AC 2011-1233: FOSTERING INNOVATION THROUGH THE INTEGRATION OF ENGINEERING AND LIBERAL EDUCATION

Cherrice Traver, Union College

Cherrice Traver received her BS in Physics from the State University of New York at Albany in 1982 and her PhD in Electrical Engineering from the University of Virginia in 1988. She has been a faculty member at Union College in the Electrical and Computer Engineering department since 1986, and has been the Dean of Engineering since 2005. Recently Dr. Traver has been involved in initiatives at the interface of engineering and the liberal arts. She has led two national symposia on Engineering and Liberal Education at Union College and she was General Chair for the 2008 Frontiers in Education conference. Her teaching interests are in the Computer Engineering area including Digital Design, Embedded Systems, and VLSI. She has co-taught international project courses in Turkey and in Spain. Her research has been focused on timing issues in digital systems. She has directed local and national outreach programs, including Robot Camp and the P. O. Pistilli Scholarship.

J. Douglass Klein, Union College

J. Douglass Klein is Dean of Interdisciplinary Studies and Special Programs and Kenneth B. Sharpe Professor of Economics at Union College. Klein joined the Union faculty in 1979, after earning a BA in Mathematics at Grinnell College, and a PhD in Economics at the University of Wisconsin, Madison. He has written on the economics of auctions, the measurement of economic efficiency, and the integration of engineering and liberal arts. As Dean, Klein oversees fifteen interdisciplinary programs which draw faculty from across the campus, including programs which integrate engineering and the liberal arts.

Borjana Mikic, Smith College

Dr. Borjana Mikic is the Rosemary Bradford Hewlett '40 Professor and Director of the Picker Engineering Program at Smith College, the nation's only ABET-accredited engineering program at an all women's College, where she teaches courses in Strength of Materials, Skeletal Biomechanics, Failure Analysis, and Introductory Engineering. Her scholarship in the area of Orthoapedic Bioengineering seeks to understand key factors that influence the establishment, maintenance, and restoration of biomechanical function in skeletal tissues such as tendon, ligament, and bone. Dr. Mikic has formerly served as the Director of the Sherrerd Center for Teaching and Learning at Smith College as well as the Chair of the Liberal Education Division of the ASEE.

Atsushi Akera, Rensselaer Polytechnic Institute

Atsushi Akera is Director of First Year Studies and Associate Professor of History in the Department of Science and Technology Studies at Rensselaer Polytechnic Institute. He has published Calculating a Natural World: Computers, Scientists and Engineers During the Rise of U.S. Cold War Research with MIT Press (2006), and is currently working on a book on the history of engineering education reform in the United States.

Author's Address: Rensselaer Polytechnic Institute, 110 8th Street, Troy, NY 12180. akeraa@rpi.edu.

Steven B. Shooter, Bucknell University

Steve Shooter is a Professor of Mechanical Engineering at Bucknell University where he has taught since 1995. At Bucknell he teaches the capstone senior design course, mechanical design, and mechatronics. His research interests involve information management for design and the design of mechatronic systems and products. Integral to this research is the exploration of approaches for the capture, storage and retrieval of product development information. He also explores techniques for enhancing innovation and leveraging assets in developing new products and systems. He is a registered Professional Engineer in the state of Pennsylvania and has been the PI on numerous projects with industry involving new product development and the design of production infrastructure. He is the co-author of "Foundations for Interoperability in Next-Generation Product Development Systems" that was recognized by ASME as one of the most influential papers in computers and information in engineering from 1980-2000. During the summer of 1997 and the year of 1998/99 he was a research faculty fellow at the National Institute of Standards and Technology (NIST) in the Design Engineering Technologies Group. Prior to graduate study he was a Process Engineer for Sony Corporation where he contributed to the start-up of their first compact disc manufacturing plant. He has consulted extensively with the Pennsylvania Small Business Development Center (SBDC) to assist entrepreneurs with new product development enterprises. He developed and implemented an award-winning product development process adopted by all 17 of the state SBDCs. During the academic year 2002/03 he was a Visiting Professor at the Swiss Federal Institute of Technology in Lausanne (EPFL). For 2008/09 he was a Visiting Research Scientist at the Florida Institute for Human and Machine Cognition. He has also participated in four NASA Bluesky workshops to explore solutions to far-reaching problems at NASA.

Ari W Epstein, Massachusetts Institute of Technology

ARI EPSTEIN is a lecturer in the MIT Terrascope program and the MIT Department of Civil and Environmental Engineering. He is particularly interested in team-oriented, project-based learning, and in bringing the kind of learning that takes place in "free-choice" or "informal" settings, such as museums, media and clubs, into more formal academic settings.

David Gillette, California Polytechnic State University, San Luis Obispo

Dr. David Gillette, Director, Liberal Arts & Engineering Studies, Colleges of Liberal Arts & Engineering. Has 20 years of multi-disciplinary collaborative team development expertise all focused on community development, documentation, educational outreach, and technology prototype development and testing. Past work has included project development for various educational and communications divisions of NASA, Universal Studios, and Disney Imagineering. Has over 16 years experience teaching undergraduate and graduate level students in technical communications, cross-disciplinary technology development and testing, and in media technology design and use for many universities in the USA, Japan and Australia.

Fostering Innovation and Entrepreneurship through the Integration of Engineering and Liberal Education

ABSTRACT: There is growing urgency to graduate more innovative engineers. This paper explores ways to foster the innovative capacity of undergraduate engineering students by challenging them with big questions, and introducing them to multiple perspectives.

Students today are inspired by big questions that matter, like the NAE Grand Challenges. Students are aided in finding innovative solutions to these big, open-ended, questions by having them learn to entertain and explore multiple perspectives. While the importance of integrative thinking is recognized in ABET's EC-2000 (e.g. criteria (c), (h) and (j)), and integrative approaches are known to appeal to women and other underrepresented groups, there is still far too little integration in the undergraduate engineering curriculum. The paper describes concrete examples of how to foster innovative and entrepreneurial capacity in engineering undergraduate students by harnessing the diverse and creative perspectives common to a liberal education.

We draw on curricular and extra-curricular examples developed by participants in the Symposium on Engineering and Liberal Education (E&LE). The Symposium was inaugurated in 2008 as a forum to explore the rationale and methods of E&LE integration. For three years, the Symposium has brought together academic leaders and scholars from both engineering and the liberal arts to explore models for integrating engineering and the traditional liberal arts.

The examples presented are grouped into five different aspects of undergraduate engineering education, addressing different phases of students' progress, recognizing that fostering innovation must be a continuous process:

1. Projects that focus on first year or introductory material
2. Projects that focus on core engineering courses
3. Projects that focus on capstone and extra-curricular experiences
4. Projects that span the curriculum
5. Faculty professional development to support projects

The paper also reviews research results linking innovative capacity to the development of integrative (divergent) thinking skills.

1. INTRODUCTION

This paper explores the theory and practice of the integration of engineering and liberal education (E&LE) to benefit the innovation and entrepreneurial capacities of engineering undergraduates. We suggest that the proposed integration will (a) build **innovation capacity** in students by making them comfortable in different learning styles, what we call "hybrid learning;" (b) prepare students to recognize different sources of potential value, and different individual leadership styles, both prerequisites to the creation of new **entrepreneurial ventures**; and (c) **inspire more students** to study engineering by engaging them early and often in important real-world problems, a method shown to appeal to students, and particularly groups traditionally underrepresented in engineering.

Authors of the paper have participated in the annual Symposium on Engineering and Liberal Education, which brings together academic leaders and scholars to explore different models for integrating engineering, technology and the traditional liberal arts.[121] Symposium participants are currently engaged in a variety of integrative activities from different stages in engineering education: first-year and introductory experiences; core engineering courses; capstone or extra-curricular projects; or full curricular initiatives. The Symposium intends to build on this network of like-minded partners, and begin to work with outside industry experts and professional organizations to address the innovation and entrepreneurship challenges.

Beginning in 2011, the Symposium will include an annual Integrate to Innovate Faculty Institute (i2iFI), at which faculty prepare to successfully provide students with integrative experiences. By showcasing successful integrative projects, the Symposium hopes to expand the impact of important work currently being carried out in isolation at member institutions and will build on and extend the Symposium's reach.

The Symposium and i2iFI will work toward **three goals**:

> **Products and Processes**: Develop demonstrated methods, processes, and educational materials for integrating engineering and liberal education at all stages of undergraduate engineering education that inspire more students to study STEM disciplines, and enhance student innovation and entrepreneurial capacities.
>
> **Network:** Grow a large network of educators, practitioners, and innovation experts who share a vision for developing innovative and entrepreneurial capacities by integrating engineering and liberal education.
>
> **Knowledge and Metrics:** Advance the knowledge of how to foster innovation and entrepreneurship in the context of undergraduate engineering education and develop effective assessment metrics and methods for evaluating major antecedents for innovation and entrepreneurship.

2. THE BENEFITS OF INTEGRATION

There are many calls to transform U.S. engineering education in order to face the challenges of the 21st Century.[7, 8, 10, 32, 39, 66, 79, 80, 81, 82, 83, 98, 110, 126] Currently, too much engineering education teaches students to solve set problems assigned to them as quickly and efficiently as possible. It succeeds, but at the expense of nurturing curiosity, divergent thinking, creativity, innovation, and entrepreneurial skills, and what we call hybrid learning. It kills creativity,[5, 28, 51, 72, 104, 107] and its divorce from "social value and relevance"[95] misses the opportunity to increase the number and diversity of students studying engineering.[60, 109]

The need for more creative and socially-aware engineers increases, while engineering educators feel compelled to pack ever more scientific and technical content into an already over-full curriculum. Although new criteria for breadth have been set,[1] and holistic solutions proposed,[21, 31, 44, 47, 109, 118] transformation has been slow at best.

We must stop thinking of engineering education as a zero-sum game. By that change in perspective, solutions follow. Engineering students can learn technical engineering content *simultaneously* – and more effectively – with other skills and content. Broadening the context in which technical content is learned can enhance the potential for innovation and entrepreneurial behavior. This new perspective ***integrates engineering and liberal education,*** rather than treating the two as separate educational components.

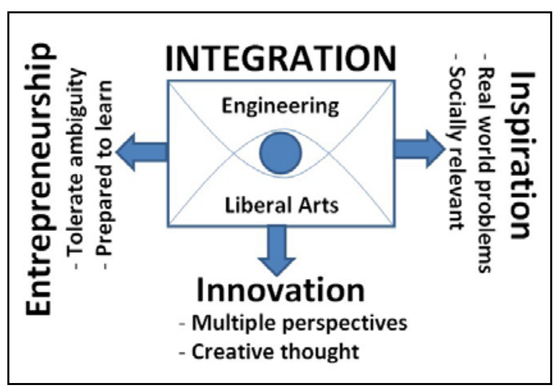
In spite of its power, the integrative perspective can not be legislated. Kuhn [68] observed that professionals do not easily change their ways of thinking. And yet, when evidence becomes overwhelming, eventually the perspective does shift. The integrative approach to engineering education supports the development of capacities associated with innovation and entrepreneurship, and models successful real-world innovation strategies.[7, 50, 53, 91, 115, 122]

In this paper, ***integration*** means activities involving people/ideas/methods/pedagogies drawn from both engineering and the liberal arts, and from inside and outside the academy. Both the professional education establishment,[1, 83, 84] and the liberal education establishment,[7, 69, 103] have suggested ending any historical distinction between "professional" and "liberal" education. The "real world" also agrees, as the demand for professionals and leaders with skills from a liberal education, is growing.[15, 30, 31, 55, 56, 57, 61, 115] Integration of E&LE fosters the capacities to access and apply information in different ways – skills that we refer to as "hybrid learning" – which are the antecedents to both innovative thought and entrepreneurial action.

As we define it, hybrid learning encompasses three factors. First, it represents a student's ability to comfortably navigate among a variety of learning styles, such as concrete experience vs. abstraction, or active experimentation vs. observation, by approaching new situations as learning opportunities and adopting from among a variety of cognitive and social tools for grasping and transforming experiences.[13, 74] Second, it represents a student's ability to recognize different forms of value creation, such as internal efficiencies vs. external opportunities, and adaptive flexibility vs. stable control, while subsequently and opportunistically acting on potential value-creating experiences.[19] Third, it represents a student's ability to recognize their individual leadership style -- creative vs. controlling, or cooperative vs. competitive -- the leadership styles in others, and the ways that the unique skills of individuals can be successfully organized into effective teams for leading innovation.[29]

In brief, integrating E&LE achieves the following:

a. Integration advances innovation
b. Integration grooms entrepreneurs
c. Integration increases inspiration



a. Integration advances Innovation

Innovation is novel insight stemming from unique and creative integration of diverse ideas. Innovation has both intellectual and social components because novel insight requires the individual to have both a thorough understanding of particular domains of knowledge,[124] and also an appreciation for the limitations of these domains and the ability to break free of disciplinary constraints and reconfigure one's own knowledge with the knowledge of others.[15, 33, 41, 107, 113] Thus, both domain knowledge and integrative experience are important antecedents of innovation.

One of the most powerful effects of E&LE integration is that of collective intelligence. Page[88] shows that in many situations calling for innovative solutions, *who* you know turns out to trump *what* you know, and Reich[93] has noted that in the modern world, successful new ventures require a team; what he refers to as "collective entrepreneurship." Leonard and Sensiper write, "Creative ideas do not arise spontaneously from the air but are born out of conscious, semiconscious, and unconscious mental sorting, grouping, matching, and melding. Moreover, interpersonal interactions at the conscious level stimulate and enhance these activities; interplay among individuals appears essential to the innovation process" [70] There is ample evidence of the power of intellectual diversity in spurring innovative ideas.[26, 37, 57, 59, 61, 88, 117]

An integrated curriculum can provide both the background skills needed for innovation and a supportive educational environment where it can flourish. Undergraduate education is the ideal time to sow the seeds of innovative behavior that generates novel ideas, and that will ultimately create value for society, especially when students have access to successful role models from outside academia.[23, 92] Students need both the domain-specific skills for mastering knowledge in certain areas as well as the integrative and social skills for combining their knowledge with that of others in hybrid learning formats. Companies like IBM and IDEO refer to people with both domain-specific and integrative skills as "T-shaped" people,[31, 61] and find them key to the innovation process.

b. Integration grooms entrepreneurs

Entrepreneurship is the ability to marshal resources in order to realize an idea or cluster of ideas that creates value for a stated stakeholder set. As Schumpeter[106] explained, entrepreneurs exploit new inventions or ideas, or they find new ways to exploit existing ones. Entrepreneurs are able to successfully change established routines by orienting people and markets to produce new forms of value. Entrepreneurship is a complex social process that is not limited to the sole notion of creating a business start-up but includes putting knowledge and innovation into action in any field of human endeavor, an idea underlying much of the recent effort to promote entrepreneurship education.[52, 116, 125]

Characteristics of successful entrepreneurs include comfort with ambiguity, tolerance for risk and uncertainty, critical thinking skills, holistic thinking skills, open-mindedness, outstanding communication skills, analytical skills, and vision. In addition, entrepreneurs need to be internally motivated, passionate and persistent, and driven by possibility. [100, 101] As engineering students work on complex real-world problems, and grapple with the social and cultural issues common in the liberal arts, they learn to tolerate ambiguity, and understand better the need to always learn from new situations.

This list follows quite closely the learning outcomes expected of liberally educated students,[50, 52, 103, 108, 115, 116] and help explain the enthusiasm with which entrepreneurship education is growing in all corners of the academy. Lemann sums up the value of exposure to liberal education on the part of professionally oriented students as follows: "The essential paradox of liberal education is that by being evidently impractical, it equips a student for life far more richly and completely, and across a far wider expanse of time and space, than does education whose sole aim is to be useful." [69, p. 14] Whatever the form of value that the entrepreneur seeks to create, the capacities to become entrepreneurial are enhanced in students by the integration of E&LE. The integration enables students to match technical capacities with social contexts and opportunities. Blending of engineering and liberal education not only provides students with the ability to articulate complex ideas to a wider audience, but more importantly to identify new opportunities.

c. Integration increases inspiration

Students are inspired by real, important, complex problems, more than by "plug-and-chug" exercises. Realistic problems not only attract more students, but result in greater motivation and more time on task. Engaged students learn more and retain more of what they study.[5, 123] Problem-Based Learning, Challenge-Based Learning, and other sorts of integrative learning activities motivate and engage students. Studies show that students respond positively in motivation and retention when given realistic problems or challenges.[12, 21, 58, 64, 74, 78, 114, 119 123] It is exactly these real, complex, socially relevant problems that graduates need to be prepared to address.

At Smith College, for example, students in the Computer Supported Intentional Learning Environment (CSILE) known as Knowledge Forum, work collaboratively to improve their collective understanding of the problem of explanation that they themselves have identified as being of interest, a key feature of intrinsic motivation. Students actively integrate knowledge from across numerous disciplines beyond engineering in their efforts to improve their understanding of the problem at hand.

A critical challenge in preparing the nation's future engineering leaders is to broaden the appeal of engineering among women and other under-represented groups. The integrative educational experiences have been documented to inspire those groups. Rhoten and Phirman,[95] review the evidence, and find, e.g., that "environmental engineering attracts more women than other fields of engineering because the former is seen as offering an integrated and interconnected approach that has 'social value and relevance' and results in work that has 'a positive impact on society.'" On Widnall's[127] top ten list of why women do not go into engineering, the number one reason is "lack of connection between engineering and the problems of our society." Schreuders,[105] concludes that women are more altruistic than men, and prefer to study subjects that deal with people than with things. There is much evidence that women and other underrepresented groups are disproportionately attracted to study interdisciplinary and socially relevant subjects.[9, 14, 40, 62, 90, 95, 105] The use of realistic though complex and socially relevant questions and problems, while appealing to these groups, works equally well in motivating all types of students.[58]

Making Change Feasible

We find wide-spread support for moving toward a more holistic, integrated engineering education through the integration of engineering and the liberal arts.[43, 46] Evidence suggests that this will attract and retain more (and more diverse) engineering students, and will develop their innovative and entrepreneurial talents. There is a long history of trying to broaden engineering education. Well before EC 2000[1] and the NAE Reports,[81, 82] some engineering educators were quite vocal about the necessity of expanding liberal education for the proper development of the engineering profession. Nevertheless, even the most thoughtful observers such as Florman[38] described effective E&LE integration as an "intractable problem."

The difficulties giving rise to this intractability have been stated repeatedly in the multiple ASEE studies of "humanistic-social" training in engineering.[6, 42, 48, 87] Difficulties cited include: lack of student engagement; curricular compaction in engineering, and the limited time available liberal arts (LA) subjects; engineering faculty who do not model and fully support the importance of LA; limited engagement of LA faculty; and poorly formulated objectives for the LA component of the curriculum.[2, 6, 34, 42, 73, 87]

In the past, obstacles have prevented transformation, and the work of Symposium participants seeks to avoid them.[22, 25, 67, 99] Previous attempts have focused within schools of engineering, and have sought to add content to the existing curriculum, raising both faculty and student resistance. For the most part, they have not been truly integrative. Nevertheless, a direction for future work is to better understand how to export successful "products" to other institutions, perhaps by gaining better understanding of the strengths and weaknesses of the approaches used by the Engineering Education Centers.[22]

The Symposium identifies existing **bright spots** in the academy, providing successful examples, led by committed faculty members, assisted by concerned external practitioners, that fit within existing educational structures, and that demonstrate that integrative learning is a positive-sum game.[102] Integration of the types described here avoid, for the most part, academic red tape by working within existing curricular structures. The goal is to foster collaborations of the willing, across disciplinary boundaries, and boundaries between academia and the outside world, leading students to experience the power and the joy of collectively tackling real, complex questions. Collectively, the examples presented here provide compelling and adaptable curricular prototypes of integrative experiences that lead students through different learning styles and prepare the next generation of innovators, entrepreneurs, and technology leaders.

We feel that the time is right for change.[67] There is a renewed urgency and vision,[7, 81, 82, 86] and early successes at individual schools and programs have begun to demonstrate the feasibility and the benefit of integration, and many have been showcased at the Symposium on E&LE.[63, 121] Next steps are to provide tools that empower more faculty to act, to create a national community of practice, and to demonstrate how the integration of E&LE elevates engineering students' capacities for innovative and entrepreneurial careers.

3. EXAMPLES OF INTEGRATION OF E&LE

Experiences and activities presented in this section all represent existing integrative activities. They illustrate ways to leverage expertise from non-engineering disciplines into important components of the engineering education spectrum. Study of these successful activities will lead to the insights and evidence needed to motivate adoption at other institutions.

The projects are organized into five groups: three that encompass standard phases of undergraduate engineering, one that includes full four-year curriculum projects, and one that builds faculty capacity to develop and teach using integrative activities. The projects address different parts of the undergraduate engineering education to systematically develop students' innovative capacities and entrepreneurial mindset. The outcomes of the projects are aligned with the ABET professional outcomes c, d, f, g, h, i, and j, providing meaningful ways to address those aspects of EC 2000 with which many programs typically struggle.

Many integrative projects can involve outside partners, including museum exhibit and game developers, entrepreneurs (alumni and local), IT professionals and venture philanthropists, radio producers, industry and engineering firms, musicians, professional instrument builders, design consultants, public agencies, hospitals, non-profit organizations, environmental groups, technology incubators and business and innovation associations. These partners can contribute to workshops and development work with faculty, evaluation of student work, guest lectures, and assessment and improvement of courses, and they will serve as project advisors and mentors, external advisory committee members for programs and courses, and customers for design courses.

As noted above, projects such as these are not without their challenges. Some of the projects cited have avoided red tape by working within existing course and program structures. Others have benefitted from external funding, and some have started as pilot projects by their representative institutions. The common thread is that the projects have been initiated and sustained by entrepreneurial faculty in both engineering and the liberal arts who are pursuing their passion for integrative learning.

The combined projects described below will impact approximately 4800 undergraduate students per year, supported by 38 faculty at 18 institutions. Each group of projects involves faculty from a range of institutions and disciplines, and implements integration using a variety of approaches. Linked by a common goal of improving hybrid learning through integration, this diverse community offers examples that can be applied to many types of engineering programs throughout the country.

a. First Year and Introductory Courses – Many efforts to improve engineering education and address attrition have focused on first-year courses and curriculum. Introductory courses that integrate engineering with science and math have been shown to improve retention, disciplinary learning, and transfer of non-disciplinary skills.[40] We argue that further integration with liberal arts disciplines and a focus on complex, socio-technical problems will develop capacities for innovative solutions that involve diverse stakeholders. The pilot projects in this group integrate engineering and liberal arts topics, and in some cases students and faculty, and direct the student's attention to the "problem formulation" phase of design. They challenge students to develop innovative and ethical approaches to complex, wide-ranging problems.

By deliberately keeping the challenges broad, and asking students to consider each problem from many perspectives, these projects encourage students to develop a better understanding of engineering in context and the need for knowledge of other disciplines. Faculty from six institutions will work on introductory course projects. The mix of institutions, including three institutes of technology, two liberal arts colleges, and a large university, illustrate first year approaches on different class sizes, organizational structures, and student populations.

University of Illinois Urbana-Champaign (Russ Korte): iEFX: Illinois Engineering Freshmen Experience provides engineering students with a broad interdisciplinary view of the field of engineering that emphasizes the remarkable place in society that engineers hold, fosters the continuous and rigorous development of intellectual skills and judgment, and emphasizes the critical importance of social connectedness and societal obligations.[65]

Macalester College (Diane Michelfelder), RIT (Wade Robison): Modules designed for generic introductory design courses (for both engineering and non-engineering students) that incorporate best practices for teaching engineering ethics in solving real-world design problems.[97]

MIT (Samuel Bowring, Ari Epstein): Terrascope: A project-based learning community open to all first-year MIT students in which participants address a single complex environmental problem that includes technical components, but that also requires expertise in the traditional liberal arts such as ethics, political science, economics, history, and art.[36, 71]

Olin College (Steve Gold): FBE: Foundations of Business and Entrepreneurship - an engineering course on entrepreneurial thinking based on a resource-driven or effectual thinking approach.

RPI (Atsushi Akera): IT & Society: A first year course for IT majors that enhances students' engagement and broadens their professional identification and development through a large scale social entrepreneurial simulation model.[3]

Union College (Jan Grigsby): An experiential and service learning course that engages liberal arts, science, and engineering students in addressing complex community problems whose solutions require input from multiple disciplines.[49]

Union College (Mark Walker): A course in the general education program that is required by students of all majors, team-taught by technical and liberal arts faculty, and assisted by an industry mentor to model and promote multidisciplinary collaboration and peer-based learning through research on real-world problems.[54]

In different ways, the first year and introductory courses all require engagement in multi-disciplinary learning, collaborative brainstorming and problem solving, and understanding the context of engineering and related disciplines. Research indicates[95] that the broader interdisciplinary view of engineering, as well as the emphasis on social connectedness and social good, appeals to many students, especially those in underrepresented groups, who typically become disillusioned in more traditional freshmen engineering programs. Industry partners, NGOs, and community partners will help to motivate the projects by bringing real-world problems into the classroom.

b. Core Engineering Courses – Bringing other disciplines to bear on courses in which the engineering science focus is predominant poses the biggest challenge to integration.[27] But as these courses form the majority of the engineering curriculum, integration in this area offers the greatest potential impact for developing an entrepreneurial mindset and the capacity to innovate. Without compromising the disciplinary knowledge base developed in the core engineering curriculum, projects that use liberal arts pedagogies, develop integrated modules, and redesign core courses to be integrative will promote a new awareness of "engineering in context" while supporting EC 2000 outcomes often left unaddressed within the core engineering curriculum. Faculty from seven institutions have focused on integration in core engineering courses. The institutions include five liberal arts universities and colleges, one small engineering college, and one public university. This group of mostly small institutions has the advantage of smaller barriers to integration between disciplines and is ideal for tackling the difficult core curricular area. Some have already partnered with large universities to transfer their approaches.

Hope College (John Krupczak): Innovators as Exemplars: Including entrepreneurs and engineers from industry in a required engineering seminar course to promote a culture of innovation through examples and connections to the liberal arts.

Olin College (Mark Somerville): A user-oriented collaborative engineering design course taught by faculty from diverse disciplines.

Rowan University (Linda Head): An electronic text with embedded Liberal Arts content packaged in modules for core disciplinary engineering courses

Smith College (Borjana Mikic, Susannah Howe, Glenn Ellis): Using Knowledge Building, an idea-centered pedagogy, via the Computer Supported Intentional Learning Environment (CSILE) to enhance integrative thinking and innovation in core engineering courses.[35]

Sweet Briar College (Hank Yochum, Scott Pierce), St. Ambrose Univ. (Jodi Prosise): Multidisciplinary faculty-student design teams in required courses work on increasing quality of life for people with physical/mental challenges utilizing project based learning with health practitioners.[89]

Union College (Palma Catravas, Dianne McMullen): A practical model for integrative study through project-based, coordinated learning activities between existing courses in engineering and the arts.[20]

Through connections to outside practitioners, design projects, contextual materials and liberal arts pedagogies, the projects in this group reveal for students the links between seemingly disparate ideas and theories. By reducing the isolation from context and other perspectives that is typical of core engineering courses, the engineering curriculum becomes more open and appealing to students. Most of these projects involve practitioners who provide further links to the outside world and ensure relevance of the material.

c. Upper-level Courses and Extra-Curricular Experiences – At the junior and senior year, students have sufficient disciplinary knowledge to engage in multi-disciplinary team projects that fully immerse them in the activities that can further develop hybrid learning. Capstone projects are where we see the results from engineering education research on project based learning and similar pedagogies most often applied,[120] but “multi-disciplinary” is still often bounded to STEM disciplines. By using complex real-world problems, and bringing students from a wider range of disciplines together to contribute significantly to project outcomes, faculty help engineering students see first hand that innovation requires creative applications of theories, perspectives and methods from beyond engineering. In the projects described here, teams consist of engineering and liberal arts students, and projects are focused on either entrepreneurial ventures or real community problems. Faculty from five institutions (Bucknell University, Cal Poly, Lafayette College, Smith College, and Union College) are working on these projects. The projects span the types of experiences typically found in engineering programs: capstone design projects, outreach projects, and projects linked to entrepreneurship courses.

Bucknell University (Mike Toole): Model for multi-disciplinary service-learning senior design projects that involve engineering and liberal arts students

Cal Poly (David Gillette, Lizabeth Schlemer): HO:ME Project - interdisciplinary team of Cal Poly students and faculty work with Housing Authority to create a housing/office/community complex.

Lafayette College (Sharon Jones): Engineering and liberal arts students collaborate with companies at the Ben Franklin Technology Partners on early-stage technology innovation and strategic technology adaptation projects. Podcasts of case studies are used in senior electives and capstone courses.

Smith College (Susannah Howe, Andrew Guswa): Engineering and liberal arts students collaborate on applied projects with real-world impact in partnership with local community organizations.

Union College (Hal Fried, Ron Bucinell): Engineering and liberal arts student form design teams based on engineering senior projects. Teams explore the potential for commercialization and social entrepreneurship, and participate in business plan competitions.[18]

The integrated approach to capstone and extracurricular projects requires students to understand different perspectives and apply them to solve complex problems. Students should also demonstrate interpersonal, leadership, and cross-disciplinary communication skills when they interact on diverse teams. Projects that focus on entrepreneurship require that students understand what it means to be an entrepreneur and develop experience and comfort with risk and uncertainty. Interaction with technology developers in incubators, with entrepreneurs, with community members as customers, and with real-world applications motivates students.

d. Programs that Span the Curriculum – While many reforms necessarily focus on existing engineering degree programs, wiping the slate clean and proposing entirely new programs is another model that should be studied for its potential to transform engineering education. Examples include existing prototype projects that result in engineering programs built around design, innovation, and Grand Challenge problems, multi-disciplinary learning communities, and integrated dual-majors. These projects integrate engineering and the liberal arts through a series of integrated courses and through learning community projects. There are three projects in this group at two institutions. (Arizona State, RPI) Both large institutions offer many engineering programs, and provide excellent test beds for studying these new approaches.

Arizona State (Thanassis Rikakis, Hari Sundaram, Aisling Kelliher): Creating organizing structure, pedagogy and tools for integrating diverse types of knowledge in curricula that are built on grand challenge problems.[96]

RPI (Dean Nieusma): A set of interdisciplinary, undergraduate courses and dual-degree options that span engineering, the humanities and social sciences, design disciplines, and management.[85]

RPI (Atsushi Akera): Enhancing student learning through a living learning community and campus-wide focus on energy resources and sustainability.[4]

Educational objectives of these programs include: “ability to understand societal needs and limitations; having this foundation as a source and inspiration for innovation” and “Increased satisfaction of industry with graduating students hired (students better prepared to work in teams to address real world problems).”

The programs represented in this group have been specifically designed to attract underrepresented students, with approaches such as offering trans-disciplinary courses, enrolling a gender-balanced set of students into the learning community, and using design studio techniques and real-world problem solving. New curricula projects involve industry as participants in projects and courses, to provide program proficiencies, and to provide stories of successful practitioners. Learning communities interface with non-profit organizations in their activities.

e. Faculty Development Projects – Faculty development has been cited as the most critical need for engineering education reform, especially in the area of design education.[120] We believe that the inclusion of faculty from other disciplines and external partners to combine engineering education research results with the broader academic, industrial and non-profit best practices helps to develop new attitudes, approaches, and skills. The five projects in the faculty development group contribute to the development of these skills at their home campuses.. Two of the projects will directly engage faculty from diverse disciplines on multi-disciplinary teaching endeavors, and two of the projects focus on the development of tools and materials to facilitate teaching integrated case studies. One of the projects will further develop the summer innovation workshops for faculty across disciplines. The institutions that are developing models for engaging faculty from many disciplines to develop teaching material include both small private colleges and a large university.

SUNY Binghamton (George Catalano): Faculty development and course modules for interdisciplinary teaching of ethical issues in the use and the management of societal and environmental resources.[11]

Bucknell Univ. (Steve Shooter): Summer innovation workshop for faculty across disciplines.[111]

Rowan Univ. (Linda Head): Course development tools for faculty to create interactive, multi-media case studies and scenarios

Smith College (Borjana Mikic, Andrew Guswa): Faculty learning communities for developing multi-disciplinary case studies involving problems requiring widely different areas of expertise.

Univ. of Georgia (Tim Foutz): Interdisciplinary faculty team to develop models for connecting the humanities with engineering; creation of learning modules to illustrate the integration principles

Faculty development projects aim to improve the skills needed for making connections between disciplines and from faculty’s primary discipline to innovation. Other goals require increasing faculty understanding of the value of cross-disciplinary collaboration, the power of reflection and other pedagogies used in the liberal arts. Examples of practical skills are recognizing opportunities for innovative curricular, co-curricular and/or civic activities, and using modern software to build case study scenarios. Several of the integrated project examples used in the faculty development work connect to the environmental and community issues that appeal to underrepresented groups of students. All of these projects include outside agencies, engineering firms, non-profit organizations, or individual engineers and other practitioners in their projects. Interactions with these individuals and organizations enhance the faculty development effort by providing practical content as well as examples of innovation.

The faculty development efforts will be presented in 2011 through workshops at the i2i Faculty Institute associated with the Symposium on E&LE, led by the faculty development group described above, with the following offerings:

- Fostering Integration: Faculty Learning Communities
- Pedagogies for Bridging the Engineering and Humanities Disciplines
- Reaching across the Disciplines: Facing the Ethical Issues of a Technologically Complex World

The workshops are distinctive in their emphasis on integrating faculty from disciplines in engineering and the liberal arts as well as external partners, and on preparing faculty to facilitate student projects that address complex and realistic challenges.

4. CONCLUSIONS AND IMPLICATIONS

The integrative approaches to engineering education outlined in this paper are designed to address the national need for an undergraduate engineering education that leads to more innovative and entrepreneurial engineering graduates, by a change in perspective. The integrative approach is key to meeting the need for more, and more innovative engineering graduates, and involves a shift from a self-contained (silo) mentality of engineering education, to a perspective that integrates engineering and liberal education. We see at least three ways that the integrative approach will improve engineering education, beyond the impacts on innovation and entrepreneurial potential, as discussed above. The integrative approach:

- changes engineering education in ways that women and other underrepresented groups find appealing
- enables engineering programs to more easily satisfy ABET's professional skills criteria, (a)-(k)
- raises the engagement and the technological literacy of non-engineering students.

Enhancing diversity in engineering: By happy coincidence, the same integrative approach to engineering education that prepares students to be more innovative and more entrepreneurial also attracts more students to study engineering, and most significantly, is shown to be more appealing to women and other under-represented groups. A by-product of integrating engineering and liberal education should be enhanced diversity among engineering students.

Satisfying (a)-(k): By incorporating integrative problems and solutions into different components of the traditional engineering curriculum (e.g., at the introductory level, the "core fundamentals" level, and the capstone design level) institutions will more easily be able to demonstrate that their students have achieved the ABET professional learning outcomes (a)-(k).

Eliminating the zero-sum mentality means it is possible to fit *more* content into the *same* time by teaching technical content in the context of a real-world problem with liberal arts (cultural, communications, socio-economic, ethical) content. This view could actually increase the number of courses with technical content for engineering students, and *at the same time* increase the number of courses with liberal arts content for engineering students, since the two arenas would not be treated as mutually exclusive.

Enhancing technological literacy: E&LE integration has the potential to have a significant impact on the rest of the nation's undergraduate educational system. As beneficial as integrative thinking and learning is to engineering students, it is equally beneficial to liberal arts and other students. The lowering of boundaries among the disciplines, and especially between engineering and the liberal arts fields, will be a huge win for the nation. The lack of technical awareness among leaders in the U.S. is shocking, and it is vastly more difficult to implement the kinds of integrative experiences we envision at the graduate level, where specialization is the watchword. It must take place in the undergraduate curriculum, and the benefits to innovation, entrepreneurship, and leadership will be felt well beyond the bounds of engineering education.

5. ACKNOWLEDGEMENTS

The authors are indebted to Peter Bacevice from Competing Values, LLC for developing the concept of hybrid learning as it is used here. They also wish to acknowledge the participation of the faculty listed in section 3 who contributed descriptions of their integrative activities and provided insights for this work.

Bibliography

1 ABET, Inc, 2009. "Criteria for Accrediting Engineering Programs: Effective for Evaluations during the 2010-2011 Accreditation Cycle," accessed 8/31/2010. <http://www.abet.org/forms.shtml>

2 Akera, Atsushi, 2010."A History of Engineering and Liberal Education (E&LE) Integration," unpublished literature review.

3 Akera, Atsushi, and Kim Fortun, 2005. "Introducing Humanistic Content to Information Technology Students," in A. Akera and W. Aspray, eds., *Using History to Teach Computer Science and Related Disciplines*, 61-84.

4 Akera, Atsushi, John Gowdy, and Prabhat Hajela, 2009. "Earth, Energy and Environment—the Vasudha Living & Learning Community @ Rensselaer," poster session, Union College, Symposium on Engineering and Liberal Education: Educating the Stewards of a Sustainable Future, (June), Schenectady, NY.

5 Amabile, Teresa M., 1998. "How to Kill Creativity," *Harvard Business Review* 76 (5), 76-87.

6 ASEE Committee for the Humanistic-Social Research Project (Burdell-Gullette Report), 1956. "General Education in Engineering," *Journal of Engineering Education* 46 (8), 619-749.

7 Association of American Colleges and Universities, 2002. *Greater Expectations: A New Vision for Learning as a Nation Goes to College*. Washington, DC: Association of American Colleges and Universities.

8 ———, 2004. *Taking Responsibility for the Quality of the Baccalaureate Degree*. Washington, D.C.: Association of American Colleges and Universities.

9 Atkinson, Robert D. and Merrilea Mayo, 2010. *Refueling the U.S. Innovation Economy: Fresh Approaches to STEM Education*. Washington, DC: The Information Technology Innovation Foundation.

10 Atman, Cynthia J., Sheri D. Sheppard, Jennifer Turns, Robin S. Adams, Lorraine N. Fleming, Reed Stevens, Ruth A. Streveler, et al., 2010. *Enabling Engineering Student Success: The Final Report for the Center for the Advancement of Engineering Education.* San Rafael, CA, Morgan & Claypool Publishers.

11 Baillie, Caroline and George D. Catalano, 2009. "Engineering and Society: Working Towards Social Justice," Parts I, II, and III, *Synthesis Lectures on Engineers, Technology and Society* 4 (1).

12 Beard, Colin and John Dover Wilson, 2006. *Experiential Learning: A Best Practice Handbook for Educators and Trainers*. London: Kogan Page.

13 Beckman, Sara L. and Michael Barry, 2009. "Innovation as a Learning Process: Embedding Design Thinking," *California Management Review* 50 (1), 25-56.

14 Beraud, Andrea, 2003. "A European Research on Women and Engineering Education (2001-2002)," *European Journal of Engineering Education* 28 (4), 435-451.

15 Bordogna, Joseph, 2004. "Capable Innovators and Innovative Capabilities," *The 4th Annual Leadership Initiative in Science Education: Partners in Innovation of the Chemical Heritage Foundation*, (May 21).

16 Brown, John Seely and Paul Duguid, 2000. *The Social Life of Information.* Cambridge, MA, Harvard Business Press.

17 Brownell, Jayne E. and Lynn E. Swaner, 2010. *Five High-Impact Practices: Research on Learning Outcomes, Completion, and Quality*. Washington, DC: Association of American Colleges and Universities.

18 Bucinell, Ronald W. and Harold O. Fried, 2009. “Engineering-Liberal Arts Entrepreneurship Seminar,” paper presented at 2009 NCIIA Conference, (March), Washington, DC.

19 Cameron, Kim S., Robert E. Quinn, Jeff DeGraff, and Anjan V. Thakor, 2006. *Competing Values Leadership: Creating Value in Organizations*. Northhampton, MA: Edward Elgar Publishing.

20 Catravas, Palmyra, Dianne McMullen, Tim Olsen, and Yu Chang, 2006. “Interdisciplinary Lightning: A Model for Networking Advanced Undergraduate Courses,” ASEE, St. Lawrence Section, Interdisciplinary Innovation and Imagination in Engineering Education, (November 17-18), Ithaca, NY.

21 Chubin, D., K. Donaldson, B. Olds, and L. Fleming, 2008. "Educating Generation Net-can U.S. Engineering Woo and Win the Competition for Talent?" *Journal of Engineering Education* 97 (3), 245-257.

22 Coleman, Robert J., 1996. “The Engineering Education Coalitions: A Progress Report,” *Prism* 6, 24-31.

23 Collins, Lorna A., Alison J. Smith, and Paul D. Hannon, 2006. "Applying a Synergistic Learning Approach in Entrepreneurship Education," *Management Learning* 37 (3), 335-354.

24 Competing Values LLC, 2009. "The Competing Values Assessment Overview," accessed November 11, <http://competingvalues.com/competingvalues.com/wp-content/uploads/2009/09/CV-Overview-16-page.pdf>

25 Cooperrider, Bryan, 2008. "The Importance of Divergent Thinking in Engineering Design," *Proceedings of the 2008 American Society for Engineering Education Pacific Southwest Annual Conference*, (March 27-28), Northern Arizona University, Flagstaff, AZ.

26 Council on Competitiveness, 2005. *Innovate America: National Innovation Initiative Summit and Report*. Washington, DC: Council on Competitiveness.

27 Crawley, Edward, Johan Malmqvist, Soren Ostlund, and Doris Brodeur, 2007. *Rethinking Engineering Education: The CDIO Approach*. New York: Springer.

28 Csikszentmihalyi, Mihaly, 1997. *Creativity: Flow and the Psychology of Discovery and Invention.* New York: Harper Perennial.

29 DeGraff, Jeff and Shawn Quinn, 2006. *Leading Innovation: How to Jump Start Your Organization's Growth Engine*. New York: McGraw-Hill.

30 Dickson, D. and R. Ford, 2010. "Founding a Science of Service: A Discussion with IBM's Jim Spohrer," *Journal of Applied Management and Entrepreneurship* 15 (3), 94-110.

31 Donofrio, Nicholas, Calline Sanchez, and Jim Spohrer, 2010. "Collaborative Innovation and Service Systems." Chap. Ch. 19, In *Holistic Engineering: Beyond Technology*, edited by Domenico Grasso and Melody Brown Burkins. New York: Springer, 243-269.

32 Duderstadt, James J., 2008. *Engineering for a Changing World: A Roadmap to the Future of Engineering Practice, Research, and Education*. Ann Arbor, MI: The Millennium Project, The University of Michigan.

33 Dym, Clive L., Alice M. Agogino, Ozgur Eris, Daniel D. Frey, and Larry J. Leifer, 2005. "Engineering Design Thinking, Teaching, and Learning," *Journal of Engineering Education* 94 (1), 103.

34 Edington, W. F. and E. J. Preville, 1974. "A Journey Toward Unity: A Candid Reminiscence of the Progress of Liberal Studies in the Engineering Curriculum," *Journal of Engineering Education* 63, 213-215.

35 Ellis, G. W., A. Rudnitsky, and M. Moriarty, 2010. "Using Knowledge Building to Support Deep Learning, Collaboration and Innovation in Engineering Education," *40th ASEE/IEEE Frontiers in Education Conference*, (October 27-30), Washington, DC.

36 Epstein, A. W., A. Lipson, R. Bras, and K. Hodges, 2006. "Terrascope: A Project-Based, Team-Oriented Freshman Learning Community with an Environmental/Earth System Focus," *Proceedings of the American Society for Engineering Education Annual Conference*, (June) Chicago, IL.

37 Fixson, S., 2009. "Teaching Innovation through Interdisciplinary Courses and Programmes in Product Design and Development: An Analysis at 16 US Schools," *Creativity and Innovation Management* 18 (3), 199-208.

38 Florman, Samuel C., 1987-88. "In Search of the Civilized Engineer," *Engineering Education* 78, 162-163.

39 Friedman, Thomas L., 2005. *The World is Flat: A Brief History of the Twenty-First Century*. New York: Farrar, Straus and Giroux.

40 Froyd, Jeffrey E. and Matthew W. Ohland, 2005. "Integrated Engineering Curricula," *Journal of Engineering Education* 94 (1), 147-164.

41 Gardner, Howard E., 1994. *Creating Minds: An Anatomy of Creativity as seen through the Lives of Freud, Einstein, Picasso, Stravinsky, Eliot, Graham, and Gandhi.* New York: Basic Books.

42 Gianniny, Jr,O. Allan, 1975. "Liberal Learning for the Engineer: An Evaluation Five Years Later," *Journal of Engineering Education* 65 (4), 301-324.

43 Goldberg, David E., 2009. "Engineering Rigor and its Discontents," *16th International Conference of the Society for Philosophy and Technology*, (July 8-10), University of Twente, Enschede, The Netherlands.

44 ———, 2006. *The Entrepreneurial Engineer*. Hoboken, NJ: Wiley.

45 ———, 2008. "What Engineers don't Learn and Why they don't Learn it: And how Philosophy might be Able to Help," *Abstracts of the 2008 Workshop on Philosophy and Engineering*, (November 10-12), London.

46 Grasso, Domenico and Melody Brown Burkins, eds. 2010. *Holistic Engineering Education: Beyond Technology*. New York: Springer.

47 Grasso, Domenico and David Martinelli, 2007. "Holistic Engineering," *The Chronicle of Higher Education*, (March 16), B8.

48 Gravander, Jerry W., 2004. "Toward the "Integrated Liberal Arts: Reconceptualizing the Role of the Liberal Arts in Engineering Education," *Humanities and Technology Review* 23, 1-18.

49 Grigsby, Janet P. 2009. "The Community Service Miniterm: An Effective Innovation in Service Learning." Annual meeting of the Society for the Study of Social Problems, (August 8), San Francisco, CA.

50 Gustafson, Jerry, 2009. "Entrepreneurship as a Liberal Art," in *Handbook of University-Wide Entrepreneurship Education*, edited by G. Page III West, Elizabeth Gatewood and Kelly G. Shaver. Cheltenham, UK: Edward Elgar Pub, 60-70.

51 Hendrick, J., 1984. "How I Overcame the Handicap of A College Education," In *Entrepreneurship: Text. Cases. & Notes.* Natick, MA: Lord Publishing.

52 Hines, Samuel M. Jr, 2008. *Creating the Entrepreneurial University to Support Liberal Education*. Washington, DC: Association of American Colleges and Universities.

53 ———, 2005. "The Practical Side of Liberal Education: An Overview of Liberal Education and Entrepreneurship," *Peer Review* 7 (3), 4-7.

54 IBM, 2010. "Smarter Planet," accessed 1/17/2011, <http://www.ibm.com/smarterplanet/us/en/>

55 IBM Institute for Business Value, 2010. "Inheriting a Complex World: Future Leaders Envision Sharing the Planet," accessed 12/7/2010, <http://www-935.ibm.com/services/us/ceo/ceostudy2010/futureleaders.html>

56 Ing, David, 2008. "Co-Evolving Innovations: T-Shaped Professionals, T-Shaped Skills, Hybrid Managers," accessed 11/29/2010, <http://coevolving.com/blogs/index.php/archive/t-shaped-professionals-t-shaped-skills-hybrid-managers/>

57 Johansson, Frans, 2004. *The Medici Effect: Breakthrough Insights at the Intersection of Ideas, Concepts, and Cultures*. Cambridge, MA: Harvard Business Press.

58 Johnson, Laurence F., Rachel S. Smith, J. Troy Smythe, and Rachel K. Varon, 2009. *Challenge-Based Learning: An Approach for our Time*. Austin, TX: The New Media Consortuim.

59 Johnson, Steven, 2010. *Where Good Ideas Come from: The Natural History of Innovation*. New York: Riverhead Hardcover.

60 Kazerounian, Kazem and Stephany Foley, 2007. "Barriers to Creativity in Engineering Education: A Study of Instructors and Students Perceptions," *Journal of Mechanical Design* 129, 761-768.

61 Kelley, Tom and Jonathan Littman, 2005. *The Ten Faces of Innovation*. New York: Doubleday.

62 Kilgore, Deborah, Ken Yasuhara, Jason Saleem, and Cynthia J. Atman, 2006. "What Brings Women to the Table? Female and Male Students' Perceptions of Ways of Thinking in Engineering Study and Practice," *Proceedings of the 36th ASEE/IEEE Frontiers in Education Conference*, (October 28-31), San Diego, CA.

63 Klein, J. Douglass, Cherrice Traver, John Krupczak, Ian Baker, Jennifer Stroud Rossman, and Andrew Guswa, 2010. "Engineering and Liberal Education," *American Association of Colleges and Universities Annual Conference*, (January) Washington, DC.

64 Kolb, Alice Y. and David A. Kolb, 2005. "Learning Styles and Learning Spaces: Enhancing Experiential Learning in Higher Education," *Academy of Management Learning and Education* 4 (2), 193-212.

65 Korte, Russell and David E. Goldberg, 2010. "Students as the Key to Unleashing Student Engagement: The Theory, Design, & Launch of a Scalable, Student-Run Learning Community at Illinois," *117th American Society for Engineering Education Annual Conference*, (June 20-23), Louisville, KY.

66 Koshland, Catherine P., 2010. "Liberal Arts and Engineering." Chap. 5, In *Holistic Engineering: Beyond Technology*, edited by Domenico Grasso and Melody Brown Burkins. New York: Springer, 53-67.

67 Kotter, John P., 1995. "Leading Change: Why Transformation Efforts Fail," *Harvard Business Review* 73 (2), 59-67.

68 Kuhn, Thomas S., 1996 (originally published 1962). *The Structure of Scientific Revolutions*. Chicago, IL: University Of Chicago Press.

69 Lemann, Nicholas, 2004. "Liberal Education & Professionals," *Liberal Education* 90 (2), 12.

70 Leonard, Dorothy and Sylvia Sensiper, 1998. "The Role of Tacit Knowledge in Group Innovation," *California Management Review* 40 (3), 112.

71 Lipson, A., A. W. Epstein, R. Bras, and K. Hodges, 2007. "Students' Perceptions of Terrascope, a Project-Based Freshman Learning Community," *Journal of Science Education and Technology* 16 (4), 349-364.

72 Lockhart, Paul, 2002. "A Mathematician's Lament," Mathematical Association of America accessed January 15, <http://www.maa.org/devlin/LockhartsLament.pdf>

73 Lyman, Frederic A., 2002. "Opening Engineering Students' Minds to Ideas Beyond Technology," *IEEE Technology and Society Magazine* 21 (3), 16-23.

74 Mainemelis, Charalampos, Richard E. Boyatzis, and David A. Kolb, 2002. "Learning Styles and Adaptive Flexibility: Testing Experiential Learning Theory," *Management Learning* 33 (1), 5-33.

75 Michelfelder, Diane, 2008. "Artes Liberales and Ethics for Engineers," Workshop on Philosophy and Engineering, The Royal Academy of Engineering, London, England.

76 Milillo, Frank, Cherrice Traver, and George Williams, 2001. "Effective Strategies for Change: Workshop on Implementing Curricular Change in Engineering Education," *Effective Strategies for Change: Workshop on Implementing Curricular Change in Engineering Education*, (Oct. 19-20), Union College, Schenectady, NY.

77 ———, 2000. "Preparing Engineers for the 21st Century: Workshop on Implementing Curricular Change in Engineering Education," *Preparing Engineers for the 21st Century: Workshop on Implementing Curricular Change in Engineering Education*, (Sept. 22-23), Union College, Schenectady, NY.

78 Moon, Jennifer A., 2004. *A Handbook of Reflective and Experiential Learning: Theory and Practice*. London: Routledge Falmer.

79 National Academies of Science, Engineering, and the National Institute of Medicine, 2010. *Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5*. Washington, DC: National Academies Press.

80 ———, 2007. *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*. Washington, DC: National Academies Press.

81 National Academy of Engineering, 2005. *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*. Washington, DC: National Academies Press.

82 ———, 2004. *The Engineer of 2020: Visions of Engineering in the New Century*. Washington, DC: National Academies Press.

83 ———, 2010. "Grand Challenges for Engineering," National Academy of Engineering, accessed August 26, 2010. <http://www.engineeringchallenges.org/cms/8996/9221.aspx>

84 National Science Foundation, 2010. "Science, Technology, Engineering, and Mathematics Talent Expansion Program Centers (STEP Centers)," National Science Foundation accessed August 29, 2010, <http://www.nsf.gov/pubs/2010/nsf10569/nsf10569.htm>

85 Nieusma, Dean. 2008. Integrating Technical, Social, and Aesthetic Analysis in the Product Design Studio: A Case Study and Model for a New Liberal Education for Engineers. Proceedings of the 2008 Annual Conference of the ASEE (June 26-28), Pittsburgh, PA.

86 OECD, 2010. *PISA 2009 Results: What Students Know and can do – Student Performance in Reading, Mathematics and Science*. Paris: Organization for Economic Cooperation and Development.

87 Olmstead, Sterling W., 1968. "Liberal Learning for the Engineer," *Journal of Engineering Education* 59 (4).

88 Page, Scott E., 2008. *The Difference: How the Power of Diversity Creates Better Groups, Firms, Schools, and Societies*. Princeton, NJ: Princeton University Press.

89 Pierce, Robert and Yochum, H., Engaging Engineering Students in a Design-Based Service Learning Course Emphasizing Connections between Technology and Society, Proceedings of the 2010 ASEE Annual Conference, (June), Louisville, KY.

90 Princeton University, 2004. "Engineering for a Better World: The Princeton Vision," Princeton University accessed January 9, 2011 <www.princeton.edu/~seasplan/PrincetonVision.pdf>

91 Ray, D., 1990. "Liberal Arts for Entrepreneurs," *Educational Theory and Practice* (Winter), 79-83.

92 Read, Stuart and Saras D. Sarasvathy, 2005. "Knowing what to do and Doing what You Know, Effectuation as a Form of Entrepreneurial Expertise," *Journal of Private Equity* 9 (1), 45-62.

93 Reich, Robert B., 1987. "Entrepreneurship Reconsidered: The Team as a Hero," *Harvard Business Review* 65 (3), 77-83.

94 Rhoten, Diana, Erin O'Conner, and Edward J. Hackett, 2009. "The Act of Collaborative Creation and the Art of Integrative Creativity: Originality, Disciplinarity and Interdisciplinarity," *Thesis Eleven* (96), 83-108.

95 Rhoten, Diana and Pfirman, Stephanie, 2007. "Women, Science and Interdisciplinary Ways of Working," Inside Higher Ed accessed 12/13/2010, <http://www.insidehighered.com/views/2007/10/22/rhoten>

96 Rikakis, Thanassis, 2009. "Innovative Faculty Evaluation Criteria for Incentivizing High-Impact Interdisciplinary Collaboration," *39th Frontiers in Education Conference*, (October), San Antonio, TX.

97 Robison, Wade, 2010. "Design Problems and Ethics." Chap. 17, In *Philosophy and Engineering: An Emerging Agenda*, edited by Ibo van de Poel and David E. Goldberg. Dordrecht: Springer, 205-214.

98 Rosen, Marc A., 2009. "Engineering Education: Future Trends and Advances," *Proceedings of the 6th WSEAS International Conference on ENGINEERING EDUCATION*, Rodos Island, Greece, July 22-24, 2009.

99 Rugarcia, Armando, Richard M. Felder, Donald R. Woods, and James E. Stice, 2000. "The Future of Engineering Education: I. A Vision for a New Century," *Chemical Engineering Education* 34 (1), 16-25.

100 Sarasvathy, Saras D., 2001. "Causation and Effectuation: Toward a Theoretical Shift from Economic Inevitability to Entrepreneurial Contingency," *Academy of Management Review* 26 (2), 243-263.

101 Sarasvathy, Saras D., N. Dew, R. Vellamuri, and S. Venkataraman, 2005. "Three Views of Entrepreneurial Opportunity." In *Handbook of Entrepreneurship Research: An Interdisciplinary Survey and Introduction*, edited by D. B. Audritch and Z. J. Acs. New York, NY: Springer, 141-160.

102 Scheessele, Michael R., 2007. "The Two Cultures: A Zero-Sum Game?" *Forum on Public Policy Online* 2007 (1), 1-27.

103 Schneider, Carol Geary, 2004. "President's Message: Liberal Education and the Professions," *Liberal Education* 90 (2), 2.

104 Schön, Donald A., 1990. *Educating the Reflective Practitioner: Toward a New Design for Teaching and Learning in the Professions*. San Francisco: Jossey-Bass.

105 Schreuders, P. D., S. E. Mannon, and B. Rutherford, 2009. "Pipeline Or Personal Preference: Women in Engineering," *European Journal of Engineering Education* 34 (1), 97-112.

106 Schumpeter, Joseph A., 1950. *Capitalism, Socialism and Democracy*. New York: Harper and Row.

107 Schwartz, David L., John D. Bransford, and David Sears, 2005. "Efficiency and Innovation in Transfer," in *Transfer of Learning: Research and Perspectives*, edited by Jose P. Mestre. Charlotte, NC: Information Age, 1-51.

108 Shaver, Kelly G., 2009. "Balsamic Vinaigrette: Entrepreneurship in the Arts and Sciences." In *Handbook of University-Wide Entrepreneurship Education*, edited by G. Page III West, Elizabeth Gatewood and Kelly G. Shaver: Edward Elgar Pub, 137-145.

109 Sheppard, Sheri D., Kelly Macatangay, Anne Colby, and William M. Sullivan, 2008. *Educating Engineers: Designing for the Future of the Field.* San Francisco: Jossey-Bass.

110 Sheppard, Sheri D., James W. Pellegrino, and Barbara M. Olds, 2008. "On Becoming a 21st Century Engineer," *Journal of Engineering Education.* 97 (3), 231-234.

111 Shooter, Steven B., 2010. "MacGyver Curriculum: Creativity, Innovation and the Engineering Design Process," accessed January 15, 2011, <http://www.bucknell.edu/x65344.xml>

112 Simonton, Dean Keith, 2000. "Creativity: Cognitive, Personal, Developmental, and Social Aspects," *American Psychologist* 55 (1), 151-158.

113 ———, 1983. "Formal Education, Eminence, and Dogmatism: The Curvilinear Relationship," *Journal of Creative Behavior* 17 (3), 149-162.

114 Smith, Karl A., Sheri D. Sheppard, David W. Johnson, and Roger T. Johnson, 2005. "Pedagogies of Engagement: Classroom-Based Practices," *Journal of Engineering Education* 94 (1), 87.

115 Smith, Roger B., 1986. "The Liberal Arts and the Arts of Management." Chapter 2, In *Educating Managers: Executive Effectiveness through Liberal Learning*, edited by Joseph Shackford Johnston. San Francisco: Jossey-Bass, 21-33.

116 Thorp, Holden and Buck Goldstein, 2010. *Engines of Innovation: The Entrepreneurial University in the Twenty-First Century*. Chapel Hill, NC: The University of North Carolina Press.

117 Thursby, Marie, Anne W. Fuller, and Jerry Thursby, 2009. "An Integrated Approach to Educating Professionals for Careers in Innovation," *Academy of Management Learning & Education* 8 (3), 389-405.

118 Traver, Cherrice and J. Douglass Klein, 2010. "Integration of Engineering and the Liberal Arts: A Two-Way Street," *Proceedings of the 2010 ASEE Annual Conference and Exposition*, (June 21-23), Louisville, KY.

119 Tsang, E., ed., 2000. *Projects that matter: concepts and models for service-learning in engineering.* Washington, DC: American Association for Higher Education.

120 Turns, Jennifer, Monica Cardella, Cynthia J. Atman, Josh Martin, Joshua Newman, and Robin S. Adams, 2006. "Tackling the Research-to-Teaching Challenge in Engineering Design Education: Making the Invisible Visible," *International Journal of Engineering Education* 22 (3), 598-608.

121 Union College, 2008-2010. "Proceedings of the Symposium on Engineering and Liberal Education," accessed August 31, 2010, <http://www.union.edu/integration>

122 Useem, Michael, 1986. "What the Research shows." Chapter 2, In *Educating Managers: Executive Effectiveness through Liberal Learning*, ed by Joseph Shackford Johnston. San Francisco: Jossey Bass, 70-101.

123 Vanasupa, Linda, Jonathan Stolk, Trevor Harding, and Richard Savage, 2007. "A Systemic Model of Development: Strategically Enhancing Students' Cognitive, Psychomotor, Affective and Social Development," *Proceedings of the Inaugural International Conference on Research in Engineering Education*, (June 22-24) Honolulu, HI.

124 Von Krogh, Georg, Kazuo Ichijo, and Ikujiro Nonaka, 2000. *Enabling Knowledge Creation: How to Unlock the Mystery of Tacit Knowledge and Release the Power of Innovation.* New York: Oxford University Press, USA.

125 West, G. Page III, Elizabeth Gatewood, and Kelly G. Shaver, eds. 2009. *Handbook of University-Wide Entrepreneurship Education.* Cheltenham, UK: Edward Elgar Pub.

126 White House, Office of the Press Secretary, 2010. “President Obama Expands “Educate to Innovate” Campaign for Excellence in Science, Technology, Engineering, and Mathematics (STEM) Education,” accessed January 4, 2011, < http://www.whitehouse.gov/the-press-office/president-obama-expands-educate-innovate-campaign-excellence-science-technology-eng >

127 Widnall, Sheila E., 2000. "Digits of Pi: Barriers and Enablers for Women in Engineering," *The Bridge* 30 (3/4), 14-18.

128 Wisnioski, M., 2009. "Liberal Education has Failed": Reading Like an Engineer in 1960s America," *Technology and Culture* 50 (4), 753-782.