Engineering Education for the 21st Century-Balancing Engineering Science, Information Technology and Multidisciplinary Studies

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Abstract

Educating engineers for success in the 21st century workforce will require continually adapting the curriculum subject matter to reflect relevancies to public and corporate stakeholders. The planet's population is growing to unprecedented levels and making vital resources even scarcer. For decades after World War II engineering education tended to focus primarily on engineering science or physics using reductionist analytics. The less mathematical sciences of design, synthesis, systems, organization and planning became relatively minor parts of an undergraduate's studies. In the latter 20th century, the end of the cold war, the IT revolution and new understandings about the affordability and benefits of manned space travel tended to redirect earlier 20th century research. Engineering research continues to increase in corporate laboratories where the focus is on developing tangible products and services to satisfy the more immediate needs of humankind. Research grants to universities are not likely to command as great of proportion of national income in the 21st century as in earlier years. Future engineers must be able to work on a variety of pressing and difficult problems such as innovation subject to severe resource constraints. Moreover, attracting students to engineering will require an inspiring vision of the prospect for exciting engineering work such as the space program provided. The nation's new problems will require undergraduate engineers to acquire complementary skills and perspectives of multiple disciplines that more explicitly recognize the practical importance of the human element *and* technical innovation. Engineers in the 21st century will face unprecedented global change and rate of change in technology, economics and social institutions. To meet these challenges, recently referred to by the NAE as a *gathering storm*, engineering education will need to embed more technology and *soft* skills into traditional science-based engineering courses *without* reducing practical STEM content and rigor. Engineering faculty will need also to create and develop challenging new multidisciplinary courses that embed engineering science and technology within the context of experiential learning and practice. This paper examines the need for and ways to integrate engineering science, information technology and multidisciplinary work. We describe how we have used the University's Honors Program to provide students with experiential learning in integrating the knowledge and perspectives of their discipline with that of others in the design and development of a virtual product.

Introduction

In recent years many leaders from corporate America and academia alike have called for undergraduate engineering curriculums that integrate more multidisciplinary experiential learning within the context of real world situations. Such innovation in engineering education while maintaining its traditional rigor presents many challenges. These interrelated challenges include the following: (1) Critical STEM competencies and professional licensing capability must be imparted in a traditional four year program of study. (2) Lecture based courses are more efficient. (3) Many faculty perceive the analytical, math-intensive courses in engineering science to have higher prestige. (4) Individual learning assessment in experiential, project-based courses is less objective and the supporting assessment pedagogies for engineers are not well developed. (5) Fewer faculty have experience and training in teaching multidisciplinary design courses. (6) The last two years of engineering studies tend to be strongly compartmentalized within the discipline specific departments. Notwithstanding these and other challenges, the nation's need for competitive and sustainable innovation in an era of unprecedented resource scarcity justifies a more concerted effort among engineering faculty to develop and teach multidisciplinary engineering courses involving experiential learning. The courses need to challenge students to think critically and deeply about complex and ill-structured problems. Students need to learn the meaning and importance of framing for solution facilitation; i.e. to ask the right questions. Lastly, students need to learn how to work outside their comfort zone in situations where they must maintain the patience, initiative and focus necessary for practical and timely solutions. For the 21st century, America needs engineers who better understand the dynamics and imperatives of innovation and wealth creation. Future engineers need to be able to analyze and design complex systems that are sustainable and can compete in the global economy. Significantly, engineering schools themselves must innovate and engineer a delicate balance among traditional engineering science, information technology and multidisciplinary studies.

Background

For the last 150 years American engineers have been crucial to the nation's security and prosperity. Inventiveness, ingenuity and innovation have been the historical hallmarks of the American engineer. However, several authors and leaders have seen a slow drift in engineering education away from its traditional moorings in design, inventiveness and innovation [Simon, 1996, Tribus, 1999]. Specifically, there has been concern about the increasing emphasis on mathematical analysis and abstractions to the detriment of concrete design, synthesis and the multidisciplinary perspectives needed in practice. This concern is not a totally new concern, but the intensity of the concern seems to have increased substantially. The reasons thought to be responsible for the evolution of engineering towards evermore mathematically-based science involve complex interactions between engineering research and the general culture of research. Other contributing factors include the 1955 Grinter Report, the cold war, the implicit criteria for government grants and the exponential growth of computing and information technologies [Engineering Education Reprint, 1955]. Herbert A. Simon noted that for several decades following WWII that the engineering schools increasingly became schools of physics and mathematics. Topics were selected from the natural sciences and those associated

with the "science of the artificial" or design were marginalized or subsumed under analysis. Simon made a cogent point that the basic cause was cultural as the engineering schools "hankered after academic respectability" [Simon, 1996]. The reason may have also been financial. With the advent of the U.S. space program really big budget research emerged. Grant proposals that included sophisticated mathematical analysis had more scientific cache and attracted a larger share of the government grants. The alternative for engineering schools was to look like the "trade schools" of yesteryear and lose potential funding. Initially, advances in computing technology reinforced the trend towards increased analysis because Ph.D.s could now solve many of those complicated partial differential equations. Ultimately, computing and communications technologies were applied to the problems of design, yet commercial interests and proprietary file formats impede progress even to this day [Prawel, 2011].

The important discipline of systems engineering emerged as defense and space systems of unprecedented complexity needed to be affordable, safe, reliable and delivered on time [BSTJ, 1962]. Systems engineering, as practiced, was strongly inter/multidisciplinary and better assured the timely delivery of a system with unified purpose. In the 1980s, leaders of the American quality revolution recognized that multidisciplinary concurrent engineering teams were needed to solve the quality problems of both product design and manufacturing. One such team of co-located technical professionals at the author's company, Bell Telephone Laboratories, worked together for more than 20 years to help realized the nation's high speed optical communications infrastructure. The development teams were collocated to foster the face-to-face shared communication and synergistic perspectives required for innovation. This approach was deemed necessary as graduate engineers did not have the needed perspectives across multiple disciplines. Today similar diverse teams are used to design, develop, manufacture and deploy complex products and systems. Notwithstanding decades-long ubiquitous use of systems engineering and cross functional team-based engineering of products in industry, formal education in the systems approach and how to work effectively in the cross-functional team environment has not found its way into the undergraduate curriculum. Lastly, the end of the cold war coupled with a rise in the global economy has lead to incipient commoditization of some engineering and technical skills and intense competition.

The Role of Engineering Science

Engineering science, underpinned by mathematics, will remain a fundamental and dominant part of the engineer's education. The 20th century has been rightly called the century of science because science and its offspring, engineering and technology, fueled the engines of economic growth and progress from beginning to end. Unfortunately, it also fueled the engines of war, pollution, scarcity and ultimately 911. Relativity, the quantum theory, atomic energy, the transistor, the double helix, the computer, the laser and the internet; these scientific breakthroughs literally transformed everyday life and many professions. Arguably, all became commercial realities by a science-based engineering education. Engineering educators have served the needs of the nation admirably for many years and the initial the focus on engineering sciences was salutary. For undergraduates, a less salutary and unintended consequence was the gradual marginalization of general design, planning and organizational skills as well as hands-on experimentation and interpersonal skills. Some universities developed engineering technology programs in response to help address expressed needs of industry and many now have ABET accreditation of programs' rigor.

Lewontin has pointed out that all sciences tend to be driven by dominant metaphors, which are used to connect and direct different areas and modes of inquiry [Lewontin, 1963]. Many years of textbook problem solving is the paradigm of education in the traditional sciences. Engineering education seems also to have evolved around the metaphor of *problem solving*. Textbook problem solving for engineers, although a vital part of teaching and learning, strongly resemble Kuhn's concept of *puzzle solving* of normal science. Kuhn's famous paradigm essay points out that the method of normal science and perhaps normal engineering focuses on *puzzle solving* [Kuhn, 1962]. Problems in engineering textbooks are a bit like puzzles. That is, these problems are *designed* to be solved because typically all the pieces will fit together in only one way. Moreover, if we have the final picture (like the required answer) any remaining pieces of the puzzle can usually be made to neatly fall into place, much like a jigsaw or crossword puzzle. If one could solve these puzzles they were said to be *ingenious*. But engineering problem solving in practice differs from textbook problem solving because real world problems are not very puzzle-like. They are not predesigned to be solved; if anything the very opposite is the case. The few pieces one may have do not fit together so well, many pieces may be optional and there is no final picture in the mind's eye to fill in the blanks. The practicing engineer not infrequently has to construct new pieces on the fly to achieve a fit with the rest of the pieces. And in today's complex systems, engineers' must often design an interface. Most quality problems and product failures occur at interfaces and few engineering students get training in interface engineering. Thus, our real world problems are said to be ill-structured and open-ended. The foregoing analogy between the engineer's textbook problems and puzzles is not complete however. Indeed, there is an undeniable benefit of textbook problem solving and it correlates well to an engineer's on-the-job technical, if not managerial, successes. Textbook problem solving can serve as a surrogate predictor of crucial elements of technical success—tenacity, perseverance, and extended focus on a goal, even in the face of failure, until one wrests a solution from nature. In the world of the design engineer, an on-paper design has an element in common with an end-of-chapter puzzle. It most always has

a solution in theory. The practicing engineer's "anomalies" first emerge when one first tries to make a physical prototype. The anomalies appear in even greater number when one tries to mass produce the design. The harshest anomaly occurs in the market when customers try to use the product or service and the supplier must turn a profit. Only an engineer's *ingenuity* can minimize and overcome these real world anomalies.

It is the author's opinion that, in its original sense, the engineer's *ingenuity* developed primarily through extensive *laboratory* experience; much like a physician or surgeon's ingenuity is developed in a clinical setting. In both instances one must deal with the holistic situation and not abstractions. The model of medical education for the physician is designed to be holistic early in medical school. Their first course is gross anatomy. Clinically based medical education is far more effective, if not very efficient, as one can surmise from the cost of medical school. Even though engineering educators do not have eight year programs, except for Ph.D. s, engineering education might still profit some from the context of medical education, which introduces clinical experiential learning early and continues throughout the program and into residency.

The abstractions and reductive nature of teaching engineering science are highly efficient in terms of the metrics of cost and time and are reasonably predictive of success in practice. In terms of its growing specialization and depth of focus on engineering science, engineering education may have become less effective for today's work environment and concerns about this have been growing since the mid to late 1970's. Engineering educators will not know if they can better satisfy the nation's current needs without some level of structured innovation in engineering education. A directed evolution of engineering science in the undergraduate experience seems to be more appropriate than a revolution from the ground up. There seems to be no compelling need to reduce engineers' education in the fundamentals of engineering science. However, perhaps we could teach more than just the textbook puzzle-problems in traditional engineering science courses. Creating problems that start from a local physical embodiment could provide a more holistic situation and might be useful for better engaging students with physical reality. Secondly, increasing laboratory work might also be useful. Unfortunately, there seems to be a lower value placed on teaching laboratory courses as evidenced by these courses being frequently assigned to graduate assistants. Having experienced both analytical and experimental work, there is no doubt in the author's mind that analytical and deductive engineering courses take less time to teach and are easier to assess than their iterative and inductive counterparts. Those who have worked in engineering laboratories know well how difficult it can be to get stubborn observations to cooperate and agree reasonably well with our theoretical abstractions. Lastly, it might not be required to drill down quite as deeply for undergraduates.

The Role of Information Technology

As a result of the information revolution, information technology will play an essential and ever changing role in the education of engineers. Characterizing the role of IT, even for the traditional engineering disciplines, is difficult because not only is it continually evolving, but also because its use is highly variable both among the traditional disciplines and even within a single discipline. Notwithstanding these difficulties, the various engineering disciplines must try to leverage and balance the role of IT as it relates to their fundamental mission and to engineering science and multidisciplinary studies. Information technology enters an engineer's education in three ways. First, IT in the form of software and computers is used as a calculation and data visualization tool. Secondly, through global, mobile, broadband communications, IT has increased the scope and scale of knowledge management, data acquisition and communication almost beyond the imagination. Lastly, through distance learning, IT is directly influencing how teachers teach, how students learn, and how well teachers can assess that learning.

Through an ever growing number of commercial and open source software packages, IT provides calculation tools for solving textbook problems, and for modeling and simulation. Contemporary desktop software has bewildering functionalities. However, just because software enables us to do things in a course that formerly we could not does not mean that we should. One should be reminded that the engineers who helped put man on the moon were educated with slide rules. In fact, a slide rule was taken on Apollo 13 to the moon in 1970 [Smithsonian Air and Space Museum]. Learning to use complex commercial software can easily become time wasted, like the waste of overproduction in manufacturing that the Japanese so astutely recognized and avoided. Moreover, the visible time wasted in teaching the use of such software in the classroom may be the tip of the iceberg compared to the mouse work that engages students outside the classroom. The lost opportunity for deep thinking and personal dialog, like lost sales due to poor quality, is unknown and unknowable; but, it is not likely trivial and, it must be managed. Learning specialized software can also distract young minds from the extended focus and practice required to internalize important powerful physical concepts that students will use at some point in their career.

The author's experience is that many managers tend to distrust complex computer calculations that are not backed up with laboratory data. Simple models that robustly describe complex data and that have a mechanistic foundation and intuitive appeal are best for communicating with managers. Ironically, experience indicates that beyond a point the less complex models even tend to *predict* new complex data more accurately; and, the messier the data the better simple models perform. Simple models tend to be highly efficient and can provide up to an order of magnitude more economic value than just experimental data [Gauch, 1993]. Over reliance on deduction from theory or inductive empiricism can result in ambiguous, if not inaccurate, inference, representation and interpretation of results [Jackson, 2010]. Moreover, accurate physical property data and other parameters required for prediction or simulation are often the largest source of error.

It may well be that efficient and effective use of IT for communications and knowledge management will prove to be the most important for innovation. IT will enable engineers to communicate literally anywhere and anytime through multiple

media of voice, text and video and in ways we have yet to imagine. The innovation process is no stronger than its weakest link and that link is often the last link- the introduction of a new product or service to a large market of eager and able buyers. Ideally, the use of IT as a broad knowledge management and communication tool would be covered in undergraduate core classes in communications. Yet there is much room for teaching engineering students more about the emerging field of knowledge management. Examples include conducting a patent search, finding accurate and reliable physical property data, identifying and sourcing high quality components and equipment, and analyzing customer, supplier, and competitor information are all important.

The direct influence of IT on engineering education in the form of distance learning is becoming pervasive, but its use remains controversial and cumbersome for courses that require real time problem solving involving the physical sciences and mathematics. The use of IT to enable distance learning of engineering subjects has real advantages and disadvantages and one rarely hears well-reasoned balanced discourse that is free from bias. Commercial vendors clearly and understandably have a positive bias about their products suitability for use in any field of study. Web enabled education increases students' access to a college education and this makes it popular with legislators who also have been told of its *future* potential for cost reduction. Administrators see the potential for cost reduction as positive because they must address the concerns of legislators and the continually increasing cost per degree granted. Much of the real cost of IT for online education with time can become subsumed and hidden under general IT costs and it will be difficult to untangle for accurate estimation and management. A thorough activity based cost study might be enlightening. Administrators must also worry about losing students to other institutions, as the boundary between the traditional brick and mortar university and the rest of society becomes more diffuse.

Faculty tend to have a conservative bias against change in proven pedagogies to avoid any possibility of risk that might impair the quality of their students' education. Small impairments to the education of the population of new engineers can have serious consequences for a nation that must compete globally. There are also less altruistic reasons for conservatism because of the large amount of time it takes to prepare and maintain online course content relative to that of traditional classes. There is also time wasted in learning and relearning the stream of new course management tools, which promise to solve the limitations of existing course management systems. Another waste of time involves the serial nature of the interface for communicating with students about their assignments which is not experienced in a traditional classroom environment. Many, if not most, engineering faculty do not advocate the use of "PowerPoints" for teaching engineering analysis as it "chops-up" the learning experience into discontinuous frames, which inhibit students' complete visualization of the reasoning process. Moreover, pre-prepared solutions tend to give students a false impression of the difficulty of the problem solving process. Tablet PCs can be used for real time problem solving in distance learning classes, but the size of the frame presented to the students is still considerably less than that of a traditional whiteboard.

Course management system vendors have not responded as well to the needs of engineering, math and science faculty as seems to be technologically possible. Part of

the reason may be that vendors committed early on to a restricted course management system architecture, which may have been designed largely for asynchronous courses that use primarily text-based activities. In contrast, engineering students use traditional pencil and paper analyses that integrate sketches and equations with a little handwritten text. The Tablet PC helps solve this integration problem, but software is needed that better integrates with streaming applications for synchronous online delivery. Another reason for restricted functionality may be that the intellectual property rights have become highly fragmented among the various vendors and no single vendor can offer a complete system without infringing on the rights of a competitor. The multiple software packages that must be purchased to achieve complete functionality are expensive, both in terms of the first cost and the time to use and to maintain them. Another concern is the scale and scope problem, which involves the important distinction between a mere existence proof for a design and a design that is suitable for routine and profitable "mass production". Course designs that can be made to work once or once every 2 years because of extraordinary teacher effort may be unsustainable for offering every semester with multiple sections per semester. Lastly, will industry leaders value engineering programs that are taught predominantly online the same as they do for traditional engineering degrees? One can expect that over time most of these issues will be resolved.

In summary, IT will form an increasing and important part of the engineer's education in the 21st century. The author believes that specialized commercial software packages will have the most limited role in engineering education. Distance learning will have an increasing and more important role, especially for access and for teaching graduate subjects to adult learners. The use of IT for knowledge management will grow in importance. The weakness in online teaching of engineering subjects is the serial human interface and the small screen size of the laptop. As information technology and its interface to humans improve and mature, IT can become a valuable part of engineering education. The limitations of distance learning are more likely to be overcome by the use of new and better hardware such as pen-based PCs and smarter whiteboards than by software alone. Engineering educators must continually and rigorously critique and adapt IT as it evolves so that it adds value to the students' education. IT should be demonstrated to enhance long term learning of engineering concepts, principles and problem solving skills. Ultimately, as for products in industry, the effectiveness of information technology for engineering education will determine the extent to which it will be used. America should continually conduct disinterested benchmark studies of our use of IT in engineering educations with other highly developed nations.

The Role of Multidisciplinary Studies

In the late 1980s, businesses noted that most value was created through a few cross-functional processes and not through their functional organizations. Thus, value was created through cross disciplinary or multidisciplinary processes. These value generating processes, for example, product innovation needed to be managed as a single entity through permanent multidisciplinary teams that were an orthogonal analog of the organization functional departments and disciplines. Significantly, companies discovered that the knowledge created by teams of interacting members can be greater than that which could be created by the individual members working alone. Moreover, the concurrent team approach helped to avoid local optimization. The new product development teams typically comprised engineers, IT specialists, patent attorneys, chemists, material scientists, marketing, finance and accounting, manufacturing, process analysts and lastly, customers, suppliers and other outside stakeholders. It became necessary for engineers to understand the paradigms, metaphors, perspectives, terminology and most importantly, the interfaces among the various disciplines with which they were required to integrate their technical work. Engineers needed new interpersonal, communication and negotiation skills to work in the new team environment and many companies provided that training. Engineers of the future need to experience working in a team-based environment at the university and not through many years of on the job osmosis. They also need to learn basic knowledge about the other disciplines with whom they will likely be required to work. Moreover, when the various disciplines are distributed over the globe, engineers must also learn how to function on teams in a multi-cultural context. Engineers, perhaps more than other professionals, need to improve their interpersonal skills. This will require more direct face-to-face interaction and collaboration with other disciplines than engineering students have traditionally had an opportunity to experience.

The call for increasing engineering students' exposure to multidisciplinary studies should not be misinterpreted to mean changing the fundamental knowledge that gives engineering and engineering technology their identity. Engineering and engineering technology will remain being defined by grounding students in mechanics, materials, thermal sciences and transport phenomena, electromagnetics, and in experimentation and laboratory technique. In addition, more multidisciplinary studies should be taken by students in all of the engineering disciplines. There is nothing intrinsic which make graduates in any one of the engineering disciplines better suited for interacting with customers, the general public or other cultures. The same holds true for managerial aptitude, whether in consulting, civil work, manufacturing or research and development.

The Honors Program for Teaching Students to work on Multidisciplinary Teams

As a first step, we have used our universities' Honors Program to teach students how to work better on multidisciplinary teams in a multicultural context. The vehicle is an honors course, titled "Bringing a New Product to Market from Concept to Launch" [Jackson and Reichert, 2010]. In this course students design, organize write, present and defend a launch plan for a virtual product. The virtual product is selected by the professor. Students are required to give brief project updates, maintain a journal, present their contribution and write a final report. These and peer evaluations count about 65 percent of their grade. Students learn the basic body of knowledge of the disciplines used in new product design and development. Quizzes and homework assignments on this material count about 35 percent of the final grade. Homework assignments are used to elaborate textbook principles and are designed to relate directly to students' virtual design project. The problem assigned may be one aspect of a problem that the university or community faces or expects to face, or it may involve both technology and intergenerational issues. Typical problems have included a cell phone for seniors, and a classroom environment to support pen-based Tablet PCs. Students learn through experience that although their own specialty may be necessary for success it is not sufficient.

Students are given extended experience planning, organizing, communicating, collaborating, integrating and coordinating their work because these are important navigation and competitive skills for students entering the workforce. Honor students tend to exercise a higher level of self-management and organizational skills and are often better prepared for the systems level thinking needed to attack ill-structured problems. Although they include those who are best prepared, they ironically often include students who can benefit most from experience in solving problems of the types encountered in the workplace. Honor students tend initially to discount the value of systems thinking, planning and organizing as just much "common sense", perhaps because it does not involve the relatively fast solving of the analytical puzzles at which they have traditionally excelled.

The course differs from capstone design courses in that the student teams come from diverse disciplines and cultures and the problems are more open ended. Yet these small differences can present unique challenges for students and professors alike. We try and balance the team composition across technical and nontechnical disciplines, gender and national origin. The professor teaches coaches and mentors. Instructors with experience in practice and in teaching are well suited for developing and teaching multidisciplinary design courses. Although the course has been received well by students, more work remains, including how to best design a course more suited to the general student population.

Conclusion

In the 20th century science became *democratized* and many technological disciplines including engineering appended the modifier, "science", to better describe themselves. Many engineering programs continually increased their focus on teaching engineering science and over time other important skills needed for workplace success and innovation became marginalized. Engineering includes science as it foundation, but it is much more. Engineering is a creative profession that is eminently practical and essential for innovation to solve contemporary problems and to promote societal progress. In the 21st century, the engineer's education will need to be extended beyond the traditional core and fundamentals of engineering science in order to help solve America's need for more innovation. The education of the engineer in the world of tomorrow will need to carefully balance engineering science, information technology and multidisciplinary studies. This will include how to use information technology more effectively to learn, and to manage knowledge. Engineers will need more exposure to learning experiences involving open ended problems requiring collaboration of diverse multidisciplinary teams. Addressing America's innovation concerns will also require engineering schools to innovate. At SPSU, we have used an honors course focused on bringing a new product to market to introduce students to working on diverse multidisciplinary teams and to learn the body of knowledge of new product design and development. The innovations that are being called for in engineering education may prove to be *disruptive* if only those universities who start new engineering schools are those who recognize and act on the challenges and the opportunities.

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