# AC 2010-758: TEACHING NON-ENGINEERS TO ENGINEER

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Teaching Non-Engineers to Engineer

**Abstract**

There are challenges inherent in any program that strives to introduce engineering principles to non-engineering majors. These challenges are greatly exacerbated, however, when the goal is not merely to introduce, but to get the non-engineers to actively apply engineering principles to achieve specific design goals and to make solid, informed decisions based on their designs. At the United States Air Force Academy, every cadet is required to take several core engineering courses, regardless of the major, with the stated goal of being able to apply the engineering principles that are learned. This paper will explore the pedagogy developed by the Air Force Academy's Department of Electrical and Computer Engineering designed specifically to overcome the inherent challenges of teaching non-engineers to engineer. Moreover, the paper will discuss an effective approach to incorporating meaningful learning opportunities such as projects, labs, and hands-on experiments in the context of electrical engineering and "systems level" thinking. Finally, we will also discuss challenges and solutions in the assessment of engineering ability and in designing a course in which specific goals, learning opportunities, and assessment are well aligned.

**Introduction**

There is value added in beginning this paper with a working definition of the term "engineering". Simply put, before we can figure out how to teach non-engineers how to do it, we need to know what it is. For this paper, we will define engineering as the application of technical principles for the purpose of deciding how to solve a particular problem.

This definition has three main components:

- Engineering deals with technical issues
- Engineering deals with making decisions
- Engineering deals with solving problems

For several years, the core Electrical Engineering course taught at the United States Air Force Academy did not attempt to teach engineering as defined above. Instead, it offered a wide assortment of technical topics, with no strong, unifying themes. These topics included:

- Resistive circuits
- Transformers
- AC to DC conversion
- Transducers

- Transducer interfaces
- Amplitude modulation
- Graphing of AM signals (in time and frequency domains)
- Analog to digital conversion
- Digital to analog conversion
- Logic gates
- Flip flops
- State machines
- Radio transmissions
- Radar transmission
- Line of sight restrictions
- Doppler radar

Certainly, we tried to get the cadets to apply knowledge of these topics to solve problems, but the solutions to such problems usually involved little more than selecting the correct equation from an equation sheet and plugging in the right numbers. Furthermore, there was no emphasis on decision making, which we contend is an essential part of engineering.

Within the last two years, however, the academy's core Electrical Engineering course has been completely restructured to encourage cadets with non-engineering majors to actively apply engineering principles to achieve specific design goals and to make solid, informed decisions based on their designs. This process was neither easy nor trivial, nor is it complete. While we believe great strides have been made towards the goal of getting non-engineers to engineer, we know we still have much work ahead of us.

The purpose of this paper is to discuss the pedagogy developed by the Department of Electrical and Computer Engineering at the United States Air Force Academy designed specifically to overcome the inherent challenges of teaching non-engineers to engineer.

**Background**

The Air Force is an organization implicitly dependent on technology. This dependence is becoming even more prevalent as the tools needed to defend this great nation become increasingly more high tech. To help prepare tomorrow's leaders for the technological challenges they may face, all cadets at the United States Air Force Academy are required to take several core engineering courses, regardless of the cadet's major.

Accordingly, all cadets at the academy are required to take one of two Electrical Engineering courses. One course is offered for those cadets pursuing an Engineering or Physics degree and the other is for those cadets in non-engineering disciplines.

Over the past several years, the senior leadership at the academy has developed a forward-looking strategic plan that was used to restructure the core curriculum to achieve a set of desirable outcomes for cadets who graduate and join the officer ranks of the US Air Force. These 19 outcomes are grouped under three main categories--responsibilities, skills, and knowledge--and serve a dual purpose of preparing cadets for officership as well as providing a guide for a premier college education.

As a result of this strategic vision, two key changes were made in the core Electrical Engineering course for non-engineers:

- The course was moved from the sophomore year to the junior year in order to better align with other required science and engineering courses, such as sophomore level physics and mathematics.
- The course was tasked to directly support two of the academy's outcomes: Decision Making and Principles of Engineering and the Application of Technology..

The benefit of these changes cannot be overstated. By moving the course one year later, we gained an increased and palpable level of maturity of the cadets in the class. Additionally, we were able to mandate the sophomore-level physics course as a prerequisite, which measurably increased the level of technical understanding and dexterity of cadets beginning the course.

Perhaps most importantly, these changes also provided the impetus for a revamping of the entire course. Not just in what material was taught, but also why it was taught and what the cadets would be able to do once they learned it.

**Changes in Course Material**

As discussed earlier, the original content of the course was a large body of material which lacked strong unifying themes. Individual topics were introduced and developed and then abandoned as the next topic was introduced. While some topics were necessarily related, most were not. This lack of cohesion among the various topics was largely due to the previous course being the result of a hasty combination of a previously required course in digital logic with another course in basic circuits and electronic communications.

A significant part of restructuring the course involved developing central, unifying themes and eliminating those topics which did not readily align with those themes or were not particularly relevant to what a non-engineering officer would reasonably expect to encounter in the Air Force. After reorganizing the course, we decided on six unifying themes:

- Aircraft electrical systems
- Power distribution systems
- Unmanned aircraft systems
- The Global Positioning System (GPS)
- Radar
- Electronic Warfare

While there were certainly major changes made in the material covered, the biggest change was one of packaging, rather than content. The only topics removed from the original course were those dealing with digital logic and state machines. Neither of these topics were deemed essential as digital logic is already covered in the required freshman-level engineering course and feedback from cadets and faculty indicate that few of the non-engineering majors need--or retain--an understanding of detailed state machine design.

All of the other topics were incorporated into the themes listed above, with additional material added where needed.

The primary advantage gained by this approach is relevance. We accept as a fundamental truth the notion that students will more fully learn, understand, and retain a subject if they believe the subject is relevant to them. Packaging the several topics of the course into a handful of relevant systems allows us to maintain a high level of relevance throughout the course.

An advantage to this systems-level approach is that relevance seems to be transitive. This is, if the whole is relevant, then the parts are more likely to be relevant as well.

GPS is one example of this principle. Because of the ubiquitous presence of GPS devices in today's society, many students have a genuine interest in understanding how this system works. Because GPS is relevant to them, understanding signal to noise ratio becomes relevant as well. Furthermore, the relationship between signal to noise ratio and the power received in a signal that has traveled tens of thousands of kilometers becomes relevant as well.

Because of the unique audience we have in Air Force Academy cadets, we have been able to leverage the principle of relevance by a careful selection of systems. Nearly half of the cadets who take the course will go on to pilot training after graduation. Of the rest, most will have an opportunity to fly in one of the several aviation programs available at the academy and all appreciate the singular importance of aviation in fulfilling the mission of the Air Force. Therefore, by couching electrical engineering principles within the context of aircraft systems, we gained an invaluable resonance with the student.

**Course Readings**

Perhaps the most needed change in the course was the text itself.

The original text was written and revised over the course of several years by various instructors in the department. While parts of the book were genuinely good, the overall text fell short in three key areas

- It was difficult to read and understand
- It was no longer aligned with what was actually being taught
- It was not sufficiently targeted to non-engineers

Naturally, there is value added in having a text that is not only easy to read and understand, but which also actually covers the material that is being taught. The need to target the text to non-engineers is of equal importance.

The key issue is the simple fact that non-engineers don't think like engineers. By way of a specific engineering analogy, consider an ideal transformer, which is used to increase or decrease the voltage in an electrical system.

The relationship between the current and voltage on the primary side of the transformer and the current and voltage of the secondary side is given by the equation:

$$V_1 * I_1 = V_2 * I_2$$

From an engineering perspective, this equation tells us everything we need to know about the transformer. If $V_2$ is greater than $V_1$, then $I_2$ is necessarily less than $I_1$. Therefore, if a transformer steps up the voltage, then it must also step down the current. Additionally, since the equation for power is $P = IV$, we know that the power on the primary side is equal to the power on the secondary side. Therefore the ideal transformer itself consumes no power.

The point here is that engineers tend to think like engineers. Accordingly, from an engineering perspective, if a concept can be boiled down to a single, simple equation, then learning must unavoidably occur. For non-engineers, however, this is often not the case. Instead, the inherent relationships that stem from such equations must be specifically and explicitly discussed. They must also be reiterated and, in some cases, re-reiterated.

But writing for non-engineers involves more than just carefully explaining equations. A key stumbling block for non-engineers is the unavoidable fact that engineering texts tend to be boring. The root cause of this is in the incremental manner in which many texts are written.

For example, before the original text allowed a student to analyze a circuit with a transformer, it first subjected the student to a long and arduous explanation as to how a transformer really works. It began by defining AC signals and then moved on to a discussion of the magnetic properties of wire coils, which in turn led to a discussion of inductors. Eventually, the text put two inductors together to form a transformer, which then led to a derivation of whatever equations were deemed important.

While there may be nothing inherently wrong with this approach, it can easily and irreparably reduce relevance from the perspective of the non-engineer, who often has no vision as to why these intervening steps are important.

In the text we developed, we intentionally shied away from the incremental approach. Instead, we often start a particular lesson in the middle, or even the end, of where a more traditional text might begin.

In the lesson which introduces transformers, for example, we established relevancy by starting the reading by discussing the efficiency of a power distribution system that did not use transformers. By showing that power transmission is inherently inefficient, we were then able to show that transformers are essential to efficiently transmit power over large distances.

**High Impact Learning**

We believe that to learn engineering, you have to do engineering. Towards this end, we incorporated a set of three student projects to provide high impact learning opportunities. The tasks for the three projects were

- Design a power distribution system for an aircraft
- Design a digital communication system for an aircraft
- Design radar and satellite control systems for an aircraft

Each of the projects required teams of 3 to 4 students to write a detailed technical report. The third project also included an oral briefing. These projects were unmistakably the highlight of the course, in terms of getting the students to actually do engineering. Using the definition offered at the beginning of this paper, these projects allowed the students to apply technical principles to make decisions as to the best solution to each of the problems.

Because of the very limited experience level of the students, the tradespace between alternative solutions was necessarily small. Nevertheless, the projects allowed for a range of viable options with no single solution. The existence of multiple viable options initially caused confusion for some of the students as they were looking for the single “approved solution.” However, most groups quickly recognized that they had latitude to perform engineering trades based on measures of merits which they could define. This “ownership” of the criteria led to several groups becoming much more engaged and creative in the projects and led to a deeper understanding of the basic electrical and computer engineering principles and systems level thinking that we were trying to achieve.

An example of this ownership was allowing the students flexibility in determining the relative importance or weighting of the design criteria for each problem. We established key performance requirements which were required to be met and then gave other requirements for which we requested desired requirements. For instance, in the third project we established a minimum detection range for the radar system, but also established a maximum power dissipation for the radar. There were multiple options in the viable design space which met the range and power requirements, and the teams were encouraged to define their own rationale for further optimization beyond meeting the minimum requirements. This led to substantially increased discussion among the team members and faculty as to the operational impact and benefit of these key parameters.

In one section, a team created an additional decision matrix to include secondary impacts in order to improve their overall decision. This team compared the relative value of additional power for future upgrades versus the increased flexibility afforded by using the power for increased standoff range. This type of discussion greatly increased the depth of conceptual learning and far surpassed the types of learning we were able to achieve in the previous version of the course.

The ownership demonstrated by the cadet teams significantly increased their interest in applying the engineering principles once they were "unshackled" from finding the one right answer and instead began to investigate a range of acceptable or viable solutions for which they could define the relative measures of merit.

In addition to serving as high impact learning opportunities, the projects also revealed gaps between what we thought the students were learning and their ability to practically apply engineering principles. We intentionally scheduled the projects to follow a traditional written exam under the premise that studying for the exam would provide the basic engineering knowledge, while the projects would provide a venue for demonstrating application of the EE principles. The results were quite illuminating as we found that the written exams often did not adequately test the scope of basic knowledge. For example, in one class all 5 teams erroneously assumed that a 190 volt source rated at 30 amps would always provide 30 amps regardless of the load. The instructor did not realize the error in thinking until reviewing preliminary designs which included options for "dumping" the excess current into a dummy load. The class scored well on the traditional written exam but the project illuminated the issue and provided a forum for a great discussion on the practical design and use of voltage sources.

**Alignment**

Ultimately, the success of a course comes down to alignment. If properly aligned, all the elements of a course work harmoniously together towards achieving a set of published goals. The readings support the classroom discussions which support the labs which support the exams which support the projects which support the goals. This is not to say that the interrelationships between elements of a course only flow in one direction. Any of the elements can support the readings or the classroom discussions or any other element.

For the most part, we were able to develop a course that was fairly well aligned. The readings for each lesson contained a set of learning objectives, so that students and instructors all knew what was expected of the student. The four major exams in the course, including the final exam, were all built to carefully align with these stated objectives. Hands-on exercises and labs reinforced the key concepts in the reading material and the group projects worked to tie all of the principles together.

In fact, several students seemed incredulous that the reading, lecture, and homework for each lesson were consistent. Some instructors noted an increased number of epiphanies as students working on a lab realized that the display on the oscilloscope was showing the same amplitude modulation signal as was depicted in the homework problem from several lessons earlier.

Because of a desire to align the course, we were also able to eliminate pieces that clearly did not fit. One example of this was the elimination of a soldering lab, which did not contribute to the course goals. Getting rid of this lab was somewhat emotional, as some faculty were highly invested in the lab, which was universally considered to be both interesting and fun. Unfortunately, it did not fit and had to go.

The advantages of such reductions and re-focusing of course content reaped tangible benefits. By getting rid of material and activities that were not aligned, we were able to free up additional lessons, enabling the students to spend more time on the student projects.

While we believe we did well with aligning the course, we know there is much room for improvement, especially with respect to assessment.

In order for a course to achieve its stated goals, the goals for the course need to be stated and they need to be achievable. To be achievable, the goals need to measurable.

The relationship between the goals and how the goals are measured is critical. To be useful, the goals need to express what the course is ultimately designed to do: what will the students learn and what will they be able to do after completing the course. To be useful, the measurements must clearly convey how well the goals have been met.

Under the current iteration of the course, we have not sufficiently aligned what we want the students to learn and how we assess whether or not they have learned it. Although the exams were well aligned with the learning outcomes published with each lesson’s reading, we are not convinced the learning objectives sufficiently address what we wanted the cadets to be able to do after taking this course.

In designing a course, we now realize the absolute importance of developing an assessment plan very early in the process. Without such a plan, we fell into the common trap of trying to assess what was taught, instead of assessing what should have been learned. This is a subtle, but important distinction.

Fortunately, we have identified the issue and can now begin to choose and articulate specific and measurable behaviors for students who have take the course. With these in hand, we will then be able to revise the learning outcomes associated with each lesson and, when necessary, to change the text itself.

**Conclusion**

Through the experience of designing this course, we have learned several key concepts that could be of use to those tasked with designing engineering courses:

- Organizing the course according to unifying themes, such as a systems-level approach, significantly increases the relevance of the material from the perspective of the student.
- Developing (or choosing) a text which is easy to understand, which covers the material to be taught, and which is written for its target audience is very important.
- High impact learning activities, such as student projects, are crucial in allowing the students to transcend the level of understanding needed to merely pass the exams.
- Alignment is absolutely essential and needs to be incorporated throughout the course design process.
- An assessment plan should be drafted very early in the design process.

As mentioned in the introduction, we know that this effort is not complete, but is instead a work in progress. We are confident, however, that we are on the right track and look forward to more fully teaching non-engineers to engineer as the course continues to progress.