AC 2010-999: A 21ST CENTURY UNDERGRADUATE ENGINEERING EDUCATION PROGRAM

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Abstract

Engineering in the 20th Century was marked by a significant number of inventions that resulted in sweeping societal changes. The National Academy of Engineering proposes that the current century's major global engineering efforts will be focused on a number of societal benefits that need large scale systems approaches to resolve. The question this paper addresses is whether or not current undergraduate engineering education offers the appropriate educational content to prepare young engineers for this dramatic change in direction. Recommendations are discussed to make some of the necessary curriculum adjustments.

Background

At the beginning of March 2009, the authors attended a symposium held at Duke University that was sponsored by the Colleges of Engineering of Duke University, the University of Southern California and Olin College. The topic of the symposium was the academic announcement of the fourteen Engineering Grand Challenges identified by the National Academy of Engineering. The symposium was a two-day event with keynote speakers and panels discussing the grand challenges. Many engineering students were in attendance especially from the three sponsoring programs. Each panel session ended with input or questions from the audience. There may have been as many as 800 attendees and the symposium was quite interesting because of the diverse nature of the grand challenges. The breadth of topics placed the symposium at the opposite end of the spectrum of typical single topic engineering symposia or conferences. But what was the process that had led up to this symposium?

In 2006 the National Academy of Engineering started a project titled Grand Challenges for Engineering. The stated purpose of this National Academy of Engineering project[1] is

> In a fourteen-month project, the NAE will convene a select, international committee to evaluate ideas on the greatest challenges and opportunities for engineering. The committee will draw upon many sources of engineering expertise (including the NAE membership and foreign associates, the NAE's international Frontiers of Engineering program, and engineering societies worldwide) as well as ideas from the broader public.
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> The NAE committee will create a ranked list of the grand challenges and opportunities for engineering during the world's next few generations. It will also point to engineering or scientific research and innovation that look promising for addressing each challenge as well as suggest currently unmet research needs.

As a result of this project, fourteen engineering grand challenges were identified[2]

- Make solar energy more affordable

- Provide energy from fusion
- Develop carbon sequestration methods
- Manage the nitrogen cycle
- Provide access to clean water
- Restore and improve urban infrastructure
- Advance health informatics
- Engineer better medicines
- Prevent nuclear terror
- Secure cyberspace
- Reverse engineer the brain
- Enhance virtual reality
- Advanced personalized learning
- Engineer tools of scientific discovery

The first thing to note is that these fourteen engineering grand challenges are not U.S. centric. Challenges such as making solar energy more affordable, providing energy from nuclear fusion, developing carbon sequestration methods, managing the nitrogen cycle, providing access to clean water, restoring and improving urban infrastructure, advancing health informatics, engineering better medicines, preventing nuclear terror and securing cyberspace are world problems that need to be addressed by the creation of teams of international problem solvers from around the world.

In checking out the NAE website readers will notice that the NAE actually developed two lists: the first list consists of the greatest engineering achievements of the 20th Century as selected by the NAE members, and the second list enumerates what the Academy thinks are the engineering grand challenges for this, the 21st Century. As Lucky[3] states so succinctly,

> What strikes me now about the old (read: first) list is that, although each achievement resulted in sweeping societal changes, it began with an invention in the classic sense, made by a small number of inventors, that focused on solving a relatively narrow problem. Moreover, the invention itself was a discrete thing, as opposed to a large system or collection of ideas.

Examples of inventions that did this were the automobile, the airplane, the transistor, the telephone, the computer, the Internet, the laser, and others. Clearly, the 20th Century was the century of transportation and information/communications.

The second list turns this all upside down. Again as Lucky states, "An important social benefit is postulated and engineers are challenged to make an invention or more likely a system, that accomplishes the designated social upheaval." If we accept Lucky's observations, then the approach of engineering in the future will be markedly different from past practices. Engineering's future will be defined by large global problems seeking solutions instead of small-scale solutions growing into larger-scale global applications. What might this mean for undergraduate engineering education? This was the question that the authors discussed after their return from the Engineering Grand Challenges Symposium.

Response

The authors were motivated by the Engineering Grand Challenges Symposium to propose to the College of Engineering’sCurriculum Committee an experimental first-year, three-credit hour, engineering course. The Curriculum Committee accepted the proposal and the authors began to develop a new first-year engineering course to serve the growing number of students admitted into the college who had not declared one of the departments as their chosen specialty (so-called open option students) –a status allowed to persist only through the first year. The course was numbered ENGR 180 and titled “Engineering Grand Challenges” to directly associate the course with the National Academy of Engineering’s effort. The course was scheduled for the Fall Semester 2009.

Ninety-six students enrolled in the course. Of these, ten were declared engineering science majors, the only major for whom the course would actually count towards meeting their first-year engineering credit requirements; sixty-nine were the so-called open option students; and seventeen were students admitted into the University but not into the College of Engineering. At the end of the semester, ninety-four students had completed the course. Of the original sixty-nine open option students, only twenty had not declared a major in engineering –students are not required to choose a major until the end of the freshman year so each of these twenty studentsenrolledin department-based courses even though they remained open option students.

Unlike many traditional introductory engineering courses where there are sessions on the various engineering disciplines, this course was structured to focus on the grand challenges as the context for discussions on the future of engineering. The course goals included:

1. By investigating some of the "big" challenges predicted for this century, students will develop a perspective of great technological challenges facing society and how solutions are being formulated.
2. As we probe deeper into the challenges students will develop an understanding of how the different engineering disciplines contribute to solving these problems.
3. Within the context of the big societal challenges, students will start to understand the role engineers play in solving these problems; a role that requires engineers work together with other segments of society to create new solutions.

Classes met in a high-technology classroom at 8:00 am for fifty minutes every Monday, Wednesday and Friday for fifteen weeks. The classroom was outfitted with an overhead digital camera, a Windows-based Personal Computer, a DVD/VCR player, and would accommodate plug-in laptops of either the PC or Apple Mac variety. All display information was output to a large 22-foot screen located above the small stage and podium. All controls were centralized on the podium and the classroom included WiFi Internet access, again supporting both PCs and Macs.

During the first week of this new course offering, instead of presenting the grand challenges as being a set of established problems, the authors sought ideas from the students as to what they thought the challenges for this century are –since they are the ones to likely spend the majority of their lives in it. In essence, the authors chose not to paint the challenges too fully –thereby leaving white space on the syllabus so that the students could add to the course's interpretation! What was found was significant overlap between the students' ideas and the grand challenges but with significantly less specificity on the part of the students. The students named the following

- Energy
- Pollution
- Sustainability
- Clean Water
- Infrastructure
- Population
- Transportation
- Military
- Education
- Exploration
- Health care
- Agriculture
- Environment
- Efficiency
- Politics
- Technology dependency
- Immigration
- Aids/cancer
- Economy
- Urban sprawl

As might be expected, the students defined their issues in more general terms than the specialists on the NAE committee. This follows naturally from their lack of expertise at this stage in their careers. But this broader view should not be discounted because of the students' lack of knowledge –they still represent important participants in the challenges of the 21st century.

The students' list provides an interesting contrast with the NAE list. On the one hand, the NAE list is a very specific set of challenges that seem to reflect the expertise of the committee members whereas on the other hand, the students' list consists of a broad view of people with less specialized knowledge. The authors' contention is that both lists are necessary! Exclusively using the NAE list can result in missing important challenges because of its specificity. Using the students' list exclusively can result in missing important details such as what is feasible and realistic due to lack of technology underlying the challenge's definitions. The authors chose to blend the two lists into what was hoped was a coherent whole for the students that allowed engagement in some divergent, non-specialized thinking and discussion followed with some convergent, specialized thinking and discussion.

For the next fourteen weeks, the authors described and led discussions on eight of the engineering grand challenges, both from the students' list and the NAE list. Those covered were health care (students' list), provide access to clean water (NAE and the students' list), reverse-engineer the brain (NAE list), provide energy from fusion (NAE list), restore and improve urban infrastructure (NAE list and students' list), secure cyberspace (NAE list), carbon sequestration (NAE list), and exploration (students' list). Obviously, the authors spent slightly less than two weeks on each grand challenge. At the beginning of each engineering grand challenge, one of the authors would provide an overview of the problem including describing various roles for each type of engineer. Videos were used in some of the challenges, in particular, reverse-engineering the brain[4] and providing energy from nuclear fusion[5]. In other challenges such as restoring and improving urban infrastructure both photos and the American Society of Civil Engineers' infrastructure website[6] were used. In fact, many websites were used throughout the course for one feature of the class was that nearly half the students came to class with their laptops so using their laptops in class to retrieve data, or definitions, or other attributes necessary for discussion followed easily.

After a grand challenge was introduced the remaining class time was devoted toprobing deeper into the technical and societal issues related to the challenge. This typically resulted in lively discussions where both the students and the instructors would acknowledge their lack of foundational scientific skills that are requiredto fully understand the challenges. At the same time, the instructors would highlight the roles of the traditional engineering disciplines in working towards solutions to the grand challenges.

The students also surprised the authors in their expressed desires concerning assignments. In the beginning weeks of the course, student understanding of each challenge was evaluated using short essay assignments. Several weeks into the semester, the students requested an opportunity to submit something other than an essay. What seemed to be a straightforward request to limit the required writing component of the course by the students opened a creative response by students that was unexpected by the authors, until later reflection on how different today's students are, often characterized in the literature as the millennial generation. Once we allowed the students to be creative in the assignments we received some very unusual and unexpected submissions. First many students requested the opportunity to make in-class group presentations –consistent with the collaborative mentality associated with the millennial generation[7]. But these were some of the more conventional submissions. The coverage of reverse engineering the brain resulted in the more creative submissions. We received a children's book written by two students that illustrates the workings of the brain and how to protect the brain when playing. A hand-made plaster-of-paris model of the human brain showing all of its major components was also submitted during this time. Probably the most daring and creative submission related to the brain challenge was a short in-class presentation on the connection between the human brain, music, and dance, followed by a couple of minutes of hip-hop dance by the student to demonstrate this connection! (So how does an engineering professor assign a grade to a hip-hop dance?) Finally, one group of students produced a documentary film on drug use effects on the brain by interviewing students from across campus. Then during the discussion on nuclear fusion, a group of students submitted a model of a thermo-nuclear bomb to illustrate how nuclear fission explosions could be used to initiate a nuclear fusion reaction.

Clearly, the types of broad-based challenges that formed the basis for this course stimulated students' thinking in ways that challenged the authors to be very open to the students' need to be creative in their engagement with the course content. The course topics also resulted in the students seeing the value and need for a range of scientific knowledge for solving the types of engineeringproblems listed by the NAE. By teaching the course, this conclusion also became one of the important lessons for the authors. Even though the students are now enrolled in traditional engineering curricula, they now at least have an appreciation of the complexity and interdisciplinary nature of the future of the engineering profession.

Outcomes

What did the authors learn? Both agree that the course was one of the most difficult they have ever taught. The primary reason for the difficulty was the wide range of topic areas that the Engineering Grand Challenges encompass. One author's educational background was aerospace/mechanical engineering; the other's was civil engineering. The first author also has research experience in alternative energies, and formally taught in the computer science department at Colorado State University for many years. Together they had a broad range of experiences. Interestingly, the first author who graduated from his undergraduate engineering program nearly twenty years earlier than the second author, had significantly more credits in both mathematics and physics than the second author. This probably resulted from the educational push to include more design courses in the undergraduate engineering program as well as an overall decrease in credits required for graduation over the intervening twenty years.

In many ways the courses that have made up the science fundamentals and even mathematics courses required during the first two years of an engineering undergraduate program have remained unchanged for about sixty years. The knowledge contained in such courses represents learning up until about the end of the 19th century although some programs do require students to take a course in so-called modern physics, which usually ends with the state of physics at about 1926, or so. Courses based on the science of the late 19th century might have been adequate in the mid 1950s but we are now in the early part of the 21st century and this no longer seems appropriate.

Before intelligently addressing possibly modifying or transforming the undergraduate engineering curriculum we need to understand its current state. The current structure and organization of a typical undergraduate engineering curriculum consists of a curriculum with five components: (1) the fundamental sciences; (2) mathematics and its associated groups of statistics and computer science; (3) the engineering sciences that provide the bridge from mathematics and the sciences to engineering; (4) the discipline specific engineering courses along with engineering design and project courses; and (5) a group that designated as other courses which usually consist of composition, speech, any university cultural and diversity requirements, and perhaps a course in history, economics, psychology as program electives. The breakdown roughly goes as follows: 15% fundamental science (usually classical physics and chemistry), 15% mathematics (usually calculus, differential equations, linear algebra and perhaps a course in statistics or computer programming), 15% engineering science (usually engineering mechanics, strength of materials, thermodynamics, fluid mechanics and electrical networks), 40% discipline specific engineering courses, design and project courses and 15% for all the other curricular requirements. This curricular model has been worked out over the past fifty years and seems relatively balanced and in place in nearly all colleges of engineering across the United States. The result is a couple of million engineering graduates who have successfully entered the workforce and the incredible results of the twentieth century confirm the success of the approach.

However, in even a cursory examination of the NAE's engineering grand challenges, it is obvious, that cross-disciplinary teams will be required. The teams will consist not only of engineers, but physical scientists, mathematicians, computer scientists, medical professionals, social scientists, business people, legal professionals, as well as many others who will be responsible for developing these large complex systems, policies and procedures.

Taking a closer look at the grand challenges list, it is readily apparent that many of them require scientific knowledge that is not taught in the current engineering curriculum. For example, fusion power not only requires modern physics (up to about 1926, already neglected in typical engineering curricula) but may also require the contemporary physics of particle physics, quantum mechanics and laser physics. As well, note that many of the challenges on this list have to do with biological systems and for most engineering students a course or two in biological systems would be at most unusual. Additional chemistry courses may also be required for developing 21st century materials and the engineering of better medicines challenge may require quantum chemistry. And so it seems clear from these examples that the 15% portion of the engineering curriculum devoted to the fundamental sciences may have to increase in order for engineers to be engaged in solving these grand challenges.

In challenges such as cyber security, bioinformatics and even reverse engineering the brain, our current students are ill served by the lack of formal computer science courses. So, an increase in credit hours here may also be justified.

The current level of courses used to bridge from the sciences to discipline specific courses is probably justifiable so where will the necessary cuts be made to include more fundamental sciences and related mathematics courses come from? It is safe to say that they will not come from university-wide requirements which are used to meet ABET criteria. These courses will also become more critical in teaching the necessary societal interactions that the grand challenges will force on the teams of scientists, engineers, and others. This only leaves the discipline specific engineering courses. Here the various professional societies will raise their collective voices through the accrediting processes. This will be a hard fought issue but it seems clear to the authors that the notion of including more science, mathematics, and computer science courses may not be accommodated which may mean that future engineers will take a back-seat in resolving many of the societal issues of this century. Let the debate begin!

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