Freshman Engineering: Current Status and Potential for the Future

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First-Year Engineering Courses: A General Structure for an Overview
Understanding of Engineering

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Abstract

This paper is an evidence based study of first-year engineering courses based on a number of interviews with course coordinators as well as a theoretical analysis of the problem of what first-year engineering students should know about the field of engineering. The one common denominator for first-year engineering courses is that they are all different. They range from a single class taught by a single professor in an engineering department to 2000 to 3000 students from an engineering college broken into a number of very large sections each year. The emphasis of these classes ranges from teaching a programming language to teaching design using a team environment to engineering analysis. Many times programming languages are a primary emphasis of these courses with a single platform or a combination of platforms being taught, including MATLAB, C, C++, Fortran, Excel, visual basic, Java and Python. There is clearly no consensus on what or how first-year engineering students should be taught.

By examining the goals of these courses we can better understand how the current state evolved and where we can go from here. The goals of these course in general involve preparing the first-year student for the remainder of their academic and professional career and take the form of teaching students what engineering really is and why it is important to society, how to work in teams, how to implement design, how to program a computer, how to solve engineering equations, how to solve engineering problems and how to develop models. While these are noble goals, most students fail to understand the significance of what they have been exposed to and how it relates to the courses that they will be taking in their sophomore, junior and senior years. Moreover, the emphasis of these courses can distort the student’s perspective of what engineering is, e.g., many times the students that take classes that primarily emphasize design leave these classes thinking that design is all that engineers do. To the professor that understands the full extent of design, the design experiences in these classes are perfectly logical, but the uninitiated student lacks the overall perspective to appreciate what they have been exposed to. Based on my interviews, I did not find a single first-year course that provided a balanced view of engineering and a structure with which a student could organize their academic and industrial training and meeting this need is the objective of this paper.

Based on this perspective, we will examine the full range of engineering fundamentals (i.e., ethics, problem solving, modeling, analysis, design, economics and communications) in an effort to layout an approach that prepares first-year students for their future careers in a manner that is consistent with their current knowledge and experience (i.e. high school math and science). That is, in a general sense engineering reduces to either engineering analysis or engineering design both of which rely on
problem solving and modeling. Engineering economics provides a means to consistently evaluate the performance of an engineering project by using optimization while engineering communications allows for the effective dissimilation of the engineer’s results. Finally, engineering ethics provides a means for navigating complex legal, social and ethical issues. Moreover, we will demonstrate how this approach can be applied and still expose the student to teamwork, design, programming, etc. This approach provides a simple, but powerful structure with which to understand engineering and its practice. In this manner, the student will be able to understand how each class that they take in the future relates to their overall goal of becoming a successful engineer and after they graduate and become practicing engineers, they can continue to effectively use this structure to build their base of knowledge.

INTRODUCTION

First-year engineering courses have been added to the engineering curriculum over the past 30 to 40 years in an effort to engage the students in engineering at an earlier time\textsuperscript{1}, improve retention\textsuperscript{2}, provide an introduction to engineering disciplines\textsuperscript{3}, inspire the student for the study of engineering, have students recognize the importance of engineering in our modern way of life, etc. Even though there is general agreement on the objectives of the course, the course content used for these courses varies widely\textsuperscript{4}. First-year engineering classes take two general forms: classes taught by individual engineering departments and a common engineering class taught at the college level. The common engineering approach is used by less than 1/3 of engineering colleges and many of these require that first-year student wait until their sophomore year until they declare their engineering major.

I contacted approximately 25 engineering colleges that have adopted the latter approach to determine the scope of their first-year engineering programs. I found that there is an extremely wide range of approaches used for first-year engineering education and that many of the approaches used are strongly influenced by intra-college politics. The course credit hours range from one to six hours while there is a wide range of topics taught by these classes:

- the various activities that the different branches of engineering perform
- working in teams
- performing engineering design
- performing engineering analysis
- developing engineering models
- solving equations
- programming a computer

MATLAB is clearly the most commonly used programming language although other programming languages such as MS Excel, C, C++ and Python are used as the programming language or in some cases are used along with MATLAB. The one common denominator for first-year engineering courses is that they are all different. When first-year engineering classes are taught at the department level, the content varies even more broadly because these classes are many times designed to meet the immediate
needs of the department, e.g., providing an introduction to statics or teaching a particular programming language that is used in the upper division classes. Moreover, the emphasis of these courses can distort the student’s perspective of what engineering is, e.g., many times the students that take classes that primarily emphasize design leave these classes thinking that design is all that engineers do. To the professor that understands the full extent of design, the design experiences in these classes are perfectly logical, but the uninitiated student lacks the overall perspective to appreciate what they have been exposed to. Based on my interviews, I did not find a single first-year course that provided a balanced view of engineering and a structure with which a student could organize their academic and industrial training based on my academic experience, my experience as a practicing engineer and interactions with industry. Therefore, the remainder of this paper is aimed at meeting this need.

The material that follows will examine the opportunity to introduce first-year students to an overview of what engineering entails and the concepts that are used by all engineers instead of attempting to teach specific engineering skills. Nevertheless, there is still a need to teach certain specific skills, such as computer programming and unit conversions.

THE GENERAL STRUCTURE OF ENGINEERING

Engineering can be broadly broken into one of two categories: engineering analysis and engineering design. Engineering analysis deals with improving an existing process or device while design involves creating a new process or device.

Figure 1 is a block diagram representation of the procedure used to apply engineering analysis. Engineering analysis involves improving an existing process (e.g., increasing the production rate) or an existing device (e.g., correcting problems with the device). In any case, engineering analysis deals with solving a problem and overall is based on applying problem solving techniques. Engineers rely on models to solve engineering problems while the models can range from accumulated engineering experience to a prototype of a device to detailed numerical simulations based on the physics of the system. When the results of the model are combined with economic parameters for the system, the economic performance can be quantified. Many times optimization algorithms adjust aspects of the system under study until the optimum performance (i.e., maximum profit) is determined. Note that the optimization of the economic performance of the system is generally an iterative process based on evaluating the results of the model and the economics a number of times until the optimum performance is determined.
Figure 1 A diagram representing the engineering analysis process.

Figure 2 is a block diagram representation of the procedure used to apply engineering design. Engineering design involves developing a new process or device to satisfy a perceived need. Many times the primary problem during the design process is to identify a variety of potential design solutions and this problem is addressed using problem solving techniques. Note from Figure 2 that, in general, each potential design can be evaluated using engineering analysis. Therefore, engineering design can be viewed as the application of a series of engineering analysis problems until the best design is identified. In this case, the overall design process is only as good as the process of generating potential design approaches. While for the case for engineering analysis the system is specified, the design process determines the specification of the system (e.g., size of process equipment or the material and shape of a device) that satisfy the perceived need and result in maximum profit.
In summary, the structure presented in Figures 1 & 2 is based on having a general understanding of problem solving, modeling, engineering economics and optimization. Moreover, this structure is both a simple and general representation of the full range of engineering activities.

PROBLEM SOLVING

Problem solving can be systematically approached using the Engineering Method as shown in Figure 3. Note that, in general, the Engineering Method is iterative as indicated by the spiral toward the solution. The two most important steps in this procedure are defining the problem and evaluating the solution because if the problem is not properly defined, the solution is not likely to be useful and evaluating the solution ensures that the solution is valid. The engineering method is the basis for modeling and design as shown later.
A good example to demonstrate the application of the Engineering Method is to determine if the ideal gas law provides sufficient accuracy for the molar density of a gas using experimental measurements for the gas. Another good example to demonstrate the engineering method for estimating the impact velocity of a baseball tossed vertically because it involves assumptions (e.g., neglecting wind resistance) and defining the problem based on what can be measured (e.g., estimating the maximum height of the toss instead of estimating the initial velocity of the ball). Moreover, during the validation step, the assumption of neglecting wind resistance can be shown to be invalid requiring one to estimate its effect on the impact velocity.

MODELING

Most engineers use models to solve technical problems. The typical way to represent a model is shown in Figure 4a showing an input and an output from the model. A model can also be represented by considering the parameters of the problem as inputs as shown in Figure 4b.

This representation can be understood by considering the model of a spring: the input is the applied force $F$ to the spring, the output is the displacement $x$ in the spring and the parameter is the spring constant $k$, i.e., the model is $x=F/k$. 
From Figure 4b, when the input and parameter are known, the output can be calculated, which is analysis. When the input and output are known, the parameter can be calculated, which is design. Finally, when the parameter and output are known, the input can be calculated, which can be used for control. Therefore, this input/parameter/output representation of a model can be used to represent analysis and design in simple terms.

The Engineering Method can be directly applied for the development of a model. Likewise, the model development process tends to be iterative in nature.

Empirical models are based on assuming the functional form (i.e., usually a linear relationship) between the input and the output. For example, reaction rate are many times represented as linear functions of reactant concentration. Then from a set of reaction rate versus concentration data, the rate constant can be estimated. Using the rate constant, this empirical model can be used to calculate the reaction rate given the reactant concentration. It is important to emphasize that empirical model are highly useful, but should never be used outside the range for which they were developed.

Phenomenological models are generally more accurate and tend to have a wider range of applicability than empirical models. Phenomenological models are normally based upon conservation or balance relationships and listed below are common examples:

- Force balances
- Torque balances
- Material balances
- Energy balances
- Balances for electrical circuits

The solution of simple examples, which are based on high school math and physics, for each of these cases can be used to convey the concepts associated with each type of balance. Consider the following examples:

**Force Balance:**

![Force Balance](image)

*Figure 5 (a) Ball hanging from a cable resting against a flat surface; (b) Free-body diagram for this case.*
Torque Balance:

![Torque Balance Diagram]

Figure 6 A balanced seesaw with a light person ($F_L$) and a heavy person ($F_H$).

Material Balance:

![Material Balance Diagram]

Figure 7 Mixing process.

Energy Balance:

![Energy Balance Diagram]

Figure 8 Schematic of a steady-state continuous process with heat transfer.

Balances for Electrical Circuits:

![Balances for Electrical Circuits Diagram]

Figure 9 A simple circuits for applying: (a) Ohm's law (b) Ohm's and Kirchhoff's law.
ENGINEERING ANALYSIS

Engineering analysis is the process of developing an understanding of a system by decomposing it into its parts, analyzing each part to understand its function and recombining each part in order to fully understand how the parts work together to produce the overall system behavior. Models are particularly useful in this regard because they afford the ability to investigate the workings of a system on a highly detailed level beyond what can be seen or measured physically.

System optimization and system troubleshooting are the primary examples of engineering analysis. Optimization is such an integral part of engineering because it is directly related to maximizing profit. Therefore, it is important to introduce first-year students to simple examples of optimization. Figure 10 shows a simple example of an optimization problem for which the energy usage increases product value, but the rate of increase of the product value decreases as the energy consumption increases. As a result of these competing factors (i.e., cost of the energy used and the value of the product), the optimum energy usage results in the maximum net profit indicated by point A in Figure 10. There is not need to introduce multi-dimensional constrained optimization because one-dimensional optimization conveys the concept without overwhelming the student.

![Figure 10 An example of an optimization problem.](image)

Troubleshooting is determining the source of a problem with a process or system and involves a problem that could have a large number of causes. The most common engineering problem requiring troubleshooting occurs when a product is off-specification, i.e., it does not meet critical specifications. A good everyday example of troubleshooting is how you get your car to start if it does not start in the morning.

ENGINEERING DESIGN

Engineering design is a process for creating something new that meets a defined need. There are two general types of design: standard design applications and open-ended designs. Standard design applications are design procedures that are generally accepted by a specific engineering community, such as the design of a road or the design of a distillation column. Usually, computer design packages are available for applying
these designs. Open-ended designs are the types of design problems that have not been routinely solved many times, and therefore, creative new solutions are required, e.g., new product design. Figure 11 shows a design procedure based on the Engineering Method that can be applied to both types of design problems.

![Figure 11 Schematic of the iterative design spiral.](image)

In conjunction with the procedure presented in Figure 11, the triad of desirability, technical feasibility and economic viability must each be satisfied for a viable design as shown in Figure 12.

![Figure 12 The interaction between desirability, technical feasibility and economic viability for design.](image)

Topics such as sustainable designs, materials selection and standards and codes are also important as they relate to the design process.

It has been estimated that 70-80% of all new product designs use the Stage-Gate Design process (Figure 13). The idea is basically to critically and thoroughly evaluate the viability of new product designs at a number of points from the early phase scoping activity to the testing and evaluation of the new product so that if the project is determined not to be viable at any stage, it can be terminated as soon as possible saving
time and money and thus reduce the overall risk of the project. In order to accomplish this task, multi-disciplinary teams are used for each stage and different levels of management are used to evaluate the results of each stage (i.e., a gate) to determine if the project should (1) go forward, (2) return to an earlier stage or (3) be terminated.

![Figure 13 Schematic of the Stage-Gate process for new product design.](image)

**ECONOMICS**

Engineering projects involve expenditures and revenues that occur over the life of a project and engineering economics provides a means of combining these cash flow streams into a single value so that different versions of a project can be compared on a consistent basis. Because engineering practice is generally based on economic performance, it is important for engineering students to have a general understanding of the time-value of money. For example, the present value $P$ of a cash flow (income or expenditures) of $F$ that is to occur $n$ years in the future is given by

$$P = \frac{F}{(1+i)^n}$$

where $i$ is the relevant interest rate. Cash flow diagrams (e.g., Figure 14) are useful for visualizing a project. In this manner, it is relatively simple to apply the previous equation to each element of a cash flow diagram and add the results together to evaluate the net present value of a project.

![Figure 14 The cash flow diagram for a project that involves purchasing a piece of equipment for $50,000 that generates income of $25,000 each year with annual expenses of $10,000.](image)

Everyday examples of economic project evaluation can be used to illustrate the procedure. For example, evaluating whether to take the cash-back option or zero percent interest rate for a new car purchase or whether to take the lump sum payment or yearly payments for a lottery winner can be presented to make relevant the importance of being able to consistently evaluate the economic performance of a project.
ETHICS

Many engineering programs wait until the senior design to expose their students to ethics. In my opinion, it is important to expose engineering students to ethical issues as soon as possible because they will be exposed to situations as a student that will test their ethics. A good way to approach this topic is to pose situations for a student that tests their ethical conduct. For example, what do they do if they find a copy of an exam that they will be taking later that day? A key point here is that the toughest ethical questions arise when doing the ethically correct thing appears to cost you in some manner.

Engineering ethics boils down to being fair and honest while performing engineering duties, but ultimately protecting the interests of the public. That is, it is the ethical duty for an engineer to protect the public even if it costs the engineer his/her job. Finally, understanding what is a conflict of interest and how to handle them is an important concept.

UNIT CONVERSIONS

When I interviewed the course coordinators for first-year engineering courses, I had several of them tell me that they “expected the students to know how to apply unit conversions before they entered as first-year students”. First-year engineering students come from a wide range of backgrounds and my experience of over 30 years of teaching undergraduates is that most undergraduates do not have a strong command of unit conversions. This is easy to determine by giving your class a pop quiz. Ask them to determine the potential energy of 10 lbm 100 ft above the ground in Btu using \( PE=mgh \) if 1 Btu=550 ft lb and \( g=32.2\text{ ft s}^{-2} \). My experience is that a significant number of undergraduates (not just first-year students) are not proficient at applying \( g \) for unit conversions. Because units are such an integral part of engineering calculations, it just makes sense to invest a little time to ensure that all freshmen know how to systematically apply unit conversions including the use of \( g \).

COMMUNICATIONS

It is also helpful for first-year students to understand the methods by which engineering results are communicated to co-workers, management or the general public: graphs and charts, drawings and diagrams, written communications and oral presentations. Some general guidelines can be quite useful (e.g., keep in mind the intended audience and their background and knowledge) without having to undertake the complete instruction of the students in these modes of communication.

CONCLUSIONS

It is my thesis in this paper that first-year engineering students should be exposed to a general structure of how engineering is applied by focusing on the general concepts without going into a great deal of detail by relying on examples that use high school
physics, math and chemistry. For example, students can be exposed to how force balances can be applied by using very simple systems without having to teach them how to apply force balances to a complex truss. Moreover, by exposing students to a few key concepts, the student can be provided an overview structure of engineering the details of which will be provided as they take their upper division classes and later gain experience as practicing engineers. Even if a first-year engineering class has students undertaking NAE grand challenge problems or using the inverted classroom, the students will be better prepared to understand the scope of what they are doing if they are provided an overall understanding of the full scope of engineering.

A single one-credit hour class can expose first-year students to these important concepts or a more substantial course can reinforce these concepts with more examples and problems. Even a course that primarily emphasizes design and working in teams can integrate these concepts in their classes because it compliments the primary emphasis of these classes without requiring an inordinate amount of time. As a result, students can leave first-year engineering classes with a more balanced understanding of the approaches that comprise engineering and better understand the importance of the courses that they will take during the remainder of their university studies. This can be accomplished by describing and illustrating problem solving, modeling, engineering economics and optimization and demonstrating how these elements can be combined to accomplish engineering analysis and design (i.e., Figures 1 & 2).

REFERENCES