# A Breadth-First Approach to Electrical and Computer Engineering Curricula

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## Abstract

In our previous curriculum in Electrical and Computer Engineering, we have observed some impediments to students gaining a broad understanding of the field. The core material was taught in 3 segments: Linear Circuits, Electronics, and Signals and Systems, a structure similar to many conventional curricula. Retention and comprehension of the subject matter from one course to another was often sub-optimal, and there was no experiential content in Signals and Systems. To ameliorate these drawbacks, we have restructured our curriculum to incorporate a breadth-first approach. The three previous courses have been renamed to the Fundamentals Series and are taught in successive semesters. In each of these courses, students are exposed to material from all 3 of the courses in our first approach, and each course in the sequence presents the material at a deeper level of understanding. Additionally, each course is taught in a studio environment with tightly coupled lab and lecture material.

## Keywords

experiential learning, studio, breadth-first

## Background

At the University of Virginia, Engineering students declare a major at the end of the first year and begin in-major classes in the second. Our previous curriculum structure was based on a relatively standard sequence of core courses for the second and third years of our program.

In the first semester, students took a course in basic linear circuit theory, "Linear Circuits". This course dealt strictly with passive devices and had an associated bi-weekly laboratory that was separate from the lecture. Many of the laboratory exercises were of a "measure this" mindset and there was very little content to encourage creative thought. Also, due to scheduling, the laboratory material was frequently not up to date with the lecture and the lecture material was not fresh in the mind of the students when doing the laboratory exercise.

In the second semester, students took a course in basic electronic devices, "Electronics 1". This course focused on the most fundamental devices, i.e. diodes, operational amplifiers, MOSFET's, and bipolar junction transistors. Laboratory courses were offered on a weekly basis, which kept content somewhat more in synchronism with the lectures, and some design-related content was incorporated in the later laboratory experiments. However, we consistently observed that students had to re-learn some of the essential elements of "Linear Circuits" such as Thevenin and

Norton equivalents and were uncomfortable with the concepts of models and non-linear elements.

In the third semester, students took "Signals and Systems" which covered the basic continuous-time transforms, i.e. Laplace and Fourier, and included an introduction to their discrete time counterparts near the end of the course. There was no associated laboratory experience, although there were some exercises using MATLAB(TM). Many of our students tended to think of this as a math course, and not connected with any of the other parts of our curriculum.

In the fourth year, students take the Electrical Engineering Capstone Design course, and this is where we began to notice some of the drawbacks of our earlier curriculum structure. Our Capstone is organized as a single semester design-prototype-build sequence on an accelerated schedule as is typical of a new product "alpha stage prototyping process" in industry. Indeed, we go to great lengths to ensure that the experience is similar to that might be likely encountered later in their careers. Students appeared to struggle in putting together the "big picture" concepts required for a successful project, and many of the earlier course material concepts that they were to draw upon were lost.

There is a substantial body of pedagogical research that suggests that better overall concept retention results from successive presentations of material, with each iteration progressively requiring a deeper level of understanding.[1,2] Also, it is clear that in a dynamically changing field, such as electrical and computer engineering, that curricula must adapt on a continuous basis in order balance the needs of students that wish to pursue a graduate degree as well as those interested in entering the workforce.[3] It has also been demonstrated that courseware that incorporates project-based learning with an emphasis on hands-on experimentation along with concepts from across the breadth of the electrical engineering curriculum enhances both student comprehension as well as satisfaction.[4]

In response to our perceived needs, we have restructured our introductory course sequence and now refer to it as the "ECE Fundamentals Sequence." In each course in this sequence, students are exposed to concepts from each of the three previous courses described above, with a deeper level of understanding required at each level. Also the courses are offered in a studio format, with each daily course session including both a lecture component as well as an in-class experiment. Each course also includes a substantial design project element as well. We have previously reported on our first efforts with this approach, and in this paper we provide updates based on successive offerings of "Fundamentals 1 and 2".[5,6] We will also briefly describe our first offering of "Fundamentals 3" as well as how this approach has been employed in other parts of our curriculum, i.e. E&M Fields.

## Fundamentals 1

All of our courses are delivered in a studio style with brief introductory lectures followed by experiments that are relevant to the discussion. Our physical classroom arrangement is shown in Figure 1 below. An essential requirement for the studio approach is compact test equipment requiring little bench space. The enabling technology for this teaching style is the *VirtualBench* from National Instruments, shown in Figure 2.[7] This compact instrument combines a triple power supply, a dual channel 100 MHZ oscilloscope, a function generator, logic analyzer, and

DMM. Its low profile enables good visibility throughout the classroom that gives the students a sense of "space" even in a relatively compact and crowded classroom.

Figure 1 Typical lecture and lab bench setup

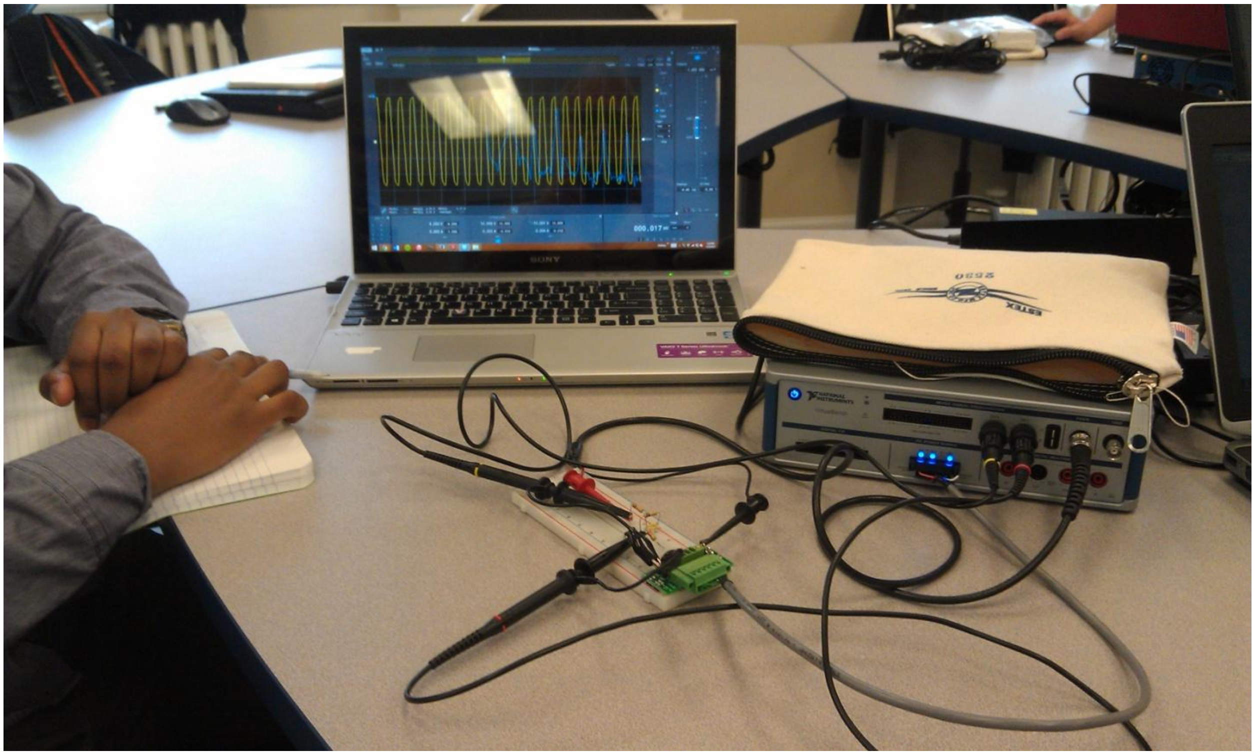


Figure 2

Fundamentals 1 is the first class in the new sequence, and it establishes foundations for both the approach and the content of the series. Several changes were made between the first and later offerings of this first class to improve upon on the early experiences. The initial offering of this course had included most of the passive device and circuits content from the more traditional linear circuits class, but it had also introduced non-linear devices including the diode and MOSFET. It further introduced the Fourier series at an introductory level to begin establishing the relationship between circuits and signals. The studio lab experiences were tightly tied to the lecture and discussion content, but they continued to be significantly directed. A small project was included that required student groups to design printed circuit board implementations of a simple MOSFET-based linear audio-frequency amplifier. The boards were fabricated commercially, and the final project of the semester involved populating and testing the boards.

The first offering of Fundamentals 1 was considered to be a significant improvement over the previous linear circuits class based on student performance and faculty and student subjective evaluation. However, the class instructor thought that the order of content delivery and the form and substance of the studio lab experiences should be modified. The most recent offering of the course has been amended to address those concerns. The following is a summary of the new content ordering:

1. Basic techniques of linear circuit analysis: resistors, independent sources, KVL, & KCL
2. Voltage and current dividers, series and parallel simplification, Wye-Delta transformations
3. Network theorems: Node Voltages, Loop Currents
4. Thevenin and Norton Equivalents, Superposition
5. Dependent sources, the ideal operational amplifier
6. Energy storage: the capacitor in the time domain
7. The Fourier Series as an introduction to the frequency domain, characteristics of AC waveforms
8. RC circuits in the time and frequency domains
9. Sinusoidal Steady State analysis and the notion of impedance
10. Phasors
11. Inductors, power in sinusoidal steady state
12. Non-linear devices and circuits – the diode
13. Analysis of circuits containing a non-linear device: analytical, graphical, piecewise-linear, and incremental approaches
14. The n-channel MOSFET as a switch
15. Digital logic from analog circuits, signal reconstruction, and noise margin
16. Large signal and small signal models of the MOSFET in a linear amplifier

New studio laboratory assignments were prepared to align closely with this topic sequence. Also the new assignments were adjusted to provide less guidance and a higher expectation for student thought. The ideal op amp material was new to this class, and it was timed to ensure that the students would be prepared to design and prototype a multiple op-amp circuit early enough in the semester for them to complete a printed circuit board design for their circuits. The final lab experience for the semester involved populating and testing their boards. The purpose for including the printed circuit board project was primarily to expose the students to this technology in anticipation of further, more advanced, printed circuit board design in future classes.

## Fundamentals 2

Fundamentals 2 builds upon the introductory concepts of Fundamentals 1. We explore solid state devices and introduce device models to ameliorate the analysis of circuits in a deeper fashion than Fundamentals 1. For example in Fundamentals 1, diodes are explored using the ideal and constant forward voltage drop models. In Fundamentals 2, we expand our coverage of diodes to include the exponential model. We also explore MOSFETs in detail and tie in important concepts from the frequency domain to define the appropriate limits of small signal modeling and distortion.

As in any first offering of a course, much is learned about the optimal order of presentation of concepts, and which ones need more coverage as well as that can be more limited. In our second offering of Fundamentals 2, we refined our approach and streamlined the way the material is presented. We build upon the fundamental circuits knowledge introduced in Fundamentals 1 and apply it to understand more complex circuits involving active electronic devices in a more systematic fashion. The material includes op-amp amplifiers, the MOSFET common source configuration, fundamentals of diodes and LEDs, the BJT common emitter circuit, and simple active and passive filters. The behavior of the systems is described theoretically and then tested experimentally. The theory includes signals and systems notions of Fourier series, Fourier Transform, and Laplace transform. The Fourier series is used to verify when the small-signal assumption fails by measuring the power in the harmonics. The Fourier transform is used to understand the high-pass filtering needed at the input and output of transistor amplifiers. Filter design based on zero-pole location in the system transfer function requires Laplace transform concepts.

Several changes were made compared to the first offering of Fundamentals 2.[6] The laboratories were organized such that one concept flowed more logically into the next. Matlab, a programming language entirely new to the students, was introduced with more guidance and instruction. In Fundamentals 2 we decided to eliminate the MOSFET common gate and drain configuration to allow for a deeper understanding of the common source architecture. Every topic was introduced as it relates to the end-of-year project, to give the students context for why we are studying the material. The schematic capture and simulation program, Multisim from National Instruments was used throughout the course by the instructors as well as the students.[8] Lab reports required simulation of the circuits for comparison with the measured results.

The Fundamentals 2 project aims to convert an audio signal into an LED display showing base and treble rich portions of the sound. The music enters the circuit via an audio jack, after which the right and left branches are added using an op amp summer circuit. The signal is subsequently split into two branches, sent to lowpass and highpass Sallen-Key filters. The cut-off frequencies are selected by the students to be appropriate for their taste in music. The two signals then proceed to peak detectors designed using diodes feedback through op amps, and then MOSFET transistors are used as current drivers for the LEDs. This project truly applies all the concepts explored throughout the semester-long course. The students used Multisim to select component values for their designs and exported the results to UltiBoard, the companion layout tool, also from National Instruments. Boards were fabricated directly from their data generated by UltiBoard. The students then populated and tested their designs.

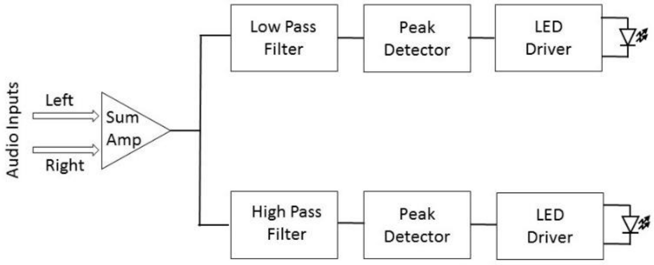


Figure 3 Block diagram of FUN 2 student project

The resulting printed circuit layout is shown in Figure 4

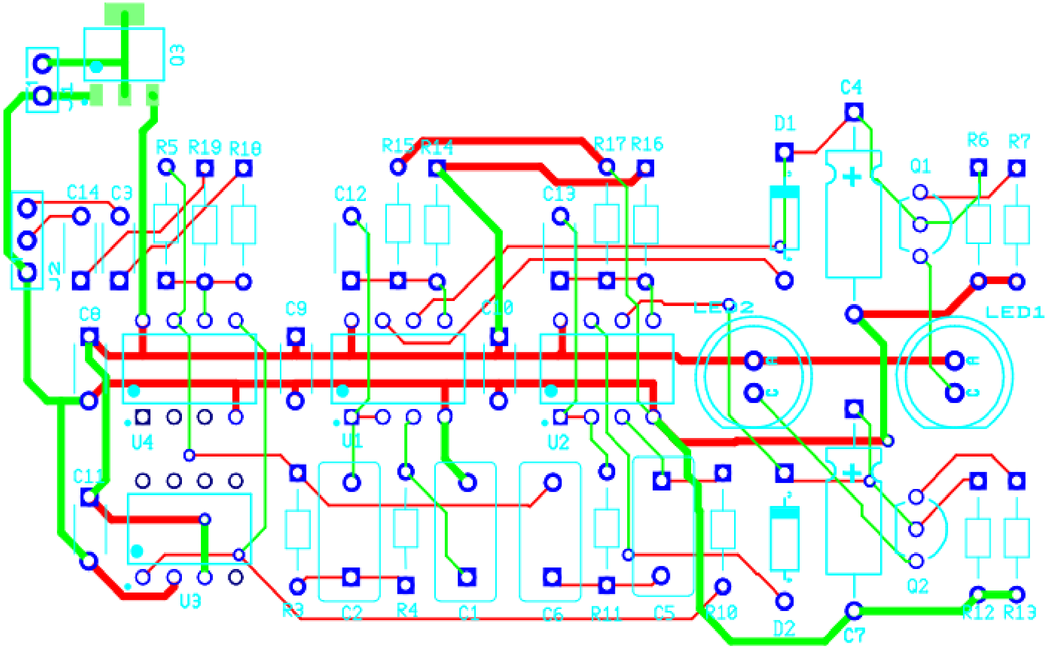


Figure 4 Student layout for FUN 2 Project.

## Fundamentals 3

In the current Fundamentals 3 offering, students are exposed to the deepest level of understanding that naturally fits within the expectations of core knowledge. Topics presented in previous courses are all reviewed and solidified by applying them to new and more sophisticated problems. For example, the simple second-order Butterworth filter introduced in Fundamentals 2 is cascaded to form higher order filter structures. The Laplace transform is used to explain how the simple PI controller works to track a reference signal using negative feedback. Fourier transform properties are applied to explore amplitude modulation and demodulation, both in theory and practice. Multiple op-amps are combined to show the construction and operation of an instrumentation amplifier. More detail on the validity of electronic components abstractions are discussed, such as the notions of op-amp common-mode rejection ratio and input offset voltage. We show the students how to measure excellent approximations of these critical parameters using simple instrumentation, such as illustrated in Figure 5.

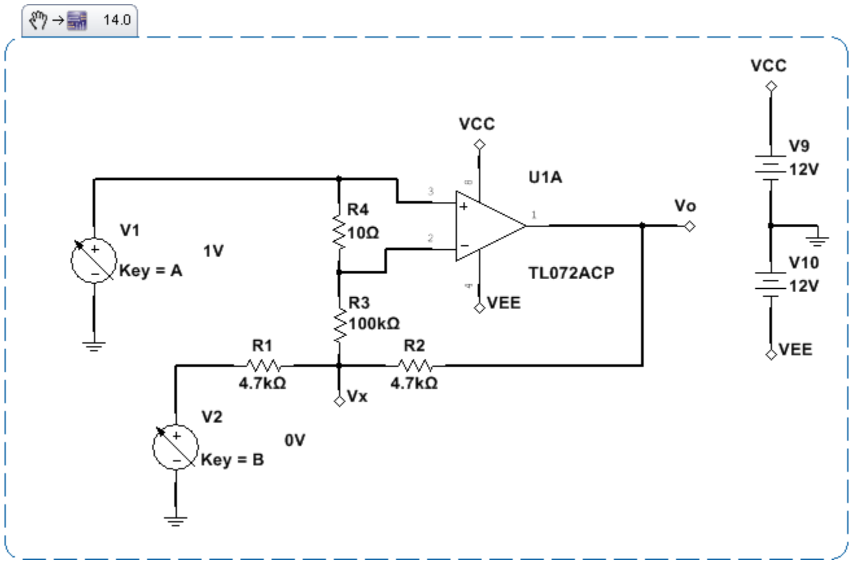


Figure 5 Opamp parameter estimation circuit

Fundamentals 3 is also where the fundamental transition between analog and digital processing is explored, a notion that is nowadays essential to both electrical and computer engineers. The material is presented within the context of an end-of-semester project: an electromyography (EMG) sensor and processor. The subtleties of sampling and evils of aliasing are taught. Discrete-time signals and systems concepts such as the discrete-time Fourier transform (DTFT), the discrete Fourier transform (DFT), the fast Fourier transform (FFT), and the Z-transform, are presented. Students explore the behavior of finite impulse response (FIR) and infinite impulse response (IIR) discrete-time filters as they apply them to canned data obtained from the Physionet database.[9]

Digital electronic devices are also discussed. Students are introduced to basic CMOS concepts and course coverage includes basic inverters and gates. We study the different operating regions that transistors go through in the switching transitions and develop equations for energy consumption as a function of frequency and voltage, leading to an intuitive understanding of dynamic voltage scaling concepts.

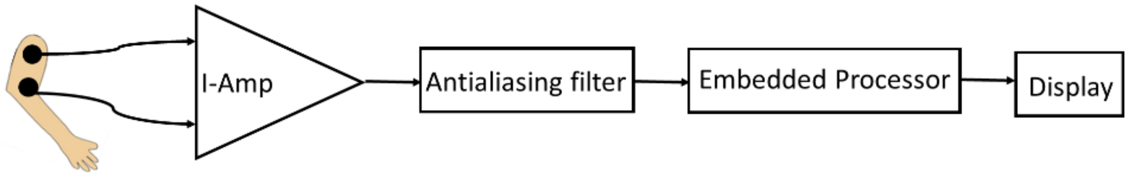


Figure 6 Student Project in Fundamentals 3: EMG sensor

The semester culminates in the design and build of an EMG sensor, as shown in Figure 6. Two electrode sensor pads connect to a circuit designed to amplify the difference using an instrumentation amplifier. The signal proceeds through an antialiasing filter implemented as a cascade of two low-pass Sallen-Key circuits. The signal is sampled using a National Instruments MyRIO embedded system.[10] Simple signal processing to extract salient features such as heart rate are coded in Matlab and uploaded onto the platform, and eventually displayed. The students experience the difficulties of circuit design, board layout, soldering, software design and debugging. They also get to feel the exhilaration of seeing the fruit of their labor come together into a working product, reminding them of why they chose engineering. The board layout for this project is illustrated in Figure 7. It is gratifying to see how students progress in dealing with design complexity is depicted by comparing this to the layout for Fundamentals 2.

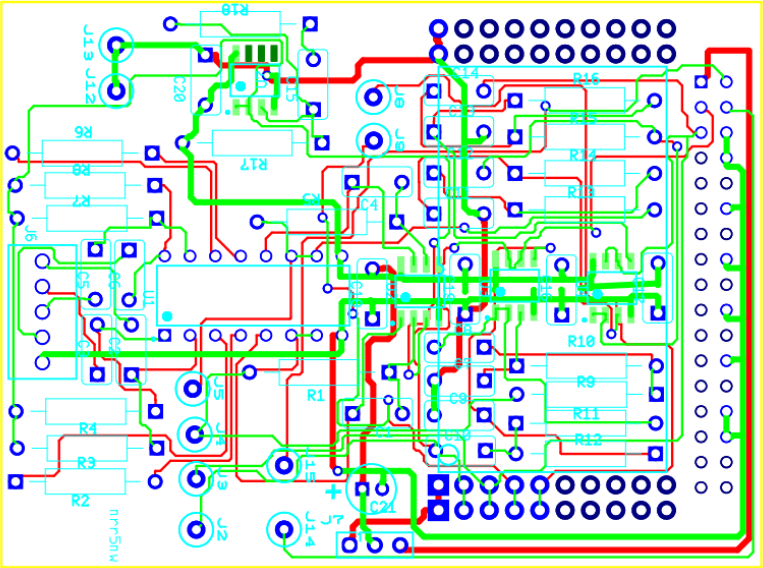


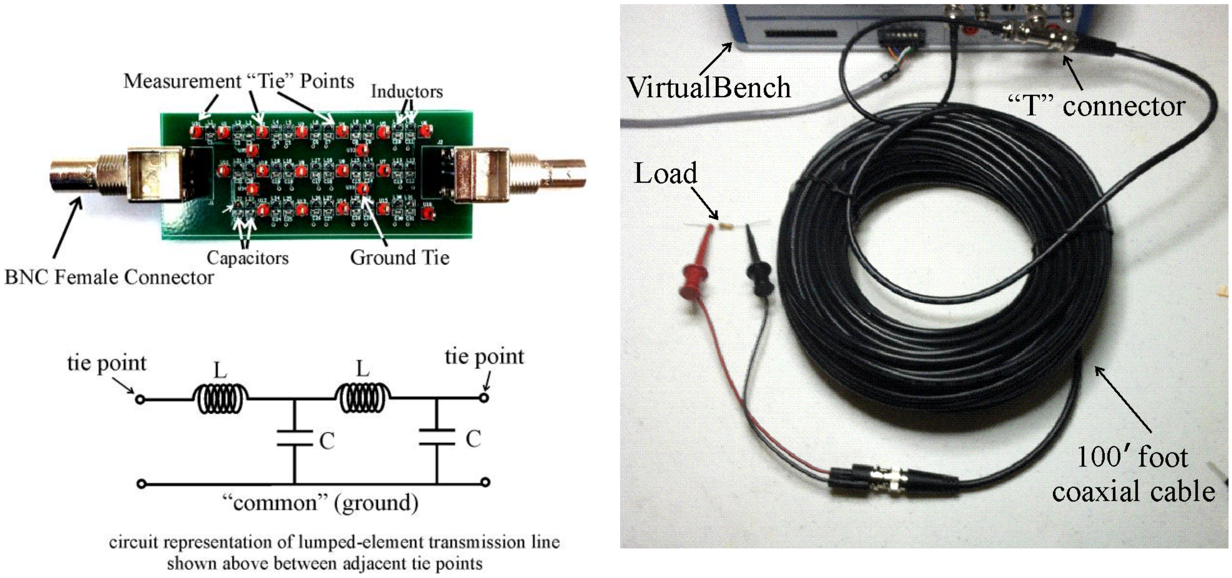
Figure 7 Fundamentals 3 Board Layout

## Adaptation to Other Coursework

The studio model that has been implemented for ECE Fundamentals 1, 2 and 3 at the University of Virginia is beginning to be adopted by a broader range of courses in the undergraduate curriculum, notably our junior-level one-semester course on Electromagnetic Fields (ECE 3209). Traditionally, ECE 3209 has been taught in a standard lecture format with no associated laboratory. There are a number of reasons for this, historically. The foundation of electromagnetic field theory centers largely on sophisticated mathematical techniques (vector calculus and differential equations) — topics that do not lend themselves readily to direct hands-on experiments. Moreover, the nature of the experiments and measurements that are usually implemented to study fields and explore phenomena associated with them (such as those often used for lecture demonstrations in elementary physics classes) are difficult to translate in a classroom setting without specialized or dedicated experimental apparatus.

The studio version of ECE 3209 that is being developed at the University of Virginia addresses these issues and builds upon the infrastructure already in place for the ECE Fundamentals courses described previously. To incorporate meaningful hands-on exercises that utilize this existing infrastructure, the material of the electromagnetics course was restructured to begin with a study of transmission lines. By introducing transmission lines at the beginning, a direct connection is made to the foundation in circuit analysis with which students are familiar from ECE Fundamentals 1 and 2. Also, new phenomena such as wave propagation and reflection at discontinuities are introduced, paving the way for a full study of electromagnetic waves later in the semester. This revision of the course material also permits hands-on projects to be readily incorporated into the class as the VirtualBench platform provides all the necessary measurement support (function generator and oscilloscope) for characterizing and investigating transmission line behavior.

To implement the studio portion of the class, the second half of the class period is dedicated to a number of transmission-line based “mini-projects.” These mini-projects take the form of additional homework problems in which students are asked to perform a set of measurements and address a set of questions related to the project. A short sample of the mini-projects used for the transmission-line portion of the class includes assignments where students are asked to (1) measure and determine parameters associated with wave propagation on transmission lines (for instance, characteristic impedance, propagation delay), (2) find the impedance of different circuit elements by measuring the standing waves on an artificial transmission line, (3) determine unknown loads terminating a coaxial cable from the reflection of a pulse launched onto the cable, and (4) design and implement a set of impedance matching circuits, including a 50 Ω power splitter. As an example Figure 8 (a) shows an image of an “artificial transmission line” (consisting of series of surface mount inductors and capacitors) designed for the class that allows students to sample the voltage waveform at discrete tie points along the line. This experimental platform was used in for a wide variety of mini-projects that explored standing waves. Figure 5 (b) shows the set-up for characterizing loads by observing the reflection on a 100 foot long 50 Ω coaxial cable.



circuit representation of lumped-element transmission line shown above between adjacent tie points

(a)

(b)

Figure 8

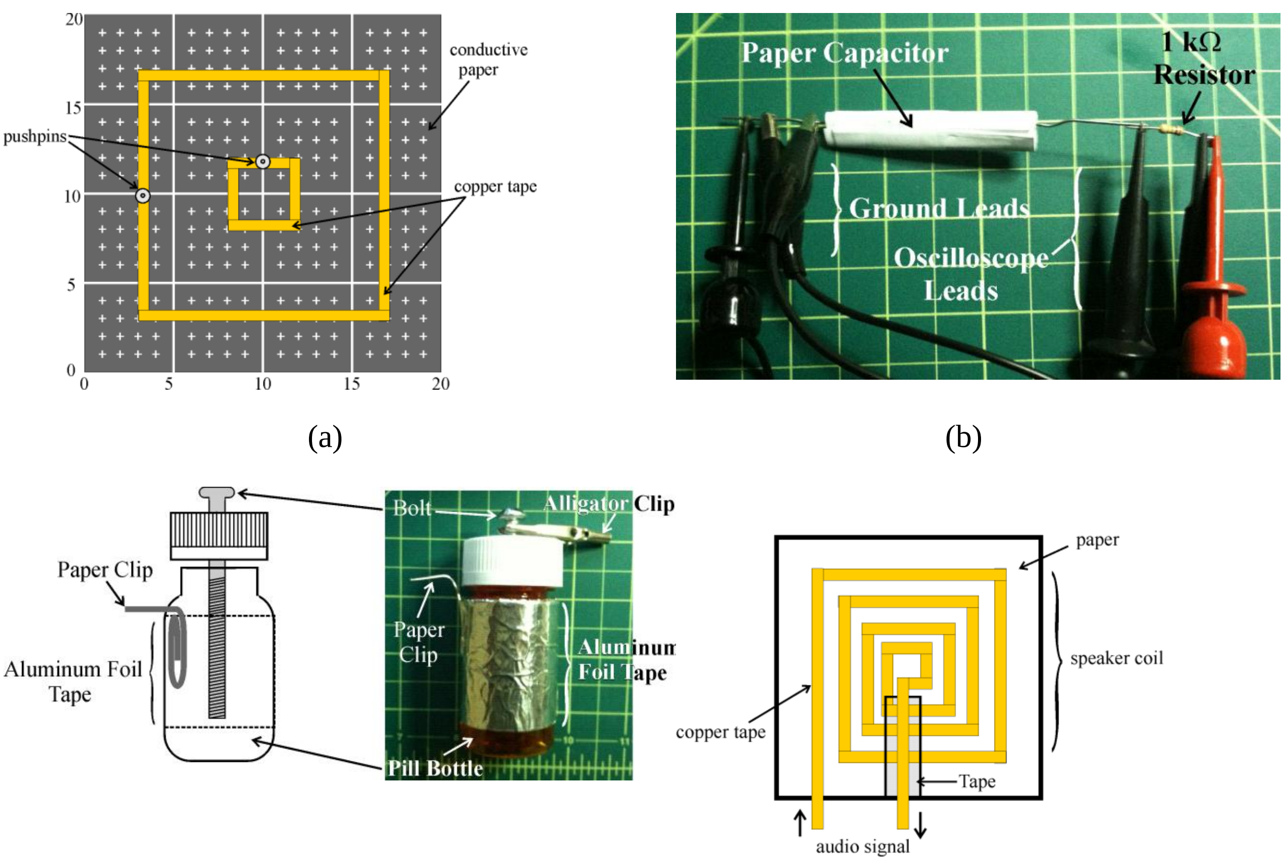
(a) Photograph of an artificial transmission line implemented for investigating wave propagation in ECE 3209. (b) Test set-up for characterizing coaxial cable and reflection coefficients.

Following the transmission-line portion of the class, ECE 3209 moves directly into field theory with several weeks devoted to electrostatics and several more weeks focused on magnetostatics. During this section of the class, a set of experiments or small design projects are assigned in the studio to demonstrate electromagnetic principles and provide students an opportunity to design some basic components based on electromagnetism. The focus of these projects is for students to (1) investigate fundamental principles and (2) design electromagnetic structures that can be characterized with the instruments available in the VirtualBench. Among the projects associated with this material are:

1. Two-dimension Field Mapping using Conductive Paper and Copper Tape
2. Design and Characterization of "Paper Capacitors"
3. Measuring Dielectric Constants using a "Pill Bottle" Capacitor
4. Demonstrating Magnetic Forces by Building a Paper Audio Speaker

Figure 9 shows images of a number of the electromagnetic-based structures implemented by the students including (1) copper tape-based electrodes for mapping equipotential contours, (2) a paper capacitor, (3) a "pill bottle" coaxial capacitor, and (4) a paper audio speaker.

The final portion of ECE 3209 focuses on time-varying electromagnetic fields, including Faraday's Law and electromagnetic waves. The hands-on activities for these subjects are currently being developed and will include projects investigating electromagnetic induction (transformers and simple motors) as well as polarization and propagation of waves in free space (using monopole antennas and diode detectors).



(a) (b)

(c) (d)

Figure 9 Sample of projects used to demonstrate basic electrostatic and magnetostatic phenomena in ECE 3209, including (a) copper tape electrodes for two-dimensional field mapping, (b) a rolled-paper capacitor, (c) a pill bottle capacitor for measuring dielectric constants, and (d) a paper speaker (used with a neodymium magnet) to produce audible tone.

## Summary and Conclusions

We have found excellent results from our studio approach in teaching the Fundamentals Sequence of courses. Student response has been very positive, and we have also seen increased interest in electrical engineering from first year students in the process of making a decision on their majors. The hands-on components of the coursework have been very instrumental in maintaining student interest and enthusiasm.

We have also seen excellent success in the migration of our approach to other coursework. E&M fields has long been perceived as a purely math course and bringing these concepts to tangible experiments has been key in cementing understanding.

We are currently in the process of evaluating students from our previous cohorts, i.e those in our program prior to our current approach. We began this evaluation in the Fall of 2014 and continued through the Fall of 2015. Due to class scheduling and our phased-in approach these students are the last classes to have gone through completely under our older system. We plan on comparative studies beginning in the Fall of 2016. These students will be the first cohort to have gone through under the new course series. We will report on these results in future publications.

The most persistent student comment that we now hear at middle of the third year is : *"I am really looking forward to doing my Capstone next year. I think we are now prepared to do a really great project".* This is the most gratifying experience for all of us and we believe that it makes the effort worthwhile.

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