculty focused initiative to raise the profile of research in the arts through funding, mentoring, and partnership development. Pamela served as a Program Director at the National Science Foundation Computer & Information Science & Engineering directorate. She led the CreativeIT program and co-managed the Human Centered Computing, Cyberlearning Transforming Education and Computer Research Infrastructure programs. Pamela served on the Federal Council for the Arts and Humanities and the Networking & Information Technology Research and Development Alliance (NITRD) Social, Economic and Workforce Coordinating Group (SEW). As a champion of interdisciplinary research between the Arts and Design and STEM (Science, Technology, Engineering, and Mathematics) she funded research projects, workshops, conferences, and meetings that convened stakeholders in the field to develop strategic plans for strengthening the STEM + Art or STEAM research and pedagogy platform. Prior to her position at the NSF, Pamela was the Director of the Advanced Research Technology Lab at the Banff New Media Institute in Banff, Alberta and adjunct faculty in the Department of Computer Science, University of Calgary in Canada. From 2001 to 2008 Pamela was a Professor at Carnegie Mellon University with a joint appointment in the School of Art in the College of Fine Arts and the Human Computer Interaction Institute in the School of Computer Science. She developed new curriculum and research projects that engaged students from academic disciplines from the Fine and Applied Arts to Computer Science and Engineering.

Pamela received her PhD in Human Centered Systems Design and Digital Media, School of Computer Science, University of Plymouth, United Kingdom; MBA, Ross School of Business, University of Michigan; MFA in Computer Art, School of Visual Arts; MA in Studio Art, International Center of Photography/New York University Program; and BA in Psychology, Oberlin College.

Youngmoo Kim is Director of the Expressive and Creative Interaction Technologies (ExCITe) Center and Associate Professor of Electrical and Computer Engineering at Drexel University. His research group, the Music & Entertainment Technology Laboratory (MET-lab) focuses on the machine understanding of audio, particularly for music information retrieval. Other areas of active research at MET-lab include human-machine interfaces and robotics for expressive interaction, analysis-synthesis of sound, and K-12 outreach for engineering, science, and mathematics education.

Youngmoo also has extensive experience in music performance, including 8 years as a member of the Tanglewood Festival Chorus, the chorus of the Boston Symphony Orchestra. He is a former music director of the Stanford Fleet Street Singers, and has performed in productions at American Musical Theater of San Jose and SpeakEasy Stage Company (Boston). He is a member of Opera Philadelphia's newly-formed American Repertoire Council.

Youngmoo was named "Scientist of the Year" by the 2012 Philadelphia Geek Awards and was recently honored as a member of the Apple Distinguished Educator class of 2013. He is recipient of

Drexel's 2012 Christian R. and Mary F. Lindback Award for Distinguished Teaching. He co-chaired the 2008 International Conference on Music Information Retrieval hosted at Drexel and was invited by the National Academy of Engineering to co-organize the "Engineering and Music" session for the 2010 Frontiers of Engineering conference. His research is supported by the National Science Foundation and the John S. and James L. Knight Foundation.

Tom Nelson Laird is Director of the Center for Postsecondary Research (CPR) as well as principal investigator for the Faculty Survey of Student Engagement (FSSE), a companion project to the National Survey of Student Engagement (NSSE). Tom is also an associate professor in the Higher Education and Student Affairs program at IU and an associate editor for The Journal of Higher Education. As a member of the CPR staff, he is responsible for the center's overall management and for FSSE operations. Tom received a PhD in higher education from the University of Michigan (2003), an MS in mathematics from Michigan State University (1997), and a BA in mathematics from Gustavus Adolphus College (1995). His work focuses on improving teaching and learning at colleges and universities, with emphasis on the design, delivery, and effects of curricular experiences with diversity. Through dozens of journal articles, book chapters, scholarly papers, and reports, his work has appeared in key scholarly and practitioner publications. Tom also consults with higher education institutions and related organizations on topics ranging from effective assessment practices to the inclusion of diversity in the curriculum.

Robert Martello is Professor of the History of Science and Technology at Olin College of Engineering. Martello received his Ph.D. from MIT's Program in the History and Social Study of Science and Technology, following his completion of a Master of Science degree in civil and environmental engineering and Bachelor of Science degree in earth, atmospheric, and planetary science from MIT. Prior to joining the Olin College faculty in 2001 during Olin's "partner" year, Martello lectured in MIT's history of technology program and served as the Producer for the "Digital History" component of Inventing America, an American history textbook. Martello's Ph.D. dissertation and ensuing research use Paul Revere's many manufacturing and entrepreneurial endeavors to tell the story of America's transition from craft practices to industrial capitalism. He published his first book, Midnight Ride, Industrial Dawn: Paul Revere and the Growth of American Enterprise, in the fall of 2010, and is currently researching his next book project, a study of Benjamin Franklin's innovative printing career and identity as an artisan. Martello frequently offers public history talks on the subjects of Paul Revere's groundbreaking manufacturing career or Benjamin Franklin's adventures as a printer, and enjoys collaborating with the Paul Revere Memorial Association on different educational initiatives. At Olin, Martello frequently co-chairs the Arts, Humanities, and Social Science committee and helps students cross disciplinary lines and apply their communication and contextual analysis skills to global challenges. He is the co-principal investigator on three National Science Foundation grants studying the integration of humanities and technical pedagogies, the development and deployment of lifelong learning skills, and the importance of intrinsic motivation. Martello has also delivered numerous talks and has facilitated many workshops for fellow educators interested in student motivation, interdisciplinary education, and project-based teaching.

Gunalan Nadarajan is Dean and Professor at the Penny W. Stamps School of Art and Design at the University of Michigan. His publications include Ambulations (2000), Construction Site (edited; 2004) and Contemporary Art in Singapore (co-authored; 2007), Place Studies in Art, Media, Science and Technology: Historical Investigations on the Sites and Migration of Knowledge (co-edited; 2009), The Handbook of Visual Culture (co-edited; 2012) and over 100 book chapters, catalogue essays, academic articles and reviews. His writings have also been translated into 16 languages. He has curated many international exhibitions including Ambulations (Singapore, 1999), 180KG (Jogjakarta, 2002), media_city (Seoul, 2002), Negotiating Spaces (Auckland, 2004), DenseLocal (Mexico City, 2009) and Displacements (Beijing, 2914). He was contributing curator for Documenta XI (Kassel, Germany, 2002) and the Singapore Biennale (2006) and served on the jury of a number of international exhibitions, including ISEA2004 (Helsinki / Talinn), transmediale 05 (Berlin), ISEA2006 (San Jose) and FutureEverything Festival (Manchester, 2009). He was Artistic Co-Director of the Ogaki Biennale 2006, Japan and Artistic Director of ISEA2008 (International Symposium on Electronic Art) in Singapore.

He is active in the development of media arts internationally and has previously served on the Board of Directors of the Inter Society for Electronic Art and is on the Advisory Boards of the Database of Virtual Art (Austria), Cellsbutton Festival (Indonesia) and Arts Future Book series (UK). He currently serves on the International Advisory Board of the ArtScience Museum in Singapore. In 2013, he was elected to serve on the Board of Directors of the College Art Association. He has also served as an advisor on creative aspects of digital culture to the UNESCO and the Smithsonian Institution. He continues to work on a National Science Foundation funded initiative to develop a national network for collaborative research, education and creative practice between sciences, engineering, arts and design. He is a member of several professional associations including Special Interest Group in Graphics and Interactive Techniques (SIGGRAPH), Association for Computing Machinery (ACM), College Art Association, National Council of University Research Administrators, International Association of Aesthetics, International Association of Philosophy and Literature and the American Association for the Advancement of Science. In 2004, he was elected a Fellow of the Royal Society of Art.

He has served in a variety of academic roles in teaching, academic administration and research for over two decades. Prior to joining University of Michigan, he was Vice Provost for Research and Dean of Graduate Studies at the Maryland Institute College of Arts. He also had previous appointments as Associate Dean for Research and Graduate Studies at the College of Arts and Architecture, Pennsylvania State University and Dean of Visual Arts at the Lasalle College of the Arts, Singapore.

Lynn Pasquerella is President of the Association of American Colleges and Universities. Assuming the presidency of the Association of American Colleges and Universities on July 1, 2016, throughout her career, Lynn Pasquerella has demonstrated a deep and abiding commitment to access to excellence in liberal education regardless of socioeconomic background. A philosopher, whose career has combined teaching and scholarship with local and global engagement, Pasquerella's presidency of Mount Holyoke College was marked by a robust strategic planning process, outreach to local, regional, and international constituencies, and a commitment to a vibrant campus community.

A graduate of Quinebaug Valley Community College, Mount Holyoke College, and Brown University, Pasquerella joined the Department of Philosophy at the University of Rhode Island in 1985, rising rapidly through the ranks to the positions of Vice Provost for Research, Vice Provost for Academic Affairs, and Dean of the Graduate School. In 2008, she was named Provost at the University of Hartford. In 2010, her alma mater appointed her the eighteenth President of Mount Holyoke College.

Pasquerella has written extensively on medical ethics, metaphysics, public policy, and the philosophy of law. At the core of her career is a strong commitment to liberal education and inclusive excellence, manifested in service as senator and vice president of Phi Beta Kappa; her role as host of Northeast Public Radio's The Academic Minute; and her public advocacy for access and affordability in higher education.

Suzanna Rose is the Senior Associate Dean for the Sciences and Professor of Psychology & Women's Studies in the College of Arts & Sciences at FIU. She previously served as Chair of Psychology and as Director of Women's Studies at FIU. Prior to coming to FIU, she was Professor of Psychology and Director of Women's Studies at the University of Missouri-St. Louis. Dr. Rose has published extensively on issues related to women and gender, including professional networks, career development, leadership, and personal relationships. Dr. Rose has been a member of eight editorial boards for journals in psychology and women's studies and also served on APA grant panels. More than thirty universities nationally and internationally have consulted with her concerning strategies for recruiting and retaining women faculty in science and engineering.

Bonnie Thornton Dill is dean of the University of Maryland College of Arts and Humanities and professor of Women's Studies. A pioneering scholar studying the intersections of race, class and gender in the U.S. with an emphasis on African American women, work and families, Thornton Dill's scholarship has been reprinted in numerous collections and edited volumes. Her recent publications include an edited collection of essays on intersectionality with Ruth Zambrana entitled Emerging Intersections: Race, Class, and Gender in Theory, Policy, and Practice (Rutgers University Press, 2009), and numerous articles.

Prior to assuming the position of dean, Thornton Dill chaired the Women's Studies Department for eight years. In addition, she has worked with colleagues to found two research centers that have been national leaders in developing and disseminating the body of scholarship that has come to be known by the term “intersectionality.” Today she holds the title of Founding Director for both the Center for Research on Women at the University of Memphis and the Consortium on Race, Gender and Ethnicity at the University of Maryland. She is currently President of the National Women’s Studies Association (2010-2012) and prior to that was Vice President of the American Sociological Association. Thornton Dill also serves as Chair of the Advisory Board of Scholars for Ms. Magazine.

Professor Thornton Dill has won a number of prestigious awards including two awards for mentoring; the Jessie Bernard Award and the Distinguished Contributions to Teaching Award both given by the American Sociological Association; the Eastern Sociological Society’s Robin Williams Jr. Distinguished Lectureship; and in 2009-2010, was appointed Stanley Kelley, Jr. Visiting Professor for Distinguished Teaching in the Department of Sociology at Princeton University. Her current research pulls together her knowledge and experience as a teacher, mentor and institution builder around issues of race/ethnicity, class and gender in higher education to examine the experiences of historically underrepresented minority faculty in research universities, focusing specifically upon the impact of occupational stress on their physical and mental health and their career paths.

Laura Vosejpka is a Professor of Physical Science at Mid Michigan Community College in Harrison, Michigan. She is responsible for the Physics program and the Non-majors Science program and she shares responsibility for the Chemistry program. As chair of the General Education Committee, she leads work in mapping General Education program goals to both transfer agreements and the DQP. She is also leading the college’s participation in the Michigan Community College Association Guided Pathways Institute aimed at improving retention and completion rates for MMCC students. Her organic chemistry students, were recently awarded First Prize in the college wide T-Summit Student Showcase for their hands-on presentation of the history and chemistry of organic dyes.

A 25 year resident of the Mid Michigan area, Vosejpka has held a number of academic and industrial positions in the immediate area. Prior to joining MMCC, she served as the Executive Communications Director for Global R&D for the Dow Chemical Company. There she was responsible for providing internal and external executive communications support for the Chief Technology Officer, William F. Banholzer, and the R&D Leadership Team. Laura led all initiatives in Innovation and Technology communication, developing strategy and creating materials for internal & external use by numerous groups, such as Media Relations and Investor Relations. She coordinated the role of R&D in VIP visits and external events including executive speeches, R&D displays and tours and led Dow’s participation in national TED conferences. Laura had an earlier role at Dow as an R&D Specialist in Core R&D, working in the areas of biocatalysis, and electroactive organic polymers (pLED). She is the author of 6 internal Dow research reports and was awarded the 2002 Chemical Sciences Technical Award for her work on pLED polydispersity and lifetime relationships.

A passionate advocate for liberal arts education, Vosejpka was a dual major in science and the humanities, graduating with Honors from The Ohio State University with BA degrees in both chemistry and English. She earned her Ph.D. in Organic Chemistry from the University of Wisconsin – Madison in 1989, working in the research group of Professor Charles P. Casey, and then spent 18 months as a postdoctoral research associate at the University of Maryland in the synthetic organic chemistry labs of Professor Philip DeShong before beginning her position at Alma College.

Lisa M. Wong is a musician, pediatrician, and past president of the Longwood Symphony Orchestra. She grew up in Honolulu, Hawaii where she attended Punahou School, an independent school centered on education, the arts and community service. She began the piano at age 4, violin at age 8, guitar at age 10 and viola at age 40. Wong is married to violinist Lynn Chang. They have two grown children, Jennifer and Christopher Chang. Wong graduated from Harvard University in East Asian Studies in 1979, and her M.D. from NYU School of Medicine in 1983. After completing her pediatric residency at Massachusetts General Hospital in 1986, she joined Milton Pediatrics Associates and is an Assistant Clinical Professor of Pediatrics at Harvard Medical School.

Wong is inspired by the work of Nobel Peace Prize laureate Dr. Albert Schweitzer, a humanitarian, theologian, musician and physician. During her twenty year tenure as president of the Longwood Symphony Orchestra, was honored to work with remarkable leaders in healthcare and humanitarianism including Dr. Lachlan Forrow, Jackie Jenkins-Scott, Dr. Jim O'Connell and Dr. Paul Farmer. Although she retired as President of the LSO in 2012, Wong continues her involvement with the orchestra as a violinist in the section. A passionate arts education advocate, Wong has worked closely with the New England Conservatory of Music's Preparatory School and traveled with NEC's Youth Philharmonic Orchestra to Brazil, Cuba, Guatemala, Panama, and Venezuela as a pediatric chaperone. Wong continues to be actively involved in El Sistema USA and has had the privilege of observing El Sistema in Venezuela several times over the past ten years.

Wong served as Board member of Young Audiences of Massachusetts for over 15 years and helped start Bring Back the Music (now renamed Making Music Matters), a program that revitalized in-class instrumental music instruction in the four Boston public elementary schools. In 2009, Wong was appointed to the Board of the Massachusetts Cultural Council by Governor Deval Patrick. In April 2010, Wong received the Community Pinnacle Award from Mattapan Community Health Center for LSO's pivotal role in their capital campaign to build a new neighborhood healthcare facility. Her first book Scales to Scalpels: Doctors Who Practice the Healing Arts of Music and Medicine, co-written with Robert Viagas, was published in April 2012 by Pegasus Books. It was released as a paperback in May 2013, and recently translated into Chinese. The AudioBook version will be released in early 2014.

Speaker Biographies

William "Bro" Adams is the tenth chairman of the National Endowment for the Humanities. Adams, president of Colby College in Waterville, Maine from 2000 until his retirement on June 30, 2014, is a committed advocate for liberal arts education and brings to the Endowment a long record of leadership in higher education and the humanities. A native of Birmingham, Michigan, and son of an auto industry executive, Adams earned his undergraduate degree in philosophy at Colorado College and a Ph.D. from the University of California at Santa Cruz History of Consciousness Program. He studied in France as a Fulbright Scholar before beginning his career in higher education with appointments to teach political philosophy at Santa Clara University in California and the University of North Carolina at Chapel Hill. He went on to coordinate the Great Works in Western Culture program at Stanford University and to serve as vice president and Secretary of Wesleyan University. He became president of Bucknell University in 1995 and president of Colby College in 2000. In each of his professional roles, Adams has demonstrated a deep understanding of and commitment to the humanities as essential to education and to civic life. At Colby, for example, he led a $376-million capital campaign – the largest in Maine history – that included expansion of the Colby College Museum of Art and the gift of the $100-million Lunder Collection of American Art, the creation of a center for arts and humanities and a film studies program, and expansion of the College's curriculum in creative writing and writing across the curriculum. He also spearheaded formal collaboration of the college with the Maine Film Center and chaired the Waterville Regional Arts and Community Center.

Richard K. Miller was appointed President and first employee of Olin College of Engineering in 1999. He served as Dean of the College of Engineering at the University of Iowa from 1992-99. The previous 17 years were spent on the Engineering faculty at USC in Los Angeles and UCSB in Santa Barbara. With a background in applied mechanics and current interests in innovation in higher education, Miller is the author of more than 100 reviewed journal articles and other technical publications. Together with two Olin colleagues, he received the 2013 Bernard M. Gordon Prize from the U.S. National Academy of Engineering (NAE) for Innovation in Engineering and Technology Education. A member of the NAE, he received the Marlowe Award for creative and distinguished administrative leadership from the American Society for Engineering Education in 2011. Miller served as Chair of the Engineering Advisory Committee of the U.S. National Science Foundation and has served on advisory boards and committees for Harvard University, Stanford University, the NAE and the U.S. Military Academy at West Point in addition to others. Furthermore, he has served as a consultant to the World Bank in the establishment of new universities. A frequent speaker on engineering education, he received the 2002 Distinguished Engineering Alumnus Award from the University of California at Davis, where he earned his B.S. He earned his M.S. from MIT and Ph.D. from the California Institute of Technology, where he received the 2014 Caltech Distinguished Alumni Award.

Bob Root-Bernstein is a scientist, humanist, and artist at Michigan State University. He earned his A.B. in Biochemistry (Bob Langridge) with a minor in Science in Human Affairs and a Ph. D. in History of Science from Princeton University (Thomas Kuhn). He then did his post-doctoral research in Theories in Biology and autoimmune disease research with Jonas Salk at the Salk Institute for Biological Studies. A MacArthur Fellowship (1981-1986) encouraged his multidisciplinary activities. He is currently a Professor of Physiology at Michigan State University where he studies the evolution of metabolic control systems, autoimmune diseases, drug development, and the creative process in the sciences and arts. He exhibits his artwork both in group and solo shows and collaborates with the transmedia artist Adam Brown. They are currently exhibiting a sculptural installation-performance piece called "ReBioGeneSys" that doubles as a working scientific experiment (http://adamwbrown.net).

In addition to being on the editorial boards of several scientific journals, Bob is an editor for LEONARDO, the journal of The International Society for Science, Technology and the Arts, for whom he edits a regular section on ArtScience. ArtScience explores the intersections of artistic and scientific practice from personal, methodological, historical and cultural perspectives.

Bob has written four books, including Discovering (nominated for 1990 L. A. Times Best Book of the Year) and, with Michele, Sparks of Genius (which won Korean Book of the Year when translated in 2009). He is at work on two more, one on artists and musicians as scientists and inventors, and the second on modern scientists as visual artists.

INTEGRATION OF EDUCATION IN THE SCIENCES, ENGINEERING, AND MEDICINE WITH THE ARTS AND HUMANITIES AT THE UNDERGRADUATE AND GRADUATE LEVELS

**A Project of the
Board on Higher Education and Workforce**

An ad hoc committee overseen by the Board on Higher Education and Workforce (BHEW), in collaboration with units in PGA, NAE, IOM, and DBASSE will produce a consensus report that examines the evidence behind the assertion that educational programs that mutually integrate learning experiences in the humanities and STEM lead to improved educational and career outcomes for undergraduate and graduate students. In particular, the study will examine the following:

- Evidence regarding the value of incorporating more STEM curricula and labs into the academic programs of students majoring in the humanities and liberal arts in order to understand the following: (1) how STEM experiences provide important knowledge about the scientific understanding of the natural world and the characteristics of new technologies, knowledge that is essential for all citizens of a modern democracy; (2) how major technological dimensions are essential to make sound decisions across all professional fields; and (3) how STEM experiences develop the skills of scientific thinking (a type of critical thinking), innovation and creativity that may complement and enrich the critical thinking and creativity skills developed by the humanities, as graduates in such fields enter the workforce and build careers.

- Evidence regarding the value of incorporating curricula and experiences in the humanities--including the arts, history, literature, philosophy, culture and religion --into college and university STEM education programs, in order to understand whether and how these experiences: (1) prepare STEM students and workers to be more effective communicators, critical thinkers, problem-solvers and leaders; and (2) prepare STEM graduates to be more creative and effective scientists, engineers, technologists and health care providers, particularly with respect to understanding the broad social and cultural impacts of applying scientific and technical knowledge to address challenges and opportunities in the workplace and in their communities.

- New models and good practices for mutual integration of the humanities and STEM fields at 2-year colleges, 4-year colleges, and graduate programs, drawing heavily on an analysis of programs that have been implemented at Harvard, Dartmouth, MIT, Princeton, Stanford, Florida International, Montgomery College, Arizona State University, SUNY-Binghamton, and other institutions of higher education.

The report will summarize the results of this examination and provide recommendations for all stakeholders to support appropriate endeavors to strengthen higher education initiatives in this area.

Often Asserted, Rarely Measured: The Value of Integrating Humanities, STEM, and Arts in Undergraduate Learning

Dr. Hannah Stewart-Gambino, Lafayette College

Dr. Jenn Stroud Rossmann, Lafayette College

INTRODUCTION

We want one class of persons to have a liberal education, and we want another class of persons, a very much larger class of necessity in every society, to forgo the privilege of a liberal education and fit themselves to perform specific difficult manual tasks. Woodrow Wilson, 1909 Address to the NYC High School Teachers' Association

At the turn of the 20th century Woodrow Wilson famously cast higher education in the United States as a privilege reserved for an elite cadre of the nation's future leaders. Today, however, the public views higher education as the path to broad social and economic mobility. STEM education – science, technology, engineering, and math – is widely assumed to be the key to this role in American higher education, particularly in the most dynamic sectors of the economy and, thus, in American innovation and global competitiveness. Higher education is still considered vital for preparing future leaders; however, at the beginning of the 21st century, the prevailing view is that education must be extended to prepare a broadly informed citizenry in order for the US to meet the technical challenges of modernity and to maintain its democratic leadership in the world. Yet, the perception of a conflict between these two aims persists in the American imagination. At least since the mid- 20th century, C. P. Snow's classic delineation of academia's "two cultures"[1] has helped define the view of higher education as perennially caught in the tension of a dual mission – providing society with a technically and scientifically literate workforce and a citizenry with the analytical perspectives gained from the traditional liberal arts, particularly humanities and the arts.

Kwame Anthony Appiah (2015) recently characterized the tension between the two contemporary strains in higher education as the choice between "utility" or "utopia". This language echoes the classical notion of disciplines as belonging to either the "liberal arts" or the "useful" ones. In fact, however, U.S. higher education claims *both* to train the modern workforce that fuels economic growth *and* to educate the citizenry in the perspectives necessary for a free, democratic marketplace of ideas and values. Even in the pre-professional fields, college and university curricula historically combined both economic and social purposes. Although the particular mix varies widely across the U.S higher education landscape, students can follow career-oriented and job training tracks at the same time that they complete general education requirements which typically include courses in humanities and the arts (e.g., American Association of Community and Junior Colleges, 1988).

[1] Snow himself was joining an ongoing discussion that may have begun with Descartes' distinction between materialist and idealist thinking, and these philosophical premises, colored by capitalist economic objectives, continue to foment debate, as texts such as *The One Culture?* (Labinger and Collins, 2001) illustrate.

Still, the questions of whether higher education is an elite privilege or an accessible public good, and what its purpose(s) may be, are contentious. And they are not rhetorical questions. In large part due to stagnated wages and steadily increasing costs of higher education, today's public fears that the educational pathway to socioeconomic security now lies beyond the reach of more and more Americans. The result is a perceived crisis not only for individual's access to career-enhancing education but also for creating a workforce for the challenges of heightened international economic competition. The uneasy marriage between "utility" and "utopia" seems to some – like the author of the commentary in the Harvard Crimson entitled "Let Them Eat Code" – like a quaint legacy of a bygone era that the country can no longer afford. Heightened competition for resources, perhaps particularly in public institutions, has led to concerns "that humanities instruction may recede into the small number of elite institutions that can afford the luxury of quasi-market-inefficient activities" (Taylor et al., 2010, p. 699). This sentiment is not unique to the US. For example, Japan's education minister, Hakuban Shimomura, recently called on all of Japan's 86 national universities to take "active steps to abolish (social science and humanities) organizations or to convert them to serve areas that better meet society's needs" (Grove, 2015). These developments appear to fundamentally change the meaning and content of what an educated citizenry knows or ought to know, and the result is an embattled liberal arts, humanities, and arts community fighting to defend their relevance and value to an increasingly skeptical public.

Measuring the "worth" of higher education generally and particular majors specifically has been the focus of policy makers, employers, and accrediting bodies for some time. However, little attention has been paid to the notion – widely held among most college and university administrators and faculty – that STEM and humanities and the arts not only contribute to the strength of the nation, but they contribute to the strength of *each other*. An effective counterpoint to Wilson's remarks is Noah Feldman's invocation to 2014 college graduates: "The whole point of the liberal arts education – that fragile, extraordinary, valuable thing, which is being put in your hands – is to teach you to participate as full partners in the making of the world around you" (Feldman, 2014). To be "full partners" would seem to require a full complement of methods, content, and values, achieved by a wide-ranging education. Higher education leaders – particularly at liberal arts institutions and flagship research institutions – paint optimistic pictures of the financial and personal rewards of becoming both a scientifically literate and broadly educated citizen. While many claims are made about these mutual benefits, robust evidence is harder to find, despite the educational assessment revolution and the public's fascination with rankings, scorecards, and measures of the return on investment in higher education. This study reviews both the claims and the existing research on ways educational endeavors toward "utility" or "utopia" might enrich one another in US undergraduate education.

STEM, HUMANISTIC INQUIRY, AND ARTISTIC EXPRESSION: WHAT SHOULD WE EXPECT?

The problem is that making rigid binary (or even tertiary) divides between intellectual pursuits seems misguided and limiting: there may be more similarities and convergences between the arts and the sciences than this binary divide acknowledges: the humanities have more rigour and method than they are often given credit for, and a scientist needs the kind of imagination and flair more often associated with the arts…So, researchers working on the human genome, the poems of John Keats, dark matter, the Tractatus of Wittgenstein, the Bible and the movement of refugees are all engaged in the same ultra-human tasks – how do we interpret ourselves, our bodies, our minds, our environment, our history and our morality? Marilyn Deegan, 2014, p. 26.

The terms "STEM," "humanities," and "arts" all serve as umbrella terms under which a variety of intellectual endeavors fit, sometimes neatly and often not, which complicates any examination of whether learning in STEM and the humanities and arts is synergistic or complementary. A brief review of the aims and nature of inquiry under these broad umbrella terms can help define what we might expect or not expect to find.

The National Science Foundation (NSF) first coined the acronym "STEM" in the early 2000s to bring greater focus to the need for the US to train more and better prepared students in basic science, mathematics, and engineering/technology. "STEM" as a construct easily conveys to the public the national importance of continued US leadership in basic science and applied technology across a host of issues that are too complex to easily explain – for example, technology and economic growth in a globalized world, security in a highly armed and unstable world, well-being in conditions of climate change, or the bio-medical advances that promise to solve life's most feared diseases and conditions. Yet, for colleges and universities attempting to build programs and responsibly advise students about the benefits of learning different modes of inquiry, the acronym can obscure as much as illuminate.

Academic natural scientists (in biology, chemistry, physics, and geology, for example) view their research agendas as contributing to the expansion of the frontiers of knowledge about the natural world, albeit with some expectation that their discoveries may inform widespread applications that can contribute to society and human life. Mathematicians expand our understanding of human and natural complexity by discovering underlying patterns and offering a precise language for expressing them. Engineers, on the other hand, primarily work in applied settings, resolving the vast technical challenges of achieving individuals' and society's aims. "STEM" not only collapses significant differences in the aims and modes of inquiry across these fields, but also obscures other fields – notably the social sciences – whose scholars employ both the scientific method and mathematical and computational tools to study individual behavior and social institutions. Perhaps not surprisingly, therefore, students of different STEM fields may gain distinctly different competencies as a result of their disciplinary mastery.

Similarly, a range of disciplines are grouped under the "humanities and arts," an umbrella that is more meaningful to academics who understand the historical origins of today's educational administrative divisions than to the public at large. While STEM is associated with practical science and math skills necessary for the complex modern world, the humanities – the study of the human condition - suffers from association with the "softer" pursuits such as ethical, historical, theoretical and cultural understanding. Housed together in humanities divisions is a wide range of disciplines, such as literature, languages, religious studies, philosophy, art history, musicology and music history, classics, linguistics, film and media studies, and cultural and area studies. The arts, in turn, range from visual and performing arts to the creation of art in new media and in non-traditional spaces.

Are STEM and humanities and arts disciplines so different? On the one hand, yes – the scientific method and textual analysis, for example, are distinct methodologies, with one more concerned with determining facts about the natural world and the other more concerned with deepening our understanding of the complexities of the human condition. On the other hand, no – one can think of examples such as the similarities between the frontiers of philosophy and higher level mathematics or physics. Engineering design may share more in common with theater than with basic science research. In many ways, when we say "integration" we are really talking about "re-integration" of fields that were once not as distinct or as divided. Science was born of natural philosophy, and "STEM" fields are modes of inquiry carried out by humans in a social context. Their objectivity, as Lorraine Datson and Peter Galison have made clear, is an illusion (Datson and Galison, 2008). "We have to remember that what we observe is not nature in itself but nature exposed to our method of questioning," wrote Werner Heisenberg in 1948: science is subjective, value-laden, and thus "humanist" (Heisenberg, 1948). And Thomas Kuhn made the case that scientific "truth" is a social and cultural construct, a consensus of a very specific scientific community (Kuhn, 1962).

Given the great breadth of aims and the differences in the nature of inquiry and expression within and between STEM and the humanities and arts, we might expect to find either an enormous array of educational synergy (at some level, learning itself deepens individuals' capacity to learn) or very little (the degree of specialization in modern education makes "renaissance" learning more an ideal than a reality).

HUMANITIES AND ARTS CONTRIBUTIONS TO STEM EDUCATION

The prevailing tendency in the public discourse regarding STEM and liberal arts education is to frame the value of the humanities and arts as a way of "topping up" or "rounding out" the perspectives of STEM graduates. The argument is that taking humanities and arts courses teaches STEM students the historical, philosophical, social considerations that complement their technical and science skills so that they can understand the societal, economic, and political implications of scientific discovery and technological development (Campbell, 1985). A corollary argument is that the humanities and arts encourage the cultivation of creativity for STEM problem-solving (Adkins, 2010; Adams et al., 2003).

The confluence of claims and motivations from both the "utility" *and* the "utopia" sides of the scale, coupled with the emphasis on assessment and accreditation, may be the reason that of all the integration efforts surveyed for this report, those involving engineering education were the most numerous as well as the most thoroughly assessed. The ASEE Liberal Education and Engineering Science Division, and Union College's annual Symposium on Engineering and Liberal Education, establish networks for those interested in pursuing integration and provide dissemination platforms for ideas and assessment. Among those who have implemented these programs, integration is valued for its contributions to both currencies.

It is often asserted that engineering, distinct from science and math, is fundamentally sociotechnical (e.g. Cohen, Rossmann, and Sanford Bernhardt, 2014), and thus that the more broadly or liberally educated the engineer, the more effectively that engineer will serve society. Echoing this sentiment, Grasso and Martinelli argue that "in order to serve humanity, engineers must at least attempt to understand the human condition" (Grasso and Martinelli, 2010, p 13). John Horgan (2013) writes, "The humanities are subversive. They undermine the claims of all authorities, whether political, religious or scientific... Science has told us a lot about ourselves, and we're learning more every day. But the humanities remind us that we have an enormous capacity for deluding ourselves." Such arguments resonate with those who consider education to be the development of humans, not only of "human capital" (e.g. Cassidy, 2015).

Given such arguments, one might expect to see greater evidence of a holistic approach to the liberal arts and STEM in engineering education. In fact, engineering education, created by engineering faculty, is periodically considered a candidate for redesign. As in any iterative design process, educators ask whether their curricula have achieved the initial objectives, whether those objectives are in fact the appropriate ones, and whether it may be necessary to tweak the prototype or construct a new one. The historian of technology Bruce Seely (1999) writes that "[p]erhaps the most constant feature of American engineering education has been the demand for change." This demand often takes the form of soul-searching reports such as that by Grinter (1955), or the National Academy of Engineering's *Engineer of 2020* (NAE, 2004). Each call for reform "has sought to enlarge the core identity of the engineer from a technician skilled at calculation and fabrication to a professional member of the wider culture" (Cohen et al., 2014).

Program-level integration has been a hallmark of Lafayette College's Engineering Studies program since 1970 (Rossmann and Sanford Bernhardt, 2015), though the disciplinary boundaries its idealistic creators sought to dissolve proved stronger than anticipated. Today, the program's enrollments rival those in the College's four BS engineering disciplines. The 1970's WPI Plan (Grogan and Vaz, 2003) was a re-framing of Worcester Polytechnic Institute's technical curriculum in societal context, emphasizing cooperative, project-based integrative and interdisciplinary learning. Although a proposed AB program in engineering was neither successful nor sustained, this institutional sensibility is still reflected in WPI practices at the course level (e.g. Rudolph, 2015) as well as larger-scale initiatives. Both of these initiatives reflect the mid-to-late 1960s interest in educating "socio-technologists" to bridge the gap between competing (admiring on one hand, critical on the other) visions of technology and permit holistic progress; this period is thoroughly discussed by Matthew Wisnioski (Wisnioski, 2012).[2]

Since the late-1960s moment at which boundary-transgressing programs like the WPI Plan and Lafayette College's AB in Engineering Studies curriculum were launched, there have been many years in which disciplinary boundaries remained strong, sometimes even being fortified on campuses. Integrative activities flourished only on the margins of traditional disciplines, rarely offered much institutional nourishment or light (e.g. Wisnioski, 2012). In the 1980s, a Brown University newsletter known as "The Weaver of Information and Perspectives on Technological Literacy" features reports of many pedagogically innovative activities (e.g. Morgan and Williams, 1986) that struggled to sustain themselves. In the last decade, resurgent "interdisciplinarity" has given rise to several new programs designed to appeal to (and educate) consilient thinkers. The program in Liberal Arts and Engineering at California Polytechnic San Luis Obispo faced challenges in establishing a new hybrid course of study, but has proved popular with students who find themselves both fulfilled and employable (Gillette, Lowham, and Haungs, 2015). The University of Utah's program in Entertainment arts and Engineering, and Arizona State's School of Arts, Media + Engineering, are each described as "gaining traction" (Daniel, 2015). Another intriguing new program is the integrated CS + X joint major at Stanford University, "an experiment in learning" starting in Fall 2014, with the stated goal "to give Stanford students the chance to become a new type of engineer and a new type of humanist" (Roberts, 2014).

In January, 2015, MIT's Louis Bucciarelli convened a workshop hosted by the National Academy of Engineering and National Science Foundation, to share and discuss current practices as well as potential curricular redesign concepts to integrate liberal arts and engineering content (Bucciarelli and Drew, 2015; Bucciarelli, Drew & Tobias, 2015). A primary value of this workshop was to bring people together who normally work alone at their own institutions, in the trenches and often on the margins,

[2] Although engineering education itself was not wholly transformed by these considerations, the integrative discipline of STS – discussed later in this section – grew out of these competing visions.

and shine light on a wide range of activities and perspectives. Many existing and well-tested prototypes for the proposed redesign challenge could be discussed and evaluated. Workshop discussions addressed student prospects following integrative degree programs; the diverse range of institutional obstacles to integration; and the need for engineers both to become broadly educated *and* to recognize the limits of their expertise, and when to reach out to other experts (e.g. Klein, 2015). Gary Downey has published both the provocation for this particular workshop, as well as many participants' contributions and responses, in a special issue of the journal *Engineering Studies* (Vol. 7(2)).

Strong examples of course-level innovation include Olin College's integrated course blocks, in which two disciplines were taught in complementary ways, linked to a semester-long hands-on project that asked students to draw on both subjects. Although this ambitious curricular model was later revised, some interdisciplinary courses remain on the books, notably a team-taught class that combines materials science and history (Stolk and Martello, 2007). In the view of the Olin College faculty members, "Successful integration depended on the presence of two faculty members who had some appreciation for each other's disciplinary approach, and this appreciation soon transformed into familiarity." Team development and instruction is an aspect of other successful courses, including courses that blend art and flow visualization (e.g. Hertzberg et al., 2014; Rossmann and Skvirsky, 2010), in which students develop mutual literacies. In these courses, some outcomes are shared by both disciplines, and student achievement is highest in the common outcomes. Students generally report increased interest in both subjects as well as in interdisciplinary work as a result of completing these courses (e.g. Rossmann and Skvirsky, 2010).

David Billington of Princeton pioneered an integrative approach to the history of technology in his courses and texts (Billington and Billington, 2006). Billington's flagship course was designed to fulfill general education requirements. For example, a writing-intensive version counts as a history course for engineering students, and the same lectures with a hands-on lab course fulfill a science/engineering literacy requirement for non-engineering students. While this ingeniously ensures high enrollments of students from all backgrounds, it limits the active interaction of those students to only their shared meetings in a large lecture hall. Billington received NSF support to host an annual workshop on his teaching methods, and many institutions now offer at least one "Billington-inspired" course.

Social justice and engineering concepts have been integrated effectively by Donna Riley (Riley, 2008) and Juan Lucena (Lucena, 2013). In addition to rigorously evaluating the effects of integration in her own courses, Riley has developed modules for other instructors to include within "traditional" thermodynamics courses (Riley, 2012), and has studied and reported on the effectiveness of these modules in a wide range of educational settings (e.g. 2014 Symposium on Engineering and Liberal Education, Union College). As one example, students studying a technical subject might juxtapose a standard textbook with a history of the field, as is done at Smith (Riley, 2012) and Lafayette (Rossmann and Sanford Bernhardt, 2015) Colleges to highlight the social construction of technology and engineering theory. Natalie Jeremijenko's teaching, as well as her professional projects and installations, often critique technology and technocentric politics through an artistic lens (e.g. Jeremijenko, 2015; Schwendener, 2010).

Yet engineering education, while attentive to accreditation's insistence on "continuous improvement," and inclined to create many innovative integration sites as just described, has proven resistant to holistic overhaul and reform. Such dramatic revisions are often avoided because of the sense among engineering educators that (a) the requirements of accreditation would not permit such changes; and/or (b) the “rigor” and math-reliance of engineering education must be maintained.

Both of these assumptions demand scrutiny. The accreditation criteria are often cited as motivations for (rather than obstacles to) the development of integrative instructional methods, courses and projects. The EC 2000 criteria issued by ABET are seen by many as offering “freedom” (Ollis, Neeley, & Luegenbiehl, 2004), and many of the eleven criteria relate directly to liberal education. They require that students achieve effective communication skills; an appreciation of ethical and professional responsibility; the ability to collaborate on “multidisciplinary teams;” “the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context;” a knowledge of contemporary issues; an appreciation of the importance of “lifelong learning;” and other outcomes. While some likely view these outcomes as those most readily outsourced to other departments on campus, the same outcomes have led many to create thoughtfully integrated courses and programs. Furthermore, alumni and employers frequently report that so-called “soft skills” are as important as, if not more important than, “technical” ones to the success of graduates in the workplace (e.g. Wolfe, 2010). This challenges the second assumption of educators resistant to change. Indeed, the importance of these skills to the effectiveness of graduates often provides additional motivation, and potential institutional leverage, for those educators wishing to innovate and integrate.

Science and mathematics education also have created some fruitful integration sites with humanities and arts. The practice of origami provides a nexus for artistic and mathematical energies, as evidenced by interdisciplinary symposia on many campuses (including our own, in 2013), and by the popularity of computer programmer-turned-origami artist Robert Lang as a guest speaker, and further by the Guggenheim Award recently awarded to MIT’s Erik and Martin Demaine (Hull, 2006; Lang, 2012; Lovelace, 2014). Similarly, the synthesis of mathematics and music has given rise to countless courses, often using one of the topics to recruit students who may be fearful of the others. Researchers have demonstrated that the inclusion of music helps students learn the mathematical concepts more effectively (e.g. Courey et al., 2012). Science, mathematics and social justice courses can help both STEM students and those from other disciplines both appreciate the societal relevance of scientific and mathematical concepts and develop a critical eye for the (mis)use of evidence in public discourse. (Chamany, 2006; Watts and Guessous, 2006; Skubikowski et al., eds, 2010, Suzuki, 2015).

Mary Flanagan of Dartmouth promotes the humanist analysis of computer games in the development of socially-conscious game design, reading games as you might a text. “The class, instead of pushing interdisciplinarity in an obvious way, relies on it in a fundamental way. One can’t make games about the world without actually understanding a little bit about that world” (Barber, 2010). In the games we make and play, Flanagan argues, we reveal our cultural biases and values (Flanagan, 2014). Flanagan’s game design courses intersect with digital studies courses in Film and Media Studies, Computer Science, English, Philosophy, and Studio Art.

MIT’s Terrascope program integrates the production of topical radio programs into a first-year STEM experience which has helped STEM students develop communication skills and ability to contextualize their work (Epstein et al., 2010). Topical courses of current interest are often used to unite disparate fields: forensic science, climate change, sustainability and the environment, genetics, energy, stem cells, AIDS, and the like. In each, a blend of literature, history, science, technology, and cultural anthropology – in combinations specific to the particular topics and courses – addresses the central issue. Many of these courses have been evaluated and disseminated by the SENCER organization (Burns, 2012).

Since Rachel Carson's *Silent Spring*, or perhaps since Thoreau, there has been a strong link between environmental science and the humanities. Carson's descendants now populate a field that might best be called "environmental justice" (Ottinger and Cohen, Eds, 2011). At many institutions, courses are offered that integrate scientific and humanist texts, methods, and values; this integration is critical to most degree programs in environmental studies and science (e.g. Whitman, 2015; Hope, 2015). Carolyn Merchant braided together gender and environmental studies (Merchant, 1980). At Harvey Mudd College, humanities, art, and media studies courses address environmental and life sciences questions (Mayeri, 2014).

Many universities with both strong STEM and liberal arts programs have a long history of offering programs in Science, Technology, and Society (STS, sometimes called or viewed as part of "science studies"). Generally, these programs apply the methods and values of humanities and social science inquiry to the natural sciences and engineering. They teach students to understand and critique science and technology in their historical, political, and cultural contexts, and to appreciate the social construction of scientific knowledge and engineering artifacts (Ackay and Ackay, 2015; Han and Jeong, 2014). These programs can achieve true integration in that students must understand the nature of scientific and technical inquiry and innovation as well as develop the critical thinking skills associated with political science, history, sociology/anthropology, and ethics. Each of these programs has its own particular niche, both in the broader field of STS and at its own institution. For example, the programs at Virginia Tech and the University of Virginia are housed within engineering schools and offer courses including engineering ethics to engineering undergraduates. Others, for example Lehigh University's program, are housed in arts and sciences and were founded with the vision of attracting both engineering and liberal arts students. Trevor Pinch's work integrating sociology with science and engineering education demonstrates that STEM students appreciate the "relevance" of sociology to their intended professions (Pinch, 2008). He also notes that similar courses are rarely taught within sociology departments, but were more likely to be found in STS programs.

The profound ethical questions resulting from rapid scientific and technological advances, particularly in medicine and technology, create natural sites for potential humanistic and STEM integration. Both pre-med and engineering curricula, perhaps because they also are more obviously oriented toward professional tracks, bring together philosophical, sociological, and humanistic modes of inquiry and content in integrated ethics instruction. Bioethics, in particular, is a formerly novel and now well-established integrative discipline. In bioethics courses, students develop the tools and context for moral discernment in life sciences, medicine, and biotechnology, infusing their analyses with content and perspectives from law, policy, and philosophy (Vaughn, 2012; Lewin et al., 2004; Leppa and Terry, 2004). In physics and other natural sciences, ethics is a standard (and often required) component of sponsored research programs (Hicks, 2013).

Many integrative practices are organized under the heading of "STEAM," which includes arts in STEM. John Maeda (e.g. 2013) argues that STEAM makes STEM into something more powerful, capable of generating transformative innovation. There is undeniable elegance to such arguments, including the notion that both science and art pursue (and prize) truth and beauty. STEAM initiatives have significant momentum in both K-12 and higher education (Miller, 2014; Maldonado and Pearson, 2013; Cooper and

Heaverlo, 2013). STEAM efforts have gained legislative support through House Resolution 319, introduced in 2012 and still under Committee consideration, which "expresses the sense of the House of Representatives that adding art and design into federal programs that target Science, Technology, Engineering and Math (STEM) fields, encourages innovation and economic growth in the United States." Notable STEAM efforts include instruction in hand drawing (Leake, at Illinois), and narrative and role playing (at the University of Delaware), both celebrated by Maeda (2013). One study of two university programs that integrate arts with STEM education finds that such programs can boost STEM students' retention of material, learning enjoyment, and career choices. Yet, the author questions whether "there is a disproportionate emphasis on solely improving STEM learning" and notes that the evidence is not clear about whether "there are similar sentiments about STEAM programs as a vehicle to exposure to STEM fields" among non-STEM students (Ghanbari, 2015).

Within medical education, there has been a push toward medical humanities and the use of "narrative medicine" – viewing patient histories as stories, and analyzing them as one might unpack a novel's themes and plot strands. While this movement is beyond the scope of the current study's focus on primarily undergraduate education, it is a useful example of the methods and values of the humanities being integrated for enhanced STEM outcomes. The development of this methodology from a "good idea" (Charon, 2001) to a widespread practice provides a useful model for other integration efforts.

STEM CONTRIBUTIONS TO HUMANITIES AND ARTS EDUCATION

The times demand that we use all of the tools we have to improve our students' scientific literacy. To successfully open a dialog with those who are doubtful about science, we must speak clearly about the benefits and risks in scientific advances. We must listen carefully to those outside the science enterprise and recognize that there is no monolithic viewpoint. If people and institutions have the will, then we can turn the tide for scientific literacy. Time is not our ally, and action is needed now. Wayne Clough, Secretary, Smithsonian Institution (2011)

Similar to the view that humanities and arts can "round out" STEM students' perspectives in ways that may sharpen their creativity, design, and diagnostic skills, we might expect to find a corresponding suggestion that STEM "tops up" the skills students gain in the traditional liberal arts. There are few claims that infusing STEM education into humanities and arts majors helps students become better scholars of humanities or arts, per se. Rather, STEM education is broadly viewed as necessary for non-STEM students in their capacities as future voters, potential policy-makers, or managers. Polls demonstrate that disturbing percentages of Americans have (at best) superficial understanding of such issues such as climate change, medical research, gene mapping, or other complex issues in the modern world. The perceived crisis of "scientific illiteracy" among those who will fill the ranks of the citizenry – for example, teachers, parents, employees, non-profit leaders, and politicians – receives attention among STEM educators who fear that the US political structure will not be able to cope with the scientific and technological choices that are necessary in the 21st century. In short, humanities and arts graduates must be armed with an understanding of technical and scientific knowledge that informs the study of the human condition.

Sometimes claims about the potential for greater exposure to STEM education to complement and support the liberal arts curricula are most passionately made by STEM scholars themselves (e.g. Frankenfeld, 1992; Schachterle, 2008; Rossmann, 2014). When Americans read about wind farms, fracking, ethanol subsidies, or have to decide whether to buy an electric car for their families, they would be well served by some knowledge of thermodynamics. Discussions of climate change are strengthened by an understanding of the relevant earth science *and* of scientific methods. Frankenfeld (1992) coined the term "technological citizenship" to describe exactly this. Being a good technological citizen means asking questions and not thinking of your phone or your car or an airplane as a "black box," whose workings are abstract and mysterious. Agile intellectual curiosity fed and fueled by a liberal education should, by this reasoning, *include* technology: how it works, how it is made, how it was developed, how it is distributed. Noted philosopher Martha Nussbaum agrees that democracies need "complete citizens who can think for themselves, criticize tradition, and understand the significance of another person's sufferings and achievements" (Nussbaum, 2010, p. 2). A liberal education that includes STEM methods and values prepares this citizen more fully.

Advocates for technological literacy have created a variety of courses and experiences, and a wide range of these have been surveyed and evaluated (e.g. Krupczak, 2004; Krupczak and Ollis, 2005 and 2006; Ebert-May et al., 2010). In a 2007 workshop co-hosted by the National Science Foundation and the National Academy of Engineering, John Krupczak and colleagues defined four main categories of such efforts to foster technological citizenship: survey courses; courses focused on a particular topic; design courses that involved students in technology creation; and "technology in context" courses in which technology is critically connected to other disciplines. (It is worth observing here that a curriculum in "science and technology studies," or STS, would likely contain all of these.) While these reports emphasize the benefits these courses have for non-engineers, historian and ethicist of technology Sarah Pfatteicher has pointed out that many engineers' educations would also be strengthened by such experiences (quoted in Krupczak, 2007). These longitudinal studies of technological literacy efforts have yielded a relatively robust set of technological literacy outcomes and methods for their assessment, all of which build on two NAE/NRC reports (*Technically Speaking*, 2002 and *Tech Tally*, 2006).

Some humanists make the broader claim that STEM pedagogies can strengthen humanities learning outcomes. For example, Cavanaugh (2010) argues that humanists should borrow from cognitive science that shows that techniques like problem-based learning, wikis, service learning, and other software tools boost the outcomes associated with the humanities. "Among the features of brain-based learning are active uncertainty or the tolerance for ambiguity; problem solving; questioning; and patterning by drawing relationships through the use of metaphor, similes, and demonstrations" (p. 140). Other examples of course-level integration of STEM concepts and context into humanities learning include, for example, a literature course in which "useless design" objects are constructed by students as they read Heidegger, Charles Keller, Matthew Crawford, and others (Crawford et al., 2014). Ogilvie and Scagnetti (2015) involved communication design students and methods in Ogilvie's research on endangered languages, using digital tools "to support efforts to preserve and revitalized endangered languages."

Others make a more instrumental argument for the utility of STEM education for the liberal arts. For humanities and arts students who face a difficult job market without a clearly pre-professional degree, additional proficiency in technical and computational tools that are valued by employers can add to individual's job competitiveness. Although humanities and art scholars always have used technical tools in their research and pedagogy, more and more scholars and their students will engage with the sophisticated technical tools grouped under the umbrella terms like "digital humanities" and "big data." These include Geographic Information Systems (GIS) mapping (Bodenhamer, et al., 2010), the use of databases for research, rapid prototyping or "3D printers," and other technologies. It is important to note, however, that the instrumental value of adding proficiency with technical tools to enhance one's resume, without additional instruction or discussion, does not "integrate" STEM education into the humanities or arts curriculum – just as incorporating writing or artistic assignments into STEM courses is not automatically an act of meaningful integration.

Much as humanities and arts content often serve to contextualize STEM content, some humanists have turned their lenses on technology, making STEM the context for application of humanist and artistic methodologies. The interdisciplinary discussions fostered by the Society for Literature, Science, and the Arts in its journal *Configurations* served as a forum for such scholars as Katherine Hayles and Donna Haraway to discuss what it means to be human in a "post-human" (e.g. Hayles, 1999) or increasingly techno-philic (e.g. Haraway, 1994) world.

Overall, however, infusions of STEM content, context, and methods into humanities and arts experiences are much rarer than their inverse. Furthermore, like the technological literacy and STS curricula, these experiences appear motivated by the opportunity to develop "full partners" and "complete citizens" rather than to strengthen the humanities and arts as valuable endeavors in their own right.

A shift away from a search for evidence that might suggest that STEM content might help strengthen humanities and arts student learning, per se, yields other examples of successful educational outcomes. The section below examines multidisciplinary experiential learning *in addition* to disciplinary work. The advantage of framing the endeavor as a mutually-beneficial collaboration across disciplines is that it allows educators and students to sidestep the perceived "utility" versus "utopia" tension, concentrating instead on developing each team member's skills and perspectives in service of a larger goal.

THE PROMISE OF EXPERIENTIAL, MULTIDISCIPLINARY LEARNING IN CONTEXT

The United States has many advantages when it comes to creativity, including freedom of thought and speech, a diverse population, an open society, capital markets that quickly move to support new and exciting ideas, and a heritage of risk taking and pushing back frontiers. For these reasons, the changes in the global environment play to our strengths. We are well-positioned to maintain and even increase our prosperity over the coming decades, and colleges and universities will play a critical role in this national endeavor as centers for a creative, liberal education. Deborah L. Wince-Smith, President, Council on Competitiveness (2006, p. 14)

Multidisciplinary, experiential learning experiences offer students from various disciplines an opportunity to appreciate both their own and others' contributions and importance to a shared outcome. Such projects may be commercially or socially entrepreneurial, community-based, concerned with social justice, or any combination of valued goals. And, they may be framed with varying pedagogical tools such as problem-based learning, design thinking, or other collaborative processes.

A platform for collaborations between STEM and humanities/arts (in addition to other fields) often can be found in campus-based centers for innovation, creativity, and/or entrepreneurship. President Obama made the case in his 2011 State of the Union address that the vitality and strength of the US economy rests on our ability to produce a creative, innovative workforce, and he has called repeatedly for strengthening the K-12 STEM pipeline toward this goal. Wince-Smith (2006) echoes that "creativity and innovation have become essential to generating the jobs that we will need in order to sustain our standard of living over the coming decades…In today's economy, that means focusing on the most creative aspects – generating intellectual property, emphasizing design, and taking risks on completely new ways of doing business" (p.14). But, unlike President Obama whose rhetoric and initiatives emphasize the centrality of STEM education for building an innovative economy, Wince-Smith argues "It is important to recognize that while science and technology are critical to the innovation process, innovation is not the sole preserve of scientists and engineers. A truly cross-disciplinary team must span the arts, humanities, and social sciences as well as the sciences….An innovative economy depends on creative people in the arts, literature, design, marketing, management, and a range of other areas" (p. 14).

Coining the acronym ICE (innovation, creativity, entrepreneurship), Buller (2011) argues that transcending the binary conception of STEM versus liberal arts allows higher education to consider that "what constitutes original thought might be similar across professional programs, the liberal arts, STEM disciplines, and other academic fields." Many examples of non-profit and public sector improvements through the implementation of a new practice or existing tool show that social innovation is as relevant as innovative commercial ventures (Tidd and Bessant, 2011; Windrum and Koch, 2008 cited in Gulbrandsen and Aanstaad, 2015). Buller points to programs such as those at DePaul and Wake Forest that invite students from all disciplines into opportunities from first year seminars through graduate programs as examples of successful integration of multiple disciplines. In addition to the claims that such programs can fulfill President Obama's call for higher education to produce graduates ready for global competition, these programs might provide the kinds of experiences that strengthen both STEM and non-STEM students' abilities to value the merits of their own disciplinary training while learning more about the contributions of others' (Brown and Kuratko, 2015). Whether these programs strengthen students' learning in their own fields, or deepen their understanding of others, requires further research.

The National Academy of Engineering in 2008 issued a set of "Grand Challenges" to motivate engineering educators and practicing engineers to consider problems such as clean water, energy availability, and global health. These challenges are inherently socio-technical and are intertwined with geopolitical, economic, philosophical, and cultural factors. Institutions that develop Grand Challenges project experiences recruit student from many majors, in at least one case developing new descriptions of the Challenges that emphasize their interdisciplinarity (e.g. Rossmann and Sanford Bernhardt, 2015). In working together to define design problems and to identify possible solutions and context-specific issues, students from all backgrounds gain appreciation for the methods, values, and history of other disciplines. When designed to explicitly include non-engineering students, the aim is for students to develop a mutual literacy in one another's disciplines and collaborate in this shared space (NAE, 2012).

Worcester Polytechnic Institute's Great Problems Seminars (Savilonis, Spanagel, and Wobbe, 2010) address a wide range of vexing global sociotechnical problems, including the Grand Challenges. Since 2007, this team-taught problem-based learning course has engaged first-year students in "interdisciplinary, not multidisciplinary" discussions and design projects related to these global concerns. Faculty teams are multidisciplinary: for example, a chemist teamed with an economist. WPI has used both internal and external assessment results on the seminars to refine the course outcomes, structure, and delivery. The faculty members have also developed a handbook to enable additional WPI faculty to join the Great Problems teaching team, and to disseminate their effective strategies.

In addition to programs that invite STEM and non-STEM students to work on complex projects that require multiple disciplinary lenses, global education also can offer opportunities for building integrative competencies. For example, the University of Rhode Island's successful International Engineering Program in which engineering students double major in a foreign language and an engineering discipline (coupled with a study abroad experience) has grown steadily and expanded to several language tracks. Perhaps more intriguing, however, is that the IEP program has produced other, less-anticipated benefits: "Women have enrolled in engineering in increasing numbers…(while) the academic quality of Rhode Island's engineering students has improved" (Fischer, 2012). Although such programs are built to couple STEM with language ability, their appeal to students suggests that multidisciplinary projects such as the Grand Challenges in a global context may not only strengthen all students' global citizenship, but also strengthen the perceived relevance of the contributions of both the STEM and liberal arts. Blue, et al. (2013) and Nieusma (2011) and others have documented the challenges and rewards of such global projects for a wide range of students.

Within these multidisciplinary project teams, whether the focus is local or global, or on capital or social entrepreneurship, students are often brought together to define and address a design problem. The engineering design process synthesizes humanistic, social, creative, and analytical skills, and is thus one logical forum for meaningful integration of a range of disciplinary methods and values.

Frameworks for the engineering design process use varying nomenclature to describe the same essential elements: need-finding (or empathy); problem definition and framing; creative idea generation (sometimes, "ideation"); prototyping; and testing and analysis. The process is iterative and communication with multiple stakeholders is critical throughout the process. (Engineering design differs profoundly from the scientific method, and from mathematical problem solving, and the use of a monolithic "STEM" acronym elides their key distinctions.) While this is an engineering methodology, it shares with the arts an emphasis on creativity, and with the humanities and social sciences a comfort with the ambiguity of non-unique, context-specific solutions. Design experiences develop self-efficacy and creative confidence (Kelley and Kelley, 2013).

Effective [engineering] design begins with, and maintains, "empathy" or "understanding" for people and for the societal, cultural, ecological, political, etc. contexts in which they live. This is sometimes called "need finding" or "need identification;" both terms emphasize that design is for people, and that designers must learn enough to appreciate how people might use and interact with designed products and processes, how people might gain access and/or what might prevent people from adopting new designs, and who else's needs or interests designers ought to be considering. Empathy has been shown to be a skill (e.g. Cameron et al., 2015) that can be further developed by paying careful attention to literature (and other artistic expressions) from a range of cultures and perspectives (e.g. Kidd and Castano, 2013). Effective design teams must draw on this empathy and also comprehend the larger societal and cultural issues affecting *all* possible stakeholders in the manufacture or implementation and distribution of their design; they must value this sociological, political, and economic expertise, and must view such experts as partners. It is hard to imagine a stronger argument for the broadest possible education, or for multidisciplinary collaboration that respects and values the contributions of all disciplines.

Establishing empathy and appreciation for the complex societal and social contexts in which one's stakeholders reside enables designers to consider the *definition* of relevant problems, rather than the mere solution of pre-defined and possibly ill-posed ones. Downey (2009) has eloquently justified the centralization of problem definition to design processes: “practices of collaborative problem definition that …had been performing in the margins did not have to be marginal.” Thoughtful process definition meaningfully involves non-engineering participants, including those engaged in a critique of science and technology, and in his own experience, “those who held stakes in the dominant image of problem solving as well as others engaged in struggle over that image and its practices could see themselves in it” (Downey, 2009, p. 71).

Another key “step” in the iterative design process is prototyping and testing a design. Whether this is a device, a process, or an experience, it is crucial for designers to build a representation a physical model, or a storyboard of users interacting with the design, or some other way of allowing prospective users to interact with and respond to the design. Engineers must consider the feasibility of their designs at this stage; manufacturing concerns may force designs to be revised. Much is learned from observing users’ interactions with and responses to prototypes, allowing designs themselves, or even the initial problem definition, to be refined to better fulfill a user’s needs (Houde and Hill, 1997). In turn, humanists can “see” how their own cultural, ethical, or philosophical lenses “play out” in these design contexts.

The overlap between prototyping and making means that makerspaces and design studios are often housed in engineering spaces, but these activities, like design itself, are not limited to engineering students. In fact, making is also a studio art, an act of creation – what is “designed” might be a story, or a textile, as easily as a 3D printed widget. In critical making, students apply analytical faculties from humanities and social sciences to this creative endeavor (Somerson, Hermano & Maeda, 2013). Matthew Crawford has persuasively contented that such handwork is also “soul craft,” enriching students’ humanity and person-hood as well as their professional development (Crawford, 2010).

The importance of effective communication with various parties, and of collaboration with fellow designers, integrates additional elements to the design process. Interpersonal dynamics and written and oral communication are critical to effective and successful design. Through such project-based collaboration, students develop both skills and confidence in the value of their own expertise to the success of a collaborative project. Again, the best examples of this kind of collaboration are ones in which all members bring distinct skills and disciplinary perspectives to bear on shared goals, rather than ones in which humanities and arts students serve as mere supports in solving an essentially technical design challenge.

Notable multidisciplinary design project-based experiences include MIT’s Terrascope, a first-year living-learning program that supplements the fundamental introductory courses with problem-based experiences and cross-disciplinary teams has had a powerful effect on student engagement and retention (Lipson et al., 2007). The iFoundry program at the University of Illinois began as an infusion of philosophical and other perspectives into engineering education and is now a multifaceted, “cross-disciplinary curriculum incubator” for project-based learning, entrepreneurship and innovation experiences, and methods for enhancing students’ intrinsic motivation (e.g. Goldberg, 2008).

We particularly admire an initiative at Smith College to involve faculty, students, and staff from all disciplines in a design thinking community to reimagine the liberal arts. This project embraces “radical collaboration to encourage the unconventional mixing of ideas, thereby creating a culture where ideas (and the technologies that help us realize these ideas) belong simultaneously to no one and everyone" (Mikic, 2014).

The potential for such multidisciplinary collaborative design projects to integrate, and value, the contributions of a variety of disciplines is enormous. Not only do these projects improve design *products*, they also underscore the intrinsic value of learning *both* STEM and humanities and arts. Such projects are "expensive" in the academic currencies of faculty time and energy, and they may require faculty development efforts as well as consumable supplies, but the rewards may be great enough to justify the investment.

ADDRESSING DIFFERENCE: RECRUITING AND RETAINING UNDERREPRESENTED GROUPS

Through our research and teaching, we educators can foster inclusion of the varied manifestations of diversity in our students and our courses, grappling with the difference and sameness not as conundrums, but as synergistic and intersecting dynamics that reveal the human experience and ways to improve it. Johnnella Butler (2014, p. 4)

Some observers of persistent inequalities in US higher education access and retention examine the question of STEM and liberal arts integration through the lens of gender, race, socio-economic status, and ethnicity. The concern in these debates is not simply whether STEM and liberal arts deepen students' understanding of disciplinary content within a broader conception of society; rather, the question focuses on who is missing at the table and whether a more integrative approach helps diversify the so-called "leaky pipeline" into all areas of higher education.

Once again, widespread public assumptions mask complex realities. For example, the characterization of "hard" STEM fields versus the "soft" humanities maps onto widely shared gender assumptions that men are attracted to modern, useful STEM inquiry and women are drawn to or excel at the softer, traditional, utopian humanities. Closer examination of the evidence shows that the reality is more nuanced; women are well represented in some STEM fields (albeit with a pay gap) (Broyles, 2009), although clear gender differences remain particularly in engineering, computing, and physics.[3] Yet gendered dualisms run deep in Western thought and are difficult to dislodge from the public imagination which, in turn, influence the institutionalization of higher education.[4]

The assumption that men are better suited than women for the "hard" STEM fields also maps onto racial stereotypes.[5] Studies "confirm the enduring presence of racism and sexism in STEM education" in spite of programs aimed at recruiting and retaining women and people of color (Charleston et al., 2014; Chakraverty, 2014) which, in turn, reinforces the notion that institutional culture is a significant consideration in the study of underrepresented and underserved populations (Museus, 2011; Museus et al., 2011).[1] Barone's (2011) study of gender differences in Europe concludes that "the influence of gender categorizations is so resistant to change because it operates not only through the internalization of sex stereotypes but also through the evaluation of opportunities and

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[3] Women comprise 77% psychology, 60% biology, 54% social science, and 50% chemistry student populations. At the same time, however, women's share of bachelor's degrees in computing, mathematics, and engineering remain disproportionately low (National Science Board, 2010). The majority of bachelor's degrees awarded in engineering, computing, and physics (81%, 81%, and 79%, respectively) were awarded to male STEM aspirants (National Science Board, 2010).

[5] The National Science Board reports that over 70% of the country's 3.5 million scientists and engineers are white.

constraints. For instance, the overrepresentation of female graduates in care-oriented fields reflects both their intrinsic occupational preferences and the increasing job opportunities created in service economies" (p. 43). Joshi and Knight's research shows that inequalities in perceived status based on demographic attributes (for example, gender, race, or ethnicity) are reinforced in patterns of deference afforded to white men in teamwork that involve STEM expertise, further explaining the persistence of stereotypes (Joshi and Knight, 2015).

Examination of inequalities and higher education is a useful lens for understanding whether the integration of community-based and social justice applications might help to recruit underrepresented and/or underserved populations to STEM and especially engineering fields (Nilsson, 2015). One study finds that female students' attitudes toward the relevance of introductory science courses to problem-solving improves when taught with a social, context-based (or STS) pedagogy (Perkins, 2011). The success story of Computer Science at Harvey Mudd College hinges on casting its introductory courses as problem-solving and creative endeavors (AAUW, 2015). California State University – Monterey Bay, recognized as a national leader in engaged or civic learning, finds that STEM programs that require students to work with community partners using a social justice frame not only boost civic engagement and critical thinking among STEM students, but they also may attract students from underrepresented groups into STEM study (Calderon and Pollack, 2015). Cleveland State University has recruited more diverse students into health professions programs through close partnerships with eight urban neighborhoods targeted for their low health indicators (Whyte, White, and Menscer, 2015). Mount Sinai Medical Center's groundbreaking program, originally called the Humanities and Medical Program, intentionally recruits students whose interests in humanities will likely improve their understanding of patients and their contexts (Whyte, White, and Menscer, 2015).

It is worth noting that women's and gender studies scholars warn against focusing on differences – in confidence, in preparation, or in motivation – in ways that make outreach transparent and ineffective: "engineering lipstick [Hollar et al., 2002], Barbie® computers (and 'cooperative' or 'nonviolent' games for girls [Cassell and Jenkins, 1998])" (Riley and Pawley, 2011). Instead of addressing the underlying issues, the authors argue that these strategies reinforce gender hierarchies: "We should not be surprised if this gender essentialism gives way to gender determinism, where certain areas of engineering that fit gender stereotypes – for example, areas with environmental or humanitarian ends, for example – are carved out as "women's sphere" [Bix, 2004] much the way home economics was in the 20th century" (Riley and Pawley, 2011, p. 3).

It is also a concern that these efforts emphasize recruitment of under-represented groups to STEM at the possible expense of retention. Retaining female and other under-represented students will be made even more challenging if the early, "attractive" experience feels distinct from the curriculum that follows in tone, content, or style. Still, efforts made to make STEM more inclusive, more richly contextualized, and more attractive to a more diverse student body yield benefits for all STEM students. It has even been observed that the broadening of the most in-demand STEM populations – women and other underrepresented groups – may have made them less likely to enter the workforce as STEM practitioners (Wang et al., 2013). This joint study by the Universities of Pittsburgh and Michigan revealed that women have more options when they have both verbal and mathematical abilities and that these options often pull them away from STEM-only fields.

The number of examples of integrative, contextualized learning that appear to be effective in recruiting women and other underrepresented populations raise the question of why STEM education ever felt it necessary to “strip out” the historical and societal contexts of its disciplinary content. Although this question lies beyond the scope of this report, the answer may lie in a combination of factors: the complex history of 20th century institutionalization of modern education, Cold War-era attitudes that prioritized technical content, the particularly-American ambivalence about the role of the state in public and private education, or in a familiar professional drive to establish disciplinary “rigor” (Riley, 2008). Amy Slaton’s work (2010) that documents the many ways this insistence on rigor established and fortified an effective “color line” in STEM education and professional engineering practice provides a promising starting place for this discussion.

EMPLOYERS

With a shriveled vision of what the nation and the world needs, (some) attack the humanities with special vindictiveness, shoving to the side a long educational tradition in which these fields have served as the very glue that combined together knowledge, values, and civic agency. In its place jobs and wealth are proposed as the new gold standard. Carol McTighe Musil (2015, p. 244)

Given the almost universal assertion that the national economy needs more graduates from STEM fields, it is not surprising that observers pay attention to STEM graduates’ employment rates and salaries relative to those from non-STEM fields. These data show some preference for STEM graduates in the marketplace (Miller, 2014); for example STEM graduates are more likely to secure employment within six months of graduation and receive higher starting and career salaries than their fellow graduates from non-STEM disciplines (Langdon, et al., 2011; Skorton and Altshuler, 2011). Longitudinal data, however, suggest a more nuanced picture of salary differences over a career span (Humphreys and Kelly, 2014; Hiner, 2012). Non-STEM graduates are more likely to pursue additional post-graduate education that boosts income potential. While STEM graduates on average continue to earn more than non-STEM graduates (among whom there is great variability), there is less variation between successful, high earning non-technical graduates and their STEM counterparts over career trajectories (Herschbein and Kearney, Hamilton Project, 2014; Humanities Indicators, AAAS, 2014; Xu, 2015). Many factors such as mentorship, networking, and self-confidence appear to contribute to career success, possibly explaining the narrowing of career differences between STEM and non-STEM graduates over time (Blickle, et al., 2009; Scandura, 1992).

Perhaps more important than salary data, surveys of employers underscore the promise of interdisciplinary, experiential, and integrative educational opportunities across all disciplinary tracks. Studies show that on average employers are looking for broad competencies in college graduates rather than specific, content knowledge (AAC&U, 2013). The types of competencies typically cited by CEOs can be characterized as systemic rather than disciplinary – for example, written and oral communication, information literacy, along with civic responsibility and engagement, ethical reasoning, intercultural knowledge and actions, and propensity for lifelong learning. The degree to which students gain these broad skills more successfully in traditionally disciplinary or multidisciplinary, integrative experiences cannot be easily teased out of existing data. Labor statistics allow observers to gauge the career success as measured by salaries of graduates from a wide variety of undergraduate majors. Yet, as Bradburn and Fuqua point out in their comprehensive examination of the effects of humanities course completion on post-graduation outcomes, U.S. Department of Labor statistics do not include measures that correlate to the educational aspirations of the humanities or arts, such as cultural participation or communication, analytical, and interpersonal skills (Bradburn and Fuqua, 2013).

CONCLUSION

Examples of faculty reaching across disciplines not only to better teach specific academic content but also to excite and inspire their students to think critically and creatively is more than merely encouraging on pedagogical grounds. Such examples vividly demonstrate that many faculty on both sides of C.P. Snow's "two cultures" resist the perceived primacy of STEM as the driving imperative of U.S higher education. Rather, many faculty – notably in the STEM disciplines, themselves – embrace a holistic mission of higher education that serves both individuals and the nation, technological innovation and democratic vitality. STEM literacy **and** the ability to imagine and contest what an educated citizenry knows or ought to know are equally critical for both economic and democratic ends. STEM and non-STEM fields are vital in themselves, but more importantly they inform and enliven intellectual pursuit in *each other*.

Some program-specific attempts to measure student learning on individual campuses appear to support the plentiful anecdotes about the merits of integrative approaches both in terms of student learning as well as recruitment and retention of underrepresented groups in STEM fields. But additional focused attention and study, beyond discipline-level and/or general education assessment, is warranted.

National organizations such as the American Association of Colleges and Universities (AAC&U) and Imagining America provide the clearest examples of efforts to develop measurable outcomes for integrative curricular work. To some degree, such organizations have been successful in drawing attention to the educational merit of innovative, integrative courses and programs. Equally importantly, their attempts to ground localized programs in a national conversation about appropriate assessment and reward structures elevate their visibility and transformative potential. Some national organizations, such as the National Academies, National Science Foundation, and Teagle Foundation, are also able to achieve a panoramic perspective on many such efforts, enabling broad review, categorization, and evaluation of an array of integrative activities. By shining their own light on interdisciplinary integration, in fact, these organizations communicate its importance to the larger higher education agenda.

Beyond these organizations, one might expect accrediting bodies (both regional and discipline-specific) to foster a greater appetite for evidence of learning in integrative STEM, humanities, and arts initiatives, especially given their expanded role demanding evidence of student learning. However, most integrative course and program learning outcomes are not easily captured by broad accreditation standards. Because these kinds of courses and programs tend to be built at the curricular grassroots, they often fall beneath the institutional accreditation radar – leaving the vision, theoretical grounding, pedagogical skills, and assessment lessons learned in the trenches.

Continued institutional (and external) support necessary for the sustainability of such efforts would seem to require more than simply the use of metrics and benchmarks to determine whether these endeavors – costly in terms of faculty time and energy, often team-taught – are achieving the existing student outcomes. The measure of success of such initiatives is not as simple as applying standard measures for "un-integrated" courses to gauge whether students' disciplinary knowledge is achieved or even enhanced by integration. The value of interdisciplinarity and integration is not merely to improve the learning of standard content by additional contextualization, but to achieve something **more** than could be attained by any single discipline alone – much as effective multidisciplinary collaboration yields a product better than any individual member could have generated. Successful student learning in integrated courses and programs includes the consideration of both standard disciplinary outcomes *and* outcomes specific to interdisciplinary learning. Borrego and Newsander's (2010) content analysis of 129 successful NSF proposals identifies five key outcome categories for interdisciplinary instruction: disciplinary grounding, integration, teamwork, communication, and critical awareness. However, the authors lament the relative paucity of benchmarks and assessment methods for interdisciplinary and integrative work. Lisa Lattuca's work (e.g. Lattuca et al., 2006) in defining interdisciplinarity, and differentiating it from multidisciplinarity and other related but distinct activities, remains a somewhat solitary standard. Through interviews and analysis of student work, Veronica Boix Mansilla (2005) composed an assessment framework highlighting four dimensions of student interdisciplinary work: Purpose, Disciplinary Grounding, Integration and Thoughtfulness. Both this framework and a timed design-based assessment tool known as a "charette" were reviewed and endorsed by a Teagle Foundation white paper on the assessment of interdisciplinary work (Rhoten et al., 2006). Diane Michelfelder et al. (2013) warn that an interdisciplinary approach may alter disciplinary "purity" and transform student outcomes into something possessing "hybridity," which may not be captured by traditional assessment metrics.

As important as the efforts to adequately measure the worth of integration are, these efforts often bog down in methodological debates about measurement itself. Given the power of our contemporary empirical and computing tools, it is not surprising that quantitative data generated from coding artifacts of student work appears to be a more trustworthy measure of educational outcomes. The promise is that quantitative measurement eliminates the "bias" that passionate instructors or eager students might use to describe their own educational experiences. Similarly, student or instructor reports on their own perceptions of learning, interest, motivation, or meaning – especially when they are gathered with qualitative methods – typically are dismissed or, at best, considered weak supplements to "real" measurement. To be sure, methodological debates are important, especially when concrete resource implications rest on perceptions of the authority of the measures. But, as Joseph (2014) suggests, the focus on accountancy or measurement rests on the assumption that "student learning" is equivalent to decontextualized or "objective" observations of the natural world (and, hence, a world best evaluated with STEM-like precision) rather than complex individual interactions with knowledge in a human context. The focus on accountancy, therefore, can eclipse the larger question of accountability. If we embrace the notion that the examples reviewed in this paper are, in fact, examples of the *re*-integration of fields, and that re-integration both enlivens the inquiry itself and broadens the range of student interest, then how do we – educators, policy-makers, and the public - hold ourselves accountable for fostering this approach? Our methods should follow our inquiry; testing the value of re-integration is best pursued with integrative methods. A methodological approach that embraces both our computational sophistication and the human drive to make meaning out of experience and knowledge – although messy – will strengthen the authority of our findings.

In spite of consistent voices from the academy, employers, and citizens calling for integrative educational efforts, some policy-makers continue to assert the primacy of STEM as though economic utility is all a contemporary individual or society needs. Such a myopic vision of human intellect has real policy implications: reducing federal funding for humanities and arts while increasing funds for STEM-related teaching and research; shifting the costs of access to cultural expression to private or foundation support; or privatizing national cultural production as simply another commodity in an entertainment market.   According to this view, only decontextualized STEM knowledge is a public good; the public can no longer afford the examination of knowledge's meaning in human context. Not only is this a dangerous experiment that takes for granted the foundation of democracy in an informed and fully-literate citizenry, it is a view of the human intellect that is foreign to most educators and that, ironically, may result in scientific and technological stagnation.

Here, the conflict between "utilitarian" and "utopian" aims is clear: utility is easier to measure. Whether students are made more employable, or see an increased starting salary, or perform well in standard ways – these outcomes will not disappoint those who value integration, but neither will they be sufficient. Integration promises to deliver improved learning of disciplinary content within a broader goal of strengthening ideals of citizenship, mindfulness, and empathetic engagement with the world. Yet, it may be difficult to articulate outcomes that are measurable and meaningful. In addition, students may manifest these outcomes on a timescale far beyond a semester or other curricular milestone. The "narrative" of these efforts is also meaningful, though context is important – a narrative of success tells us what works at some institutions, for some faculty members, for some students; and what "works" varies with the goals for integration. And, we as educators should listen to these narratives because they are often spoken by our most impassioned and enthusiastic colleagues, motivated to improve and evolve their own teaching. (Put another way, the characters and setting of these narratives are as worthy of attention as the plot points.) In order to make these context-specific narratives useful to a broader discussion in higher education, and potentially transferrable, the methods of humanists and social scientists may provide a complement to the STEM-infused quantitative measurement tools to determine which questions about student learning are most important, and how they can be addressed.

Perhaps it is more instructive to ask why – given many local efforts grounded in the practical perspective that students often learn more readily and feel more confident about their knowledge in multidisciplinary, contextualized, experiential opportunities – these initiatives remain both under-examined and under-funded. Why do faculty who invest their time and energy in these kinds of efforts remain the minority of faculty across STEM, humanities, and arts disciplines? Why do endeavors such as Grand Challenges, global citizenship, or centers for innovation/creativity/entrepreneurship struggle to find campus leadership champions or national support across the whole spectrum of US higher education? The specifics of the obstacles likely vary among institution types, suggesting that the most effective incentives and resolutions to those obstacles will vary as well. The current climate of intense resource competition, both nationally as well as on individual campuses, may strengthen disincentives for faculty collaboration, multidisciplinary risk-taking, or development of measures of long-term educational value to students and society. Particularly for the humanities and arts, disciplines that have seen the sharpest rise in the proportion of contingent versus tenure-track faculty, incentives to "double down" in traditional measures of faculty excellence rather than collaborative work can be at play. STEM faculty, under pressure to deliver increasingly sophisticated graduates in an era of rapidly shifting frontiers of knowledge, may resist the call to inject their courses with additional content. As Kezar and Gehke suggest (2014), the increasing complexity of managing higher education may undermine administrators' ability to strategically create conditions conducive for integrative programs. Meanwhile, the STEM "branding" acronym reinforces a perception of practical value – as opposed to the impractical, "utopian" humanities and arts - that intensifies competition for scarce resources. Investing in research regarding the obstacles – from national funding priorities to campus (dis)incentives for faculty and staff – also is warranted.

Without sustained focus and leadership at the campus and national level, it is likely that similar essays in 2025, 2050, or beyond will bemoan the false assertion of the “two cultures,” leaving the impression that faculty continue to teach in their insular and traditional ways while the economy searches for adequately prepared workers and the country yearns for the informed citizenry that 21st century democracy requires.

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Why the Hard Science of Engineering is No Longer Enough to Meet the 21st Century Challenges

by

Richard K. Miller

*"It's in Apple's DNA that technology alone is not enough — **it's technology married with liberal arts, married with the humanities, that yields us the results that make our heart sing**…"*
STEVE JOBS (UNVEILING THE IPAD2), MARCH 2011[1]

EXECUTIVE SUMMARY. It has been more than fifty years since the engineering curriculum in the U.S. has changed significantly. In the 1950s, a strong emphasis on applied science and mathematics was introduced and since then it has become the heart of the engineering curriculum. However, much has changed in the last fifty years. The world has become much more complex and the Grand Challenges[2] we face now involve human behavior as much as they do technology. It is time to rebalance the engineering curriculum again, restoring some of the emphasis on professional skills[3]. This paper examines the reasons why now is the time to undertake such an ambitious project and what this will entail.

HISTORICAL BACKGROUND. The last major rebalancing of engineering education occurred after 1955 when the Grinter Report[4] marked a "sea change" in engineering education. This report established a sudden comprehensive shift in the undergraduate curriculum toward the hard sciences and mathematics. Calculus and physics became requirements for all engineering majors and faculty were expected to have a Ph.D. and participate in original research published in archival journals—just like their counterparts across campus in the natural sciences. In order to shift the balance in the curriculum, a shift in faculty credentials and interests was necessary, and the more ambiguous and less analytical aspects of the practice of engineering were no longer dominant. This major rebalancing was achieved over a few decades. Since then, the culture in academia (driven largely by the interests of the faculty) has continued to grow in the direction of applied sciences, with the underlying belief that the most important new developments in engineering will always flow directly from discoveries in the basic sciences. From an educational viewpoint, the foundational belief is that knowing more advanced science and math is inherently beneficial and increasing specialization is the key to making more important contributions as well as career success.

Without question, the rebalancing of the 1950s played an important role in propelling the nation to success in the Cold War and in building and sustaining the world's most powerful economy and standard of living. The role of engineering in creating the greatest technological achievements of the twentieth century is documented in a recent book[5] published by the National Academy of Engineering.

Emergence of complex Grand Challenges. However, the world has changed in many ways in the last half century, while our educational paradigm for engineering has not. For example, the technical challenges we face today are inherently more complex and global[2]. They transcend academic

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1 Carmody, Tim, *Without Jobs as CEO, who speaks for the arts at Apple?,* Business, ***Wired***, August 29, 2011.
2 The **National Academy of Engineering** identified 14 Grand Challenges for the 21st century that cluster in four areas: Sustainability, Security, Health, and the Joy of Living. http://www.engineeringchallenges.org/
3 Professional skills are sometimes referred to within engineering schools as "soft skills." They generally do not depend on an understanding of science or math. However, they have proven much more difficult to define and teach than the more traditional subjects. In that sense, the term "soft skills" may be a misnomer.
4 *Summary of the Report on Evaluation of Engineering Education*, **Journal of Engineering Education**, September 1955, pp. 25-60.
5 Constable, George, and Somerville, Bob, *A Century of Innovation: Twenty Engineering Achievements that Transformed Our Lives*, National Academies Press, 2003.

disciplines, political boundaries, and time zones. Challenges such as global security, sustainability, health, and enhancing the quality of life in an age of exploding world population will require more than new technologies or science. They will require more comprehensive and complete situational diagnoses, involving interdisciplinary understanding of the root causes and the consequences of any new technology introduced into the world. They will require global systems planning and analysis, involving social, economic, political, and even religious factors to obtain desired changes in human behavior on both local and global scales[6].

Many of the challenges of today involve unintended consequences of the technologies developed in the last century. These consequences can often be traced to original conceptualizations that were too narrow or failed to include these "non-technical" dimensions to the problem in the first place. Those technologies often arose from analyses that ignored or underestimated the human behavioral aspects of the problem. To avoid this in the future will require multidisciplinary teams working together to diagnose problems and design solutions that result in fewer unintended consequences. The stakes are very high and are increasing with each generation, in part due to the increasing population, and in part due to the increasing power of (and relentless advances in) technology which, generally, enables a smaller and smaller number of people in each generation to affect the lives of a larger and larger number of others, both intentionally and unintentionally, and both for the better and for the worse.

The successful multidisciplinary teams needed to address these Grand Challenges must, of course, include members with advanced knowledge of the natural sciences and mathematics. The importance of continued advances in these fields has not and will not decline. It is implicit that we will continue to need experts and innovators in the pure and applied sciences and in mathematics, which has become the primary focus within our universities.

However, unless these advances are motivated by and integrated with equally sophisticated understanding of the complex human dimensions of the problems we face, they are unlikely to succeed. Furthermore, the need for synthesizers and integrators leading such teams is of fundamental importance. Like the conductor of the orchestra rather than a soloist, these multidisciplinary leaders are needed to shape the overall effort and produce an effective integrated result[7].

These special integrative skills are more closely related to the field of design than to analysis—which had been the hallmark of engineers before the Grinter report. Now that fewer engineers are prepared with these skills, the job of leading such teams in formulating and solving complex problems of this type often falls on others with much less preparation in the natural sciences—like politicians and business leaders. As a result, the critical need today for new insights that bridge technical disciplines and human behavior too rarely involves engineers. The academic field of engineering today does not adequately value broad thinking, synthesis, teamwork and consensus building, entrepreneurial mindset, and creative design as much as it does advanced analysis and new science. These "professional" skills were perhaps inadvertently de-emphasized in the curricular rebalancing a half-century ago.

Since much of the complexity of the Grand Challenges is the result of the inherent coupling between the technical and the human/social dimensions of the problems we face, the importance of the humanities and social sciences in the engineering curriculum must increase. In this context, a recent report by the American Academy of Arts & Sciences[8] lays out a compelling case for the humanities and social sciences in any education today. They conclude that "the humanities and social sciences are the heart of the matter, the keeper of the republic—a source of national memory and civic vigor, cultural understanding

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[6] National Academy of Engineering, The Engineer of 2020: Visions of Engineering in the New Century, 2004, National Academies Press, Washington, DC.

[7] Nobel Prize winner Murray Gellman, in addressing this concern, identified what he called the need to take a "crude look at the whole" (CLAW). "*People must therefore get away from the idea that serious work is restricted to beating to death a well-defined problem in a narrow discipline, while broadly integrative thinking is relegated to cocktail parties. In academic life, bureaucracies, and elsewhere the task of integration is insufficiently respected*." (The Quark and the Jaguar: Adventures in the Simple and the Complex, 1995, p. 346)

[8] **AAAS**, *The Heart of the Matter: The Humanities and Social Sciences for a Vibrant, Competitive, and Secure Nation*, Cambridge, MA, 2013.

and communication, individual fulfillment and the ideas we hold in common." It is these subjects that not only provide the essential insights for addressing the Grand Challenges, but also provide the nourishment for human understanding and wellbeing beyond the physical and financial. It is time to give our engineering students more opportunity to integrate them into their world.

> *"All of these problems at the end of the day are human problems," he said. "I think that that's one of the core insights that we try to apply to developing Facebook. What [people are] really interested in is what's going on with the people they care about. It's all about giving people the tools and controls that they need to be comfortable sharing the information that they want. If you do that, you create a very valuable service. **It's as much psychology and sociology as it is technology**."*
>
> Mark Zuckerberg (speaking at BYU)[9]

The rise in global competition. In about 1920, global human population reached one billion for the first time in history. Today, less than 100 years later, it is slightly above seven billion, and we are expecting about nine billion by mid-century. Every human society is likely to experience the effects of this sea change in population. It will create increased demand for clean water, food, energy, security, education, transportation, communication, and every other dimension to civilized existence. We have already seen major shifts in the geopolitical balance and more shifts are certain to follow.

In just the last few decades the BRIC[10] countries have experienced a rapidly rising middle class. One of the primary interests of the middle class is education for their children. As a result, each of these countries is currently involved in massive investment in increasing access to higher education. For example, in India alone, several thousand new engineering colleges have been created in the last decade, and China has been building entire new universities at a fast pace for the past decade. As a result, the world's largest airport is now in China. GE has now located the majority of its R&D personnel outside of the United States. China has now replaced the United States as the world's number one high-technology exporter. Eight of the ten global companies with the largest R&D budgets have established R&D facilities in China, India, or both. China has a $196 billion positive trade balance, while the United States balance is negative $379 billion. During a recent period in which two high rise buildings were under construction in Los Angeles, over 5,000 were built in Shanghai. The world is changing rapidly and the role of the U.S. is destined to become less dominant in all areas[11].

These emerging nations are looking forward with an attitude that they will do whatever it takes to build an innovation-driven economy. As a result, of the nearly 500 universities that have visited Olin College in the last five years for the purpose of gaining insight into how to produce engineering innovators, 70% of them are from abroad. These nations are very serious about making investments in education that will catapult them into a leadership role in the innovation economy. They implicitly assume that change and improvement are needed, and they are willing to make substantial investments to initiate it. In contrast, many American universities are relatively complacent. As a wise mentor once told me: "there is no more powerful force for conservatism than having something to conserve." America is still widely regarded as the world leader in higher education, so we have a LOT to conserve. But if we remain flat footed while the rest of the world races ahead, they will eventually over-take us.

Decline in student interest in STEM subjects. Another major change of equal importance that has occurred in the last fifty years is the decline in student interest in STEM fields and the decline in quality and rigor of their preparation in K-12 in these fields. Fewer than 5% of the bachelors degrees awarded across America last year went to students who majored in any kind of engineering at any university in the

[9] Larson, Chase, *Mark Zuckerberg speaks at BYU, calls Facebook as much about psychology and sociology as it is technology,"* **Deseret News**, March 25, 2011.
[10] Brazil, India, Russia, and China
[11] National Academy of Engineering, **Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5**, National Academies Press, Washington, DC, 2005, p. 7.

nation[12]. Less than half of all incoming students who choose engineering as their major will graduate in engineering. And many of the students who drop out of engineering have higher grades than those who stay[13]—so it is not a lack of skill or intelligence that drives students out of engineering. Students today are highly motivated to tackle the Grand Challenges of our age, but they don't see the narrow study of the fundamentals of natural science and math as the key to these problems[14]. They see the problems as more human than scientific. They are looking for a way to make a positive difference in the world—in the lives of people. They don't often see the study of engineering science and math as being directly related to the problems they see or care about.

This disconnect is frustrating, even heartbreaking. It too often leads to disillusionment and abandoning the field altogether. In the current generation of young college graduates, the problem of finding their "calling" seems separated from their college degree more than in previous generations. Too many students graduate from college only to return home to think about what they want to do with their life. To a degree that is much higher than previous generations, they postpone marriage and family, struggle with identity and purpose, and seem overwhelmed with the complexity and frustrations in life.

Emergence of extracurricular competitions that inspire students. A few bright spots that have emerged in the last few decades might offer some insight into how to improve the situation. In the last decade, more K-12 students have encountered robotics than ever in the past. The excitement of team competitions that parallel those in traditional athletics has been brought to an increasing number of schools, largely through the efforts of Dean Kamen and Professor Woodie Flowers (with support from John Abele and others in industry) through the FIRST organization[15]. The impact of student experiences in actually making and competing with complicated robotic systems while in high school is undeniable. It is clearly capable of transforming lives and leaving students with a sense of empowerment and intrinsic motivation to study STEM subjects.

Another example is provided by the large number of K-12 students today who discover the ability to create their own computer code or an "app" for their smart phone. The experience of creating something that works, something that is valued by peers, and something that can be shared broadly with others is similarly transformative for many students. It can also result in a sense of empowerment and intrinsic motivation in computer science and math. A recent example of this type of student engagement is provided by code.org and its "hour of code" program[16].

It is hard to avoid the observation that these two recent trends are inherently ***experiential***, involve ***making*** things (rather than learning about things), and lie outside the traditional school curriculum. They require a complex number of non-technical skills including creativity and self-expression, taking the initiative to learn independently (since these topics are not part of the traditional curriculum), collaboration with others, perseverance and determination to succeed (now sometimes referred to as "grit"), and communication—including advocacy—with others. The power of these experiential learning opportunities to address many of the major concerns in education is hard to overlook. It is also tragic that they had to be developed outside the school curriculum[17]. The impact on students often extends beyond their knowledge and abilities, and includes a sense of empowerment, purpose, and direction in life.

Similar experiential learning opportunities are transformational during the college years, too. These include largely extra-curricular activities like the SAE Mini Baja race car competition[18], the ASME Human-

[12] National Science Board, *Science and Engineering Indicators*, 2014.
[13] This is especially true of those who are women.
[14] Wadwa, Vivek, "*Students may resist geek studies. But they'll flock in for the opportunity to change the world.",* The Grand Challenge for Science and Math, **BusinessWeek**, March 9, 2009.
[15] www.usfirst.org
[16] www.code.org
[17] The widespread emphasis on standardized testing creates little incentive or opportunity for educational experimentation, although some non-traditional schools (such as High Tech High School in San Diego—and a growing number of others) are successfully pioneering a very experiential learning environment that provides nearly everything described in this paragraph.
[18] www.bajasae.net

Powered Vehicle competition[19], numerous computer “hackathons,” entrepreneurial and business plan competitions, even some experiences in community service, music, athletics, and philanthropy, such a Toastmasters[20]. Students who find such opportunities and can successfully integrate them into their lives very often have better outcomes, educationally and in careers.

In addition, it is well known that students who complete a program with a required corporate internship have consistently better outcomes than those who do not. Corporate internships provide a well known example of what can happen if the engineering curriculum embraces the development of professional skills rather than ignores it. Students who graduate with an internship experience have a more realistic understanding of the context of engineering, and generally receive more and better career opportunities. Many companies give preference to candidates for employment that have internship experience and some companies restrict their recruiting efforts to students that have completed an internship within their company.

It is glaring that the missing professional skills in the preparation of engineers may be traced to the last rebalancing of engineering education, while many of the problems with student motivation and achievement in education today also appear to be related to the absence of these same contextual experiences that lead to enhanced professional skills.

The Internet and the shift from the “knowledge economy” to the “maker economy.” One final observation about the changes in the last fifty years may have a bearing on this issue. Before the Internet age, knowledge was much harder to come by. Just finding the facts was often a time-consuming chore involving books, libraries, and consultation with “experts.” An important goal of education then was to produce experts who were recognized for their specialized knowledge of the facts. This expertise often translated into a professional career with financial success. Just knowing things was often intrinsically valuable and respected. (The popular TV game ***Jeopardy!*** epitomizes the implicit value our society has historically placed on “knowing things.”)

But after the widespread establishment of the Internet (and powerful free search engines like Google), finding facts has become immensely easier and cheaper. The intrinsic value of knowing things has declined drastically—and permanently. To a large extent today, it matters much less what you know than it does ***what you can do*** with what you know.

Learning to make things is inherently experiential, as compared to learning about things, which is much more cerebral. Those who work in the arts have always understood this. The arts have long focused on self-expression, design and studio “thinking,” and pedagogies that involve long hours of practice and emotional engagement—like recitals and concerts. Mastery, rather than knowledge, is the primary goal of the arts. In the arts, it matters as much or more ***how*** you say or do things than it does ***what*** you say or do. Technic is the hallmark of artisanship, not knowledge alone.

As a result of the Internet revolution, higher education is beginning to shift. MOOCs have emerged to provide widespread access to high quality educational content at very low cost. The old pedagogical paradigm of the expert professor as “sage on the stage” delivering content to rows and rows of quiet students who take notes and prepare to demonstrate knowledge on tests is beginning to shift. Now, we see the emergence of more experiential learning in the ***mainstream*** of higher education. The sage on the stage is increasingly being replaced by the professor in the role of coach, as “guide on the side,” with students now arranged around tables in small groups working together during class on a “maker” project. The room is no longer quiet, and the students are more personally engaged in their learning, with public speaking and presentation a common expectation.

As a result, professional skills are becoming much more important in this new “maker university” format, taking center-stage as students must learn to collaborate and produce results together as they develop mastery. More and more, the focus of educational topics in this approach involves complexity, ambiguity,

[19] www.asme.org/events/competitions/human-powered-vehicle-challenge-(hpvc)
[20] www.toastmasters.org

diagnosis, judgment, and human behavior, not simply mathematical answers or scientific facts. In the maker approach, the percentage of questions that have unique "correct" answers is declining. Judgment is increasing, and the skill of consensus building is becoming a prerequisite. In the university, as in industry today, students must learn to work productively with teams of others who have a different perspective or worldview. As a result, the ability to work effectively in teams and to assume a leadership role when needed has become much more common and important in the last fifty years, mirroring a shift in the organization of labor in the workplace during this period.

THE TIME HAS COME FOR ANOTHER REBALANCING OF UNDERGRADUATE ENGINEERING EDUCATION. For the first time in more than fifty years, the time has come to significantly "rebalance" engineering education. No amount of doubling down on hard sciences and math will provide the professional skills that are needed now. The relative emphasis between hard sciences and professional skills in the degree requirements for engineering graduates must change to address the changing needs of our times. When corrected, there will be more required activities for students that involve "maker" projects, and fewer that involve learning just-in-case knowledge about topics that are never actually used. Teaching students how to learn independently, how to improvise in the face of the unexpected, and how to master the skills needed to make an impact will be more important than relentlessly trying to increase the scope and number of new scientific topics that cannot be covered in depth. The many extracurricular projects that today succeed in inspiring and empowering students—often in spite of, not because of our curriculum—need to be moved into the core curriculum. This can and is being done with success in some programs already. The result will be no less than a revolution in engineering education.

While our focus is on engineering education, it is important to recognize that a similar revolution is needed more generally throughout STEM education, and perhaps all of higher education.

> *"Innovation is not simply a technical matter but rather one of understanding how people and societies work, what they need and want. **America will not dominate the 21st century by making cheaper computer chips but instead by constantly reimagining how computers and other new technologies interact with human beings**."*
> FAREED ZAKARIA[21]

WHAT DO WE MEAN BY PROFESSIONAL SKILLS? In order to move forward with any large-scale movement like this, it is necessary to answer a number of important questions. These begin with a more detailed discussion of what we mean by professional (or soft) skills.

In recent years, many employers have complained about the need for more attention to professional skills in new engineering graduates. The list of concerns almost always focuses on non-technical abilities or "people skills" that represent attitudes, behaviors, skills, and motivations and not just knowledge. A precise and unambiguous description of these dimensions to the abilities of engineers is very hard to find, although many recurrent themes are apparent.

For example, the **ABET** accreditation criteria for all engineering programs (Criterion 3 Student Outcomes, (a)-(k)[22]) contains 13 requirements for an accredited engineering degree. Six of these relate to professional skills rather than the use of the hard sciences. The professional skills they seek are described as follows:

(d) an ability to function on a multidisciplinary team
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively

[21] Zakaria, Fareed, *Why America's obsession with STEM education is dangerous,* **The Washington Pos**t, March 26, 2015.
[22] http://www.abet.org/wp-content/uploads/2015/04/eac-criteria-2013-2014.pdf

(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and social context
(i) a recognition of the need for, and ability to engage in life-long learning
(j) a knowledge of contemporary issues

Many other employer and professional groups have provided descriptions of the professional skills that are needed for engineers today. Many of these groups have independently concluded that professional skills are of greater importance today than ever before, and that the educational process for engineers does not adequately address them.

For example, more than two decades ago, **IBM** began a call for the creation of the "T-shaped" engineer. Beginning with a study in 1990 of hybrid managers[23] then progressing to a call for T-shaped skills and finally to T-shaped professionals, IBM became convinced that a new hybrid field of "service science, management and engineering[24]" is needed in the 21st century. This field depends on a workforce comprised of T-shaped individuals. The IBM concept of the T-shaped individual is illustrated in Figure 1.

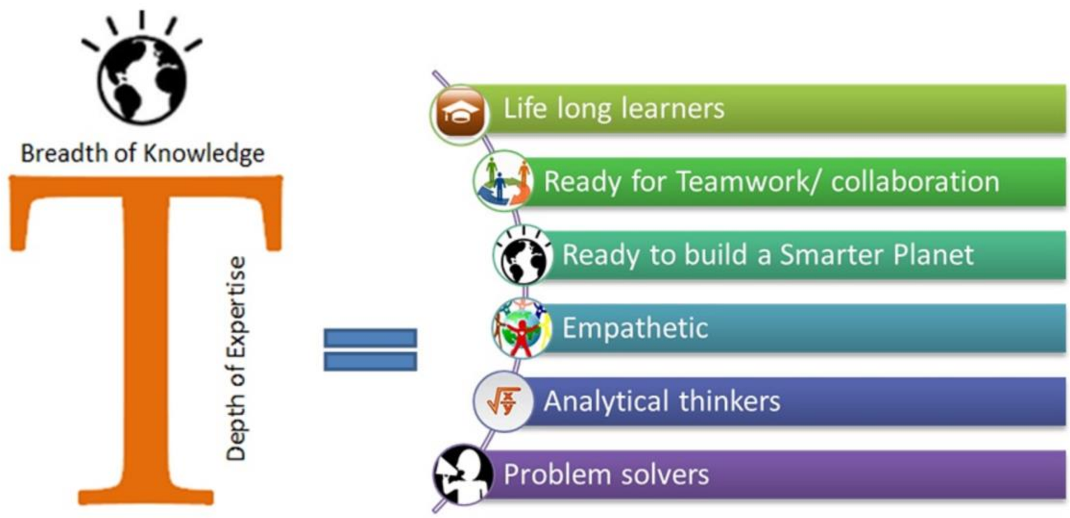

Figure 1 – **The IBM Concept of the T-Shaped Individual**[25]. The vertical bar represents depth in a single technical discipline, and the horizontal bar represents the ability to apply knowledge across disciplines and to work with others.

The inclusion of human services within the engineering disciplines is gaining recognition within the engineering profession. In 2015, IBM chairman, president, and CEO Virginia Rometty was elected to the National Academy of Engineering for her leadership at IBM in establishing the field of services science.

Recently, the **Council on Competitiveness** with support from Lockheed Martin Company and others sponsored the National Engineering Forum[26]. According to their website, *"The National Engineering Forum (NEF) is a movement focused on creating solutions for challenges facing the U.S. engineering enterprise – capacity, capability, and competitiveness – the 3C's. Momentum-building regional dialogues involve leaders from industry, academia, the media, non-profit organizations, and government in shaping*

[23] Palmer, Colin, *"Hybrids—a critical force in the application of information technology in the 1990s,"* **Journal of Information Technology**, Vol. 5, (1990), pp. 232-235.
[24] http://researcher.watson.ibm.com/researcher/view_group.php?id=1230
[25] "*Why Do You Need to Become a T-Shaped Person*," **Students for a Smarter Planet**, blogpost, July 3, 2013. http://asmarterplanet.com/studentsfor/blog/2013/07/why-do-you-need-to-become-t-shaped-person.html
[26] http://nationalengineeringforum.com/our-focus/#.VTRdVs74tlI

the agenda and building a community of action. The dialogues will culminate in a national cornerstone event in 2017." They explain that "capability" relates to the concerns about the need for **multi-disciplinary training** of engineers to meet the Grand Challenges, and "competitiveness" relates to concerns that **more creative and collaborative leadership** is required to build **partnerships with society through government and the media**. The NEF has sponsored about 20 regional meetings around the U.S. to discuss this agenda with a wide range of stakeholders and plans to convene a major national summit in 2017.

The **Business Higher Education Forum** (BHEF) is another broad-based group of industry and academic leaders dedicated to shaping the U.S. engineering workforce of the future. According to their website[27]: "*The Business-Higher Education Forum is the nation's oldest organization of senior business and higher education executives dedicated to advancing solutions to U.S. education and workforce challenges. Through the member-led National Higher Education and Workforce Initiative, BHEF is committed to developing new undergraduate pathways needed to keep regions, states, and the nation economically competitive. BHEF and its members drive change locally, influence public policy at the national and state levels, and inspire other leaders to act. BHEF works with its members to develop undergraduate programs in emerging fields that can be applied to a variety of professions to correct workforce misalignment."* The BHEF is active in developing definitions of "**workplace competencies**" and "academic content knowledge" that align better with emerging national needs and launching partnerships between industry and academia aimed at creating innovative new programs to shape the future workforce in engineering.

The **STEMconnector** is another organization involving a broad community of more than 3,700 national, state, local, and federal STEM organizations. As described on their website: *"STEMconnector® is a consortium of companies, nonprofit associations and professional societies, STEM-related research & policy organizations, government entities, universities and academic institutions concerned with STEM education and the future of human capital in the United States…"* Of particular interest is a recent STEM Innovation Task Force (SITF) that has been working for many months on the demand-side requirements of STEM professionals. Their report, STEM 2.0[28], provides an outline of their view of the professional skills needed for the STEM workforce of the future. The graphic in Figure 2 highlights their relevant findings.

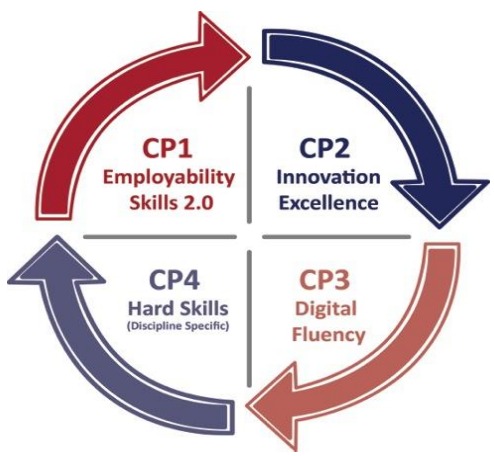

Figure 2 – STEMconnector Innovation Task Force report (STEM 2.0) on the competency platforms (CP) needed in the workplace today

As described in the report, "STEM 1.0 focused, rightly, on STEM content, whereas the next stage for our students and future workforce is to master **context**." The graph in Fig. 2 illustrates the four "competency

[27] www.bhef.com
[28] *STEM 2.0: An Imperative For Our Future Workforce*, STEMconnector Innovation Task Force, STEMconnector: Washington, DC, June 2014.

platforms" (CP) identified by the SITF as necessary to achieve STEM 2.0. In particular, CP1 and CP2 require a quantum improvement in professional skills.

Employability Skills 2.0 (CP1) are identified as "the **behaviors above and beyond technical skills** that enable STEM employees to create stakeholder momentum to commercialize ideas, or in short career skills. It is the ability to **present and 'sell' their ideas to others; to function in teams; to develop business acumen; to develop leadership skills; to navigate across a complex matrix of global organizations**."

Innovation Excellence (CP2) requires developing the "process of transforming ideas into new and improved systems, services or products that enhance the value of existing resources or create new ones. Innovators **identify opportunities** and use them to **drive change**. Innovation excellence requires a **'hollistic' multi/trans disciplinary skill set**."

In addition to these recent industry studies and reports, the **National Academy of Engineering** has also endorsed similar increased emphasis on professional skills. For example, the **NAE Grand Challenge Scholars Program**[29] was launched in 2009 to recognize and reward those engineering students who graduate with additional preparation in five areas beyond technical competence, including (1) a **hands-on project** or research experience related to a Grand Challenge; (2) an **interdisciplinary curriculum** that involves **public policy, business, law, ethics, human behavior, risk, and the arts, as well as medicine** and the sciences; (3) **entrepreneurship experience** that prepares students to develop market ventures that scale to global solutions in the public interest; (4) a **global dimension that instills awareness of global marketing, economic, ethical, cross-cultural, and/or environmental concerns**; and (5) **service learning that deepens students social consciousness and their motivation to bring their technical expertise to bear on societal problems**.

On March 24, 2015, more than 120 deans of engineering from across the nation presented letters of commitment to President Obama to establish a Grand Challenge Scholars Program on their campuses and graduate more than 20,000 engineers in the next decade with these enhanced professional skills[30].

These industry and academy reports are also supported by research results. For example, a recent thesis at MIT[31] involving a survey of nearly 700 mechanical engineering graduates about 10 years after commencement reported that students learned an extensive list of engineering science and mathematics subjects at MIT, but that they found much less use for this material in their career than they did for professional skills—which they mostly had to learn on their own after graduation. They reported that their current position required relatively little direct competence in the engineering sciences, but instead required substantial proficiency and even leadership in professional skills in order to advance. They reported that they used the professional skills daily but engineering and science much less frequently.

More recently, the NAE published a report titled **Educate to Innovate**[32] that, among other things, identifies the factors that influence innovation. As presented in the report, "the United States must significantly **enhance its innovation capacities** and abilities among both individuals and organizations. Innovation capacity should be a new indicator of US workforce readiness to compete successfully in the global economy…A **new educational paradigm is needed** to help current and future American workers remain competitive… Academic environments, from the earliest ages through continuing education, can be improved—and even designed—to enhance this ability…The skills and attributes identified in the study include: (1) **creativity**; (2) **dissatisfaction with the status quo**; (3) **intense curiosity**; (4) the **ability to identify serendipitous moments**; (5) **willingness to take risks and to fail**; (6) **passion**; (7) knowledge

[29] http://www.pratt.duke.edu/undergrad/students/grand-challenge-scholars-program
[30] http://www.nae.edu/Projects/MediaRoom/20095/130169/134046.aspx
[31] Wolfe, Kristin E., "*Understanding the Careers of the Alumni of the MIT Mechanical Engineering Department,*" S.B. thesis, Advisor: Warren E. Seering, **Massachusetts Institute of Technology**, Cambridge, MA, 2004.
[32] Bement, Arden, Jr., Dutta, Debasish, and Patil, Lalit, *Educate to Innovate: Factors That Influence Innovation*, National Academies Press, Washington, DC. 2015.

of their field; (8) the **ability to identify good problems/ideas**; (9) the ability to **work at the interface of disciplines**; and (10) the ability to **sell an idea**."

Although not directly aimed at engineering graduates, it is noteworthy that the **World Economic Forum** also recently published a report[33] that presents a new summary of the skills needed for the 21st century of all graduates. From the executive summary: "To thrive in a rapidly evolving, technology-mediated world, students must not only possess strong skills in areas such as **language arts**, mathematics and science, but they must also be adept at skills such as **critical thinking, problem-solving, persistence, collaboration, and curiosity**.

Now, collecting ideas from all of these sources, a partial list of the professional (or soft) skills that are needed might include the following:

A Summary of Professional Skills

- Ethical behavior and trustworthiness
- Employability skills, including self-confidence and positive outlook, accepting responsibility, perseverance, sincerity, respect for others, good judgment, etc.
- Effective communication, including advocacy and persuasion
- Effective collaboration including leadership, followership, and consensus building
- Resourcefulness and the capacity for independent learning
- Entrepreneurial mindset and associated business acumen
- Inter- and multi-disciplinary thinking
- Creativity, curiosity, and design
- Empathy, social responsibility
- Global awareness and perspective

(It's important to note that the skills identified here may not be completely independent. To my knowledge, there are no substantial research studies that undertake to identify the level of interdependence among these skills.)

DO THESE PROFESSIONAL SKILLS MAKE A SIGNIFICANT DIFFERENCE? The proliferation of independent industry reports calling for an improvement in professional skills while remaining nearly silent on the need to keep up with emerging developments in the hard sciences and technology demonstrates widespread agreement that more improvement is needed in soft skills than anywhere else. Except for a few special cases (such as cyber-security) it is difficult to find industrial reports that call for additional or new technical subjects in the engineering curriculum.

However, this raises the question of whether individuals that make the investment to develop these skills experience a difference in their personal career trajectory. One of the ways to approach this question is to review the advancement and financial opportunities available to those individuals in comparison to those with lesser professional skills. Naturally, competent engineers with well-developed professional skills stand out when leaders look for individuals to promote into leadership positions. In fact, in most cases, professional skills are far more important for senior leadership appointments than high levels of technical competence. Substantial financial reward usually follows advancement into leadership positions. Recent reviews of salaries of engineers[34] confirms that those who ascend into leadership (management) positions experience a significant increase in salary and benefits.

In addition, college placement officers also confirm[35] that for graduating seniors with similar technical preparation, those with well-developed professional skills consistently receive more employment offers and higher starting salaries than those without these skills. Interestingly, about 14% of the new

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[33] *New Vision for Education: Unlocking the Potential of Technology*, **World Economic Forum**, Geneva, Switzerland, 2015.
[34] http://www.hamiltonproject.org/papers/major_decisions_what_graduates_earn_over_their_lifetimes/
[35] Sally Phelps, Director of Post-Graduate Planning, Olin College (personal communication)

employees selected at Google last year[36] had no college degree at all, in spite of the fact that Google receives tens of thousands of qualified applications. Lazlo Bock, Senior Vice President for People Operations at Google, explained that they sometimes look for qualities that do not line up with college transcripts. So, certain forms of professional skills are weighted more highly than a university degree at Google.

Finally, studies of companies that excel in the market place often reveal that the corporate culture plays a substantial role in their success[37]. Those companies with a culture marked by higher levels of professional skills tend to out-perform those that do not over the long term[38]. It is hard to identify a downside to building a company on a foundation of widespread professional skills.

> *"I want to talk with everyone about innovation. We often say that America and Europe are more innovative than us, that China's innovation is not good and that the education [jiaoyu] system is to blame. Actually, I think China's jiao is fine. The problem is with the yu. In terms of jiao, China's students test better than anyone in the world, but yu is about fostering culture and emotional IQ…* ***"[Innovations] will only come regularly if we rethink our culture, our yu, our having fun****… our entrepreneurs need to learn how to have fun, too..."*
>
> JACK MA (FOUNDER OF ALIBABA)[39]

BUT CAN PROFESSIONAL SKILLS BE TAUGHT? Reviewing the list of professional skills, it is clear that these abilities extend beyond traditional course content knowledge and focus instead on a set of attitudes, behaviors, and motivations. Collectively, we might refer to these as a "mindset." But can education produce these attitudes or mindset? Is it possible to write a textbook, provide a set of lectures, and create a set of exams that will guide students to reliably develop the skills we seek? This is a difficult question that extends well beyond the boundaries of traditional engineering courses.

The fact is that attitudes and behaviors are only minimally affected by knowledge alone. They almost always require personal experiences that challenge beliefs and require extensive practice to build habits of mind. These psychological factors are largely unfamiliar to engineering faculty (and to many others, as well!). However, it is important to realize that business schools have long specialized in providing instruction aimed at improving teamwork and leadership skills, sales and marketing, entrepreneurship, etc. There are well established educational programs in these areas, although they may focus more on skills and knowledge than attitudes.

Consider the first professional skill in the list above: ethical behavior. Nearly every time a national scandal occurs in the financial world (like Enron, Bernie Madoff, or the recent Global Recession) business schools increase their emphasis on courses in business ethics. However, these courses are usually based on intellectual content derived from the philosophy of ethics with a focus on very complex decisions in cases involving trade-offs between two or more imperfect options. As fascinating and valuable as such courses may be to public policy debates, there is very little evidence that they are effective in reducing the likelihood that business graduates will avoid ethical violations themselves[40,41].

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[36] Bock, Lazlo, "*Becoming a Googler…and Other Opportunities*," New York Times and Tom Friedman's ***Next New World Forum***, San Francisco, CA, June 12, 2014: http://www.nytfriedmanforum.com/videos/becoming-a-googlerand-other-opportunities.aspx

[37] Collins, Jim, **Good to Great: Why Some Companies Make the Leap…and Others Don't**, Harper Business, 2001.

[38] Collins, Jim, and Porras, Jerry I., **Built to Last: Successful Habits of Visionary Companies**, Harper Business, 1994.

[39] Custer, C., *Jack Ma explains why China's education system fails to produce innovators*, **TechInAsia**, December 9, 2014.

[40] Gentile, Mary C., Senior Research Scholar, Babson College, personal correspondence.

[41] Gentile, Mary C., "*Values-Driven Leadership Development: Where We Have Been and Where We Could Go*," **Organization Management Journal**, Vol. 9, pp. 188-196 (2012).

However, a different approach that focuses on personal behaviors involved in confronting ethical violations in the workplace, together with practice in role-playing to build confidence and personal skills, has shown promise in changing mindset and behavior[42]. As in other examples of professional skills, the problem often lies not in a failure to understand at an intellectual level, but rather in a failure to develop the conviction and the skill to take personal action to address obvious problems when they occur—in spite of the personal inconvenience involved.

One of the most common goals of a liberal education is to produce “critical thinking” among graduates. Nearly all colleges and universities claim this as an important objective. But what, exactly, is critical thinking? One example might be provided by Dr. James Ashton[43] who, in the 1980s while serving in a leadership role at General Dynamics Corporation in producing the Trident Submarine, became concerned in comparing his personal observations with corporate reports on financing of the project. In an attempt to make sense of the situation, he drew the independent—and most inconvenient—conclusion that something was fundamentally wrong. This led him to confront top management with his independent analysis and ultimately to leave the company, eventually participating in a 60 Minutes interview with Geraldo Rivera and testifying before Congress. This sense-making, independent conclusion and personal action are all important ingredients in what we hope “critical thinking” really means.

However, it is interesting to compare this example with the most common method for producing critical thinking in higher education. In essence, critical thinking is assumed to result from the collective experience of taking a series of lecture courses for four years from highly educated faculty members who are experts in their research disciplines (but rarely in corporate practice). The courses are selected from several lists of approved electives, three from list A, two from list B, etc. However, some people have begun to question whether this whole approach is effective in producing the critical thinking we seek. After all, the students are exposed only to faculty members, not to practicing professionals. The environment they experience is that of academia that is marked with academic freedom, and not that of the competitive marketplace. There is rarely an independent assessment process intended to monitor the cumulative development of critical thinking.

For example, some years ago, President Liz Coleman of Bennington College in Vermont concluded that this process is fundamentally inept in producing critical thinkers (and other things), and she led a process of gut-wrenching change in her institution to literally reinvent a liberal arts college. She is now an outspoken advocate for such profound change throughout higher education[44].

Another of the professional skills on the list is that of an entrepreneurial mindset and associated business acumen. Over the last two decades, engineering schools have begun to accept that students should learn the basic principles of entrepreneurship. Twenty years ago, it was rare to find an engineering school that was willing to make room in the curriculum for this subject, whereas today it is difficult to find an engineering school that does not already have such a program or is in the process of creating one[45].

To meet the growing demand for teaching entrepreneurship in engineering, several well organized independent programs have been developed. One of the most successful is the Kern Entrepreneurial Engineering Network (KEEN)[46]. This network of 19 engineering schools around the U.S. is focused on graduating engineers with an entrepreneurial mindset, not just technical skills. The KEEN network has a well-developed educational approach involving four cornerstones: business acumen, customer engagement, technical fundamentals, and societal values. But developing an “entrepreneurial mindset” is their highest goal. (Other well organized educational programs focused on engineering entrepreneurship also exist, including the EPICENTER program at Stanford University[47].)

[42] http://www.givingvoicetovaluesthebook.com
[43] http://www.olin.edu/about/presidents-council/james-e-ashton
[44] https://www.ted.com/talks/liz_coleman_s_call_to_reinvent_liberal_arts_education?language=en
[45] McMurtrie, Beth, *“Now Everyone’s an Entrepreneur,”* **Chronicle of Higher Education**, April 20, 2015.
[46] http://www.keennetwork.org
[47] http://epicenter.stanford.edu

There are many possible definitions of an entrepreneurial mindset. However, at the foundation it may rest on a powerful "can-do" spirit, a focus on opportunities rather than challenges, and the "abundance" mindset (which I will return to later). Of course, it takes much more than a mindset, but it may be hardest to define and cultivate the mindset.

I recently read an article in the Wall Street Journal that included an interview with President Peretz Lavie, President of The Technion in Israel[48]. The Technion is regarded as a significant factor in Israel's becoming known in many circles as the "start-up nation." The persistent existential threats faced by Israel would seem to fly in the face of this reputation as the engine of entrepreneurship for the entire region. However, in the article, President Lavie explains: " 'We have to be on our tiptoes and have to think ahead,' he said. To live here, he adds, one has to be optimistic—an essential attribute for entrepreneurs"[48]. Clearly, he believes that the unusually challenging environment in Israel may have strangely contributed to the development of an entrepreneurial mindset there.

Unpacking this for a moment, I believe what Professor Lavie is saying is that entrepreneurs are people who <u>must</u> be optimistic. They must naturally have a mindset that predisposes them to imagine a better future is always possible, and that future depends on our taking initiative and creating the change that will make it so. This is in contrast to an opposite (cynical) mindset that believes future improvement is hopeless, imagines we are victims of some larger system or circumstance, and focuses efforts on finding someone else to blame.

This explanation of an entrepreneurial mindset is clearly related to the contrast between a "scarcity" vs. "abundance" mindset. These concepts were explained by Stephen Covey:

> *"Most people are deeply scripted in what I call the Scarcity Mentality. They see life as having only so much, as though there were only one pie out there. And if someone were to get a big piece of the pie, it would mean less for everybody else.*
>
> *The Scarcity Mentality is the zero-sum paradigm of life. People with a Scarcity Mentality have a very difficult time sharing recognition and credit, power or profit – even with those who help in the production. The also have a very hard time being genuinely happy for the success of other people. …It's difficult for people with a scarcity mentality to be members of a complimentary team.*
>
> *The Abundance Mentality, on the other hand, flows out of a deep inner sense of personal worth and security. It is the paradigm that there is plenty out there and enough to spare for everybody. It results in sharing of prestige, of recognition, of profits, of decision making. It opens possibilities, options, alternatives, and creativity. …It recognizes the unlimited possibilities for positive interactive growth and development, creating new Third Alternatives. …It means success in effective interaction that brings mutually beneficial results to everyone involved."*[49]

It is much easier to teach "business acumen" and techniques like accounting or business plan development than it is to promote an entrepreneurial mindset. Obviously, this involves personal attitudes and behaviors, and derives from a special learning culture.

So, is it really possible in education to shape a student's mindset or mental outlook? I believe it is, at least to some extent. In fact, I believe it may be happening every time we interact with students—whether we are aware of it or not.

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[48] Wolfe, Alexandra, "*The Technion's Peretz Lavie on Technology and Education*," **Wall Street Journal**, Feb. 13, 2015.

[49] Covey, Stephen R., **<u>The 7 Habits of Highly Effective People: Powerful Lessons in Personal Change</u>**, Simon Schuster, 2004, pp. 219-230.

For example, last fall I heard in the popular press[50,51] about an experiment with young children related to the Thanksgiving holiday. Apparently, the teachers had noticed that their students had a very weak sense of the meaning of the holiday. The students did not associate Thanksgiving with a sense of gratitude. So, they applied a curriculum to develop a sense of gratefulness. This consisted of asking students in one classroom to keep a journal in which each day they wrote down a few things that happened for which they were grateful. At the end of the week, the teacher conducted a brief class discussion of journal entries, and after several weeks they conducted an open class discussion in which the students were asked to envision the future as they expect it to be. Not surprisingly, the students envisioned a future with many positive possibilities, and were looking forward to an opportunity to engage in making a positive difference in the world. However, in another classroom down the hall, they applied a curriculum that instead of requiring students to identify several things they were grateful for, they identified several things that they regarded as hassles. In other respects, the process was identical. It might not surprise you that at the end, they found that the hassles curriculum produced a student outlook on the future that was much less positive. Students in this case saw a future with negative events, frustration, and little to be grateful for. It did not result in a mindset of abundance. These results are consistent with published research in experiments with college students in the field of positive psychology[52].

"*Reflect on your present blessings, of which every man has many, not on your past misfortunes, of which all men have some*"
Charles Dickens, (M. Dickens, 1897, p. 45)

WHO SHOULD TAKE RESPONSIBILITY FOR TEACHING PROFESSIONAL SKILLS? Since engineering faculty members were hired for their expertise in the technical disciplines, rather than in professional skills, few of them are likely to be well-prepared to take responsibility for teaching the professional skills. Furthermore, in previous generations many people just assumed that the responsibility for preparing the attitudes and behaviors of students was that of the parents, not teachers. Other people have noted that students who have a co-op experience in industry (or similar substantial personal experience working in a professional environment) seem to develop professional skills at a noticeably higher rate than students who have no such experience. Furthermore, teaching professional skills appears to be much more complex and nuanced than teaching knowledge of even skills that may be easily defined and measured. As a result, there are many good excuses to not take responsibility for teaching these skills. Undoubtedly, this fact plays an important role in creating the unfortunate situation we find today where they are largely overlooked.

Perhaps engineering schools should begin by sending their students to a business school to take the programs already developed there. It is hard to ignore the well-developed educational programs in this area that are available in most business schools today. However, this avenue is rarely taken by engineering schools. Why is that? Is it because of the logistics or financial consequences involved? Is it because of cultural factors between the faculty in each school, or the cultural factors between students?

While it is perhaps the most costly alternative in terms of time and resources for an engineering school, I think a good case can be made that the best alternative may be for engineering schools to take responsibility for teaching these skills within their own programs. For example, when attempting to teach another of the professional skills—effective communication and writing—it is much more effective if these skills are embedded in every course in the school (i.e., "writing across the curriculum") than it is when sending the students to the English Department to take a course or two there. If we understand how

[50] Marsh, Jason, and Keltner, Dacher, "*Thanksgiving and Gratitude: The Science of Happier Holidays*," **The Wall Street Journal**, November 28, 2014.
[51] Lyden, Jackie, "*Try and Be Grateful (You'll Thank Us Later),"* **On Point**, National Public Radio, December 24, 2014.
[52] Emmons, Robert A., and McCullough, Michael E., "Counting Blessings versus Burdens: An Experimental Investigation of Gratitude and Subjective Well-being in Daily Life," **Journal of Personality and Social Psychology**, 2003, Vol. 8, no. 2, pp. 377-389.

important professional skills are, and we want our students to respect them, then we should embrace them in everything we do. Adding at least a few faculty members within the engineering school who can take the lead in developing not just a curriculum, but a culture that builds professional skills, is perhaps the best approach. Then building a learning model that not only teaches about engineering, but teaches students to be engineers is how this can be integrated into the entire curriculum. This learning model should include a substantial engagement with industry, where the culture is authentic and is driven by market forces, rather than concerns about ideas alone and publishable research.

In summary, the time has come to embrace the professional skills and fold them into the mainstream in the engineering curriculum. No longer can we afford to pass the responsibility to someone else. We are the last stop on the educational train for our students—if they don't get these skills from us, where will they get them?

DISCUSSION QUESTIONS

1. How important do you feel professional skills are for engineers today? Which two or three skills do feel are most important for career success and for society?

2. Whose responsibility do you think it is to teach professional skills in engineering?

A Review of Studies Demonstrating the Effectiveness of Integrating Arts, Music, Performing, Crafts and Design into Science, Technology, Engineering, Mathematics and Medical Education, Part 1: Summary of Evidence that Integration Is Professionally Useful and Effective.

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Abstract: This is Part 1 of a three part analysis of studies concerning useful ways in which visual and plastic arts, music, performing, crafts, and design (referred to for simplicity as Arts-Crafts-Design or ACD) may improve learning of Science, Technology, Engineering, Mathematics and Medicine (STEMM) and increase professional success in these subjects. We address: 1) what are the ways in which arts and STEM can interact fruitfully; 2) which of these have been explored using well-devised studies and what do these tell us about efficacy; 3) where are the gaps (and therefore the opportunities) that can readily be addressed by new studies; and 4) what kinds of methods can be used to generate reliable data? Part 1 summarizes studies demonstrating that ACD are valuable to STEMM professionals, providing a taxonomy of twelve fundamental ways that STEMM professionals employ ACD ranging from shared mental "tools", creative processes, and aesthetic considerations, to the discovery of novel problems and phenomena, analogies, materials, principles, methods and even mental recreation. Not all STEMM professionals find ACD useful; those who do believe that all knowledge can be unified through "integrated networks of enterprise"; and integrators are very significantly more likely to achieve greater success than those who do not. Moreover, STEMM professionals who use ACD always connect disciplines using specific ways of thinking, skills, materials, models, analogies, structures or processes. These findings make the issue of near and far transfer between ACD and STEMM disciplines irrelevant: the question of far transfer reduces to whether specific links between the two can be found that create direct "near-transfer" bridges between "far-apart" subjects.

"The greatest scientists are artists as well."

~Albert Einstein, pianist and violinist, Nobel Prize, Physics, 1921.
In: The Expanded Quotable Einstein, 2000, pp. 155, 245.

"The creative scientist needs… an artistic imagination."

~Max Planck, pianist, Nobel Prize, Physics, 1919.
In: Autobiography, 1949, p. 14.

"If I were asked to select the best chemist in any gathering,
I should find out first who played the 'cello best."

~T. W. Richards, Nobel Prize, Chemistry, 1914, cellist and painter.
In: Gordon, 1932, 366.

Introduction: Why Integrate Arts, Crafts and Design in Science, Technology, Engineering, Mathematics and Medical Education?

Various studies that will be reviewed below suggest that training in arts, crafts and design (ACD) may improve the learning and performance of science, technology, engineering, mathematics and medical (STEMM)subjects, but available research on the best ways to integrate with STEMM subjects is sparse and it is evident that there are many ways that such integration can be done badly or even harmfully. To understand how best to integrate ACD with STEMM it is therefore necessary first to understand the nature of the skills and knowledge that each requires in and of itself and among these, the ones that may contribute fruitfully to their combination.

From the very first introduction of STEMM subjects into school and college curricula during the late nineteenth century, people involved in science education, policy, psychology and other disciplines have tried to characterize the kinds of skills and knowledge required to teach STEMM subjects to general students and more particularly to train creative STEMM professionals. Thomas Henry Huxley, the biologist most responsible for the introduction of science as a required subject in secondary and collegiate education in the United Kingdom, surprisingly tied ability in scientific research to competency in arts and crafts. A talented watercolorist, a fine draughtsman, and fond of singing, he insisted that any school or college introducing science into its curriculum make art and music mandatory as well. When he founded the Department of Science and Art at the Normal School of Science in South Kensington (which was later absorbed into the Imperial College of Science and Technology and then the University of London), he required his biology students (who notably included the novelist H. G. Wells) to take painting and drawing lessons (Bibby, 1960).

The requirement had its purpose. As Huxley (1900) argued, "The business of education is, in the first place, to provide the young with the means and habit of observation; and secondly to supply the subject-matter of knowledge either in the shape of science or of art, or of both combined" (v3, 175). How, he asked, can a scientist be trained in the habits of observation if they do not train their eyes, ears, and hands through art and music?

> I should make it absolutely necessary for everybody, for a longer or shorter period, to learn to draw… you will find it an implement of learning of extreme value. I do not think its value can be exaggerated, because it gives you the means of training the young in attention and accuracy, which are the two things in which all mankind are more deficient than in any other mental quality whatever..... You cannot begin this habit too early, and I consider there is nothing of so great a value as the habit of drawing, to secure those two desirable ends. (v3, 183-184; See also, v3, 409-410)

In addition to the arts, Huxley also advocated an education that required the development of technical skills. One must, he argued, have direct hand knowledge of things to understand them: "Clever talk touching joinery will not make a chair; and I know that it is of about as much value in the physical sciences. Mother Nature is serenely obdurate to honeyed words; only those who understand the ways of things, and can silently and effectually handle them, get any good out of her" (Huxley, v3, 408). Huxley spoke from experience, asserting in an essay on “Technical Education” in 1877, that although his title proclaimed him a biologist, he was also a “handicraftsman”:

> I am, and have been, any time these thirty years, a man who works with his hands… I do not say this in the broadly metaphorical sense... I really mean my words to be taken in their direct, literal, and straightforward sense. In fact, if the most nimble-fingered watchmaker among you will come to my workshop, he may set me to put a watch together, and I will set him to dissect, say, a black beetle’s nerves. I do not wish to vaunt, but I am inclined to think that I shall manage my job to his satisfaction sooner than he will do his piece of work to mine. (v3, 406).

As a result of Huxley’s arguments, many universities founded, and still retain, a “College of Arts and Sciences”, though most have forgotten the history and rationale that led to this particular combination of disciplines.

Unfortunately, Huxley’s synthesis of arts, crafts and sciences was rapidly undermined in the UK by disciplinary specialization and the social stigmas that separated people who worked with their hands from “intellectuals” who did not. The separation was less evident in the United States, which lacked a class-based intellectual elite and derived a large portion of its emerging scientific talent from farming and industrial backgrounds in which handwork was highly valued. When World War II created the need to recruit scientists for war work, these social and national differences had very practical implications that became the focus of a mammoth study led by the Nobel laureate (Physics, 1915) William Lawrence Bragg. Bragg, himself an excellent craftsman fully capable of making his own laboratory equipment and also a talented painter, was put in charge of a group of eminent scientists (including the physicist-novelist C. P. Snow of "Two Cultures" fame) who interviewed and placed every scientist in the UK into some type of war work.

Bragg and his colleagues quickly realized that US scientists were outstripping UK scientists in devising new inventions such as radar, for the obvious reason that very few UK scientists had any practical skills. Bragg (1942b) concluded in a public report that "the training of our physicists is literally too academic." Like Huxley, he believed that arts and crafts were germane to scientific education. Thus, when the UK government threatened to shut down all arts schools to free up manpower for the war, he argued strongly against the move because "more study of arts subjects… [will foster] those who will later follow science" (Bragg, 1942b). In 1963, he expanded his argument to include craftsmanship along with the arts as necessary skills for budding scientists, maintaining that "practical work is far more effective than book-reading in giving them [future science students] a feel for science. School training provides the background.... but a perhaps even more important incentive comes from their hobbies…" (Bragg, 1963).

Among the Nobel Laureates who joined Bragg in his campaign to make scientific training more practical was P. M. S. Blackett (Physics, 1948), who wrote an essay on the necessity of arts and crafts in the laboratory: "The experimental physicist is a Jack-of-All-Trades, a versatile but amateur craftsman. He must blow glass and turn metal…he must carpenter, photograph, wire electric circuits and be a master of gadgets of all kinds; he may find invaluable a training as an engineer and can profit always by utilising his gifts as a mathematician" (Blackett, 1933, 67). Similarly, as recently as 2012 Professor Heinz Wolff of the British Institute of Engineering and Technology bemoaned the "death of competence" due to the loss of arts and handicrafts in education:

> Apart from typing, we don't use our hands. Girls don't embroider; boys don't play with Meccano [Erector sets]. With these things you effectively develop an eye at the end of the finger, and you do this when you're seven years old. And it's really very clever. But it's gone…Our engineering students can't make things. They might be able to design things on a computer, but they can't make things. And I don't believe that you can be an engineer properly, in terms of it circulating in your blood and your brain, without having a degree of skill in making things. (cited in Borovik, 2012)

Bragg, Blackett, and Wolff are joined by the British embryologist C. H. Waddington, who was also a talented dancer, artist, and historian. in his book *Behind Appearance* (1969), a study of the interactions between sciences and arts in the 20th century, Waddington asserted that the hands-on requirements of science and art profoundly connected the two domains:

> There is a peculiar affinity… between the experimental scientist and the painter in their experience of coaxing parts of the material world – paint, canvas, stone, or ultramicrotomes, bubble-chambers or simple hypochondriac embryos – to do what they want them to do. Painters and laboratory scientists have to recognize and respect the 'green-finger' ability of some people to pull things off when others just make a mess…. [This] affinity between technical mastery in painting and in laboratory work is much closer than between either of them and 'writing well'. All three, including writing like an angel, depend mainly on non-conscious mental processes; but outstanding execution in scientific experimentation and painting have in common a dependence on ability -- probably ultimately muscular -- to handle the physical stuff of the world in a way which is not at all demanded by literary composition. The values which some modern painters see in calligraphy are already part of the scientific ethos. (p. 158)

Physicist, novelist, and historian of technology Mitchell Wilson (one of Enrico Fermi's valued collaborators) provided a similar explanation for why such broad skills are necessary to STEMM professionals. Beyond basic technical knowledge and mathematical skill, the scientist required a heightened communicative skill:

> The particular kinds of sensibilities required by a scientist… [include an] intense awareness of words and their meanings.... [The scientist must be] capable of inventing new words to express new physical concepts. He must be able to reason verbally by analogy.... The scientist must also think graphically, in terms of dynamic models, three-dimensional arrangements in space... Formulas and equations printed on a two-dimensional page have three-dimensional meaning, and the scientist must be able to read three dimensions to 'see the picture' at once…. [for] unless a man has some kind of spatial imagination along with his verbal sensibility, he will always be – as far as science goes – in the role of the tone-deaf struggling with a course in music appreciation. (Wilson, 1972, 11-12)

Wilson incorporated this insight into his novels. In Live with Lightning, for instance, the physics student Erik Gorin, develops a literal "feel" for materials in the invention and building of scientific devices:

> Copper was so soft and chewy that one had to be tender with it. Brass was good and brittle and could be worked with relaxing ease. Steels were unpredictable; some tough, and others soft with knots of hardness spread throughout like seasoning. Whenever he had to work on nickel, he approached the job with dread. He preferred to work with glass because glass blowing… was an artist's medium. One came to it with no tools but one's breath, an eye, a sense of timing, and the jets on the torch (Wilson, 1959, 71).

Beyond Anecdotes to Formal, Large-Scale Studies of the Relationship between ACD and STEMM

The forgoing, qualitative accounts of what makes for the most creative or innovative STEMM education are, of course, biased by personal experience. Nevertheless, it is striking that all individuals thus far cited remark that arts, crafts, design, and even literary skill may be invaluable for the highest levels of achievement. Even more striking, various larger, controlled studies have validated these individual observations. For example, in 1962, David Saunders of the Educational Testing Service performed a study of engineers working for five industry powerhouses: AT&T Bell System, Detroit Edison, B. F. Goodrich, IBM and Westinghouse. He found that those engineers who excelled at research and innovation could be distinguished from other engineers working on similar development and applications problems. They displayed a higher tolerance for ambiguity, greater empathy for other people, and finer skill at inducing patterns. In short, they were "less practical" and "more artistic" than their colleagues (Saunders, 1963, 326).

Two years later, Joseph Rossman published a study of inventors with multiple patents, characterizing them in many of the same terms—practical, analytical, self-critical and persistent. In addition, they were "ingenious," "imaginative," of an "artistic or poetic nature," "observant," "unusually cultured," and "mechanically skilled" (Rossman, 1964, 35-55). Root-Bernstein, et al. (2013) have confirmed these previous studies, demonstrating that professional engineers are significantly more likely to have avocations involving crafts, music, visual arts, and photography than are members of the general public. Moreover, as Saunders (1963) had found previously, the most innovative engineers, those who had produced five or more patents or had founded at least one company, were significantly more likely than those engineers who had not to participate in crafts, photography, and fine arts over their lifetime (Root-Bernstein, et al., 2013).

Studies of scientists and mathematicians have yielded findings similar to those for engineers. P. J. Möbius (1904) (the nephew of the famous mathematician who invented the Möbius strip) reported in a study of working methods that the majority of mathematicians he surveyed engaged in musical, literary, poetic, and artistic avocations. His study is apparently the first to support the claims of various eminent mathematicians that an artistic sensibility lay at the heart of their creativity: "Mathematics and music! The most glaring possible opposites of human thought! and yet connected, mutually sustained! It is as if they would demonstrate the hidden consensus of all the actions of our mind, which in the revelations of genius makes us forefeel unconscious utterances of a mysteriously active intelligence," proclaimed the physicist and musician Hermann von Helmholtz (1857). "May not Music be described as the Mathematic of sense, Mathematic as the Music of reason?" asked mathematician-musician Joseph

Sylvester. “The soul of each the same! Thus the musician feels Mathematic, the mathematician thinks Music” (Sylvester, 1864).

In the same vein, Sofia Kovalevskaya, celebrated mathematician as well as poet and playwright, wrote that mathematics is a “science [that] requires great fantasy, and one of the first mathematicians of our century [Weierstrass] very correctly said that it is not possible to be a complete mathematician without having the soul of a poet” (cited in Kennedy, 1983). Studies following in the footsteps of Möbius also found that mathematicians had a hand in music at much higher rates than was common among the general population or even among other scientific specialists. Claparède and Flournoy (1902; 1904), for example, found that 52% of the professional mathematicians they surveyed reported music as an avocation. This figure compares with the 23% of Nobel prizewinning scientists who listed music as an avocation, 16 % of U. S. National Academy of Sciences members, and 15% of U. K. Royal Society members (Root-Bernstein, et al., 2008).

From the mid-19th century on, studies of uncontrolled, convenience samples of eminent scientists came up with similar results. Like the best mathematicians, the best scientists across many fields were more likely than not to engage in crafts, arts, and design avocations than their average colleagues. Sir Francis Galton, one of the founders of modern psychology, found that members of the British Royal Society were unusually likely to be visually, artistically, musically, and mechanically skilled; he strongly urged that students preparing for careers in science be rigorously trained in five subjects: mathematics, logic, experimental science, drawing, and mechanical skills (Galton, 1874). J. H. van’t Hoff, the first Nobel Prize winner in Chemistry (1901), studied a convenience sample of several hundred scientific biographies and reported that the more creative a scientist was, the more likely he was to display his creativity in some form of art, music, invention, poetry or literary composition, as well (van’t Hoff, 1878). (Van’t Hoff was, himself, a flautist, poet, and artist.) Roe (1953), the first modern psychologist to study scientific creativity formally, found that members of the U. S. National Academy of Sciences were characterized by extraordinary visualization skills. Anzai (1991) found that increasingly skilled use of drawings and diagrams was a direct correlate of increasing expertise in physics. D. W. Taylor (1963) found that literary ability and experience with tools (i.e., craftsmanship) were also skills differentiating the most successful scientists from their more average peers in industrial laboratories.

Eiduson (1962; 1973) also noted that the best scientists differed from their more average colleagues in arts and literary interests. In what may be considered the first longitudinal study of scientific careers, she tracked forty male scientists, including four men who won Nobel Prizes, two more nominated for that Prize, eleven members of the U. S. National Academy of Sciences, two dozen average scientists, and three who failed to obtain tenure. Over a 30-year period, data revealed, individual participation in artistic, musical, and literary pursuits, in crafts, and in physical recreations correlated highly with various measures of career success (Root-Bernstein, et al., 1995). Those scientists who painted, drew, sculpted, photographed, wrote poetry or engaged in wood- or metalworking were significantly more likely than the rest of the scientists in the group to have authored very highly cited articles (>100 citations in a 10-year period – a figure that included all of the Nobel laureates and members of the National Academy). The most successful of the scientists were what Eiduson herself characterized as “gentlemen of science,” meaning erudite, cultured individuals who were clearly distinct in their range of learning and non-academic pursuits from the average scientist.

Subsequent studies of larger groups of scientists using various types of control groups have yielded similar results. Root-Bernstein, et al. (2008) compared the avocational interests of all Nobel laureates in the sciences (to 2000) with those of an average group of scientists (represented by Sigma Xi, the research organization that any working scientist may join) and with those of the general U. S. public. On the one hand, the avocational interests of average scientists were not significantly different than those of the public. On the other, Nobel laureates proved at least twice as likely to be photographers or musicians as the typical scientist, and between fifteen and twenty-five times as likely to participate actively in visual and plastic arts, in crafts such as woodworking and metalworking, in performing arts such as acting and singing, and in creative writing. Indeed, a substantial subset of these Nobel laureates not only had arts and crafts avocations, but engaged in concurrent or second professional careers in the arts or literature. Members of the U. S. National Academy of Sciences and the U.K. Royal Society engaged, on average, in music, arts, and crafts at about half the rate found among Nobel Prize winners, but still about twice the rate found among average scientists and the general public. In other words, the more time devoted to ACD across a lifetime, the greater a scientist’s probability of achieving scientific eminence.

Root-Bernstein, et al. (2013) also investigated the avocations of mid-career Michigan State University Honors College graduates who had gone on to have careers in the sciences. Those who had produced patents or founded scientific companies (i.e., entrepreneurial innovators) were compared with those who had done neither. The entrepreneurial innovators were significantly more likely to display sustained participation over their lifetimes in drawing and photography, in musical composition, in dancing, and in crafts such as mechanics, woodworking, and electronics than their equally successful but less innovative cohort. Interestingly enough, playing a musical instrument as opposed to composing music correlated negatively with patent production in this study, an observation also made during the longitudinal analysis of a very different type of population.

In a large sample of American youth (N=7,148) surveyed in 1979, Niemi (2015) tracked over time how "leisure time interests in the arts relate to entrepreneurship and innovation at work… Self-reported interest in visual arts, music, and literature was analyzed in relation to occupational innovation as indexed by history of business ownership, contributions to work leading to patent applications, and considering oneself an entrepreneur." Additionally, Niemi controlled for "personality characteristics previously suggested to underlie innovation and creativity, including self-mastery and a willingness to take risks, as well as general educational attainment and math and verbal aptitudes." By the time they were 52 years old, approximately one percent (n = 96) of participants had contributed to a filed patent application. Yet of all the factors investigated (arts interests, verbal and mathematical SAT scores, and psychological factors) only interest in visual arts (painting; drawing or prints; architecture; sculpture) proved a statistically significant predictor of that innovative behavior.

In sum, personal testimonies and sampled outcomes as presented above offer somewhat disparate evidence: musical engagement appeals profoundly to many mathematicians, yet playing an instrument in and of itself provides little benefit to entrepreneurs. It may be that unexamined qualities of ACD engagement—whether active or passive, whether conceptually relevant or irrelevant to STEMM—play as much of a role in the relationship between ACD and creative practice in the sciences as duration of engagement. At this point, such a proposition remains to be determined. What is clear at present in this: the weight of current evidence demonstrates a strong correlation between success in STEMM careers and serious, persistent avocational participation in ACD over a lifetime.

Possible Explanations of Why ACD Are Associated with Success in STEMM Careers.

Correlations are not, of course, causation. What one would like to see are interventions that demonstrate not only *that*, but also *how* ACD can improve STEMM performance. The second part of this paper will provide such evidence. First it is necessary to consider what kinds of connections or bridges one might reasonably expect between ACD and STEMM. Much as it would nice to be able to say that practicing any ACD will improve STEMM performance across the board, the evidence summarized above does not support such a conclusion. In addition to the conundrum posed by musical avocations, there are others. Craft skills (such as mechanical ability) appear to have no relationship with mathematical ability, for instance, but a relationship almost certainly exists between craft skill and inventiveness, craft skill and experimental ability. In short, it would appear that some ACD, or perhaps more particularly *some* specific types of skills and knowledge obtained through the practice of ACD, are valuable to *some* aspects of STEMM practice. We need to tease out those specific skills and aspects and the bridges that connect them.

Interview or survey responses in many of the studies summarized above provide a way forward. The kinds of connecting bridges STEMM professionals perceive between their professional work and ACD avocations or training often appear idiosyncratic (a point to which we will return below). Nevertheless, perceptions of connection do fall into about twelve relatively distinct categories that can direct further analysis of how ACD and STEMM learning might most fruitfully be integrated. Many of the articles and books cited above (especially Roe, 1951; Roe, 1953; Root-Bernstein, et al., 1995; Root-Bernstein, et al., 2008; Root-Bernstein, et al., 2013; Lamore, et al., 2013) contain multiple examples of how STEMM professionals have made these links between ACD and STEMM practices, so we will provide here only one exemplar to illustrate each interdisciplinary bridge.

- **Bridge 1. Mental skills or "tools for thinking" such as observing, imaging, abstracting, pattern recognition and pattern forming, analogizing, empathizing and playacting, body thinking, dimensional thinking, modeling, playing, transforming and synthesizing,** which are required to perform any kind of observational or experimental science (Root-Bernstein, 1989; Root-Bernstein & Root-Bernstein, 1999). Good examples of how these "tools" are recognized to be of value to STEMM professionals can be found in the descriptions of skills provided above by Huxley, Bragg, Blackett, Waddington, and Wilson. An additional study by Van Herzelee, et al. (2010) found that visuo-spatial ability, fine motor control, and imaging ability were each independently, and also as a group, predictive of endovascular surgery performance among medical student trainees.

- **Bridge 2. Experience with materials, tools and methods of using them that may then inform STEMM practices**. Alexis Carrel, the 1912 Nobel Laureate in Medicine or Physiology, "learned [as a child] the intricate stitching required for his [later surgical experiments] from the renowned lace makers of Lyon, one of whom was his mother" (Bishop, 2003, 140).

- **Bridge 3. Techniques and phenomena previously unknown to STEMM professionals.** The artist Marcel Duchamps experimented with various effects of moving images on human perception through a form of art he invented called "Rotoreliefs." Some of these effects, such as a rotating disc in which the image appears to spiral both in and out simultaneously, pose explanatory challenges for perceptual psychologists, who have used them psychology investigations (Sekuler & Levinson, 1977).

- **Bridge 4. Novel principles and structures that reveal new aspects of natural processes**.

Attempts by Leonardo da Vinci to understand how to draw trees realistically led him to contemplate the principles underlying their structures. The result is something called “Da Vinci’s Principle.” The rediscovery of this principle in da Vinci’s notebooks about a century ago led to the flowering of botanical studies around his “principle” that are ongoing today (e.g., Williams, 1965; Long, 1994).

- **Bridge 5. Recognition of unsolved problems lying at the junctions of ACD and STEMM**. Modern

theories of “plication,” the science of folding structures, have direct connections to investigations by STEMM professionals such as Robert J. Lang of the mathematical and physical bases of the art of origami. In turn, the elucidation of these mathematical and physical principles has led to a renaissance in origami innovations in the past two decades (see Lang’s website: www.langorigami.com).

- **Bridge 6. Experience navigating the creative process more efficiently and cogently.** Georges

Urbain was the discoverer of element Lutetium and also a sculptor, musician and composer who wrote of the connections between his diverse activities that, “the musician combines sounds in the same way the chemist combines substances…. It is true that musician and chemist reason in their respective fields in the same way, despite the profound difference of the materials they use” (Urbain, 1924).

- **Bridge 7. Practice in the application of transdisciplinary aesthetic principles**. Evolutionary

biologist Per Olaf Wickman says it all in the preface to his book, *Aesthetic Experience in Science Education* (2006):

> In science education research there is rarely any mention of the aesthetic sides of science, and often aesthetics is pictured as other than science. However my own time as a researcher was both an intellectual and aesthetic experience. In saying this I have to stress that aesthetic experience was not simply a motivational drive for my engagement in science; it was continually present when working.

- **Bridge 8. Strategies for exploring and mastering new material efficiently**. The mother of

Nobel-Prize winner Dorothy Crowfoot Hodgkin was a trained artist who taught her daughter how to draw and paint everything she observed. As part of her home schooling, Hodgkin illustrated her parents’ archeological digs, especially the mosaic floors found at some of their sites. Hodgkin “began to think of the restraints imposed by two dimensional order in a plane” (cited in Ferry, 1998, 8), an exercise she subsequently associated with her ability to think about the scientific principles underlying her chosen profession, crystallography.

- **Bridge 9. Mnemonic and other mental devices that increase acquisition and retention of learned material**. Particularly common in disciplines characterized by a great deal of observational identification and/or special nomenclature, as indicated by Op Den Akker, et al. (2002):

> We describe a new method, bodypainting, to enhance courses in living anatomy… We designed a course in which the students familiarized themselves with the surface markings and subsequently painted the full organ at the site of its projection on the body surface. Based on our first experiences, we conclude that the course is a successful and enjoyable means of teaching various aspects of anatomy in relation to physical examination. This was confirmed by an evaluation among the first groups of students.

- **Bridge 10. Practice translating, transforming and transferring concepts and practices between and among disciplines**. Zoologist Jonathan Kingdon has authored a series of encyclopedias about the evolution of African mammals that many consider among the 100 most important science books of the past century (Morrison & Morrison, 1999). He began his study of animals as an artist. Indeed, he has written, "Drawing is a way of exploring. Scientists have lots of techniques. They make histograms, graphs and tables. These techniques are no different to [sic] drawing. Drawing is just as scientific” (Anonymous, 2003, 46). Explicating further, he notes that visual discoveries of form in nature translate directly to scientific concern for pattern:

> It is hardly possible to compare animals without asking questions, and drawing is an exercise in comparisons, comparing the proportions of parts with parts, parts with wholes and comparing one form with another… The comparison of forms…. raises questions, and drawing can be employed as a wordless questioning of form; the pencil seeks to extract from the complex whole some limited coherent pattern that our eyes and minds can grasp. The probing pencil is like the dissecting scalpel, seeking to expose relevant structures that may not be immediately obvious and are certainly hidden from the shadowy world of the camera lens. (Kingdon, 1983, 251)

STEMM professionals in the physical sciences similarly use art to explore “large and complicated system[s]” (Smith 1981, 9).

- **Bridge 11. Recreation (often involving re-creation) that stimulates new creation**. Frederick Banting, the 1923 Nobel Laureate who discovered insulin, wrote that some people go ‘‘for recreation and on account of high life are wreckreated, while others who go for recreation are re-created'' (1979, 36). Banting's own recreation was outdoor painting, which he treated as a type of research useful for stimulating new ideas.

- **Bridge 12. Recording and Communication**. Various types of dance notation have been adapted for recording animal behavior and for the study of neurological deficits on human movement (e.g., Benesh & McGuinness, 1974; McGuinness-Scott, 1981; Harrison, et al., 1992; Teitelbaum, et al., 2004; Wishaw & Pellis, 1991; Melvin, et al., 2005).

Integration of ACD into STEMM Must Be Explicit

As the examples provided above illustrate, STEMM professionals who find ACD useful are very explicit about the ways in which ACD affect their STEMM practices. Since we have provided only a handful of such examples, however, it is perhaps worth a moment to provide broader evidence of this claim.

Three studies prove particularly incisive. The first was carried out by Visher (1947) on "starred scientists" (those considered to be the most eminent) listed in *American Men of Science* in 1947. These scientists were asked whether the arts should be part of STEM education, and even though 39 percent had had no such training themselves, 80% replied "yes." The reasons given generally involved the notion of improving skills or creative ability. A more recent study of 235 mid-career scientists and engineers were similarly asked, "Would you recommend arts and crafts education as a useful or even essential background for a scientific innovator? Why or why not?" Again, just over eighty percent of the respondents replied that arts and crafts should be part of STEMM education (Root-Bernstein, et al., 2013). The same 235 scientists were also asked, "Does your avocation or hobby— or the skills, knowledge, esthetic, social contacts, creative practices, or just plain perseverance that you have gained from it— play any role in your current vocation? If so, please explain how." Sixty-five percent of the respondents stated that they recognized that their arts or crafts avocation stimulated their vocational practice (Root-Bernstein, et al., 2013). These survey results provide evidence that the correlations between arts and crafts participation and career success rise above some intangible and subconscious association to explicit awareness of utility. (Conversely, scientists who found no use for the arts in their own work were also very likely to argue that arts were not useful for STEMM training.)

A third, paired study isolated certain impacts that perceptions of ACD utility had on scientific creative endeavor, suggesting that explicit awareness may in fact be necessary to activate ACD/STEMM bridges. Root-Bernstein, et al. (1993; 1995) investigated the work habits and avocations of Eiduson's forty scientists, mentioned above. (To repeat, this group was notable in having several Nobel Prizewinners and eleven members of the National Academy of Sciences at one end of the spectrum and a number of scientists who did not achieve tenure at the other.) Like the two studies summarized in the previous paragraph, this one found that adult ACD avocations were highly predictive of career success; furthermore, the most successful scientists were highly aware of the positive impact of ACD avocations on their STEMM research (Root-Bernstein, et al., 1995). Three factors shed light on the ACD-STEMM connection. First, whereas the most successful scientists uniformly avowed that their avocations (whether ACD –related or involving other activities such as politics, sports or games) were sources of inspiration for their professional work, the lowest performing scientists uniformly viewed their avocations as wholly separate and unrelated (Root-Bernstein, et al., 1995). Second, self-evaluations correlated almost perfectly with the scientist's work habits. The highest-performing scientists uniformly reported that taking time off from their vocational work was an essential strategy that they used to stimulate new ideas (i.e., they employed ACD as recreations that stimulated creation) whereas the lowest-performing scientists uniformly described time away from work as a "waste of time" (Root-Bernstein, et al., 1993, 1995). Third and finally, the highest performing scientists uniformly expressed the view that C. P. Snow's "two culture" gap was a fallacy that the best scientists bridged by being themselves artists, musicians and writers, while, once again, the lowest-performing scientists were equally certain that the "two culture" gap was real (Root-Bernstein, et al., 1995).

The most successful and innovative STEMM professionals not only engage in ACD avocations, they explicitly perceive these avocations as integral parts of a holistic approach to their professional lives. Such integration of skills and knowledge from diverse life experiences has been noted previously by several investigators attempting to understand the cognitive bases of creative ability. John Dewey noted that creative people universally constructed integrated "activity sets" that linked their apparently diverse interests (Dewey, 1934; King, 1996, 6-8, 52, 228-29, 259). Howard Gruber explained Darwin's amazingly integrative insights as resulting from integrated "networks of enterprise," in which every method and fact that he learned in each of the many disciplines he studied was linked to those he learned in every other (Gruber, 1989). Root-Bernstein has called this phenomenon "correlative talents" to emphasize that innovators must also discover the *functional relationships* between sets or networks of activity (Root-Bernstein, 1989, 313-315).

We are now ready to draw some pedagogical ramifications. Simply providing STEMM students with ACD training will, in all likelihood, be no more effective in improving STEMM education than the current system of college “distribution requirements.” *If students and teachers do not recognize some STEMM-derived need that ACD training can supply, or if they find ACD training unappealing or a waste of time, then not only will integration fail to occur, but negative lessons might well ensue!* Effective integration of ACD into STEMM education must therefore include explicit recognition of those interdisciplinary bridges that make ACD training functionally effective in STEMM contexts and personally valuable. The goal of ACD-STEMM integration must be the formulation of individualized integrated networks of enterprise, not merely the integration of artists or art lessons into science classrooms. We will return to this subject at the end of our second essay in evaluating the characteristics of the most successful pedagogical programs integrating ACD into STEMM education.

ACD-STEMM Connections Are Specific, Not General

In light of the many very specific and varied ways in which STEMM professionals have utilized ACD as adjuncts to their professional work, it becomes clear that an enlightened approach to integrating arts, crafts and design into STEMM education requires two things: 1) breaking down the specific types of skills or knowledge developed in any particular art, craft or design project and 2) ascertaining how these may overlap with skills and knowledge required in a STEMM subject. Hypotheses such as “arts will make STEMM professionals more creative” are too broad and amorphous to be testable or implementable. A more nuanced approach that examines specific types of bridges between ACD and STEMM subjects is required. For example, Ainsworth, et al. (2011) and Quillin and Thomas (2015) have both provided excellent analyses and summaries of research concerning the many ways that a single artistic process, in this case drawing, can be implemented within a STEMM context. A range of implementation types (from teacher-presented to teacher-produced to student-produced, with many variants in between) effect a range of learning outcomes. Drawing can be employed to improve the interpretation of visual information, to enhance motivation to study a STEMM subject, to elicit and train students’ mental models and model-based reasoning, to enhance observational skill, to connect concepts and ideas (e.g., through mental images or “mind maps”), to emphasize science as a process skill rather than as a set of facts, to display quantitative information and communicate it more effectively, to teach design principles for scientists, or to enhance visuo-spatial ability (references to formal studies in Quillin & Thomas, 2015).

While simply drawing for the sake of drawing can *potentially* provide transferrable skills appropriate to each of these goals (as we will demonstrate below), it should be obvious that specifically designing drawing lessons *for the purpose of developing one or a small subset of these goals* will be a far more effective pedagogical strategy. Skill and knowledge transfer are much more likely to occur when student and teacher both understand and are explicit about the purpose for which a lesson is being carried out. In addition, the use of an art or craft to achieve a particular pedagogical goal must be appropriate to that purpose. It makes no sense, for example, to use dance to try to improve the memorization of lists of scientific terms, to improve observational skill in the use of a microscope, or to model static scientific objects. Dance has no characteristics that make it appropriate for such uses. Dance can, however, help students model kinetic processes, transform such processes into equations, interpret how equations "behave," and communicate their understanding to others. Attention to specific and special characteristics of ACD and their formal understanding will be a necessary step in making ACD-STEMM integration work as effectively as possible for improving any particular STEMM educational outcome.

In sum, melding ACD with STEMM is not a mere matter of presenting the two together, or using ACD more clearly to explain a STEMM concept to students; rather, such melding must have some recognizable and explicit basis in the type of ACD being used to deliver a lesson and an explicit utility for the emerging STEMM professional in terms of skills, knowledge, concepts, structures, processes, methods, problems or aesthetic criteria. Equally important, the development of ACD-STEMM–integrated programs must recognize that different STEMM professionals use different ACD for different reasons. There can be no "one-size-fits-all" approach to ACD-STEMM integration; integration must, in the end, be not only discipline-appropriate, but also personally relevant.

The Futility of Distinguishing Between Near and Far Transfer

Finally, we would like to make a very brief but important comment on the on-going debate about near and far transfer that has bedeviled many discussions of whether ACD can usefully be integrated into STEMM learning. In brief, the issue is often framed as whether skill and knowledge transfer can successfully be achieved pedagogically between disciplines as apparently disparate as, say, mathematics and poetry or music and biology, as it clearly can be between closely related areas such as still life drawing and industrial drawing (e.g., Hetland & Winner, 2004). We believe that the evidence we have compiled above makes the entire near-far issue moot. STEMM professionals can almost always point to specific ways in which their ACD and STEMM practices connect: these are the twelve types of bridges that we describe above. These bridges are capable of linking any two subjects or disciplines when properly and appropriately built. Whether near or far, the bridge creates a link that draws the subjects together – to use an analogy from Madeline L'Engle's *A Wrinkle in Time* (1963), a bridge is like a "tesseract" that folds space and time to bring together that which was previously separated. The "folds" that are bridged may be very "near" in terms of disciplinary knowledge and practice (e.g., still-life drawing and industrial drawing) or very "far," such as observing in a fine arts class and observing in a chemistry lab. The point is this: bridges are not crossed simply by having science students make art, or mathematicians play music, and hoping that some universal sense of unity somehow results, but by revealing very limited and precise functional commonalities in methods, skills, knowledge, structures, and processes through the recognition of common patterns, analogies, practices, etc. Thus, when the Dana Foundation produced as part of its neuroscience series a study on the effect of arts training on general cognition, the report did not demonstrate any effects on general cognition, but rather found much more limited but quite significant lasting benefits from visual arts, music, and dance for very specific skills such as improved observation, pattern recognition, geometrical thinking and memory (or retention) across the curriculum (Gazzaniga, 2008).

There is an important lesson to be gleaned both from what STEMM professionals themselves say about the utility of ACD for their professional work and from studies such as that by the Dana Foundation. The more specific we can be about what the bridges are between any particular ACD activity and any STEMM learning objective, the more useful ACD-STEMM integration will be. This is not a novel conclusion, but rather one that is completely consistent with the view of Perkins and Salomon (1988; 1992a; 1992b), Burton, et al. (2000) and Schwartz, et al. (2005) that any kind of trans-disciplinary transfer requires that the expected outcomes be defined through pedagogical connections that are well-defined. The converse is also true; the less explicit the "bridges" are, the more futile it will be to put ACD and STEMM teachers in the same classrooms. This conclusion will be validated by the studies evaluated in the next two parts of our review, which focus on each of the twelve ACD/STEMM bridges described above.

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