Engineering Education: Challenges, Opportunities, and Future Trends

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Abstract

Engineering contributes significantly to the economic wellbeing, social stability, and cultural development of the society. Engineering also plays an important role in global human development, sustainability, and preservation of the environment. Importance of high quality engineering education is therefore self-evident. Based on the authors' experience as professional engineers and university educators, this paper highlights the recent challenges, opportunities, and future trends in engineering education. Major challenges currently facing engineering education relate to curriculum, teaching and learning, and the educational environment. As to quality, balance needs to be maintained between general excellence and targeted areas of excellence. In terms of pedagogy, focus should be on improvement of students' problem-solving and learning skills, ability for continued learning throughout their careers, and soft skills (leadership qualities, team work, communication skills, and an understanding of economics, business, management, and innovation and entrepreneurship). Good support should be available in terms of qualified technical personnel and well equipped workshops, laboratories, and computing facilities. Some of the emerging trends in engineering education include hands-on learning labs, industry-centric curriculum, upgradation of classroom environment and facilities (to support active learning and group-based learning), and use of interactive learning technologies (such as adaptive learning software, e-learning, distance learning, etc).

Keywords
Engineering education, challenges, opportunities, future trends, pedagogy, curriculum, teaching and learning, support environment

1. Introduction
The target of good engineering education is to produce engineers who can make a meaningful contribution in the face of evolving technology and society. Reviewing the history of engineering during a workshop on Pathways for Engineering Talent [NAE 2014], conducted by the National Academy of Engineering (NAE), the NAE president Dr CD Mote Jr said that "Every engineering field was essentially formed to get the knowledge and know-how to execute tasks that were necessary for the community to make progress." Today, more than ever before, the world is witnessing a huge and rapid technological change, and major shifts in global engineering trends. Leaders in engineering education must address the question, "are engineering programs and curricula adapting well to the requirements of occupational flexibility of engineering graduates, to meet current and future demands for engineering skills and knowledge?" [NAE 2018]. Rapid advances in all major areas of science and technology require engineers to have a strong mix of technical, professional, and soft skills. The teaching and learning of engineering curricula needs to keep pace with the evolving workplace demands. Other associated challenges include effective assessment strategies, professional and pedagogical development of engineering faculty, continuous improvement and lifelong learning of engineering graduates and field practitioners, etc.

Augmenting the traditional basic courses in mathematics, physics, and chemistry, many engineering programs are now including information and computer technology (ICT), biological, social, and behavioral sciences, and humanities into their core curriculum. For instance, ABET [2017] reports that the number of accredited bachelors programs in bioengineering and biomedical engineering in the United States witnessed a 400% increase in the last fifteen years.

2. Professional and Soft Skills

The briskly changing world scenario of engineering and technology has triggered a demand for engineering graduates having strong professional, technical, and soft skills [Brunhaver et al 2017, Lynn and Salzman 2010]. Over a hundred years ago, the then hi-tech industries started to voice their need for well-rounded or T-shaped workers, who could combine in-depth knowledge and skills in their area of expertise with broad, interdisciplinary, and team-based talents [Miller 2015]. Today it has become even more important. In an interview to the New York Times in 2014, Laszlo Bock (Google's senior vice president of People Operations) highlighted five essential skills that he would look for in future candidates for his company: leadership, humility, collaboration, adaptability, and love for learning and relearning. According to him, their company's first priority is not just high IQ, but cognitive or learning ability. Second is leadership; but emergent leadership as against traditional leadership; stepping in to lead when faced with an emergency situation. Third is humility and ownership; feeling a sense of responsibility; and being modest enough to embrace ideas from others if they are better [Friedman 2014].

In the 1990s, in response to increasing employer discontent with the professional preparedness of engineering graduates, ABET articulated their well known Engineering Criteria EC2000 [Lattuca et al 2006]. EC2000 highlighted the key importance of professional and soft skills, on top of the traditional technical skills. Table-1 lists the famous (a-k) student outcomes (or abilities) set forth by EC2000. ABET has recently revised these criteria to a (1-7) format, which is not being reported here. Skill set (a-c) represented attributes in the traditional scientific, technical, and engineering areas. However, all of the other eight outcomes (d-k) describe professional and soft skills; relatively more intangible than purely technical. These include abilities such as team work (especially in a multidisciplinary context), communicating effectively, engaging in lifelong learning, being cognizant of contemporary issues, understanding of professional and ethical responsibility, and being mindful of the impact of engineering solutions in a global, economic, environmental, and societal context.

Building up on ABET's EC2000 characteristics, the NAE in 2004 came up with its own list of nine required attributes of future engineers in its report The Engineer of 2020: Visions of Engineering in the New Century [NAE, 2004]. Table-2 gives a suggested mapping between ABET's EC2000 criteria and NAE-2004 attributes for engineers of 2020 [NAE 2018]. Since EC2000, various other engineering and educational bodies have tried to coin their versions of graduate attributes for engineering and technology. Some of these organizations are the American Society of Civil Engineers (ASCE), the American Society of Mechanical Engineers (ASME), and the National Society of Professional Engineers (NSPE). The common theme is a judicious and strong mix of technical and professional skills, with emphasis on creativity and innovation, business insight and judgement, ethical standards, and adaptive leadership [ASCE 2008, ASME 2011, NAE 2005, NSPE 2013].

Table-1 Student outcomes set forth by ABET EC2000 criteria

(a)	An ability to apply knowledge of mathematics, science, and engineering
(b)	An ability to design and conduct experiments, as well as to analyze and interpret data
(c)	An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d)	An ability to function on multidisciplinary teams
(e)	An ability to identify, formulate, and solve engineering problems
(f)	An understanding of professional and ethical responsibility
(g)	An ability to communicate effectively
(h)	The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i)	A recognition of the need for, and an ability to engage in, lifelong learning
(j)	Knowledge of contemporary issues
(k)	An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

Table-2 Mapping of NAE attributes to ABET criteria; NAE (2018)

NAE attributes for the engineer of 2020	ABET criteria
Strong analytical skills	a, b, k
Practical ingenuity, creativity, and innovation	c, e, k
Good communication skills	g
Business acumen and management skills	d
High ethical standards and professionalism	f
Agility, resiliency, and flexibility	d, i, b
An appreciation for lifelong learning	i
Ability to put problems in their sociotechnical and operational context	h, j, c
Adaptive leadership	d

2.1 Development of Professional and Soft Skills

In response to these calls for fortifying technical abilities with professional and soft skills of engineering candidates, gradual changes in engineering curricula, instructional methods, and faculty preparation were witnessed in universities in USA and around the world. Lattuca et al [2006] conducted a study to assess the progressive changes in attainment of student outcomes of engineering graduates after implementation of ABET EC2000 criteria, comparing batches that graduated ten years apart (1994 and 2004). Their survey included thousands of students, and a large number of faculty and employers. From faculty responses, their key observations included significantly higher emphasis on collaborative tasks and teamwork, communication skills (oral and written), and rise in the use of active learning techniques (such as group work and course projects). On the student side, more recent graduates recounted higher interaction with instructors, increased and more prompt feedback on student work from the faculty, higher engagement in independent and sustained learning, more participation in design and other competitions, and programs becoming more amenable to new ideas and approaches. Employers reported that recently hired graduates showed better performance in oral and written communication, teamwork, and better adjustment and responsiveness to technological changes and developments.

However, more improvement is needed, and majority of employers still express concerns about the nontechnical and professional skills of engineering graduates [ASEE 2009, Brunhaver et al 2017, Jaschik 2015]. On top of robust technical skills, engineers must exhibit good competence in professional and soft areas such as oral and written communication, teamwork and leadership, interdisciplinary thinking, creativity and design, business management, innovation and entrepreneurship, and multicultural awareness.

3. Computing Skills

The use of computer programming and software tools in engineering is increasing more and more. They have become necessary tools in design, simulation, testing, and manufacturing. Some competence in computing and data science is now required in almost all occupations [NASEM 2018a, NASEM 2018b]. Just as knowledge of basic math and science was an intrinsic requirement for engineering degrees, computing skills are now an essential ingredient of an engineer's repertoire. Proficiencies that were earlier associated with only computer science (CS) graduates (programming, computing architecture, data mining, software design, data science, etc) should be used in defining the list of attributes for current and future engineers. Curricular mechanism can be flexible; computing can be taught through CS courses or included as modules in discipline-specific courses [NASEM 2018a].

The Joint Task Force for Computing Curricula [JTFCC 2006] identified five principal computing disciplines at the university level. *Computer engineering* covers the design and construction of computer hardware and systems. *Computer science* focuses on the design and application of software, and generating solutions for computing problems. *Information technology* (IT) involves repair and maintenance of computing technology tools and systems in order to satisfy the needs of business and other commercial organizations. *Information systems* tries to integrate IT solutions and business processes to fulfill information-related needs of different companies. The scope of *software engineering* is the development and upkeep of software packages and systems, concentrating on reliability and efficiency.

Knowledge and skills of these five computing disciplines are becoming increasingly fundamental for diverse engineering applications. In the US, about one-sixth of engineering graduates are directly employed by computer-related companies [NSCG 2013]. Far more are needed to use computing skills in their engineering occupations, and this proportion is projected to grow rapidly in the coming decades. Engineering schools worldwide must recognize and actively support this interaction between engineering and computer science in all disciplines.

4. New Pedagogical Approaches

Augmenting basic technical skills with enhanced professional and soft skills has been, and still is, a challenging and intimidating task for engineering educators. Engineering curricula are already saturated with required courses, and building in of all additional skills is tough. Faculty are generally already complaining of overwork, and are short on time and other resources for learning and incorporating new material and techniques. On top of this, engineering enrollments are increasing worldwide, making the issue even more demanding. In spite of these challenges, rather because of them, new teaching paradigms and technologies are continuously coming up, such as dynamic simulations (new tools) and student-centered teaching (new mechanisms). One advantage is that new students are a product of the digital age, so they are more receptive to teaching and learning strategies geared towards workplaces of today and tomorrow [NAE 2005, NSPE 2013, Sheppard et al 2009].

Outlined below are some of the more promising paradigms in undergraduate engineering education, built around a growing knowledge of how people practice, learn, and teach engineering. Coupled with general research on social and behavioral sciences, pedagogical research on issues such as student learning, engagement, and motivation has prompted both classroom and extracurricular interventions [NRC 2012]. Some of the core requirements are a clear-cut description of student learning outcomes and educational objectives, use of engaging activities, and having a judicious balance between instruction and assessment [Froyd et al 2012, Atman et al 2010].

4.1 Active Learning

Any teaching strategy that involves classroom activities and an interactive style, especially targeting reflection and contemplation, can be called active learning. The underlying concept is simple yet powerful: learning by doing has a higher value. There are various types of active learning techniques. In *collaborative or group learning*, students interact with each other to solve a problem or achieve a target. In *cooperative learning*, students still practice collaboration, but are graded individually rather than as a group. *Problem-based learning* prompts students to a learn a new topic by attempting to solve a problem, as opposed to the traditional lecture-first problem-later approach [Prince 2004]. *Project-based learning* takes group learning to a higher level, where student groups tackle a larger problem and keep working out of the class as well. *Service learning* is an extension of project-based learning, so that in-class instruction serves as a platform to tackle projects that target community welfare [Swan et al 2014]. In real-world or *experiential education*, students learn to handle open-ended and ill-defined problems involving competing realistic constraints. *Maker spaces*, focusing on hands-on design experiences and providing support equipment such as rapid prototyping, enhance the fostering of technical and professional skills [Barrett et al 2015].

4.2 The CDIO Initiative

Emulating the design-manufacturing cycle of activities in the real world, one of the new approaches is the Conceive-Design-Implement-Operate (CDIO) initiative. Instructors and practitioners from various institutions around the globe have teamed up and collaborated in the development of evidence-based teaching practices, and sharing of resources. To improve the technical knowledge and communication and professional skills of engineering students, this initiative employs active learning tools, such as team projects and problem-based learning [Queen's University 2019]. Emphasis is on both core engineering and science concepts and inculcation of personal and interpersonal skills, learning and re-learning, engaging with industry, and cooperating and collaborating [Crawley et al 2007]. This scheme divides engineering curricula into four major parts: discipline-specific knowledge and reasoning; personal and professional skills and attributes; interpersonal skills, teamwork, and communication; conceiving, designing, implementing, and operating various engineering systems, considering the enterprise, societal, and environmental impacts. Recognizing that engineering education spans over a long period, and can involve various institutions, the CDIO network welcomes and involves members from diverse range of institutions, from top-class academic-cum-research universities to less known local colleges. The system also provides resources for instructors of participating institutions to improve their teaching abilities

4.3 Enterprise and Entrepreneurship

In terms of educational philosophy, there is a big difference in producing graduates with a service mindset (to work as an employee in an engineering firm), as compared to nurturing engineers that have a vision to establish their own technology based businesses. Through entrepreneurial experience, undergraduate students can develop a range of business, management, and other professional skills in addition to their technical competencies. Entrepreneurship programs (or engineering programs with entrepreneurship modules) provide an atmosphere for developing oral and written communication skills, the aptitude to think broadly about engineering issues, to work in multi-disciplinary teams, find good employment, and have an entrepreneurial mindset. Graduates of these programs are stronger in leadership and responsibility, and are enthusiastic about setting up their own companies. Surveys and interviews of recent engineering graduates reveal that they recognize the high value of their entrepreneurship education and appreciate the related career benefits [Duval-Couetil and Wheadon 2013, Taks et al 2014]. In the US, there are quite a few well-organized support initiatives for the teaching of entrepreneurship to engineering and other majors. Some of the more notable ones are the Kern Entrepreneurial Engineering Network (KEEN), the Engineering Pathways to Innovation Center (Epicenter) at Stanford University, and the Kauffman Foundation.

4.4 Independent and Lifelong Learning

The purpose of good education is to make students independent learners. Also, with continued and fast-paced advances in science and engineering, learning for engineers cannot stop at graduation, but should be a lifelong process. Engineers of today must give due consideration to issues such as sustainability, environment and ecology, societal impact, and public policy, and give due regards to the input of more and more diverse stakeholders [NSPE 2013]. In the words of the former NAE president Charles Vest, there is a need for "a corporate and national strategy…to ramp up the quality and opportunity for lifelong learning for our engineering work-force" [Dutta et al 2012]. Rather than a single course or a certificate, lifelong learning is a new mindset about the way engineers approach knowledge acquisition [NAE 2015]. To foster this adaptive mindset, individual engineers, companies, and especially engineering universities must engage in the ongoing process of continuing education and lifelong learning, rather than treating it as an infrequent and sporadic activity.

During their undergraduate engineering programs, independent learning and lifelong learning tasks should be included in more and more courses. These may include literature search and review, independent reading of certain topics, open-ended design problems, mini projects with written and oral presentations, etc. It should be repeatedly stressed, during different courses, that learning is a lifelong activity, and must not terminate with the degree. After graduation, engineers can update their competencies through various mechanisms. One common practice is to go for alternative qualifications such as diplomas, certifications, licenses, etc [Ewert and Kominski 2014]. Licenses are generally obtained through regulatory agencies that issue Professional Engineer (PE) licenses [NSPE 2017]. Issuance of diplomas and certificates is handled from various sources, including professional societies, companies, certification organizations, and universities and other academic institutions [Mooney 2015]. In some cases, engineers can carry on continuous education through in-house employer programs.

4.5 Service Learning

Engineering service refers to the application of classroom learning and acquired engineering skills to solve practical problems for the community. Such activities enhance the abilities to tackle multidisciplinary problems, have a systems approach, and understand the broader context and impact of engineering [Litchfield et al 2016]. Development of skills such as verbal and written communication, teamwork and collaboration, leadership and decision making, etc can be furthered through experiential (or hands-on) learning [Gallup 2014]. A study conducted by the Carnegie Foundation for the Advancement of Teaching emphasized that undergraduate students should have opportunities to gain international experience, language proficiency, and intercultural aptitude [Sheppard et al 2009].

Making service learning activities (such as internships and co-op trainings) an integral part of their degree requirements will make engineering students better prepared for today's highly competitive and global economy [Alves 2015, Besterfield-Sacre et al 2015, Eljamal et al 2015]. International exposure can be gained through study, work, research, or service in other countries through partnerships such as the International Association for the Exchange of Students for Technical Experience [IAESTE 2019]. Major improvement in professional and soft skills has been observed [Litchfield et al 2016] in engineering students who participate in service learning programs such as Engineers without Borders [EWB 2019].

5. Faculty Training and Development

Results from a survey eliciting responses from faculty of various institutions [NAE 2018] are quite surprising and somewhat disappointing. Engineering and other STEM (Science, Technology, Engineering and Mathematics) faculty show significant resistance in using student-centered teaching strategies as compared to non-STEM faculty. Also, engineering faculty are generally quite reluctant to take part in workshops and other activities focusing on new pedagogical techniques. One major reason for this lack of enthusiasm is that engineering faculty who implement innovative classroom practices are generally not given extra recognition at the time of promotion and tenure rewards [ASEE 2012, McKenna et al 2011]. Due to the nature of the environment, engineering faculty are quite work-stressed routinely, and need institutional motivation and support in bringing about serious changes in teaching style and methods [Matusovich et al 2014].

New teaching and learning strategies and pedagogical methods can be included in graduate education programs [ASEE 2012, Linse et al 2004]. Current faculty can learn it through inhouse or sponsored teaching workshops. Training programs conducted by engineering faculty prove to be more effective as they generally include more engineering-specific examples [Brawner et al 2002]. In the US, various national initiatives are now available for professional development of engineering faculty. Some of these are Frontiers of Engineering Education [FOEE 2019], a program of the National Academy of Engineering (NAE); the National Effective Teaching Institutes [NET-1 2019], an initiative of the American Society for Engineering Education (ASEE); and workshops offered at the annual ASEE conferences [ASEE 2019] and Frontiers in Education events [FIE 2019].

6. Conclusions

Engineering and technology are changing at a rapid pace. Other global changes such as environment, geopolitics, and merging of cultural boundaries is also affecting engineering and science. Engineering education needs to keep pace with these changes, and with the mindset of the young generation and future employers. A short overview of the more important of these challenges, opportunities, and future trends in engineering education are presented. Critical nontraditional skills required by engineers are discussed, such as professional, soft, and computing skills. New teaching and learning paradigms are described, such as active learning, enterprise and entrepreneurship, independent and lifelong learning, and service learning. Issues related to faculty improvement and training of trainers are examined.

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