Establishing an Engineering Core – What Does Every Engineer Need to Know, Particularly About Systems Engineering?

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1. Introduction

An ABET accredited undergraduate or graduate program lays the foundation for the engineering careers of many in the US and even around the world. This accreditation certainly ensures high quality of the engineering education that is provided to the students. However, with ABET's approach of accrediting individual programs, universities (and departments) tend to develop their engineering programs largely in isolation. There is likely to be a strong overlap between the college-level math and basic sciences courses that are required by ABET, but the courses on engineering topics may or may not be common across multiple programs. There could certainly be overlap based on the history of how these courses were initially designed, the programs they were initially offered under, the faculty member(s) who designed and/or taught them, scheduling, etc. Universities and departments do take efforts to streamline and consolidate these courses, especially when there are separate courses on similar topics offered in two different programs that could be combined into a single course. However, it is not common for the motivation for these and other such efforts to be in response to the question 'what does every engineer need to know'. While this in itself is a pertinent question to be asked in today's engineering education environment, there has been a lot of discussion among the systems engineering community in ASEE and INCOSE on what every engineer should know about systems engineering. There is growing recognition of the benefits of providing a systems exposure at an early stage.

The primary objective of this paper is to establish the need for a common core of engineering topics and courses that every student of engineering needs to know, irrespective of their engineering major. And while establishing this core, there is a further need and opportunity to include appropriate systems engineering topics in the engineering core. The secondary objective of this paper is to present a specific case study of the efforts at Regent University towards establishing such an engineering core that includes systems engineering.

In Fall-2018, Regent University will be launching its first two engineering degrees ever. Recognizing that there are some topics that every engineer needs to know, an 'Engineering Core' is being established: a set of six 3-credit courses that every engineering student of Regent University will be required to take, irrespective of their individual majors. Additionally, one of the two engineering degrees being launched is a B.S. degree in Systems Engineering. Such a 'green field' launch of an undergraduate systems engineering degree is very rare. It provides some interesting challenges, yet unique opportunities for systems engineering to have a significant positive influence upon every other engineering degree (including its students and faculty), that will be launched in the coming years. The engineering core will incorporate a number of systems engineering foundations and principles, to ensure that every engineering student of Regent Engineering will graduate with a basic understanding of systems thinking and systems engineering. Some insights into the proposed implementation of this engineering core is presented in this paper.

2. What do Engineers need to know?

The question ‘what do engineers need to know’, is often addressed at the disciplinary level. For traditional engineering disciplines, there are books and other literature that is foundational to that discipline. Over the years, many textbooks and other such literature get produced based on those foundational books. This ‘collection’ of resources could be informal, but commonly recognized and accepted within the community. However, this is not the situation with some of the newer engineering disciplines that also tend to be inter-disciplinary. In these disciplines, there is a dire need to establish an explicit ‘Body of Knowledge’ (BOK) to offer a standard set of terms, definitions, and concepts that are accepted by the professionals of that discipline. Such efforts to create and maintain a BOK are usually driven by the internationally recognized professional body for that discipline. Examples of two such BOKs are the Software Engineering Body of Knowledge (SWEBOK) [1] developed by the IEEE Computer Society, and The Guide to the Systems Engineering Body of Knowledge (SEBoK) [2] co-developed by INCOSE, IEEE Computer Society, and Systems Engineering Research Center (SERC). Some disciplines use their professional societies and other bodies of practicing engineers to publish and maintain handbooks, standards, codes, etc. that form the body of knowledge or code of practice for that discipline. The Institute of Transportation Engineers (ITE) and The Society of Fire Protection Engineering (SFPE), for example, take this approach.

The BOKs and other standardization efforts by professional societies, by themselves, do little to ensure commonality among various educational programs in those disciplines. There is no way to guarantee that a graduate of a particular engineering discipline would certainly possess specific knowledge about that discipline irrespective of the university or program they graduated from. The disparity is larger in graduate programs than in undergraduate programs. This turns out to be a big challenge for employers who are then forced to establish a variety of training programs within their organization to supplement the formal engineering education that brought the recruits to the organization in the first place. Some disciplines have found a way to address this challenge by establishing reference curricula – like the ‘curriculum guidelines for graduate degree programs in software engineering’ (GSwE2009) [3] and the ‘graduate reference curriculum for systems engineering’ (GRCSE) [4]. These curricula only offer recommendations but do not prescribe specific courses – it is upon the university to make all curricular decisions.

Each engineering discipline tends to focus on their own engineers, and try to respond to questions like ‘what do mechanical engineers need to know’ or ‘what do aeronautical engineers need to know’ or ‘what do petroleum engineers need to know’. The question ‘what do <u>all</u> engineers need to know’ is not addressed effectively amidst all these discipline focused efforts, though some disciplines do look to include knowledge from constituent or closely related disciplines.

3. The Need for an Engineering Core

Today’s engineers are already working in a complex interconnected interdisciplinary environment, and one can only reasonably imagine what the immediate future might hold. This has strongly influenced the engineering programs that are currently offered. Traditional engineering disciplines have now split into specializations that are increasingly forming their own identify: ceramic engineering and textile engineering from chemical engineering; foundation engineering and wastewater engineering from civil engineering; power engineering and optical engineering from electrical engineering; and sports engineering and energy engineering from mechanical engineering. Traditional engineering disciplines are getting combined not only in the workplace but in educational programs as well: biomechanical engineering and mechatronics engineering for example. There are engineering programs that are being offered today, that many not have been considered to be engineering disciplines a few decades ago: food engineering and financial engineering for example.

With all these various kinds of engineering programs currently being offered, one begins to wonder what is common between the graduates of any of these? When someone claims to be an engineer, what does that really mean - beyond possessing an engineering degree? Can it be said with any certainty that they <u>will</u> possess some knowledge about a particular engineering topic, or <u>will</u> possess a specific engineering skill? While there is nothing that could possibly be done to limit the entrance of new engineering disciplines, some efforts could be taken to ensure that students of any engineering program will all get taught some common engineering topics that are foundational for every engineering program.

U.S. News & World Report publishes annual rankings of the best undergraduate engineering programs for programs in universities that also offer a doctorate degree and for programs in universities that do not offer a doctorate degree. The following observations can be made about the engineering programs offered by some of the universities featured in the top 10 rankings for 2018 [5], [6]. It may be noted that courses related to language, humanities, art, history, etc. are not considered in this discussion.

- Driven by ABET accreditation requirements, all engineering programs require a number of Mathematics and Science courses to be taken. These courses are usually not exclusive to engineering programs, but some specific courses are required for engineering majors. For example, Stanford recommends a MATLAB course for all engineering programs [7], and Georgia Tech requires a ‘Computing for Engineers’ for all engineering majors [8]
- Some universities offer one or two ‘fundamentals of engineering’ (or equivalent) courses for all engineering programs. Some also offer choice of a number of such fundamental courses, but across multiple engineering disciplines. The primary objective for doing this is to help freshman engineering students decide on the specific engineering major they wish to pursue. For example, Purdue University offers two courses on ‘Transforming Ideas to Innovation’ [9] to all engineering majors, and at Carnegie Mellon University, students select their major only at the end of their first year, and the first year curriculum is designed to help them make an informed decision [10].
- Within the common core of courses for all engineering programs, there is sufficient choice offered to students, that it is possible for two students of different engineering majors to have very few specific courses in common.
- In specialized universities like military academies, all students are required to take a set of core courses to prepare them for the military. The US Air Force Academy offers a Core Curriculum for all cadets regardless of academic major [11]. To meet the engineering outcome, engineering courses are required in each of the four years: 1)

Introduction to Computing and Cyber Operations, 2) Fundamentals of Mechanics, 3) Fundamentals of Aeronautics, and 4) Introduction to Astronautics, and Principles of Air Force Electronic and Cyber Systems. The US Naval Academy defines a Core Curriculum for all majors in the Engineering & Weapons Division, which includes Principles of Ship Performance, Applications of Cyber Engineering, Principles of Propulsion, Naval Weapons Systems, etc [12]. The US Military Academy identifies core courses in IT, Computing, and Cyber Security [13].

Overall, it can be seen that engineering programs have little in common across multiple majors offered within the same department or University. While some universities do offer common core courses, not counting mathematics and science courses, they tend to be on engineering fundamentals or introductory level courses helping students decide their engineering majors.

Another motivation to look at establishing an engineering core is the nature of current and future projects that engineering graduates are likely to work on. Some of the larger engineering projects include the Panama Canal expansion; Port Mann Bridge in Vancouver, Canada, the widest bridge in the world; Three Gorges dam in China; Marmaray railway Tunnel in Turkey which runs 47 miles underwater; Jubail Industrial City in Saudi Arabia; the 7.5 million square feet Beijing Daxing International Airport in China; and the Atlanta Falcons stadium in the USA. While these projects may appear to be primarily civil engineering projects, the number of engineering disciplines that really need to come together are many. It is unlikely that an engineering venture of the future, irrespective of its scale or scope, can be successfully accomplished by a single engineering discipline. It will be imperative for engineers of any discipline to work with engineers of other disciplines. In such situations, a shared vocabulary and common understanding of fundamental engineering and related concepts will be essential for effective communication and collaboration.

4. The Need for Systems Engineering

The inter-disciplinary nature of contemporary and future engineering projects also emphasizes, though implicitly in some cases, the need for systems engineering. When disciplinary experts come together bringing in their own expertise, perspectives, and contributions there is a need for systems engineers who will focus on the overall system and concentrate on optimizing the design and performance at the system level, which could imply sub-optimizing at a disciplinary perspective. Many organizations do not use the title ‘systems engineer’ or recognize systems engineering as a key discipline. But, someone does play the role of a systems engineer and performs systems engineering activities even if they are not explicitly recognized to be doing so. Atlas: The Theory of Effective Systems Engineers [14] identifies 15 systems engineering roles: 1) Concept Creator, 2) Requirements Owner, 3) System Architect, 4) System Integrator, 5) System Analyst, 6) Detailed Designer, 7) V&V Engineer, 8) Support Engineer, 9) Systems Engineering Champion, 10) Process Engineer, 11) Customer Interface, 12) Technical Manager, 13) Information Manager, 14) Coordinator, and 15) Instructor/Teacher. A typical engineer, irrespective of their disciplinary expertise or level of seniority, performs one or more of these 15 roles in whatever position or title they serve at in an organization.

Given that every engineer plays some kind of a systems engineer's role, or interacts with someone who does - either explicitly or not, it is evident that systems engineering knowledge is essential for all engineers. The Academic Forum of INCOSE held a meeting in May 2015 [15] to explore ways of understanding, promoting and enhancing the value of systems engineering knowledge in the education of all engineers, followed by a ASEE Systems Engineering Division Workshop in June 2015 on integrating systems engineering education into undergraduate engineering education [16]. The jointly developed value proposition captures the motivation: "*Engineers competent in both systematic and systemic approaches are better able to deliver complex and interconnected components / systems with predictable performance on schedule, quality, cost, and alignment within a dynamic, uncertain system of systems environment.*" Four key areas of systems knowledge that all engineers need, were also identified: 1) Systems Science and Fundamentals, 2) Systems Thinking, 3) Design and Analysis, and 4) Technical and Project Management.

No convincing evidence could be gathered of examples where some level of systems engineering education is required for all engineering programs offered at a department / college / school of engineering at a university. Given the nature of modern and futuristic engineering projects that practicing engineers would be involved with, they are likely to be a part of multi-disciplinary teams that would include engineers from other disciplines as well as experts in various non-engineering fields including management, social sciences, and other disciplines relevant to the nature of the system under development. There is a need for all engineers to know some fundamentals of systems engineering and systems thinking.

5. Establishing an Engineering Core at Regent University

Over the years, Regent University has established itself in fields like Law, Government, Psychology, and Education. Over the last decade, it started offering undergraduate and graduate degrees in STEM related areas including Computer Science, Cybersecurity, and Information Systems. In 2017, a new Department of Engineering & Computer Science was established and existing Computer Science and related degree programs were moved to it. Additionally, Regent University identified two undergraduate engineering degree programs in Systems Engineering and Computer Engineering, to be the first two engineering programs to be offered by the University in Fall 2018, pending required accreditations and approvals. The computer engineering program could utilize some of the courses already offered in other related programs, but all courses for the systems engineering program need to be designed from scratch. This is a very unique situation in two significant ways. Firstly, systems engineering is not usually the first engineering program to be offered by a University. Typically, traditional engineering programs like mechanical and electrical engineering would already be offered before systems engineering programs are launched. This leads to the second situation where all 'engineering' courses including systems engineering courses need to be designed afresh. Just one other engineering program (i.e. computer engineering) will currently be sharing some of the general engineering courses, but that program is just being launched as well. This is not only a tremendous opportunity to design a holistic systems engineering program without having to deal with any legacy courses, it is also possible to infuse systems engineering into all foundational engineering courses.

Discussions in the previous sections established the need for an 'engineering core' for all engineering graduates with the primary objective of preparing them for the complex multi-disciplinary nature of contemporary engineering projects. The need for a foundation in systems engineering and systems thinking was also established. Based on these, it was decided to establish an engineering core currently consisting of six courses, that would be 'required courses' for all engineering program at Regent University – currently just two, but many more to be launched in the coming years. Hence, every engineering graduate of Regent University – irrespective of their engineering major, will graduate as a *partial* systems engineer!

In developing the curriculum, four categories of courses were identified for the entire engineering program:

1. General Education: Regent University requires every undergraduate student to take this set of courses. Except for some limited choice of courses, these courses are largely fixed.

2. Math & Science: In order to meet the ABET accreditation requirements, a number of math and basic sciences courses are included in this category. Most of these courses are already being offered for other degree programs, and a few require some updates in content and delivery modes. A new course being developed specifically for engineering programs is 'Probability, Statistics, and Quantitative Methods', which will also be accompanied by a lab to provide hands-on experience with a variety of quantitative tools and techniques.

3. Engineering Core: A set of six courses are identified under this category, that every student of engineering will be required to take. Except one course, the remaining five will be new courses. Though not counted as one among the six, two capstone courses in the final year are also considered to be part of the engineering core, since the requirements will be the same across all engineering majors, and will even encourage formation of interdisciplinary teams.

4. Engineering Major Courses: For the systems engineering program, all these major courses need to be designed afresh. The computer engineering program utilizes some of the existing courses already being offered.

The courses that will be part of the engineering core are listed below, with details on the course content:

1. Engineering Foundations I: This course introduces various foundational concepts, history, terminology, standards, and elements of engineering as a discipline and profession. Units, dimensions, and various engineering variables are introduced, with no discipline-specific focus. While some of these topics will be covered in separate courses, a brief introduction to and correlation between ethics, economics, and management from an engineering perspective is provided. Basics of engineering drawing and CAD modeling are included. The course concludes with discussions on the future of the engineering discipline, and engineer of the future.

2. Engineering Foundations II: This course introduces the students to lifecycle models and processes, and the engineering design process. Here is an area where systems engineering is introduced as a broad holistic framework. There are various different models and processes available within and across different engineering disciplines. While there is a lot of commonality between them, there are differences in taxonomy and scope. Instead of providing a single (and perhaps narrow) view of lifecycle and design, a broad holistic perspective is presented from a systems engineering perspective. This will enable the students to better understand systems engineering and also be able to map the many variations and variety of models and processes onto a common framework. This will also enable the students to engage in meaningful conversations with engineers from another branch. For example, the steps and definitions in some other discipline's design process could be different from their own. Students will also be introduced to various traditional and contemporary engineering disciplines – their foundations, applications, special considerations, etc. The intent is to make all engineering students aware of some level of detail about other branches of engineering – not to help them decide on their engineering major, but rather to understand the foundations of other engineering disciplines that they are likely to interact with in future.

3. Systems Thinking and Approach: While deliberating on the systems engineering knowledge that every engineer needed during the INCOSE Academic Forum meeting in May 2015, top of the list by a comfortable margin was systems thinking. By focusing on specializations and super-specializations within traditional engineering disciplines or in specific inter-disciplinary aspects, engineering students seem to be losing sight of the bigger picture, a holistic approach, and an appreciation of the nature of interactions, interfaces, and inter-dependencies. By using the term systems thinking in the course title, the emphasis is clearly and explicitly on systems thinking, with the recognition that it also goes by other names like critical thinking, big picture thinking, and holistic thinking, though there is no common understanding on what these really mean. Systems theory and systems dynamics will also be introduced appropriately. It is the desire that all engineering graduates of Regent University will be systems thinkers to some degree at the very least.

4. Modeling, Simulation, and Analysis: It is not an exaggeration to say that much of engineering today is 'digital' engineering. Modeling, simulation, and analysis are integral to design and development in any engineering discipline, though the specific tools and approaches could be very different. But then, critical challenges arise when models and simulations from different disciplinary tools need to 'talk' to each other. Getting them to 'talk' is not always easy, and even close to impossible in some cases. Students will definitely get exposed to discipline-specific tools later on, but by providing them a generic tool-agnostic approach to modeling and simulation, they will always be reminded of the need not just for individuals from different engineering disciplines to communicate with each other, but for digital models and data to interact as well. Even in large complex engineering projects, physical prototypes and mock-ups are giving way to digital prototypes. And the global nature of product design and development among

geographically dispersed teams working asynchronously makes a sound foundation in modeling and simulation an absolute necessity for the engineer of the future.

5. Engineering Ethics and Profession: With unimaginable developments in modern technology and the widespread impact it has on everyone's everyday lives, engineers need some kind of a framework to deliberate and arrive at decisions that are moral and ethical. It is not just about the variety of technology options available for adoption, but the basic need or objective of the technology must be examined in the first place. There are many improper and inappropriate uses of good technology in the world today, that it is upon the engineers to focus on the fundamental need, which should always be in the interest of common good. That is the purpose of the engineering profession. The students will learn from various ethical decision-making scenarios.

6. Introduction to Computer Science: Just as modelling, simulation, and analysis is a commonly required skill for all engineers, an introduction to computer science is also such a common skill. Every engineer works with computers in some shape or form to perform their engineering activities. Software tools are the modern drawing boards, T-Squares, and calculators. Also, software is an integral part of most engineering systems that deliver critical value to the user – be it cars or washing machines. A deeper understanding of the basics of computer science is essential for all engineers.

One other course under consideration for the engineering core is 'Engineering Economics and Management'. Currently, an introductory course in economics is counted under the 'general education' category. While this would add another course to engineering core, there will be no change in the total number of credits / courses for the program.

6. Implementation Challenges and Considerations for the Engineering Core

While the preceding section presented and discussed the six engineering core courses to be included in every engineering program at Regent University, there are some specific challenges and considerations to be addressed while implementation:

- Online Delivery: The new undergraduate engineering programs will be launched exclusively as online programs, with on-campus and hybrid offerings to be considered in the near future. This makes the B.S. in Systems Engineering program at Regent University unique, and probably the first of its kind in the US. But by doing it this way and not the other way around, courses are being designed deliberately for online delivery - online versions are not being created from an already existing on-campus version. This allows for designing all the instructional material as well as all the assessments and student interactions for online asynchronous delivery.

- Resource Material: Most established and long-running courses in engineering or otherwise, tend to take the approach of selecting a course textbook and to utilize all the instructor resources, presentation slides and test banks provided by the publisher. While instructors do customize course content to reflect their personal teaching styles or to incorporate contemporary trends and developments in the field, this is still optional. But with the engineering core courses, particularly with the objective of introducing appropriate systems engineering knowledge, generating instructional material not found in the course textbook is imperative and no longer an option. This also means generating assignments and test banks. Most importantly, these courses need to be developed such that other full-time or part-time faculty who are not involved in the course development may also be able to use these resources to teach the courses effectively.

- Student Experience: It is a challenge to be able to offer an online learning experience to the remote student that is comparable to an on-campus learning experience, particularly to an engineering student. The right software and media tools need to be employed in generating and delivering the instructional material in an interactive manner. Instructional material also need to be in the form of videos and not just as presentation slides with or without audio commentary that goes along with them.

- ABET Accreditation: While acquiring ABET accreditation for the engineering programs is a huge motivator, it also highlights the necessary ability to successfully impart the learning outcomes to students upon completing each course. And, in a manner that can be verified and approved by evaluators. While ABET has accredited online engineering programs in the past, such programs are certainly rare. A digital equivalent of labs and workshops are required for the basic sciences courses like Physics as well as the engineering major courses.

7. Conclusions

Establishing a new program from scratch is by itself a unique opportunity and challenge. It is even more uncommon for systems engineering to be the first engineering program to be offered at a University where traditional engineering disciplines have not yet been offered. Hence, this is an opportunity to do some things with limited to no resistance from existing university structures, policies, and legacies that were established for engineering programs being offered for many years. While there are many universities that do offer some kind of a common core for all engineering programs, the proposed engineering core at Regent University is distinctive in some respects:

- The engineering core consists of a fixed set of six courses that every engineering student will be required to take, with no choice.
- The primary objective of the engineering core is to enable all engineering students to acquire a basic appreciation and understanding of many other engineering disciplines that they are likely to interact with in future – not to help them select an engineering major.
- The engineering core includes an explicit course on ‘Systems Thinking and Approach’, and Systems Engineering terminology and concepts will be infused into other courses in the engineering core.
- While engineering majors will study additional tools and techniques relevant to their particular discipline, a common ‘Modeling, Simulation, and Analysis’ course will be taken by all engineering students, to introduce tool-agnostic methods and model integration.

It will not be until 2022 when the first graduate of an engineering major will step out of Regent University. It will not be until a few years later that the effectiveness of the engineering core in the professional lives of the engineering graduates can truly be evaluated. Regent University is committed to graduating engineers who will go on to be transformational leaders around the world. And time will tell how good they are and if they will be partial systems engineers at the very least.

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