An Engineering Approach to Course Design

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1.0 Introduction

An essential task of our profession as engineering educators is the design of new courses. This task has become more challenging due to (a) new requirements imposed by globalization and the demands of the 21st century workplace, (b) the changing needs of our student populations, and (c) the lack of formal training in pedagogy among engineering educators. The purpose of this paper is to provide a pedagogically sound methodology for engineering course design, similar to the iterative process used for the design of an engineering product.

2.0 The Process of Course Design

A suggested process for course design is illustrated in Figure 1[1,2]. The first step is to decide where we want to take our students. This involves the definition of the course learning objectives (CLOs), which is a set of skills describing what the students should be able to do with the course material at the end of the term.

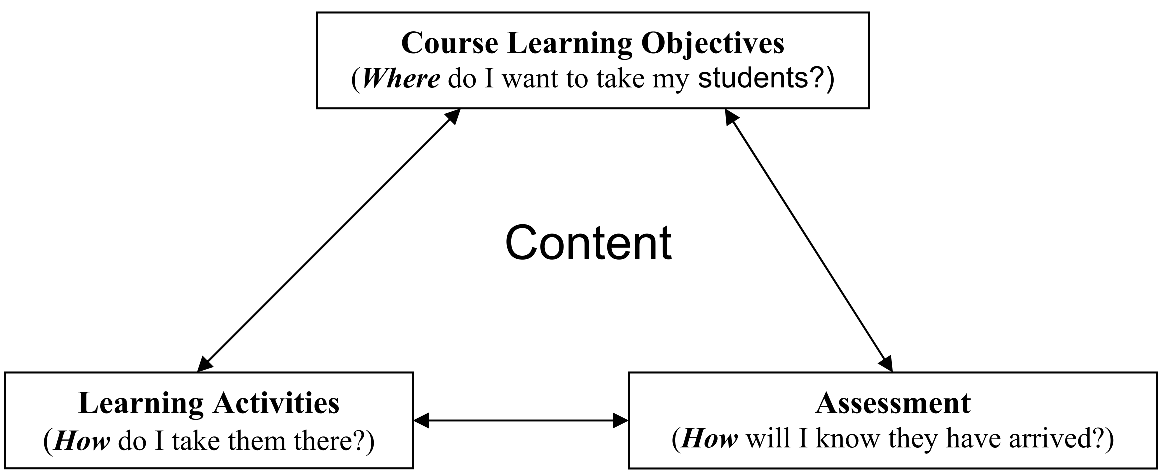

Figure 1: The course design process.

The second step is to decide what kind of evidence we need, to determine whether students have met the CLOs. What kind of information should we collect from the students or third parties (ex. industry or community supervisors with whom the students may have worked) to convince ourselves and others (ex. accreditation agencies) that our students have indeed mastered the skills specified in the CLOs? This approach is referred to as backwards design in the literature[2].

The final step in the process is the design of learning activities, inside and outside the classroom that will ensure students develop the skills outlined in the course learning objectives. As Figure 1 shows, the content is simply the vehicle in this process. This does not in any way imply that course content is not important. It does, however, imply that more important than the content, which represents the data base (knowledge) of a professional, are the skills (tools) used to manipulate this knowledge to meet goals dictated or strongly influenced by attitudes and values[3].

The arrows in Figure 1 go both ways, indicating the need for iteration just like in the design of an engineering product. If the specifications are not met during testing, the engineer goes back to the drawing board, makes any necessary modifications, rebuilds the product and tests it again. Similarly, if assessment in a course indicates that a large number of students do not meet the CLOs, the course designer (instructor or coordinator) may have to (a) revisit the learning activities to ensure they indeed help students meet the CLOs, (b) re-examine the appropriateness of the learning objectives in light of the course prerequisites and / or the abilities of the students taking the course, and (c) re-examine the assessment methods to ensure that they indeed assess the skills prescribed in the course learning objectives and not something else. In each case, the course designer may have to make adjustments to any or all of the three elements with the ultimate goal that most, if not all students will meet all the CLOs.

3.0 Course Learning Objectives

A course learning objective (CLO) is an intent communicated by a statement describing a proposed change in the learner – a statement of what the learner will be able to do when he / she has successfully completed a learning experience[4]. Course learning objectives may incorporate not only goals appropriate for the course content but also instructor specific as well as program-specific goals (ex. program outcomes specified by ABET). As Figure 1 shows, CLOs actually drive the design of the course just like the specifications drive the design of an engineering product. They influence the number and types of in-class activities, out-of-class assignments, projects, laboratory experiments, tests, etc. that the students would have to perform to acquire the prescribed skills. Moreover, CLOs guide a critical evaluation of the relative importance of topics and the allocation of instructional time per topic. Each objective requires some class time on the part of the instructor and usually much more time outside of class on the part of the student. A detailed list of objectives allows the course designer to estimate how much time, in class as well as outside of class, is needed for students to achieve all CLOs. In the process, some material may have to be eliminated.

Appropriate CLOs ensure that students acquire working knowledge of the material and higher level cognitive and affective skills. Moreover, they communicate effectively our expectations from the students while at the same time provide a clear picture of what they should be able to do if they pass the course, important information for instructors of follow up courses as well as new instructors teaching the course for the first time. Finally, CLOs are now required by ABET EC 2000 to be part of all syllabi for engineering courses.

Critical CLOs for 21st century engineering graduates include process skills, such as open-ended problem-solving, design, communication, teamwork, self-assessment, ethics, and lifelong learning skills, that address higher levels of Bloom's Taxonomy.

3.1 Bloom's Taxonomies

Bloom introduced taxonomies of educational objectives in the cognitive[5], affective[6], and psychomotor[7] domains. The cognitive domain is concerned with intellectual outcomes, such as knowledge, understanding, and skills and carries most of the weight in engineering course design. The affective domain involves emotional outcomes, such as interests, attitudes, and appreciation and it has become very relevant in engineering education with the recent emphasis on lifelong learning skills, professionalism, ethics, and teamwork, introduced by ABET EC 2000 in the eleven outcomes of Criterion 3. The psychomotor domain deals with motor skill outcomes. For engineers, such outcomes may be of interest in the operation of laboratory equipment and free-hand drawing.

3.1.1 The Cognitive Domain

Benjamin Bloom introduced in the 1950s six levels of competence in the cognitive domain[5] to provide a qualitative way of organizing thinking skills from the most basic level to higher order thinking. In the 1990s Lori Anderson (a former student of Bloom) slightly revised Bloom's taxonomy[8] replacing the original nouns that defined each level with verbs (ex. "knowledge" in level 1 was re-defined as "remembering") and switching the original levels 5 (synthesis) and 6 (evaluation) to the new levels 5 (evaluating) and 6 (creating). Examples of different level CLOs from an aerodynamics course are given in Table 1.

Table 1 – Examples of different level cognitive objectives from an aerodynamics course

Level 6: *Creating*	Design a wing for a supersonic executive jet.
Level 5: *Evaluating*	Prepare a list of the design criteria for an airfoil to be used on the wing of an ultralight airplane.
Level 4: *Analyzing*	Analyze the ground effects for an airfoil.
Level 3: *Applying*	Use the SUB-2D program to explore the effects of thickness and camber on the aerodynamic characteristics (lift slope, aerodynamic center, etc.) of airfoils
Level 2: *Understanding*	Explain Kelvin's theorem and its implications for the vortex system of an airfoil. Explain induced drag in 3 different ways.
Level 1: *Remembering*	Define the following: (a) Mach number, (b) stagnation and critical conditions for isentropic flow, (c) stagnation and critical conditions for flow with heat addition Define the following: (a) Mach number, (b) stagnation and critical conditions for isentropic flow, (c) stagnation and critical conditions for flow with heat addition

It is very important to note that levels 4, 5, and 6 require higher order thinking skills. An excellent definition of these skills is given below[9]:

Higher-order thinking by students involves the transformation of information and ideas. This transformation occurs when students combine facts and ideas and synthesize, generalize, explain, hypothesize or arrive at some conclusion or interpretation. Manipulating information and ideas through these processes allows students to solve problems, gain understanding and *discover new meaning. When students engage in the construction of knowledge, an element of uncertainty is introduced into the instructional process and the outcomes are not always predictable; in other words, the instructor is not certain what the students will produce. In helping students become producers of knowledge, the instructor's main task is to create activities or environments that allow them opportunities to engage in higher-order thinking.*

Distinguishing between Level 3 and Level 4 Cognitive Objectives

In every major topic of any engineering course at least one CLO should be level 4 or higher to encourage students' development of higher order thinking skills and working knowledge of the material. Since both level 3 and level 4 objectives may involve problem solving it is important to be able to distinguish between problems that are level 3 and those that are level 4. A problem will help students develop level 4 skills if it has one or more of the following characteristics[10]:

- There is no explicit problem statement. Rather, a scenario / case study is given and the students must define the problem themselves.
- There is no explicit statement in the problem to tell students what knowledge / technique / skills to use in order to solve the problem.
- The context of the problem is brand new.
- It requires strong oral / written communication skills to convey the essence of the problem and also to present the results.
- Several level 3 skills must be integrated to solve the problem.
- There is some ambiguity in the problem statement, so students will have to make some assumptions. Moreover, there may be more than one valid approach and more than one valid solution.

Implications for Course Design

A common problem in many courses is the emphasis on content rather than skills. As a result, most of the material is presented at levels 1, 2, and 3. This may explain why we often hear faculty members complain that students do not possess the ability to integrate previous knowledge in a given course, even though they may have earned high grades in prerequisite courses. For example, students may be able to follow procedures and solve well-defined problems if they have seen similar examples solved[10], however, they cannot apply their knowledge when the context is new. Level 4 (analyzing) is the minimum level of mastery (working knowledge) students must possess to effectively integrate and apply what they know in practical situations and follow up courses. Moreover, level 4 is the minimum level of mastery students must possess when they graduate, to be able to study new material on their own and develop as lifelong learners.

On the other hand, mastery of higher level objectives requires more time in class as well as outside of class. Using examples of CLOs from the topic of viscosity in fluid mechanics, Table 2 shows estimates of how much class time an instructor may need to present the material at each level and how much time a student may need outside of class to climb each level of competence.

Table 2 – Time estimates to reach various levels of competence in the cognitive domain

	Required class time (instructor + students)		**Required time outside of class (students)**	
Level 1: *Remembering*	1 min	State the definition of viscosity. Present Newton's law of viscosity.	1 min	Memorize the definition of viscosity.
Level 2: *Understanding*	5 – 10 min	Present / solicit examples of viscosity in nature and technology.	10 – 15 min	Review examples of viscosity presented in class and the text.
Level 3: *Applying*	50 – 75 min	(a) Present two examples on how to use Newton's law of viscosity to calculate viscous forces and other related quantities. (b) Allow students to work out a similar problem in small groups. (c) Discuss the results and address questions that will arise.	2 – 3 hr	(a) Review example problems presented in class and additional examples in the text. (b) Solve related homework problems.
Level 4: *Analyzing*	30 – 45 min	Demonstrate the process of designing a viscometer or present the solution of an open-ended problem related to viscosity.	1 – 2 hr	(a) Review the solution of the open-ended problem presented in class. (b) Solve additional open-ended problem (homework)
Level 5: *Evaluating*	30 – 45 min	(a) Compare all the different types of viscometers available in the market with regards to cost, range of viscosities they can measure, accuracy and reliability. (b) Discuss guidelines for selecting the best type of viscometer for different applications.	2 – 3 hr	Research the different types of viscometers available in the market and compare them with regards to cost, range of viscosities they can measure, accuracy and reliability. Select the best viscometer for a particular application.
Level 6: *Creating*	30 – 45 min	Present the design of an innovative viscometer that meets all the specifications and constraints of a unique application.	2 – 3 hr	(a) Review the viscometer design presented in class and any related information in the text. (b) Carry out the design of a viscometer for a particular application.

The following observations in regards to Table 2 will help establish some guidelines for course design:

- Viscosity represents only one topic (one fluid property), usually presented as a section of the first or second chapter in a fluid mechanics text. As is evident from Table 2, an instructor needs anywhere from 2.5 hrs (2 x 75 min sessions) to 3.75 hrs (3 x 75 min sessions) of class time to teach this topic at all levels of competence. In addition, students will have to spend anywhere from 7 to 11 hrs to bring themselves up to the 6^{th} level. This is a significant investment in both class time as well as study outside of class.

- It is not always necessary that students acquire level 6 competence in every course topic. As mentioned earlier, level 4 is sufficient. In the example given in Table 2, reducing the level of competence from 6 to 4 eliminates 1 – 1.5 hrs of class time and 4 – 7 hrs of study time.
- Regardless of the level of competence a topic needs to be taught, the course design presented in Table 2 is neither unique nor optimum. For example, students could take responsibility to acquire all level 1 and level 2 skills on their own, outside of class. In this particular example, it may seem that the time savings are not great, however, considering all the topics in a particular course, this approach may free up to the equivalent of 3 to 4 lectures. Moreover, students could study straightforward example problems presented in the text beforehand and bring to class questions regarding these problems. This could save an additional 15 – 30 min of class time, which could be used much more effectively to coach students on level 4 type skills. Alternatively, this time could be used on other course topics. The important issue here is for the instructor to distinguish between the skills that require his / her coaching of the students in class and the skills that students can acquire on their own outside of class. The same principle applies when coaching sports, music, and other activities.
- It is not appropriate to spend all the available class time for a given topic on levels 1, 2, and 3 and somehow expect students to acquire level 4 skills or higher on their own[11]. Higher level skills require higher level teaching.

3.1.2 The Affective Domain

There are five levels of competency in the affective domain[6]. As was the case in the cognitive domain, mastery of each level can be demonstrated through certain actions. Course learning objectives in the affective domain are expressed as statements that describe how students should behave at any time during their learning process, whether in the classroom or outside the classroom. Because behavior is value driven, we can extrapolate and draw conclusions about the values students have developed by observing their adherence or not to the standards of behavior spelled out in the CLOs. Again, objectives must be as specific as possible, so that student behavior related to them can be observed and evaluated. Table 3 gives examples of different level affective objectives appropriate for any course.

It is evident that the affective domain represents attitudes and values, which strongly influence student behavior. The development of proper attitudes and values is essential for lifelong learning because without them one cannot possibly develop skills in the cognitive domain. Levels 4 and 5 require a high level of maturity on the part of the student. Level 4 (organization) represents the minimum level of mastery students must possess when they graduate, to develop as lifelong learners[12].

Table 3 – Examples of different level affective objectives for any course

Level 5: *Characterization* (by a value complex).	Adhere strictly to the University's Honor Code. Cite appropriately all references used in laboratory and design reports. Contribute equally in every team assignment and expect teammates to do the same.
Level 4: *Organization* (of values into a system).	Balance family, work, and school responsibilities effectively. Formulate a systematic approach to learning (ex. read the appropriate sections in one or more texts while taking notes and summarizing key ideas, workout example problems, search the library / internet / bookstore for additional resources on this topic if needed, solve additional problems, interact with classmates and the instructor as necessary, etc.) and reflect frequently on how well this approach is working).
Level 3: *Valuing* (an object or a behavior).	Show commitment to the course by coming to class prepared, performing all the assignments and submitting them by the due date, seeking help from classmates, the teaching assistant and the instructor when necessary, and being available to help others in need.
Level 2: Responding (to a stimulus).	Read assigned material beforehand to prepare for discussion and problem-solving in class. Carry out assignments. Meet with teammates outside of class to work on lab reports and design projects.
Level 1: *Receiving* (a stimulus).	Attend class / field trips and arrive on time. Participate in discussions, problem solving, and other in-class activities.

4.0 Assessment

Assessment is the collection and analysis of data to inform changes that will improve an outcome. Just as student understanding of concepts develops over time, so assessment needs to consist of a collection of evidence over time. For example, informal checks for understanding during lectures provide a quick and easy preliminary assessment of student learning on a daily basis. These may be followed by weekly quiz, more formal monthly exams (midterms), and finally more substantial performance tasks, such as open-ended problems and design projects. It should also be noted that traditional quiz and exams can be used to assess primarily competence in levels 1 through 3, while higher levels of competence require more authentic performance tasks. There are three types of assessment, which are described briefly in the following sections.

4.1 Diagnostic Assessment

Diagnostic assessment is usually performed at the beginning of a course to ascertain, prior to instruction, student strengths, weaknesses, knowledge, and skills. This information can then be used to adjust the course content and pace to better suit students' needs. For example, in the aerodynamics course at SJSU (AE162) on the first day of class students take the Fluid Mechanics Concept Inventory[13], while in the compressible flow course (AE164) they take both the Fluid Mechanics as well as the Thermodynamics Concept Inventory[14]. The purpose of these tests, is to establish how well students understand basic prerequisite concepts and / or identify misconceptions, so the course can be adjusted appropriately based on the students' background.

4.2 Formative Assessment

Formative assessment can be performed any time during a term to inform quick changes in content delivery for the purpose of improving the quality of student learning during the particular offering. Informal classroom techniques are used to check student understanding of concepts on a daily, weekly, or monthly basis[15]. This kind of data can inform adjustments in pace and / or delivery methods. For example, in the first ten minutes of class students take a short quiz (2 – 3 questions) on the assigned reading. In addition, they are asked to write any questions they may have from their reading assignment, the most important of which are then addressed by the professor in class. Similarly, in the last ten minutes of class students may take a second quiz, this time on the new material presented in class. For both tests the answers can be collected and used as part of the course grade or simply shared on a voluntary basis as a way of establishing a common base of understanding.

Student surveys is another tool that can be used in formative assessment, as they provide valuable information about what works in the course and what needs to be improved from the students' perspective. However, these should always be supplemented with more authentic assessment based on actual student work evaluated by an expert (ex. midterm exams graded by the instructor, design briefings graded by industry mentor).

4.3 Summative Assessment

Summative assessment is performed upon the completion of the course to provide accountability by checking whether the CLOs have been met. This information can be used in formal reports to accreditation agencies (ex. ABET). It can also be used to inform more substantial changes in content delivery, for the purpose of improving the quality of student learning in subsequent course offerings. Comprehensive final exams and project reports, based on cumulative learning experience, are common tools for summative course assessment.

New technologies offer possibilities for longitudinal assessment of student performance over time. For example, electronic portfolios can document improvements in student performance from the freshman to the senior year.

4.4 Rubrics

A rubric is a set of guidelines for rating student work that describes what is being assessed, provides a scoring scale, and helps the instructor correctly place work on the scale. Rubrics are particularly useful when grading non-technical skills such as teamwork[16], communication, ethics, contemporary, global, and societal issues but also technical skills such as problem-solving[17], design of experimentats[18], and engineering design.

5.0 Learning Activities

The design of learning experiences that prepare students in the skills specified in the CLOs is the most critical part in the course design process. It is equivalent to the manufacturing process of an engineering product. Depending on the nature and level of each CLO, a variety of traditional and non-traditional approaches can be used to ensure student engagement and learning, taking into consideration how students learn best. Research shows that non-traditional methods such as active (AL), cooperative (CL), problem-based (PBL) / inquiry-based (IBL) learning, service learning, case studies, debates, and role playing can be much more effective in achieving critical learning objectives that involve process skills[3,19]. Brief examples of how some of these methods can be employed in engineering courses are described in the following sections.

5.1 Active Learning

All learning is active. No student has ever learned anything without first doing something. For example, he/she must read the textbook or other material, think about the concepts introduced and their applications, write papers and reports, solve problems, design a product, serve in the community, etc. In the old paradigm of teaching engineering, learning activities for the most part took place outside the classroom, as class time was used exclusively for lecturing by the professor. The students were simply passive recipients of the professor's wisdom. However, many studies have shown that pure lecturing is not a very effective teaching method. Hence a new paradigm has emerged, where AL implies that some of the aforementioned learning activities are also performed in the classroom under the guidance of the course instructor. A few examples of how passive classrooms can be transformed into AL environments are as follows:

- Socratic dialogue: this is an attempt to teach students how to reason by following an inductive process that moves from a specific case to a general principle, using a series of well designed questions. For example, rather than starting with the general principle of continuity in a fluid mechanics course, the instructor may ask students to guess the relative magnitude of the flow velocity at various points of familiar flow fields[20], leading them to the general principle of conservation of mass.
- Individual problem-solving: following the solution of an example problem on the board by the professor, the students are asked to solve a similar problem on their own. The professor walks around and checks their progress, answers any questions the students may have, and provides guidance as necessary. This approach is in tune with learning theory[21] that has established conditions for learning, two of which are opportunities to 'approximate' what is being taught and readily available 'feedback' from significant others. Moreover, it provides an opportunity for the instructor to informally assess achievement of CLOs.

5.2 Cooperative Learning

Johnson, Johnson and Smith[22] define cooperative learning (CL) as *instruction, which involves students working in teams to accomplish a common goal, under conditions that involve positive interdependence, face-to-face promotive interaction, individual as well as group accountability, and group processing*. These conditions distinguish effective CL from other forms of group work. A student team may have as a goal to summarize material presented in class or in a textbook, solve a problem, perform an experiment, design a product / process, write a report, or even take an exam as a team.

There are two good reasons for using CL in engineering classes. First, research has repeatedly shown that students learn better when working with each other than when working in isolation or competing against each other[23, 24]. When implemented properly, CL increases faculty instructional productivity[25], promotes higher order thinking skills in students[26], and improves student retention[27, 28], especially in the freshman year. Second, it offers students opportunities to practice team skills such as leadership, small group communication, conflict management, and decision making.

Cooperative learning takes AL to a higher level by taking advantage of the student-to-student interaction. A few examples of how CL can be implemented in engineering classrooms are as follows:

- Problem-solving: following a demonstration by the professor, students work in teams of three to solve problems in class. Experience has shown that students can overcome challenges and arrive at a solution much faster when working in teams.
- Case studies: students work in teams to research (outside of class) a case study in safety, ethics, and liability issues from a particular engineering product and present it in class, posing questions to be addressed in a discussion following their presentation[16].
- Contemporary, global and societal issues: students research (outside of class), present, and discuss in class contemporary engineering applications and their impact in a global and societal context[16].

In addition to the benefits mentioned above, CL provides opportunities for informal, in-class assessment of student learning. The instructor has opportunities to observe student work and provide immediate feedback. Students on the other hand, receive feedback from the instructor as well as their teammates.

5.3 Problem-Based Learning

The majority of the 'problems' solved by engineering students during their undergraduate training are well-defined, with explicit statements, providing all the information necessary to arrive at the one and only correct answer[10]. These 'problems' are sometimes referred to as exercises in the literature[10, 29]. Although a necessary step in the learning process, exercises do not prepare engineering students for the real world. Open-ended problems on the other hand, are ill-defined, provide a new context which may be unfamiliar, and have no explicit statement telling students what principles to use or what assumptions to make. Moreover, there may be more than one acceptable answer as well as more than one approach to arrive at those answers. Open-ended problems are a great tool for developing problem-solving skills[10, 29]. Students can also be encouraged to identify their own problems of interest, which integrate material from two or more courses[17].

The PBL approach takes AL and CL to yet a higher level. In PBL, students are first presented with a problem or case study. Then they work in teams to organize their ideas and previous knowledge related to the problem and pose questions on aspects of the problem they do not understand. Lecturing follows the presentation of the problem but is kept to a minimum. Instead, students are coached to search for information and work cooperatively to find answers. The faculty member acts more as a coach and facilitator, prompting with questions and providing guidance as necessary. The logic behind PBL is that topic-driven instruction makes sense for someone who already understands the subject. It is not necessarily the logical approach for someone who is trying to learn the subject. The PBL approach (from the top down rather than from the bottom up) keeps students engaged by using an interesting problem as a point of focus. Moreover, it allows students to take more responsibility for their learning, an important condition for becoming lifelong learners[21]. In the process, students become more receptive to theory, ideas, and concepts presented in class because they now have a purpose for all this: the problem at hand. Lastly, students learn how to formulate, define, and analyze problems, which is certainly not the case when they simply solve exercises.

6.0 Conclusion

A process for engineering course design was presented in this paper as a systematic way of ensuring that each course contributes towards the goal of producing engineering graduates with the skills required in the 21st century workplace. This process resembles the design cycle of an engineering product in the sense that you must start with an end in mind (specifications – CLOs), establish the criteria for success (certification – assessment), and finally make the product (manufacturing – learning activities). Just like with the design of a product, iteration and compromise are two key words in this process. Iteration is necessary because the complexity of the task precludes the possibility of being 100% successful in the first attempt of the cycle. Compromise is necessary because the specifications often include conflicting requirements. For example, the requirement to "cover" a large amount of content in a given course will conflict with the requirement to produce engineering graduates with higher level skills.

Just like with engineering design, different faculty members at different institutions may produce different courses for the same subject that are equally effective in preparing students for a given set of skills (CLOs). There is still a need, however, to define common skills (CLOs) for each engineering course. Moreover, there may be a need to establish common assessment tools as part of a common accreditation process. These two steps would go a long way towards standardizing engineering education and facilitating the mobility of engineering students as well as engineering graduates around the world.

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