Towards a T Shaped Electrical and Computer Engineering Curriculum: a Vertical and Horizontally Integrated Laboratory/Lecture Approach

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Background

The field of Electrical and Computer Engineering is expanding at an exponentially increasing pace. In every aspect of modern life, the work of this profession is evident and even essential; areas as diverse as transportation, infrastructure, entertainment, health care, and energy are all fundamentally dependent on this foundational discipline, yet the basics of a typical curricular approach have changed very little in the past decades. If we are to educate engineers for the coming technical challenges as well as the capacity to work effectively in multidisciplinary teams, new educational approaches must be considered[1]. The engineer of the future must possess both a depth of understanding within their given field as well as an appreciation for its breadth. Furthermore, we must prepare engineers for learning and adaptability in their professional lives; this too has been recognized as an important need in both academia and industry[2].

The need for simultaneously addressing both breadth and depth within an engineering education is seen as an important part of preparing engineers of the future[1]. An outgrowth of these needs is the notion of the "T-Shaped" engineer[3]. We believe that in order to educate "T-Shaped" engineers a "T-Shaped" curriculum is required. We envision that the notion of T-Shaped may be applied within a discipline as well as in cross-disciplinary efforts, motivating our efforts toward a breadth-first approach in our curriculum. Our general approach is to achieve the depth component of the "T" via repeated application of successively deeper stages of the breadth component.

A typical Electrical and Computer Engineering curriculum presents the introductory material in a sequence of courses. In many cases these are sequenced as Circuits, Electronics, and Signals and Systems. While a curriculum structured in this fashion covers the basic material, student retention of key concepts may not be optimal. Signals and Systems courses frequently do not have a laboratory component, leading students to think of this as simply a mathematics course with little practical use. Also, students tend to see Electronics with its associated non-linear components and heavy use of models as a big hurdle when presented as a follow-on to the linear circuit concepts normally presented in the first course of the sequence. This perceived disassociation between courses does not promote a breadth of understanding of the material. Furthermore, although the first two courses in a typical sequence have an associated laboratory component, the material in the laboratory may not correspond directly to the concepts presented in lectures; lecture material is likely to be "stale" in the student's mind by the time their

particular laboratory session actually meets. These factors conspire to limit a student's depth of understanding as well.

The static nature of electrical and computer engineering curricula is also a contributor to decreasing nationwide enrollments[4]. Students must consider whether or not a curriculum structure that has not been renovated in many years can give them an education that will lead to strong employment opportunities[5].

There is considerable pedagogical evidence that suggests that learning a subject thoroughly requires repeated examination of topics. Merriënboer et al. have shown that the four-component instructional design (4C/ID) method is an effective approach to obtaining deep understanding of subject material[6]. In this model learners combine just-in-time learning approaches, with repetition of material at successively deeper layers of complexity. This has proven effective at transferring knowledge and intuition without leading to cognitive overload[7]. This suggests that a breadth-first approach would be an optimal path for restructuring an engineering curriculum.

In the balance of this paper, we will discuss pedagogical considerations, current and anticipated coursework, and our infrastructure. We will also discuss feedback and overall instructor impressions from our first course offerings. Finally we will discuss current material being offered in the second course of our sequence.

Pedagogical Considerations

In order to address these concerns and observations, we instituted a major curricular overhaul for the Fall of 2014. Our previous introductory sequence consisted of 3 courses, *Linear Circuits, Electronics 1*, and *Signals and Systems* - a very traditional approach. *Linear Circuits* had a laboratory component that met bi-weekly, *Electronics 1* had a weekly laboratory, and *Signals and Systems* had no laboratory at all. The first and third courses were assigned 3 credit hours, the second 4 credit hours. In this scenario, the students viewed each course as its own entity and frequently did not make the connections between the concepts in each. Electronics 1 would require a massive review of basic circuit concepts, and students did not see how Signals and Systems was anything other than a straight mathematics course, with no relevance to working with real devices.

All electrical and computer engineering students study linear systems and the various transforms that apply to them. This is traditionally done in one or two self-contained courses on *Signals and Systems*, covering basic mathematical concepts such as convolution, the Laplace transform, Fourier series and transform, sampling theorem, DFT, and filtering. In the past, we have covered the material using a lecture format, with demonstrations of the concepts interspersed throughout the semester. A demo might consist of collecting a sound-bite using a microphone and resampling or filtering it (using Matlab™) to hear the difference. Other than these demos, the students have to wait until the following year to see applications of the concepts learned, in

courses such as *Communications, Signal Processing,* or *Controls.* The assignments for the class comprise drills of the mathematical tools followed by applications of these tools to abstract problems. For example, the students may be asked to prove some properties of the Fourier transform, derive the Fourier transform for some given time functions, and then see the effect of filtering a time series by another function using the Fourier transform. However, this knowledge is not incorporated into opportunities to solve authentic engineering problems. As a result, the knowledge developed remains abstract and difficult to apply in design scenarios.

In our new sequence, these courses are replaced with *Fundamentals of Electrical Engineering 1, 2, and 3.* Each of these is a 4 credit hour course, and is taught in a studio format. In each course we include materials from each of the three former courses, starting with a high level view in the first and then going into more depth in successive semesters.

In *Fundamentals 1* we cover the following:

- Basic Circuit Theorems, Kirchhoff etc.
- R,L, and C components
- Equivalent circuits and circuit reduction techniques
- Diodes and MOSFET's
- Introductory frequency domain concepts, Bode plots, Fourier series etc.
- Introduction to simulation, CAD, and printed circuit board design and fabrication

This course offers an introduction to material from across the curriculum and blends in some non-traditional topics such as working with CAD and printed circuit design. Additionally it offers students an introduction to non-linear circuit elements and modeling concepts. Many of our students have participated in "Maker" and robotic events before coming to the University, and we believe that keeping this element of experience in the classroom is a valuable tool in maintaining student interest. It also amortizes the learning curve required for these tools over several semesters, which will be of benefit when they enter the fourth year and are required to do a Capstone design project. We employ *Multisim™* and *UltiBoard™* from *National Instruments Inc.* as our tool chain[8].

There were 2 sections of this course, a 3 hour section that met twice a week, and a 2 hour section that met 3 times a week; details of this course were described elsewhere[9]. First offered in the Fall of 2014, we now are offering sections each semester.

Fundamentals 2 was first offered in the Spring of 2015. In it we cover the following:

- Linear circuit elements and further circuit reduction techniques
- Linear time invariant systems (LTI)
- Convolution

- Operational amplifier and BJT's
- Laplace transforms and in-depth consideration of Fourier techniques
- More in-depth use of simulation
- Further circuit design and CAD project work

In *Fundamentals 3* our content will be:

- Optimizing the use of the active devices introduced in the prior courses
- In depth look at the limitations of active devices
- Discrete time signals and system concepts
- The Z transform and using it to design digital filters
- Extensive simulation work
- Detailed project work, including a more rigorous physical design

Note that this course format now gives an extra 2 hours of course credit in the three course introductory sequence, which allows to pursue more topics, and at a greater depth overall. For example, we anticipate that Fundamentals 3 will take course content up to an area normally reserved for higher level introductory courses such as *Digital Signal Processing*. In addition, *Fundamentals 3* will be offered at a time in the sequence when most of our students will have already had or are simultaneously taking *Introduction to Embedded Systems*[10]. We expect that this will allow us to have a great correlation between the 2 courses and allow experiments in each course to enhance understanding in the other.

Classroom Physical Layout and Equipment

In our new sequence, traditional core Electrical and Computer Engineering courses are replaced with *Fundamentals of Electrical Engineering 1, 2, and 3*. Each of these is a 4 credit hour course, and is taught in a studio format. The classroom space is shown in .

Figure 1 Physical classroom

Students are arranged in groups of 3, and sit at a triangular table arrangement that allows a total of 9 students in a cluster. We provide several strategically located projectors and screens and lectures are delivered with a high graphical content. Additionally pen-enabled displays are available for the instructors such that lecture notes may be displayed and captured for posting to the class website.

One of the challenges of the studio environment is dealing with space and visibility issues. Clearly a whole rack of test equipment and a traditional bench structure would severely limit how many students could be accommodated and what the physical structure of the

classroom layout would need to be. In order to alleviate this we selected the *Virtual Bench™* from *National Instruments Inc.* as our laboratory instrument[11]. This self-contained device contains a triple power supply, digital multimeter, function generator, 2 channel 100 MHZ oscilloscope, digital I/O, and a logic analyzer.
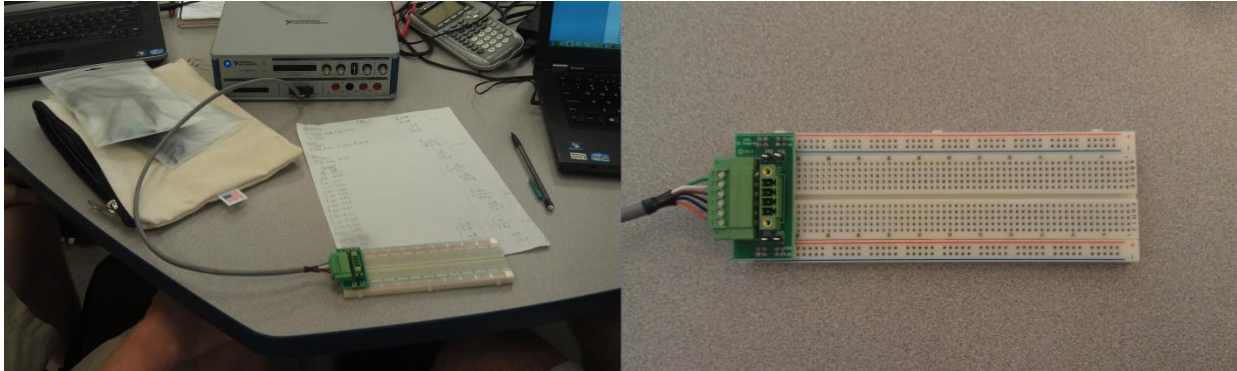

Figure 2 Virtual Bench and add-on cable

In Figure 2 we show the *Virtual Bench* along with an add-on adapter that we designed and had locally manufactured. This cable eliminated the necessity of requiring the students to manually attach power and ground wires to the screw terminals on the device and remains permanently attached to it. At the beginning and end of each class period students simply plug the header end into their solderless breadboards. An additional advantage of this approach is that the power and ground are naturally distributed down the horizontal rows which promotes a cleaner experimental layout for the students.

A typical class meeting involves a short lecture followed by an experiment that is designed to complement it. Depending on the material, a follow up lecture may be given or in some cases a longer experiment may be employed. At other class meetings, the experiment may come first, constructed in such a manner as to leave students with questions to be answered during the lecture portion.

We also make extensive use of undergraduate teaching assistants (TA's), especially with the laboratory and experiential portion of the class periods. Upper level students "apply" to the program, and are selected based in their interests and level of performance in their earlier coursework. This program has had several benefits. The undergraduate TA's universally acknowledge that this has helped them cement their own understanding of the earlier material from their own course experiences. Also, current students feel more open in discussing

the problems they might encounter in the hands-on portion of the class session, and the interaction also gives them a sense that they can also master the material. While intangible and difficult to quantify, we feel that this has led to an overall increase in enthusiasm from students across the entire ECE program. We generally have quite a few more applicants to be undergraduate TA's than we have positions for!

Instructor Assessment of Outcomes for *Fundamentals 1*

The new class in the new format was intended to accomplish three objectives. First among these was to provide an instructional methodology that would enable students to learn more material and achieve better understanding of the material. The second objective was to provide instruction that would enhance retention of important information so that this information could be better used as a foundation for future classes. The third objective was to provide a teaching and learning environment that would enhance interest and encourage excitement about the broader program and profession.

The experience with the first offering of the *Fundamentals 1* class was generally positive. The quantitative assessments of student performance based on in-class quizzes, lab reports, major tests, and a final exam demonstrated that 90% of the students achieved good understanding (grade C or better) of the topics included. The same quantitative assessments demonstrated that 60% of the students achieved excellent understanding (grade A- or better). The major tests and the final exam were judged by the instructor and by colleagues to be of appropriate breadth and difficulty to provide assessments comparable to those typical for other offerings of the equivalent class in the old format. This information suggested that students taking this new class in the new format covered more material and performed better. Thus, the initial assessment is that progress was made toward the first objective of having the students learn more material and achieve better understanding of the material.

The second objective to enhance retention of important information into future classes obviously could not be effectively assessed at the end of the first class. However, plans are in place to perform assessments of retention and understanding in future classes. This process has begun as this group of students has moved on to the next class in the sequence.

The third objective to enhance interest and encourage excitement was assessed through student surveys administered at the end of the class. Student responses were anonymous, and they were in the form of level of agreement or disagreement with various statements. The studio instruction approach melded lecture, discussion, and laboratory activities into integrated sessions, so the survey statements mostly focused this combined studio approach. Here are survey statements and summarized responses:

"Combining the class and the lab enhanced my learning"
– 84% Agree or Strongly Agree

"The hands-on activities helped me to understand the concepts more deeply"
– 81% Agree or Strongly Agree

"Doing labs during the class helped me to clarify my understanding of the topics"
– 77% Agree or Strongly Agree

"The class enhanced my lab skills"
– 86% Agree or Strongly Agree

The other responses available to the students were "Neutral," "Disagree," and "Strongly Disagree." Most of the responses that were neither "Strongly Agree" nor "Agree" were "Neutral." However, there were a few students who clearly did not like the class format or perhaps just did not like the class in general. However, on balance it appeared that most of the students liked the approach. Qualitative observations in class suggested that most students enjoyed the hands-on experiences, and many were observed to be experimenting beyond the expectations of the assignments.

In particular, the laboratory experience gained by the students proved to be far superior than the lecture course model that separates lab and lecture into separate sections and meetings (and, often, separate courses). The studio setting allowed immediate feedback of concepts and problems presented in class by providing a vehicle to test these concepts through experiment and measurement. In addition, the studio setting allowed direct involvement of the instructor and TA's with the students. The "personal" attention and interaction resulting from the studio model permitted the lab exercises to flow more smoothly, allowed every student to have hands-on experience with electrical measurements and use of the equipment, and provided a venue in which problems or issues arising during the lab could be discussed before the full class to illustrate debugging techniques or subtle points in circuit characterization that otherwise may have never been discussed.

The studio model also proved useful as an approach for attacking more "ambitious" design projects that extended over several class meetings. As each student in the class was required to purchase a modest circuit prototyping kit, circuits could be constructed outside of class allowing more time during the studio for characterization and debugging. Moreover, students could keep the circuits they had constructed and add to them in subsequent classes to create "systems"

consisting of different sub-circuits. In all, this approach appears to have been a successful step for preparing students to tackle more complex systems and concepts that they will encounter later in the curriculum.

Current Coursework in *Fundamentals 2*

While *Fundamentals 1* introduces diodes and MOSFETs as the active components, *Fundamentals 2* adds operational amplifiers and BJTs. We also begin to focus more closely on concepts traditionally associated with Signals and Systems, and relate them experimentally with circuit design and analysis techniques.

The first new active device introduced is the operational amplifier. Following conventional practice, we begin the introduction with the voltage controlled voltage source abstraction as shown in Figure 3.
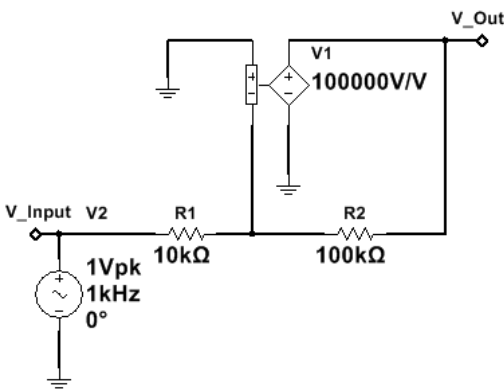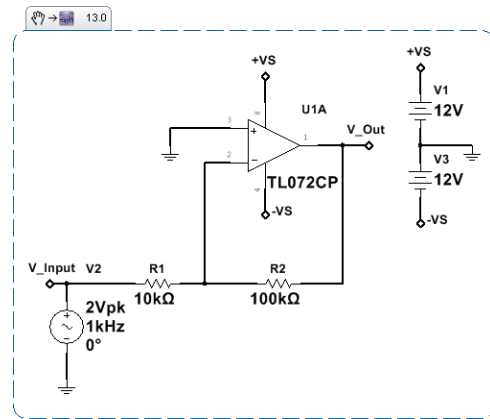
Figure 3 Opamp abstraction

Figure 4 Circuit as assembled

In a traditional lecture based course, the actual assembly and testing of this circuit would be relegated to a separate laboratory section. In our approach, once the basic abstraction is introduced, we go straight to a simple experiment in which we confirm the abstraction. We also introduce a design element into the exercise. The problem is presented to the students in this fashion:

"Design an inverting operational amplifier stage such that the overall voltage gain is -10 and the input resistance is 10K ohms. The power supplies available are +/- 15 volts".

Thus, rather than simply giving part values, we ask the students to think in terms of a circuit specification in terms of performance and give them the concept of design as opposed to simply experiment. At this point, the experiment becomes simple to construct and the final result is shown in Figure 4.

We ask students to explore the limits of the abstraction, particularly as it relates to the maximum signal amplitudes that can be handled and to the concepts of distortion. Students are asked to observe the onset of distortion by noting that once the maximum input level is exceeded, the inverting input no longer remains at virtual ground; the pulses in this condition may be seen at this node as in Figure 5. We present the experiment in this fashion in order to emphasize that there are boundaries on abstractions and models, and that once those bounds are exceeded the model no longer predicts the circuit behavior.
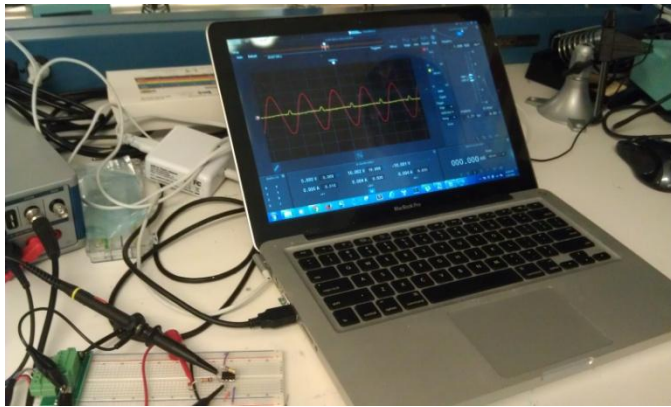

Figure 5 Exploring model limits

This approach further lends itself to introducing a more quantitative understanding of the Fourier series. From *Fundamentals 1*, the students are left with a qualitative understanding that all waveforms may be thought of as a summation of sinusoids. We can now use our experimental setup to show how the harmonic content of the output changes as greater levels of distortion are introduced. In Figure 6 we see the distorted output signal in the yellow trace, and the levels of harmonic content in the blue trace.

Additionally, integrated capabilities of the *Virtual Bench* allow us to have students download the actual data from the oscilloscope traces for further off-line analysis. This allows students to use several different tools to perform signal analysis. They may observe the Fourier magnitudes directly from the oscilloscope, or optionally may perform a full analysis using Matlab™.
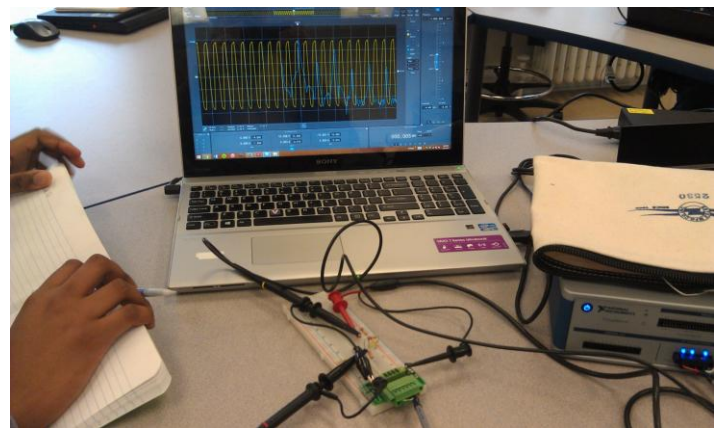

Figure 6 Time and frequency domain explorations

In *Fundamentals 2* the continuous time material from *Signals and Systems* is interspersed throughout, with an emphasis on illustrating each concept through a physical experiment. For example, in *Fundamentals 2* we introduce the notion of convolution and tie it to the impulse response of linear time-invariant systems. Following a short lecture on the impulse response, we show what convolution looks like numerically using a Matlab GUI. Then the students build a simple 1st order RC circuit and put a sharp rectangular pulse through it, emulating an impulse. Then they broaden the pulse and

observe the response of the system to a square wave. They record their results so that they can manipulate the data in Matlab. They can then compare their experimentally generated impulse response to the theoretical one, and their square wave response to the convolution of the impulse response and the square wave, as shown in Figure 7. They then look at what happens when the system is excited with a sinusoidal input. The subsequent lab explores 2nd order circuits and demonstrates the significance of complex exponentials and the effect of dampening, while reinforcing the notion of convolution. What before was a mathematical exercise in integration becomes an experience in probing a circuit with various input signals to see what happens. No rigor is lost, as they are still required to go through the drills of computing the convolution integral, but the process now has *meaning*.
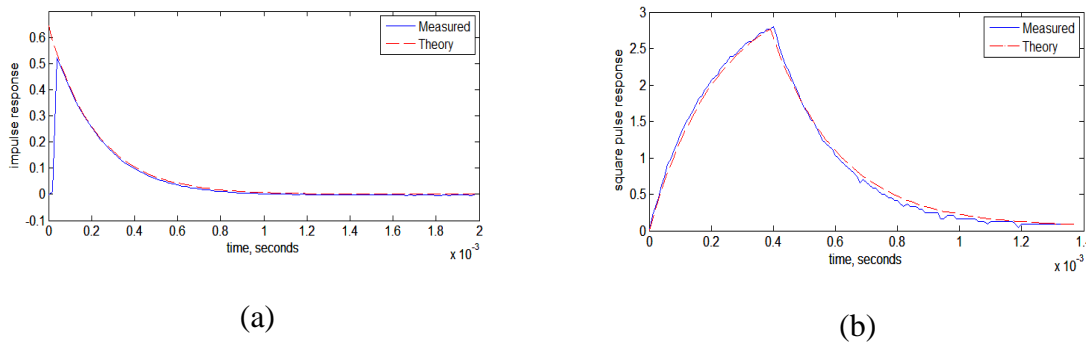

(a)   (b)

Figure 7 Measured and computed responses for an RC circuit using the hardware experiment and Matlab (a) impulse response, (b) step response.

It should be noted that a key element in making this course structure possible, especially as it relates to *Signals and Systems* concepts is the ability to gather data from the experiment in a simple fashion that is easily transported into other applications. In this respect the *Virtual Bench* meets our needs, both from a physical space requirement as well as constituting a data-rich learning platform.

Moving forward in *Fundamentals 2*, we have further experiments planned that will involve bringing in real-world signals for manipulation, filtering, and analysis. A useful source of time series data is available from Physionet[12]. This data consists of a large number of clinical observations of human physiological signals, including such diversity as EKG, ECG, and gait derived acceleration and pressure signals; both "normal" as well as "atypical" data are available and well annotated. We may exploit the arbitrary waveform generator ability of our bench setup to export these signals and have students work with filter designs for the elimination of interference and noise. We anticipate that the use of signals for which there is such a compelling source will help maintain student interest and enthusiasm. Examining the spectral content of an EKG is a far more compelling class exercise than working with square and triangle waves, which the students considered to be boring or contrived.

Summary and Conclusions

Moving from a conventional course sequence in ECE to the far more interactive and blended techniques of our *Fundamentals* series has proved to be an arduous task, but we feel that the results have been worth the effort. As we are currently moving into *Fundamentals 2* from *Fundamentals 1* we are noticing that we are able to go significantly deeper with material than would have been possible from our earlier sequence of courses, yet the students seem to be retaining the breadth that we are desirous of; a first step towards the "T Shaped" Electrical and Computer Engineering student. Also, the integrated laboratory environment keeps the physical reality of generating, manipulating, and analyzing real world signals in front of the students at all times and we are noticing a definite increase in the proficiency of laboratory skills.

We have also found that the student experience is a pleasant one and that students especially enjoy the hands-on activities. We firmly believe that including that aspect of electrical engineering, so tightly woven into the classroom, is both a learning experience as well as a motivator.

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