From the Ground Up: Rethinking Engineering Education for the 21st Century

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ABSTRACT: The engineering challenges of the 21st century will require leaders capable of addressing the Grand Challenges of our time: global security, health, sustainability, and the joy of living. In addition to solid preparation in traditional STEM[1] subjects, these leaders will need a deep understanding of non-technical issues surrounding technological invention to achieve the desired systems outcomes and avoid unintended consequences. The educational implications require preparing students early in their program for integrative systems thinking across academic disciplines, political boundaries, and time zones. Instead of continuing with the current natural science-centered foundation for a modern engineering education and attempting incremental change, perhaps it is time to start over and redefine engineering as a profession focused on innovation with the deliberate intention to change lives on this large scale. Such a change would require re-thinking the entire paradigm for engineering education.

In 1997, the F.W. Olin Foundation established Olin College for the specific purpose of inventing a new paradigm for engineering education that prepares students to become exemplary engineering innovators who recognize needs, design solutions, and engage in creative enterprises for the good of the world. With an investment of nearly a half billion dollars and ten years of experimentation, the evolving program at Olin College provides one answer to the question: how could you address the educational imperatives of the 21st century within a four-year undergraduate engineering program if you could literally start over—from the ground up? This paper discusses many of the fundamental issues encountered in this re-invention process, as well as some of the results of experimentation.

The Shift from Technologies to Solutions. The National Academy of Engineering recently published a list of the greatest engineering achievements of the 20th century[2]. These include such inventions as electrification, the automobile, the airplane, the radio and television, the computer, etc. Each of these inventions resulted in a large scale innovation that changed the way we live. A primary characteristic of such a major innovation is that people are largely unable to remember what life was like before the innovation took place. There is no doubt that the technological innovations of the 20th century changed lives on a global scale and produced enormous benefit for many millions of people. For example, the innovation of widely available clean drinking water in the U.S. is often regarded as a primary cause of the increase in life span of more than 30 years between 1900 and 2000[3].

There is a sense in which technology serves as a kind of amplifier of human behavior. In each successive generation, a smaller and smaller number of people is enabled to affect the lives of larger and larger numbers of other people through the application of technology. The effects may be intentional or unintentional, and they may be beneficial or they may not. The relentless development of new technology raises the stakes on social, economic, and political consequences in each generation.

As a result, these same technological innovations—which are the proud legacy of engineering—are also responsible for a many unintended consequences. In most cases the negative effects of these consequences are relatively small in comparison to the net benefit provided by the innovation, but when the innovation is applied on a very large scale even these relatively small negative effects can become substantial, and they do not affect all people in an equal manner. For example, the introduction of the automobile together with plentiful supplies of petroleum has contributed to the problem of a build-up of carbon in the atmosphere. Also, as mechanized agriculture has lowered the cost of food production and

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[1] Science, technology, engineering, and mathematics
[2] Constable, G., and Somerville, B. (2003) *A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives*, Washington, DC: Joseph Henry Press (an imprint of the National Academy Press).
[3] Because a relatively high proportion of the deaths in 1900 were the result of water-born infectious diseases.

helped prevent massive famine in developing countries (due to rapidly growing population in those countries), it has also contributed to growing levels of obesity among those living in poverty in the U.S.[4] Furthermore, the introduction of the Internet has provided transformational improvements in the ability to communicate across the globe with astounding convenience and low cost (the desired effect), but the resulting overwhelming choice of convenient sources of information has resulted in patterns of behavior where people often simply watch and listen to ideas and commentators with whom they already agree (an unintended consequence). These and many other unintended consequences—largely related to the collective human response to technological inventions—must be better anticipated and incorporated into the solutions to the Grand Challenges of the 21st century if we are to obtain desired outcomes across the globe. This raises an interesting question: whose responsibility is it to "engineer" these large scale human responses to technological advances?

The role of the engineer we envision is that of "systems architect"[5] of complex technical, social, economic, and political systems capable of addressing the global challenges we now face. Such engineers must be creative in conceiving, implementing, and managing the technologies that will shape our future. They must not only be applied scientists who are capable of predicting, creating, and developing the new science and technologies, but also organizational leaders and project managers capable of explaining complex socio-technical issues directly to the public, establishing trust through effective leadership, planning and implementation of integrated projects that deliver desired outcomes—not just products or devices—and do this on time and on budget. In short, they must be engineering innovators who produce innovations capable of transforming the way people live on the planet in ways that result in coherent and coordinated human behavior to address sustainability, health, security, and the joy of living.

Educational Imperatives of the Grand Challenges. The educational implications of producing such engineers are substantial. Not only must these engineers continue to possess exceptional proficiency in STEM subjects, but they must also have substantial new abilities. In particular, they must have a broad awareness of complex global issues, a passion or strong motivation to make a positive difference in the world in the largest sense, and a "can-do" attitude that is characteristic of the best "social entrepreneurs" and political or organizational leaders. These new attitudes, behaviors, and motivations are essential to the preparation of the engineers needed for the Grand Challenges.

The foundation for a broad and integrated education is awareness and interest in complex problems and the ability to communicate with experts across many disciplines. Without this foundation it is difficult to see how the broad education needed can be achieved. However, a cursory review of the structure of our current higher education system reveals that we may have created unnecessary obstacles to this communication through our efforts to provide specialization. It is imperative that we address these barriers to communication across disciplines as a first step toward providing a more integrated education for engineers.

For example, most children in the U.S. attend elementary and high school in public schools where the curriculum is relatively integrated across the full spectrum of academic disciplines. That is, specialization is limited and a high school diploma in the U.S. generally requires some proficiency in mathematics, natural science, social science, literature, the arts, etc. However, when students graduate from high school and go off to college, they are encouraged to select a specific discipline to major in, such as engineering or science, business or economics, English, history, psychology, sociology, political science, art, etc.

[4] Since the enormous increase in farming efficiency in the U.S. has produced extremely low costs per calorie of food produced, which contributed to the wide availability of low cost fast foods in poverty-ridden areas.
[5] Rechtin, E. (1990) ***Systems Architecting: Creating & Building Complex Systems***, NJ: Prentice Hall; and Rechtin, E. (1999) ***Systems Architecting of Organizations: Why Eagles Can't Swim***, CRC Press.

Students who choose to major in engineering and pursue an ABET[6] accredited program can expect to spend at least four years immersed in studies that are heavily dominated by STEM subjects. In fact, most ABET accredited engineering programs require that about 75% of the total credit hours for the B.S. degree be devoted to STEM subjects. As a result, it is not uncommon for engineering undergraduates to spend almost all of their time within the "engineering quad" on campus, surrounded by other engineering students. Three-fourths of all the faculty members they encounter and are influenced by are professors of STEM subjects. After four years of this immersion in the STEM culture, engineering graduates naturally acquire a certain bias in looking at the world.

One way of thinking about this general trend is that engineering students are immersed in a four-year study of the world through the lens of "***feasibility***." That is, the majority of their time is spent thinking and worrying about the feasibility of devices, systems, or processes—the extent to which such things are possible according to our current understanding of the laws of nature. Furthermore, they develop a specialized jargon for communicating with each other based on this view of the world, and the majority of their academic role models are engineering or science professors who are experts in assessing this aspect of human activity. When they graduate, there is a sense in which they have been (unintentionally) indoctrinated to view feasibility as the most important of all human concerns, and sometimes to view with skepticism (or worse) other disciplinary views of the world about which they have much less understanding.

On the other hand, if a high school graduate should choose to major in business instead of engineering, a similar immersion develops in the study of the "***viability***" of human activity. If he or she pursues an AACSB[7] accredited bachelors degree in business, then approximately one half of his or her total credit hours are spent studying economics, accounting, organizational behavior, management, and other subjects intended to prepare them for a career in the business world in which the focus is on whether an activity is capable of generating and sustaining financial resources. The lens here is that of the flow of finances and resources over time and the development of sustainable business activity. They often spend the majority of their time on campus confined to the "business quad" surrounded by other students and faculty members with similar interests and bias. They also develop a specialized jargon for communicating with each other based on this view of the world, and the majority of their academic role models are business or economics professors. As a result, they often leave college with a sense that viability is the most important of all human concerns.

Finally, if a high school graduate chooses instead to major in English literature, history, or art, for example, then he or she spends four years studying subjects that are often more widely varied and seldom focused on either feasibility or viability[8]. Instead, the primary focus of their study is often forms of creative and/or emotional human behavior. Understanding in non-quantitative terms the personal human interaction with the world is critically important, involving human motivations such as love, beauty, feeling, justice, and spiritual meaning. This focus is more often the subject of study in these liberal arts disciplines. Some fraction of the students in the liberal arts is concerned with "***desirability***," or what motivates and satisfies people in a range of circumstances. Their jargon and academic role models here are often chosen from these disciplines, resulting in the perception that this dimension is most important when assessing human activity, often with unintended skepticism toward other disciplinary views with which they are much less familiar.

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[6] ABET (formerly the Accreditation Board for Engineering and Technology) is the national accrediting agency for academic programs in many types of engineering and in computer science.

[7] The AACSB (Association for the Advancement of Collegiate Schools of Business) serves as the national accrediting agency for all academic programs in business.

[8] Regrettably, in the past few decades the general education requirements in many fine universities and liberal arts institutions seem to have been relaxed in the area of mathematics and natural science to the extent that these requirements may now often be satisfied either by Advanced Placement credit from high school or by subjects in college that are specifically aimed at non-majors in these fields. Furthermore, few liberal arts programs require significant exposure to the fields of engineering or business. As a result, the gap in understanding in these subjects between engineering or natural science majors and those in more general fields continues to widen, resulting in many unintended consequences such as barriers in communication and cooperation.

As a result, our educational system may unintentionally help create barriers to communication across disciplines, contributing to the perception that problems arrive with "labels" on them, announcing that they are either engineering problems, business problems, or more general motivational or societal problems. Of course, these labels are artificial, largely the result of our organizational structure in higher education. The result is an educational system which produces significant barriers to student awareness, interest in, and ability to address complex problems that require multidisciplinary approaches.

Innovation = Feasibility + Viability + Desirability. To fully appreciate the importance of these artificial barriers to communication and understanding, it is instructive to review some recent scholarship in the field of innovation. (After all, our ultimate goal is to produce engineering innovators.) When viewed analytically, large sustainable innovations—the kind that changes the world so profoundly that most people can't remember what the world was like before they were established—all have one thing in common. They all involve the simultaneous achievement of feasibility, viability, and desirability[9]. In this sense, innovation may be viewed as the intersection of the universe of things that are feasible, with those that are also viable, and with those that are simultaneously socially desirable. A Venn diagram is a natural way to envision this.

Without this insight, it is natural for engineers to imagine that innovation is just another name for the next new science or technology. But the majority of technologies or scientific discoveries are either not financially viable or are undesirable in the social marketplace. Only those technological systems that happen to also be viable and desirable have a real chance of becoming a sustainable major innovation. The other technological inventions eventually reveal themselves to be "just in case" ideas that may someday become stepping stones to other useful ideas, but often do not. The universe of all things that are feasible contains many, many more things that will <u>not</u> result in innovations than those that will[10].

Similarly, the universe of all things that are viable also contains many more things that are not feasible (cold fusion comes to mind) than those that are, and of course, the same is true for the universe of all things that are desirable (a cure for cancer comes to mind).

For the next generation of engineers to truly master the art and science of innovation, they must understand the fundamental importance of both viability and desirability, and they must develop a proficiency in addressing such needs in each project <u>from the beginning</u>. Perhaps the most practical approach is to learn to work together in teams with students from the other disciplines right from the start. If we wait until after they have completed a traditional four-year STEM-intensive education, it may well be too late. The results of our unintended indoctrination will have taken hold, like the hardening of wet cement around their feet. However, by intervening early and facilitating conversations across disciplines in each year of the academic program with both faculty and students who represent the world views of viability and desirability, we may substantially improve our ability to produce graduates who escape the perception that feasibility alone is the most important lens through which to view human activity. Deliberately creating an educational environment that includes regular exercises focused on complex issues with respected experts that represent different disciplines and points of view—in effect, deliberate intellectual collisions in the classroom—may be the most effective way to promote awareness, communication, understanding, and motivation for producing large scale innovations.

Multiple Intelligences and Creativity. Engineering is inherently a creative enterprise. While scientists ask "why?" engineers must ask "why not?" Engineers are responsible for imagining what has never been and then doing whatever it takes to bring these visions to reality. In this fundamental sense, "*to engineer*" is "*to make*."[11]

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[9] Weiss, L., *Developing Tangible Strategies*, <u>Design Management Journal</u>, Vol. 13, No. 1, pp. 33-38, Winter 2002.
[10] It is important to note that the observations on which things are feasible, viable, and desirable at any instant are prone to change over time, as new developments arise in these independent realms.
[11] It is interesting to note that the word "engineer" may be used either as a verb or as a noun, while the word "science" always refers to a noun.

Furthermore, the uncertainty about the future seems to be as great or greater today than it has ever been, in spite of the rapid growth of advanced knowledge. No one is able to predict what the future will hold in five years, not to mention in 50 years. For example, in spite of enormous professional attention on global financial affairs in many nations and in both government and private enterprise, no one was able to predict and avoid the global financial crisis of 2008-09 which took the world's many experts largely by surprise. Yet, we in higher education are responsible for preparing our students to successfully manage the challenges of the future. As a result, a good case could be made that creativity and adaptability are perhaps at least as important as knowledge in managing uncertainty, and our educational approach should reflect this through deliberate preparation of graduates in this important area[12].

However, it is surprising how little emphasis is placed on creativity within the standard engineering curriculum today. A cursory review of the titles of courses taught and required within most traditional engineering schools shows that a very small proportion include the word "design" and even fewer address creativity[13] in a deliberate way. Furthermore, many of the engineering design courses include very little discussion of creativity and the thought processes that underlie it. This is remarkable given the importance of creativity to the fundamental purpose of engineering.

Of course, engineering is not the only human endeavor with a responsibility for creativity and design. For example, art, architecture, music, creative writing, drama, cinematography, and other visual and performing arts require participants to begin with a blank sheet, imagine what has never been and then bring this vision to reality in ways that touch people's lives. Schools of design also specialize in preparing graduates to take on this role within certain domains.

A study of the methods used in these more artistic fields is instructive with regard to recognizing and cultivating creativity and inventiveness. To begin with, research in the cognitive sciences provides important insight in this area. The pioneering work of Howard Gardner led to the concept of "multiple intelligences."[14] His work and that of others that followed[15] lead to the conclusion by many that all humans have largely independent capacities for learning and achievement (intelligence) in many different areas, including, of course, linguistic and mathematical intelligence which is the central focus of most of higher education today, emphasizing symbolic representations of the world in words and numbers and manipulation of these symbols through the discipline of logic. However, all people also have independent creative intelligences manifest in such areas as visual/spatial reasoning (visual artists), music, and bodily/kinesthetic ability (as for example demonstrated by dancers, or professional athletes, or neurosurgeons). Finally, all people also have varying degrees of innate ability in interpersonal and intrapersonal intelligence, which is apparent in fields requiring teamwork, leadership, persuasion, and management.

It is important to note that except for the intelligences that involve symbolic representation and logic, ***experiential learning*** is fundamental to the learning pedagogy in the creative domain. Musicians cannot learn to perform music without spending a great deal of time actually making music through practice and performance[16]. Dancers cannot develop expertise by simply reading about and critiquing the work of others. Similarly, neurosurgeons do not become skilled through reading alone. They must learn through many hours of personal experience. Even poets learn that all important insights in life do not come from

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[12] Robinson, K. (2001) Out of our Minds: Learning To Be Creative, Capstone Publishing (a Wiley Co.).
[13] For the purpose of this discussion, it may be helpful to provide a definition of the terms creativity, inventiveness, and innovation: Creativity is the process of developing original ideas and insights. Inventiveness is the process of developing original ideas and insights that have value. Innovation is the process of developing original ideas and insights that have value, and then implementing them in ways that sustainably change the way many people live.
[14] Gardner, H. (1983; 1993) Frames of Mind: The Theory of Multiple Intelligences, NY: Basic Books.
[15] For example, Sternberg, R. (1984) Beyond IQ: A Triarchic Theory of Human of Intelligence, Cambridge University Press; Kaufman, J. C. and Sternberg, R. J. (2010) The Cambridge Handbook of Creativity, Cambridge University Press; Sternberg, R. J., Grigorenko, E. and Singer, J. L. (2004) Creativity: From Potential to Realization, American Psychological Association.
[16] Levitan, D. J. (2007) This Is Your Brain on Music: The Science of a Human Obsession, Plume/Penguin Books.

reading the work of others, but rather they often require intense introspection. To develop high proficiency in creative fields requires intense personal engagement, focused practice, and introspection[17]. Therefore, it is natural to expect that the production of engineering innovators would benefit from greater emphasis on experiential learning and creative design than exists in the current engineering curriculum.

Furthermore, an increased emphasis on experiential learning would likely provide other important benefits. For example, experiential learning—by its very nature—demands a high level of student engagement. It is not possible to learn passively when involved in experiential learning. Research in education[18] shows that students who are more engaged in their undergraduate studies are more likely to complete their program, to graduate, and to retain the knowledge gained in later years. The pedagogies of engagement therefore offer a number of important benefits in rethinking the educational process for engineers.

Olin College and the Effort to Create a New Paradigm for Undergraduate Engineering Education. In 1997, the F.W. Olin Foundation of New York announced its decision to end its decades-old grants program[19] that funded academic buildings on private university campuses and devote the remainder of its considerable resources to the establishment of an entirely new and independent residential college devoted to the undergraduate education of engineers[20]. The specific intent of the Foundation in establishing the College was to create a new paradigm for undergraduate engineering education that addresses all of the concerns that were known at the time about the need for change in this field. The decision to create a new independent institution followed a four-year period of consideration of several alternatives, including the creation of a college of engineering within a fine private university that did not already have an engineering program, and the consideration of funding an existing engineering school that appeared to already have an excellent educational program for engineers. The detailed story of the founding of Olin College is available in a recent publication.[21] This account includes some history of Mr. Olin, the legacy of the F.W. Olin Foundation, the early years in which the campus was constructed, the founding faculty, staff and students were recruited, and the innovative process by which the first curriculum was developed. It ends with the awarding of the first B.S. degrees at Olin College at the inaugural commencement ceremony in May 2006.

The need for change in engineering education was well known at the time of the founding of Olin College. The National Science Foundation (NSF) had recently concluded the Engineering Education Coalitions Program which they conducted through much of the 1990s and invested several tens of millions of dollars

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[17] A particularly vivid explanation of the role of experiential learning in developing expertise in these non-analytical areas is provided in the recent book by Daniel Coyle, (2009) The Talent Code: Greatness Isn't Born. It's Grown. Here's How. Bantam Books. In addition, recent research in brain plasticity provides important insights in the way experiential learning actually "re-wires" the brain and leads to more holistic understanding and ability, as explained in the recent book by Norman Doidge, M.D.(2007), The Brain that Changes Itself: Stories of Personal Triumph From the Frontiers of Brain Science, Penguin Books.

[18] Kuh, G. D. (2009). The National Survey of Student Engagement: Conceptual and empirical foundations, in R. Gonyea and G. Kuh (Eds), *Using student engagement data in institutional research, New Directions for Institutional Research,* No. 141, San Francisco: Jossey Bass; Astin, A.W. (1984). Student involvement: A developmental theory for higher education*, Journal of College Student Development*, 25(4), 297-308.; Kuh, G.D. (2001). Assessing what really matters to student learning: Inside the National Survey of Student Engagement. *Change*, 33(3), 10-17,66.; Kuh, G.D., Cruce, T.M., Shoup, R., Kinzie, J., & Gonyea, R.M. (2008). Unmasking the effects of student engagement on college grades and persistence. *Journal of Higher Education*, 79, 540-563.

[19] Over a period of approximately 50 years, the Foundation donated all the funds for the construction and furnishing of 78 buildings on 58 college and university campuses across the U.S. Recently, the F.W. Olin Foundation was dissolved, after transferring all of its remaining funds to the endowment of the Franklin W. Olin College of Engineering.

[20] Honan, William H, *$200 Million*, *Largest Gift Ever, Endows New Engineering College*, New York Times, Friday, June 6, 1997.

[21] Greis, Gloria Polizzotti, (2009) From the Ground Up: The Founding and Early History of the Franklin W. Olin College of Engineering, A Bold Experiment in Engineering Education, Needham, MA: Olin College.

in an effort to provoke systemic change in undergraduate education of engineers. ABET had independently committed to a sweeping revision of the accreditation process for engineering education in an effort to support these systemic changes. However, in spite of some notable successes on individual campuses and a greater awareness of the need for change, an independent assessment of the results of the NSF Coalitions program indicated that a truly systemic change had not been achieved, and results fell short of expectations.

More recently, the National Academy of Engineering published a report that reinforced the concerns about the need for systemic change, and identified specific areas that need to be strengthened in undergraduate engineering education.[22] These areas include the development of engineers with much higher levels of proficiency at teamwork, leadership, creativity and design, entrepreneurial thinking, ethical reasoning, and global contextual awareness. Since these areas are not closely related to traditional STEM subjects, they have been widely regarded as "soft skills" rather than critical knowledge and ability within faculties of engineering.

In 2009, Professor Woodie Flowers of MIT provided a keynote address[23] at the Engineer of the Future 2.0 Summit at Olin College in which he presented the results of a recent undergraduate thesis at MIT. In this thesis, a survey of nearly 700 recent MIT mechanical engineering graduates was conducted and analyzed. These results seemed to confirm the conclusions of the NAE publication[23] that engineering alumni report that the list of "soft skills" as defined above are, in general, more important to their professional career than the core technical subjects that they were required to take at MIT. Of course, MIT's educational program is widely regarded as among the best in the world and their graduates are highly sought after for the most attractive and challenging technical positions. As a result, it is reasonable to expect that engineering alumni of other institutions would respond in a similar manner.

When Olin's founding faculty (a group of about ten faculty members with diverse backgrounds, ranging from physics to engineering, math, chemistry, music, biology, etc.) were first assembled in a restored farm house on the perimeter of the campus construction site in the fall of 2000, they were told they had about two years to rethink the way undergraduate engineers are educated before Olin College would offer any courses. During this period, they would not teach courses or be responsible for competing for research grants in their field. Instead, they were to devote their full efforts to rethinking the way engineers are educated. This required consideration of what the future might hold and what role engineers would need to play. They focused on creating a learning model from the ground up that would result in producing the best possible engineers for the 21st century, as they saw it.

The Olin Foundation was keenly aware that the future is certain to hold surprises and the need for continual change in the field of engineering, so the principle of continuous improvement and innovation in the educational process was adopted from the start. No faculty members at Olin hold tenure, and nothing at Olin has tenure (except the Founding Precepts which were provided by the Foundation). The College also does not have departments that are organized by academic discipline, causing all faculty meetings to be inherently interdisciplinary and focused largely on the collective business of teaching and learning. As a result, nearly everything at Olin has an "expiration date," including the curriculum. The intent here is to anticipate the need for periodic re-invention and continued change and innovation in the future.[24]

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[22] National Academy of Engineering (2005) Educating the Engineer of 2020: Adapting Engineering Education to the New Century, Washington, DC: National Academies Press.

[23] Professor Woodie Flowers, (April 1, 2009) "*Man Who Waits for Roast Duck to Fly Into Mouth Must Wait a Very Long Time*," Engineer of the Future 2.0, keynote presentation at Summit on Transforming Engineering Education, Olin College (available on YouTube).

[24] Olin College has established a number of processes that help focus the entire community on assessment and continual improvement. These include an annual faculty retreat which is focused on the effectiveness of the curriculum; involvement of students in the assessment of nearly all aspects of the learning experience; approximately weekly faculty meetings that are always focused on educational and advising process, methods, and outcomes; etc. However, implementation of this principle has not been easy and has already presented a number of challenges that have resulted in aberrations in the intended regular calendar of renewal.

At a critical moment in the early fall of 2000, one of our founding faculty members raised a simple but profound question: "***What is an engineer?***" Also, "What does every engineer need to know? Don't we need to know this before we can develop the curriculum here?" In my approximately 25 years in engineering education to that point, no one had seriously raised this question in my presence. Obviously these are key questions that deserve very serious consideration.

We began by surveying the available definitions of engineering. Those of us with undergraduate degrees in engineering recognized that the majority of our education was devoted to the underlying applied sciences rather than the process of engineering. So, in this sense, engineering, as it is taught today, is dominated by the study of applied science. However, the Merriam-Webster Dictionary provides the following definition:

Engineer (noun): "a person who carries through an enterprise by skillful or artful contrivance"

It is interesting that this definition—presumably more representative of the general public's perception of engineers—does not even mention science, math, or technology (although it may be somewhat implicit). However, it does explicitly imply a degree of creativity or cleverness (*contrivance*), along with skill and art in the actual execution (*carries through*) of an "enterprise." One could even imagine that managing the process of establishing the enterprise may be part of this definition.

Discussions with corporate leaders often seemed to focus on the engineer in the role of project manager or product designer, where teamwork and leadership are of central importance, along with client relations, marketing and sales, budget management, time/schedule management, and integrity or quality of the final product. At the highest levels, corporate leaders sometimes refer to the engineer as the "systems architect"[5] who provides the overall vision and concept for the project and then insures its successful realization.

Perhaps because of the extensive use of the pedagogy of structured problem solving in a relentless stream of problem set after problem set in traditional core engineering courses, engineers sometimes think of themselves primarily as problem solvers. However, these problems are usually carefully framed in terms that facilitate the application of engineering sciences and mathematics to obtain specific answers. It is much less common for these problem sets to require students to begin with poorly defined but realistic situations involving many other non-technical aspects before identifying and framing the problem.

Perhaps the most basic definition of an engineer is "*one who makes*." This was the theme of the commencement address at Olin College in May of 2007, delivered by then-President Diana Chapman Walsh of Wellesley College. Her remarks identified engineers with the basic human need to "*make*", the same need for human expression and discovery that defines the arts.

In the first two years of invention of the academic program, the entire College followed a process[25] involving four deliberate steps: Discovery, Invention, Development, and Test. In the Discovery stage, we made a deliberate effort to learn best practices from other engineering institutions around the world. In particular, visits were made or hosted from about 35 other engineering schools and about 20 technology corporations. In the Invention phase, a small group of the founding faculty was assigned the responsibility to develop a proposal for the integrated Olin curriculum, for review, comment, and ratification by the entire community[26]. In the Development and Test phases, the founding faculty engaged in creating the specific educational methods and pedagogies for each aspect of the curriculum, often starting from scratch and developing original materials. Then, since these new methods and materials were untried, a special year of testing was undertaken (the **Olin Partner Year**) in which a group of 30 recent high school graduates (the **Olin Partners**) were recruited nationally to spend the 2001-02 academic year as partners with the faculty in testing the assumptions behind the new pedagogy and helping develop and refine the learning materials and approaches. The Olin Partners consisted of 15

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[25] *Invention 2000*, the first strategic plan for Olin College, available on the Olin College web site.
[26] This resulted in a very creative proposal which was presented in the form of a three-act play.

boys and 15 girls and they lived in temporary modular housing units on the soccer field while the campus was under construction.

During the Olin Partner Year, many unusual tests were performed. For example, we tested the hypothesis that young engineering students need about two years of preparation in calculus and physics before they are able to undertake the design and construction of a significant engineering device or system. In this experiment, we assigned five recent high school graduates—none of whom had any college courses—the task of designing and building a pulse oximeter, with a time limit of five weeks. In this exercise, the students were first referred to patent literature in the library for a basic schematic diagram and explanation of the purpose and function of the device. They were told that various faculty members may provide advice if asked and otherwise were expected to chart their own course to building the device. The five week time limit was envisioned as providing a convenient reason to end the experiment in the event that the students failed to complete the task, before a post-mortem could be performed.

However, we were surprised to find that the students did not fail as expected, but instead built a functioning device that performed well against a hospital version of the device brought in for calibration at the end of the experiment. We learned two things from this experiment. First, students are indeed capable of completing independent projects of this type with no formal preparation at all in science or math. However, we also observed that the pedagogical effects of this project on the students appeared to be profound. They experienced a sense of exhilaration at exceeding their own expectations and building a device that performed well. This "***can do attitude***" appears to be an important side effect of the pedagogy of unstructured design projects. It resulted in strong motivation and commitment to completing the educational program and becoming an engineer. From this experiment we developed the sense that, in general, (1) we may be significantly under-estimating the ability of students to learn independently, and (2) this type of student engagement can result in significant changes in attitudes, behaviors, and motivations which are an important outcome in themselves.

Olin College Overview in 2010. Olin College is an undergraduate residential college offering B.S. degrees in Engineering, Electrical and Computer Engineering, and Mechanical Engineering located in Needham, Massachusetts, a quiet and upscale residential suburb of Boston. The campus consists of about 75 acres and 400,000+ square feet of attractive new facilities located adjacent to Babson College, a private business college that is well-known for programs in entrepreneurship, and about two miles from Wellesley College, a highly selective liberal arts college for women. The current enrollment is about 330, with a student population that is about 45% women[27]. The student faculty ratio is about nine-to-one, with a permanent faculty of 36. The faculty at Olin all have Ph.D. degrees from the nation's top universities[28]. Olin College is committed to a vigorous program of intellectual vitality and has developed a consistent record of research expenditures of about $1 million per year, externally funded by federal agencies and private foundations.

Olin students may freely cross-enroll at no additional charge at neighboring Wellesley College, Babson College, or Brandeis University and about 1/3 of the student body is so enrolled each term. As a result of the Founding Precepts imposed upon the College by the F.W. Olin Foundation, Olin is <u>not</u> internally organized into academic departments and faculty members do not have tenure. Instead, faculty members are employed with renewable term contracts with a range of term lengths.

The Olin Foundation also directed the College to reward merit among students and to provide an excellent engineering education at little or no cost, independent of family resources. As a result, Olin

[27] This feature of Olin's student population is quite unusual since every student at Olin College must major in engineering and only about 18% of all undergraduate engineering majors in the U.S. are women.
[28] Eighty percent of Olin's Engineering faculty members have Ph.D.s from graduate programs in engineering rated in the top 10 by the U.S. News & World Report, and about 70% of all of Olin's faculty members have Ph.D.s from research universities rated in the top 20 by U.S. News & World Report.

currently provides every admitted student with an 8-semester 50% tuition scholarship based upon merit[29]. In addition, the College has a need-blind admission policy and provides full need-based aid to all admitted students. This support is made possible by a large endowment[30] which resulted almost entirely from gifts from the F.W. Olin Foundation before it dissolved. The academic quality of the Olin College student body is exceptional by every measure[31].

A particularly important aspect of Olin College is the precept requiring the College to devote itself to continuous improvement and innovation. As a result of this commitment, assessment and continuous improvement are deeply woven into the character and culture of the institution—so much so that nearly everything has an “expiration date.” This includes the Bylaws and even the curriculum[32]. Olin’s institutional commitment to continuous improvement and assessment was singled out for special recognition by the accreditation visiting team from the New England Association of Schools and Colleges (NEASC) in 2006[33].

As previously explained, Olin’s mission is to prepare engineering innovators. We believe that requires preparing graduates who are adept at creating new concepts and enterprises that are simultaneously feasible, viable, and desirable. This requires a learning model with a deep commitment to learning from fields well ***beyond technology***, and therefore including many topics that are at arm’s length from the center of gravity of the collective Olin faculty expertise. The basic strategy for achieving this integrated exposure is provided by building a strong collaboration with neighboring institutions. In particular, Olin students find a predominant focus on subjects related to feasibility on the Olin campus, a predominant focus on subjects related to viability on the Babson campus, and substantial opportunity to explore subjects related to desirability on the Wellesley campus, along with many other topics in the liberal arts and sciences. It is the intersection of these three campuses that provides the richest learning opportunities for future innovators.

Some Features of the Current Olin College Curriculum. The Olin College curriculum is continually evolving—by design. The current incarnation provides a snapshot of the best efforts of the Olin community to provide a new paradigm for engineering education. Some of the most striking features of the program are summarized below:

- *Candidates’ Weekend*: Admission to Olin requires all candidates to participate in one of several weekend interview events on campus each winter. Candidates are assigned to small teams and observed as they perform a design-build exercise[34] and develop a group presentation on a controversial topic unrelated to technology. Finally, candidates undergo individual interviews intended to explore the extent of multiple intelligences. Faculty, staff, students, and alumni participate on the evaluation teams and in the admission decisions.
- *Extensive Design Core*. Olin has rebalanced the emphasis throughout all degree programs by placing the design process on an equal footing with the applied sciences. Approximately 25% of all student credit hours are devoted to design subjects through the four-year program.
- *Corporate-sponsored Capstone Design Project (SCOPE).* All students must complete a year-long engineering design project in small teams with a corporate sponsor that provides $50,000 in

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[29] From the first entering class in the fall of 2002 until the class that entered in the fall of 2009, all students enrolled at Olin received a 100% tuition scholarship.
[30] The current value of the Olin College endowment is approximately $350 million, or more than $1 million/student. This places Olin among the 10 in the nation by this metric.
[31] The median combined SAT scores of Olin’s incoming students (M + V) is 1470, and on average, about 1/3 of the entering students are selected as National Merit Finalists each year.
[32] The curriculum currently expires every 7 years and must be actively review and either revised or reinstated.
[33] “*No other institution in the Team’s considerable collective experience is as committed as Olin College to assessing and reassessing its performance against the eleven standards of accreditation. Moreover, the results of these assessments are employed directly in improving institutional effectiveness in that performance.*” Quoted from the NEASC Visiting Team Report for Olin College, May 1, 2006, Dr. Jon C. Strauss, Chair of the Visiting Team, and then-President of Harvey Mudd College.
[34] Which is not evaluated.

support for each project. The projects require a corporate liaison engineer and often involve non-disclosure agreements and new product development.

- *Business and Entrepreneurship*. All Olin students must start and run a business for a semester in order to graduate.
- *EXPO*. At the end of each semester, every student is required to participate in the Olin EXPO in which every student must either participate in a lecture/presentation or a poster presentation for the entire campus community plus about 100 corporate and academic evaluators. The format is similar to that of a national technical meeting and feedback is provided to each student to improve communication skills.
- *Olin Self-Study*. Every student at Olin is required to complete an independent study/research project before graduation. This project requires the student to identify a question of interest, develop an individual learning program to find the answer, and obtain an expert assessment to make sure that the correct answer has been obtained[35].
- *AHS/E! Capstone Project*. Every student must complete a semester-long capstone project of their own design in either the arts, humanities, and social sciences (AHS) or in entrepreneurship (E!).
- *Study Away in Junior Year*. The Olin program was specifically designed so that any student can plan his/her academic program to study away in the junior year and still graduate in four years. Currently 25 - 30% of Olin students take advantage of this opportunity.
- *Summer Internships*. All Olin students are encouraged to pursue summer internships in technology companies or in university research laboratories, beginning at the end of the first year. Nearly all Olin students have done this at least once before graduation.
- *Nine Competencies Across All Four Years*. Olin requires every student to track his/her progress from year-to-year in each of nine independent competencies: quantitative analysis, qualitative analysis, teamwork, communication, life-long learning, contextual analysis, design, problem diagnosis, and opportunity assessment.

While many engineering programs offer some of the same kinds of opportunities, Olin requires all students to complete each of these components. This uniformity of student experience contributes to the unique learning culture that is largely responsible for the high levels of student engagement and independent learning. Other very important factors include the emphasis on intrinsic student motivation throughout the academic program.

It is this learning culture that is most important. The role of the faculty and curriculum is to create this special learning culture. Another institution might attempt to duplicate the Olin model by copying the specific courses and programs outlined above. However, unless the learning culture is duplicated, the results will not be the same[36].

Charles Vest, President of the National Academy of Engineering, has explained this point very well: *"Making universities and engineering schools exciting, creative, adventurous, rigorous, demanding, and empowering milieus is more important than specifying curricular details."*[37]

Reflections on Eight Years of Experience with the Olin Learning Model. Olin offered its first courses to freshman students in the Fall of 2002. Reflecting back on 16 semesters of experience with this program and 5 graduating classes, I would say that overall we are quite pleased with the results. In general, the students have exceeded our early expectations in their abilities as young engineers and

[35] This is an important aspect of our effort to teach students how to become independent and adaptive learners.
[36] For example, MIT has created a remarkable Open Course Ware (OCW) Project in which nearly 2,000 of their courses—including syllabi, reading assignments, exercises, exams, etc.—are available at no cost on their web site. However, another institution that attempts to implement these courses directly is unlikely to duplicate the MIT learning culture.
[37] Charles Vest, prepared remarks at Harvard University, September 20, 2007.

innovators. Furthermore, they are receiving excellent post-graduate opportunities[38] and the early feedback from employers and supervisors is that Olin alumni have distinguished themselves among their peers in various venues.

Qualitatively, we feel that the Olin learning model has resulted in intense student engagement in their education, increased motivation for learning, increased independence and autonomy, strong potential for leadership, strong interest in entrepreneurial endeavors, high levels of experience and proficiency in teamwork, and a striking ability to "stand and deliver", manage projects, and work with ill-structured problems.

The mission of Olin and its method of attracting faculty and staff have also resulted in a pervasive interest in and commitment to change in education among the faculty and staff.

On the other hand, we have some nagging concerns and worries at this point, including the possibility that Olin graduates—because of our intense focus on innovation in team-based projects—may display a slightly diminished long-term interest in purely theoretical subjects. A related concern is whether we have achieved the right balance in emphasis between design topics on the one hand, and advanced theoretical/analytical subjects on the other. Similarly we are concerned about the balance between qualitative and quantitative design subjects. The emphasis on entrepreneurial thought and action seems to have resulted in a slight preference for small start-up companies among our graduates. Answers to these questions cannot be obtained without objective data from longitudinal studies of our alumni. We are in the process of developing a set of metrics this year.

We are also concerned about the scalability of the learning model and the extent to which it may be influential in larger universities. To explore this important issue, Olin College entered into a partnership with the University of Illinois at Urbana-Champaign two years ago. The early results from this project are quite encouraging. Olin and Illinois faculty have been working side-by-side to develop parallel learning elements to several Olin courses and have implemented them in pilot courses at Illinois. The results have been sufficiently successful that Illinois plans to expand the project to include 300 students next fall.

Finally, since Olin College is no longer an early-stage start-up institution, I personally fear a growing resistance to change. This resistance is natural and part of the maturation of the institution. In the first year of the development of Olin's program I visited one of the only experienced academic leaders in the country to have personally led the effort to start a new undergraduate science and engineering college. His name is Joseph Platt, and he is the Founding President of Harvey Mudd College. Joe passed along a key observation from his experience at HMC: *"There is no more powerful force for conservatism, than having something to conserve!"* In the first years of Olin, we had nothing to conserve, but in just eight short years we have begun to believe that we have developed something special. As a result, there is a growing attitude on campus that we could lose a great deal if we make any big changes in our program.

Ultimately, our success as an institution devoted to innovation will be determined by our ability to remain open to change. The learning model that is best suited to today's world is unlikely to be optimal for the world of 10 or 20 years from now.

Student Engagement and Learning Outcomes. Olin College's pedagogical approach is distinctive, with more emphasis on pedagogies of engagement than most other engineering schools. In order to

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[38] For example, a survey of the alumni from 2006 – 2009 revealed that 99% are either employed or pursuing graduate study. Given that the national unemployment rate is currently above 10%, we consider this result to be excellent. In addition, this year's graduating class of about 85 students included three who won Fulbright Scholarships, three who won NSF doctoral fellowships (and another three who were selected for "honorable mention" for this award), and three who were accepted directly into Harvard Business School. About 35% of this year's graduating class went on to graduate school, with most of them pursuing graduate degrees in engineering or science from the top ten engineering schools in the U.S., although several are pursuing medicine, business, or law instead. Last December the first Olin alumnus completed a Ph.D.—in Physics from Oxford University; the second and third completed Ph.D.s from Columbia University and the University of California at Berkeley, respectively (in Mathematics Education and in Materials Science).

assess whether our learning model is producing any measurable difference in student learning outcomes, it is necessary to develop some objective methods of assessment. Perhaps the most direct method is to monitor the longitudinal career outcomes for our graduates. However, it is too early in our history for this approach since we have only five graduating classes at this stage.

An interesting indirect assessment is provided by the National Survey of Student Engagement (NSSE). This national assessment was developed at Indiana University[18] by researchers in education to measure the degree to which students are engaged in educational activities that correlate with favorable long-term learning outcomes. In general, the research indicates that the more students take responsibility for their own education, demonstrate enthusiasm and are engaged in their studies, the more they learn and the more they continue to learn independently. The NSSE survey involves confidential surveys of thousands of university students each year about their activities, attitudes, and experiences in their local learning environment. The questionnaire covers five major areas, including level of academic challenge, active and collaborative learning, student-faculty interaction, enriching educational experiences, and supportive campus environment. Each year the NSSE survey involves more than 500 colleges and universities nationwide, and about a half-million students. The results are now published annually by USA Today newspaper.

Olin College has participated in the NSSE survey each year for the last several years. The results indicate that our students are substantially more engaged in these positive learning outcomes that students at similar stages in their program at other universities. In fact, the overall results indicate that students at Olin College place above the 90^{th} percentile in nine out of ten of the indicators in the NSSE survey, in comparison with all colleges and universities that participated in the survey. When the data are normalized by subtracting the global mean and dividing by the global standard deviation, the results for Olin College range from about ½ to 2 standard deviations above the global mean values in each category. Results of this type have been obtained every year for the last several years.

While these results are only an indirect indicator, they are so consistent across all the metrics that it is difficult to avoid the conclusion that something unusual is happening within our program. We are anxious to explore the correlations between these NSSE results and the longitudinal measure of career outcomes for our graduates in future years. I suspect that other institutions that shift toward greater use of pedagogies of engagement will also experience an increase in their NSSE scores.