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Incorporating Studio Techniques with a Breadth-First Approach in Electrical and Computer Engineering Education

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Incorporating Studio Techniques with a Breadth-First Approach in Electrical and Computer Engineering Education

Background

The breadth of topic material in all branches of engineering is expanding at a rapid pace, none more so than in electrical and computer engineering. For example, graphene and carbon nanotubes as electronic components barely existed as a topic even ten years ago, and the proliferation of high-speed wireless networking has been rapidly accelerating. While understanding Kirchhoff's laws is still necessary, it is equally imperative to give students a sense of breadth. As electrical engineering design moves to a more systems-level approach, it is still necessary for students to assess the performance of the individual devices that comprise the system and how they interact.

Equally important is the necessity of being able to work with actual devices in a hands-on sense. When we expose students to component models without giving them an experiential context for their application, we run the risk that they will never develop a sense of what happens when the model limits are exceeded, and the implications that might have on an overall systems level design. Also, we run the risk of overwhelming them with theory and having them lose interest altogether.

In the larger picture, we must also prepare engineers to address the "Grand Challenges" of the future.[1] Virtually all of these challenges involve electrical and computer engineering to an extraordinary degree. Let us consider several that are enumerated by the National Academy of Engineering.

"Make Solar Energy Economical" would appear to be, on the surface, a problem in solid state physics, yet such an undertaking requires a large system-level understanding of the requirements of the electrical power grid as well as a low-level understanding of the devices and techniques necessary to create an effective interface between a variable energy supply and the changing demands of the load.

"Advanced Health Informatics" is not only a field of study that would encompass medicine and biomedical engineering but clearly relies on topics from both computer engineering as well as electrical. To be successful engineers will need to have a breadth of understanding of the high-level issues involved in programming and securely accessing large databases, but also the limitations of wearable electronics employed in longitudinal health monitoring.

We envision engineering education pedagogy as being at a crossroads, especially as it relates to electrical and computer engineering. We have observed at the University of Virginia that relatively few of our undergraduates gain employment designing discrete circuits, i.e. transistor amplifiers. Yet, understanding these low level concepts is seen as valuable especially as it provides students with an introduction to the concepts of tradeoffs and operational limits that are such an essential element of engineering design. An overarching goal of an engineering education is to allow students to develop an appreciation that large scale systems are assembled from smaller building blocks and that a truly professional designer must have some sense of both. Likewise, we must expose our students to core material that will be relevant to their future employment.[2]

Research in engineering pedagogy suggests several approaches that must be considered. There is clearly a need for breadth and research in educational approaches suggest that a breadth-first approach may also deepen understanding.[3] An essential focus of this approach is to balance cognitive load on the learner, and to progress across a breadth of material from an elementary level of understanding to a deeper level at each exposure to the material.[4,5] We see this approach as not only addressing the breadth and depth concerns, but also as an aid in assisting undergraduates to overcome uncertainties about their choice of discipline.[6]

We must also consider an optimal classroom approach as well. We have a deep concern for the efficacy of a traditional lecture-based approach. Admittedly the classroom of Figure 1 was staged for a photograph, yet we have all experienced something similar in lecture-based scenarios.

Keeping students engaged with the material is crucial, yet "chalk and talk" is persistently losing their interest and is not a very effective way of explaining broad concepts. Indeed, there have been studies that suggest that learning is actually inhibited via the traditional lecture approach.[7] There have been a number of alternative approaches employed and virtually all of them focus on altering the classroom environment in non-traditional ways. A common theme among all of these approaches, though, is the inclusion of a more active approach to the classroom environment; one in which the students are actively participating in the session, and not passively listening to a lecture.

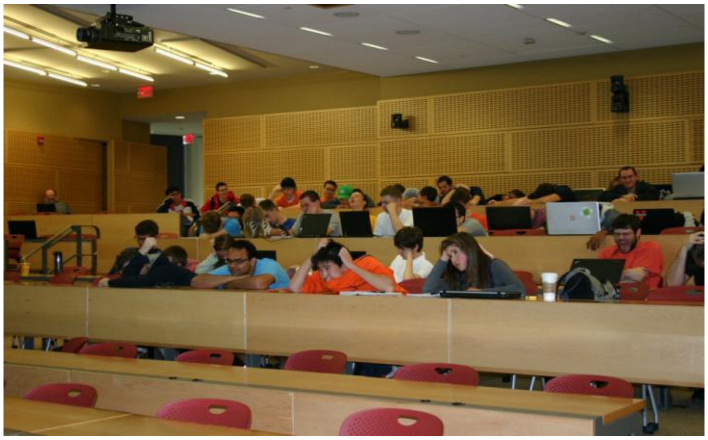


Figure 1 Traditional lecture hall

Inverted or flipped classrooms are a popular approach that has demonstrated clear advantages in knowledge retention and understanding of concepts.[8,9] Such approaches still require a considerable amount of instructor time and effort; we believe that this will be the case in virtually any shift in pedagogy. Other approaches strive to create a blended learning environment in which students receive part of the input from the professor in electronic format and include active learning in-class exercises.[10] Yet another approach is problem-based or project-based learning. In problem-based learning, students are presented with problems to solve and then discover the material needed. In contrast, project-based learning is more hands-on with physical hardware as the motivator for the solution-space search.[11] An advantage of project-based learning, in our view, is the close connection to real-world constraints including methods of manufacture and assembly. We have found that this approach is very engaging to students, and that when properly conceived, we can achieve both depth and breadth of understanding.[12]

Anecdotally, many potential employers that we speak with show a strong preference for students that have had practical experience in their undergraduate education. This opinion is further substantiated in our conversations and informal polls of our students who have gone into industry. They express a virtually unanimous opinion that the practical laboratory experience of their undergraduate curriculum was among the most beneficial, and that courses should focus more heavily on it.

We are addressing these concerns with a new core curriculum for electrical and computer engineers, the *Fundamentals of Electrical Engineering Series,* a 3-course sequence. These courses replace our prior sequence of courses for 2nd and 3rd-year students: *Circuits, Electronics,* and *Signals and Systems*. Each of the courses in the new sequence takes a breadth-first approach to electrical engineering topics and is taught studio style, with the laboratory component being tightly interlocked with the formal lecture material. Each course also covers a similar breadth of topics, but successively greater levels of detail. We have previously reported on our work in the *Fundamentals 1* and *Fundamentals 2* courses and have now offered both several times.[13] We are also through the first iteration of *Fundamentals 3*. In this paper, we present our findings on how the overall sequence intertwines, and what modifications to the earlier courses in the sequence were made as a result of our later experiences.

In the balance of this paper, we discuss our classroom approach and studio techniques. The *Fundamentals 1,* and *2* courses are covered in an overview format and we go into more detail for *Fundamentals 3*. We also include information on how lessons we learned in the *Fundamentals Series* has enabled us to modify our *E&M Fields* coursework from a traditional math-heavy course to one that includes an interactive laboratory based component.

Classroom resources and software

Our studio space is shown in Figure 2 and Figure 3 below. Currently we have sufficient classroom space for 60 students, although plans are in place to expand the space to accommodate 75. Students work in 3 person teams and each table "pod" accommodates 3 teams; we rotate team membership throughout the semester, and require that team members rotate responsibilities. The central part of each table has power outlets for student laptops and the instrumentation. One of our objectives was to maintain clear sight lines and give the laboratory an open feel. As each class typically begins with a short lecture before beginning the laboratory work, students need a clear path to the professor as well as to each other, as seen in Figure 4. Lectures are delivered using a tablet style screen, and there are a number of video displays located about the room. As a result of our first offering of courses in the *Fundamentals Series,* we came to realize that the importance of classroom layout on overall success was even more important in a studio style course than in a traditional lecture based one;


Figure 2


Figure 3

both faculty and students need to be able to freely move about the room. It is extremely important for the collaborative sense that we are endeavoring to cultivate in these courses.

Figure 4 Studio classroom with students

One of the key pieces of enabling technology for our studio approach is the VirtualBench from National Instruments.[14] This single unit encompasses a 100MHZ oscilloscope, a 10 MHZ function generator with arbitrary waveform ability, triple output power supply and a digital multimeter. As seen in Figure 5 it has a very low profile and occupies a small footprint making it ideal for use in a studio classroom. At the end of class, the equipment is stored in a cabinet and the room can be used for other purposes. We also created an adapter cable that allows direct connection of the power supply to a solderless breadboard. This eliminates the need for students to constantly attach jumper cables to the screw terminals. This compact nature allows us to lecture during the lab session if we desire, and still maintain visual contact with the students. It connects to a computer or portable device via a USB cable or WiFi, thereby eliminating the need for a built in display, seen in Figure 6.

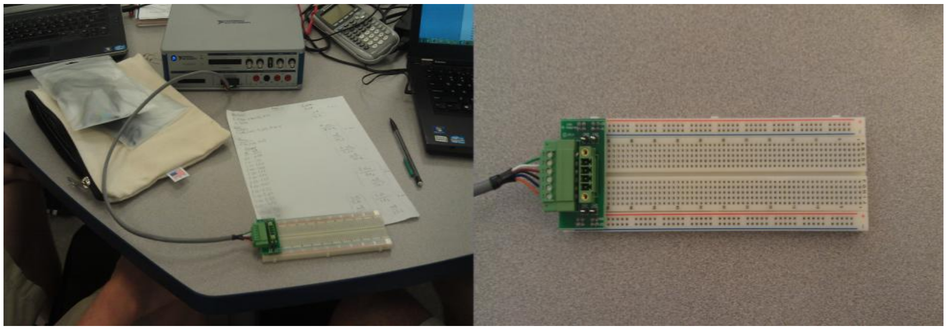


Figure 5 VirtualBench and adapter cable designed at the University of Virginia

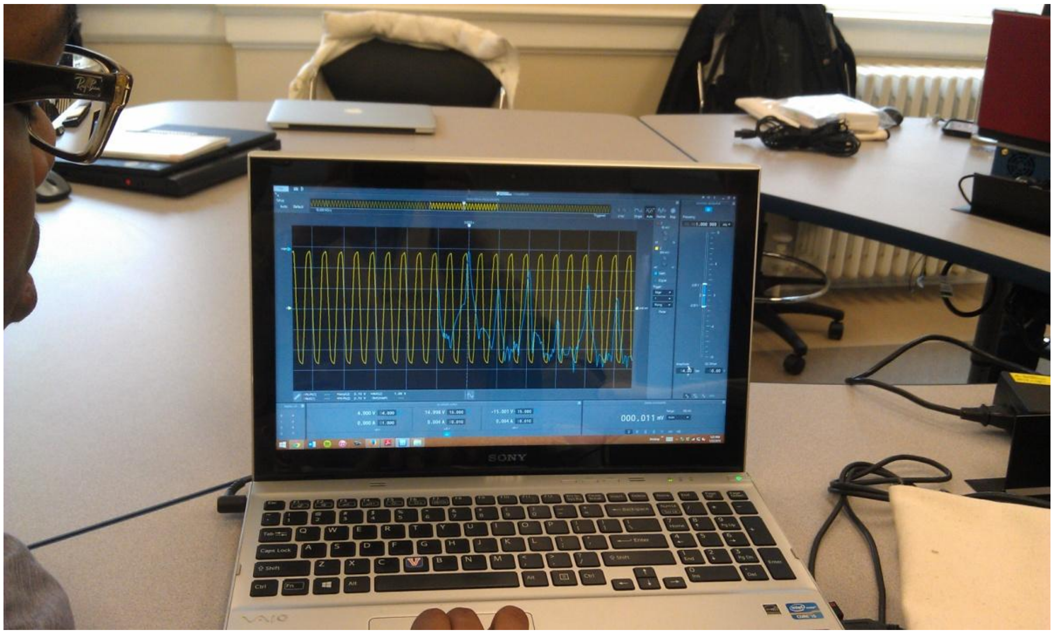
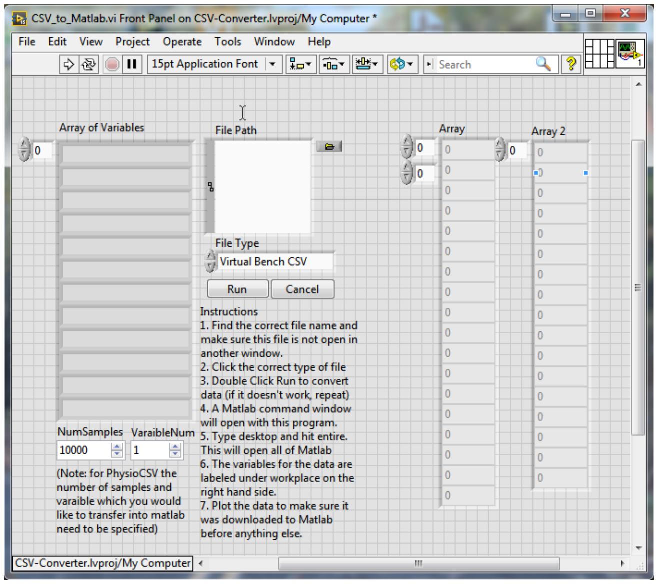


Figure 6 Front panel display of VirtualBench on laptop

The VirtualBench also has built-in functionality to export data files of all measurements and control settings. We have developed add-on software that allows us to interchange this data with popular mathematical software, such as MATLAB™ .[15] We also have developed a program that allows controlling the arbitrary waveform generation function and uploading signal files to explore signal analysis and circuit response to complicated signals, e.g., those available from the Physionet database.[16] The front panels of one of these add-ons are shown in Figure 7.



File Type: Virtual Bench CSV

NumSamples: 10000

VaraibleNum: 1

(Note: for PhysioCSV the number of samples and varaible which you would like to transfer into matlab need to be specified)

Instructions
1. Find the correct file name and make sure this file is not open in another window.
2. Click the correct type of file
3. Double Click Run to convert data (if it doesn't work, repeat)
4. A Matlab command window will open with this program.
5. Type desktop and hit entire. This will open all of Matlab
6. The variables for the data are labeled under workplace on the right hand side.
7. Plot the data to make sure it was downloaded to Matlab before anything else.

Figure 7 MATLAB interface

For our circuit simulation, we employ Multisim™ from National Instruments and for board layouts we use the companion product, UltiBoard.[17,18]

Our software add-ons allow complete data interchange throughout the entire toolset that the students would employ. For example, we can take an arbitrary EKG signal data file from the Physionet archive, move it into MATLAB and do analysis, then move the same data to Multisim to simulate circuitry, and move the same data again to the VirtualBench arbitrary waveform generator for laboratory testing of the physical hardware. After the students are satisfied with the signal handling ability of their circuitry they can then export their Multisim file to UltiBoard and render an actual printed circuit design.

This combination of tools allows us to create an extremely functional classroom environment in a compact space. Furthermore it allows the students to effectively work through all areas of design from mathematical analysis to simulation, testing, and final hardware implementation.

Fundamentals 1

The first offering of *Fundamentals 1* provided a significant learning experience for everyone involved. While much of the lecture material was similar to that presented in the old circuits course, one objective was to integrate some electronics and signals material in this first course. The addition of this new material necessitated selective removal of previously-covered circuits material, i.e. details of transient and phasor analysis, that would now be covered in future courses. The decision was made to include more exposure to diodes and to add a significant introduction to MOS transistors in this first course. An introduction to the Fourier series was added to enhance the analysis of simple circuits excited by sinusoids.

While the selection and integration of new material was somewhat challenging, much more work was required to integrate the practical laboratory experiences into the studio format. An effort was undertaken to develop a set of lab experiences before the first offering of the class, and several students were employed to help with the development and test of these labs. While the new labs were generally good, they proved to be a poor fit to the new studio format. By the midpoint of the first course offering, the instructors were already developing new lab material that was more suitable to the studio format.

The second offering of *Fundamentals 1* was in the previously off-semester with smaller enrollment. The course content was refined somewhat based on the experience from the first offering. The instructor also developed new lab material to replace those that had not worked well previously.

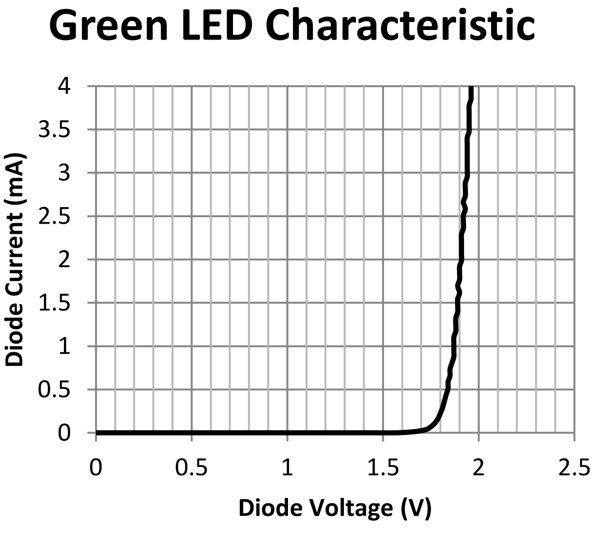


Figure 8 LED Characteristics as measure in student lab

The third and most recent offering of *Fundamentals 1* build on the previous two experiences. The instructor developed an entirely new set of lab experiences closely integrated with the sequence of topics and designed specifically to match the studio format. Recognizing that the labs and discussions needed to support and balance each other, the new labs were designed to be motivated by earlier discussions and to motivate future discussions. Also, the instructor started an effort to gather sequences of discussions and labs into modules designed to convey both specific topic information and broader integrated concepts. This aggregation of topical material into modules was just started in the most recent course offering, and it did not span all of the topics in the course. Initial impressions of this approach suggest that it should be expanded and further evaluated in future course offerings.

The earlier *Fundamentals 1* experiences also suggested some content changes for the most recent offerings. Some topics were re-ordered in the course, and material on ideal operational amplifiers was added. These changes were made to improve the flow of related topics in the course and to use operational amplifiers as embodiments of controlled sources. The addition of new material was accompanied by the removal of material on digital logic that had been used to motivate study of the MOS transistor as a switch. The discussion of digital logic had been judged to be of limited utility in previous course offerings.

Every class meeting included a lab experience, and these experiences were directly related to the topics discussed during the class period. For example, non-linear devices were discussed starting with the diode. The associated lab experience involved several activities using a light emitting diode (LED). The first task in the lab required the students to make measurements of the current-voltage (IV) relationship of the diode. The students were to find the “knee” of the IV curve as illustrated in Figure 8.

The students were then required to use the measured data to determine the power dissipation of the LED as a function of the voltage across the LED. They then used this power dissipation information as they adjusted the power dissipated and observed the light emitted by the LED. As a final step, they illuminated the LED with a changing light source and observed the voltage produced at the LED terminals.

The final examination included a question asking the students to analyze the behavior of a otherwise linear circuit containing a single two-terminal non-linear device. The circuit was excited by a constant source. The characteristic given for the non-linear device differed from the characteristic of a diode, but the techniques taught and experienced using the diode were directly applicable to the question.

Fundamentals 1 also includes an introductory printed circuit design project, a simple triangle and square wave generator. The goal of this project is to introduce students to the physical realities of the design process and familiarize them with the flow of manufacturing and the necessities of working within the constraints of external standards.

Fundamentals 2

Fundamentals 2 is in a sense the core of the three-course sequence, as it deepens the knowledge and understanding of the circuits and electronics presented in *Fundamentals 1*, covers the continuous-time signals and systems material, and prepares students to move on to *Fundamentals 3* as well as other classes in the curriculum, such as *Embedded Systems, Microelectronic Circuits, Electromagnetic Fields* (discussed below), and more advanced electives. By the time students get to this course, they have been exposed to the studio format, the class layout, the equipment, etc. They are ready for the added depth in understanding.

In our first offering of the course, we were uncertain of the familiarity and retention of material presented in *Fundamentals 1*, and we assumed too much. In the second offering of

Fundamentals 2, we made an effort to provide the students a more systematic review-depth-new material cycle for each topic covered. We also placed more emphasis on linking the Fourier and Laplace transforms to the electronics. For example, in the first offering some students remained confused as to when to use the Fourier Series versus the Fourier Transform in studying linear circuits. The second time, we emphasized the notion that a nonlinear system driven by sinusoid creates harmonics, which can be measured using the Fourier Series, while the Fourier transform is used to describe a filter response or a non-periodic signal.

The first offering of *Fundamentals 3* occurred simultaneously as the second offering of *Fundamentals 2*. Seeing the course sequence in its entirety allowed us to better plan how material should be split between the two classes. We opted to move some MOSFET amplifier configurations to *Fundamentals 3* (to further deepen material) and cover the basic common emitter BJT configuration in more detail in *Fundamentals 2*. We hope to expose students to varying levels of depth on the same concepts repeatedly to enhance comprehension and retention.

An example of a lab exercise in *Fundamentals 2* is the common source MOSFET amplifier. The lab was closely matched to the instruction. In the first segment, the concept of DC biasing and quiescent (Q) point was described with a four-resistor bias network. The lab exercise for that day was to build a biasing network and measure the voltages and currents and set the Q-point for the transistor. The next section discussed the MOSFET as an amplifier and the idea of using capacitors to block DC voltages while passing AC signals in and out for amplification. The students then added the appropriate capacitors to their circuit and measured the AC voltage gain at a fixed frequency. The last segment discussed the coupling capacitors and bias network as high-pass filters on the input and output. The students then measured the frequency response of the amplifier and compared it to expectations for the combined high-pass filters. Results were illustrated using Bode plots. In this case, the concepts of transistor amplifiers and filters were integrated in the same studio module.

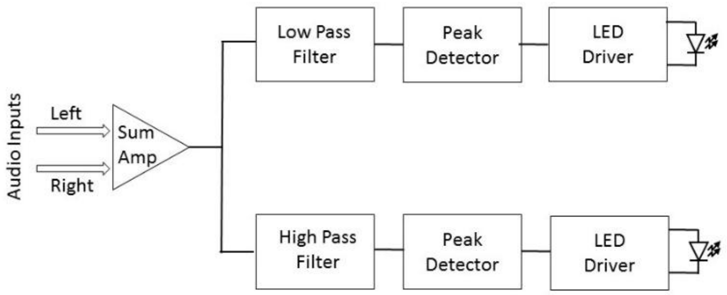


Figure 9 Fundamentals 2 Student Project Block Diagram

The final lab exercise of the semester was a student project. The student project was envisioned to encompass circuit concepts that included operational amplifiers, active high-pass and low-pass filters, active peak detection, and MOSFET voltage controlled current sources, Figure 9. The concepts of filtering and frequency domain analysis were naturally incorporated into the project. The project comprised a printed circuit board with a 1/8" audio jack input and two (red and green) LEDs as output, as shown in Figure 10. A music signal from a Smartphone, laptop or other MP3 player was the input to the system. A summing op-amp is used to combine the left and right audio signals and provide some gain. The signal is then sent to two active Sallen-Key filters, one high-pass and one low-pass. The output of each filter is then input to an active op-amp/diode peak detector with a large capacitor on the output. Each peak detector signal is used to drive a MOSFET current source that illuminates an LED in proportion to the amplitude of the signal.

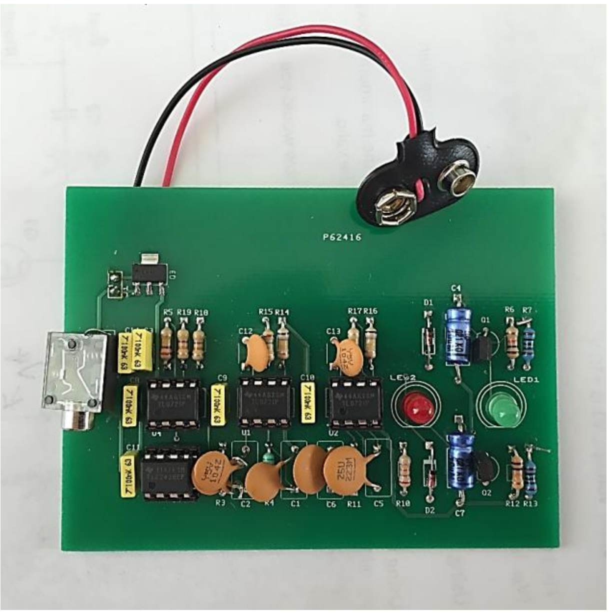


Figure 10 Fundamentals 2 Student Project PC Board Example

The students are given the general architecture for the circuit but must choose components to achieve the desired result. Some of the design considerations include choice of gain on the input stage, cut frequencies for the high-pass and low-pass filters, Q-point of the MOSFET LED driver and frequency response of the peak detector. The students then produce a printed circuit board layout using UltiBoard with a Multisim schematic as input. The students are each required to produce a viable board layout but only one board per student team (usually 3 students) is sent out for fabrication. The team decides on the best board design to be built and tested. The boards are sent out for fabrication using standard Gerber file protocols. After the boards are received, the students solder and test their designs. The final deliverables are a written report detailing their design and test methodologies and a short video (usually shot with a Smartphone) demonstrating the functionality of their circuit with their choice of music. Often, the choice of music will dictate the design choices.

Student comments in our course evaluations indicate that they find this project very enjoyable, even though it is demanding. We also receive very positive comments in terms both of the learning experience and the satisfaction of having completed a working board assembly.

Fundamentals 3

Fundamentals 3 is the final level of the central curriculum offering and extends concepts from both *Fundamentals 1* and *2*. In this course we are able to take some basic understanding of concepts such as MOSFETS, BJTs, and operational amplifiers and reinforce previous levels of understanding while exploring the circuit models in more depth and understanding how concepts such as the Fourier and Laplace transforms are employed in designing more complicated systems. This is also the course in which we present, develop, and use discrete-time signals and system concepts, allowing us to take experiments that are usually taught completely within the context of electronics or circuits and expand them to show how a broader knowledge of the topic that includes frequency domain understanding can yield both a deeper level of understanding as well as a more refined final design.

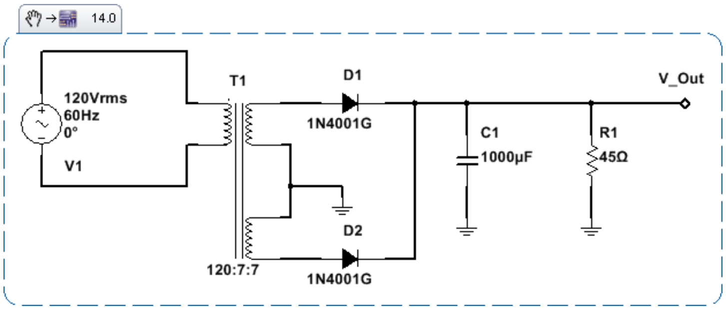


Figure 11 Typical power supply experiment

Consider a very typical laboratory experiment with rectifier-capacitor power supplies as is frequently encountered in an undergraduate electronics course; the schematic is shown in Figure 11. When students are exposed to this circuit in a typical undergraduate electronics class, they will usually quantify the ripple voltage at V_Out and perhaps see what effect the capacitor size and load resistance will have on it. These experiments typically do not encompass measurement of the transformer currents or have consideration, outside of mention in a text, of the implications of the wave shapes of these currents. Nor is any consideration given to frequency domain concepts and how harmonics might affect the power distribution system.

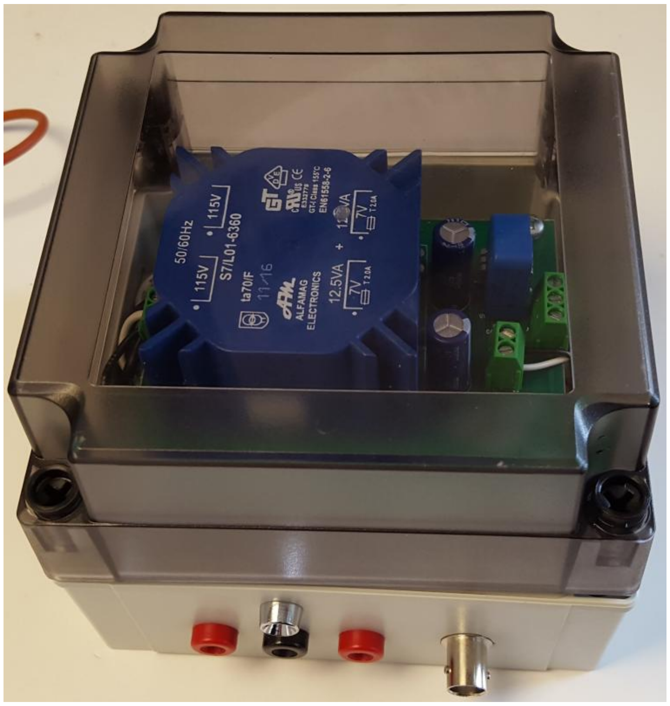


Figure 12 Instrumented Transformer

We have designed and manufactured an instrumented transformer, Figure 12, for a series of experiments in rectifier-capacitor power supply design. This transformer unit contains a standard center-tapped transformer of the sort that is typically used in undergraduate experiments in electronics. It also has a Hall Effect current transducer which is both lossless and of sufficient bandwidth that students can observe the current flow in the transformer as well the voltage output. A typical undergraduate laboratory for power supplies will ask the students to quantify ripple voltage and perhaps make a simple zener diode regulated power supply. However, other than text references little mention is made of the relatively high amplitude current pulses in the transformer windings and how this might affect the output. Armed with the ability to measure the actual current waveforms, students can develop an understanding of how changing filter capacitor values might affect the peak transformer currents as well as ripple. Also, by virtue of the topic coverage in our Fundamentals Series, we are able to have students examine the harmonic content in the transformer currents as well.

A typical power supply experiment is shown in Figure 13. The students are observing the output voltage as well as the current pulses (the yellow trace on the VirtualBench display) and quantifying how variations in the load current and filter capacitance affect them. Additionally, they use the FFT ability of the VirtualBench to examine the frequency content of the current, which leads to a discussion of the deleterious effect of harmonics on the power grid. With our approach, we can use a relatively simple experimental setup to explore concepts from electronics, power supplies, filtering, frequency domain implications, and power distribution.

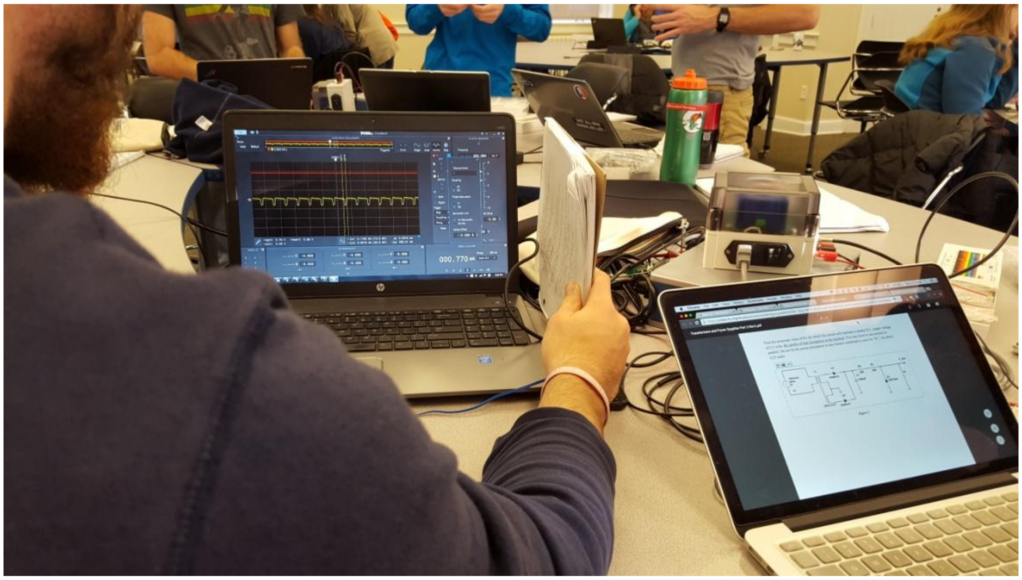
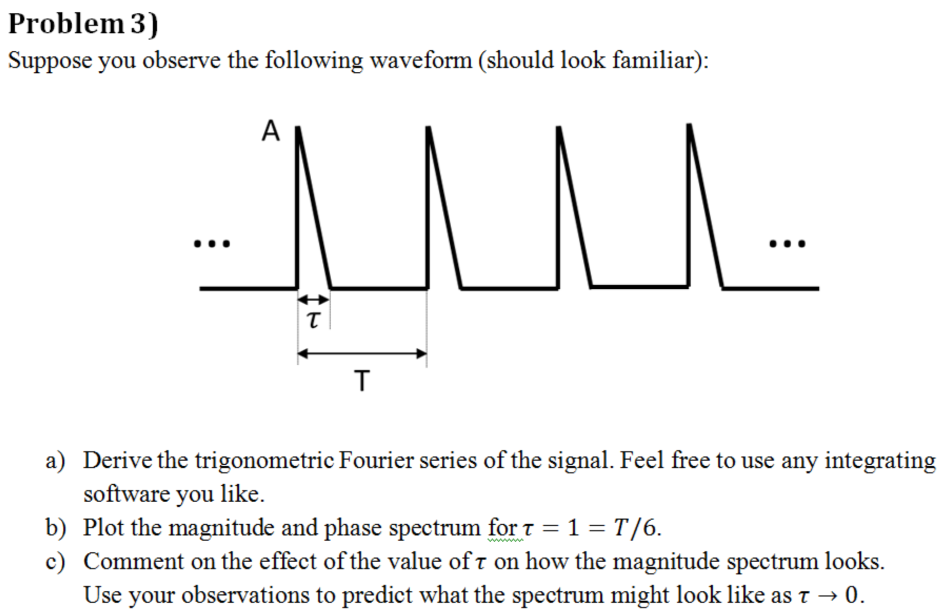


Figure 13 Typical power supply experiment

We then follow up this experiment with homework problems that directly relate these concepts with the laboratory. There are the typical ripple and load power problems, but with our broader approach we are able to push further. The problem shown in Figure 14 is asking the students to work with a Fourier series of waveforms that are virtually identical to those seen in the experiment and examine the spectral content as the pulse width varies. Problems such as these coalesce experiential understanding obtained from working within the experimental domain as well as the analytical.



Problem 3)

Suppose you observe the following waveform (should look familiar):

a) Derive the trigonometric Fourier series of the signal. Feel free to use any integrating software you like.

b) Plot the magnitude and phase spectrum for $\tau = 1 = T/6$.

c) Comment on the effect of the value of τ on how the magnitude spectrum looks. Use your observations to predict what the spectrum might look like as $\tau \to 0$.

Figure 14 Typical power supply experiment homework problem

We extend studio work into our tests as well. For example, we go into detail with small signal models of BJT amplifiers. A typical circuit that is explored in the laboratory work is shown in Figure 15. This circuit, an emitter follower, is explored with concepts including biasing, input impedance, output impedance, the small signal model, amplitude limits, and frequency response; all of these are typical for an electronics course. In addition to testing in the laboratory portion of the class, the students work with simulations and homework problems similar to those shown above for the power supply experiment. However, since we are also exploring concepts from signals and systems, we have an opportunity to go further here as well. We examine a more formalized approach to the overall transfer function of the circuit. In our test on this material, there are typical questions about the quiescent point etc, but we also ask questions related to signals concepts, tying those concepts to the physical hardware on which they are realized. An example of such a test question is shown in Figure 16.

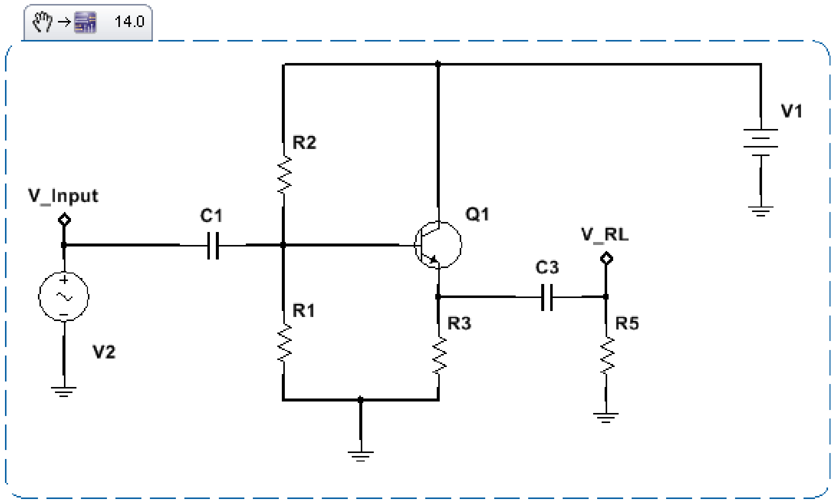
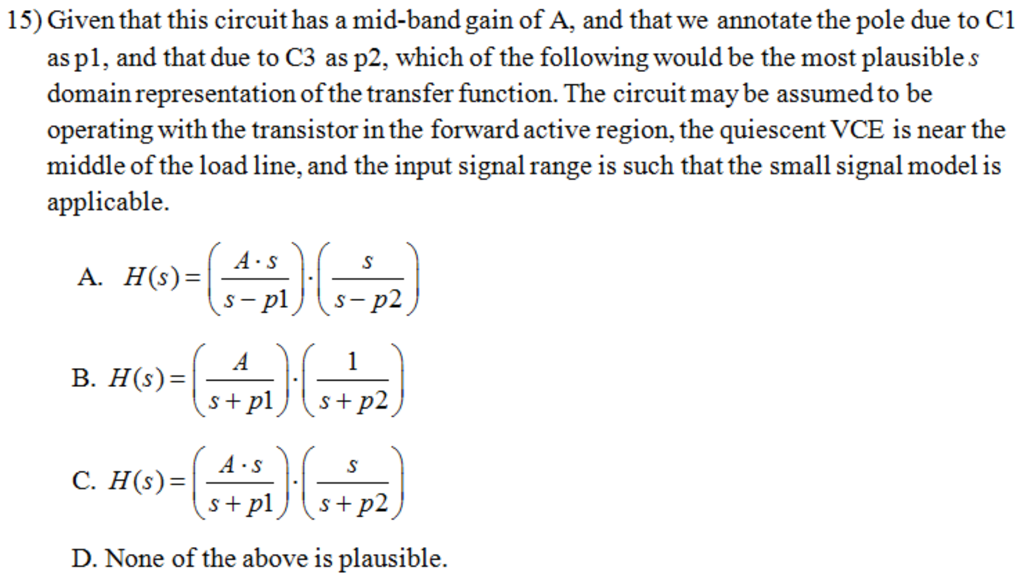


Figure 15 Typical BJT experiment



15) Given that this circuit has a mid-band gain of A, and that we annotate the pole due to C1 as p1, and that due to C3 as p2, which of the following would be the most plausible *s* domain representation of the transfer function. The circuit may be assumed to be operating with the transistor in the forward active region, the quiescent VCE is near the middle of the load line, and the input signal range is such that the small signal model is applicable.

A. $H(s)=\left(\frac{A\cdot s}{s-p1}\right)\cdot\left(\frac{s}{s-p2}\right)$

B. $H(s)=\left(\frac{A}{s+p1}\right)\cdot\left(\frac{1}{s+p2}\right)$

C. $H(s)=\left(\frac{A\cdot s}{s+p1}\right)\cdot\left(\frac{s}{s+p2}\right)$

D. None of the above is plausible.

Figure 16 Test Question emphasizing transfer function concepts

Further topics covered in a similar fashion include:

1. Reference tracking
2. PI Controllers
3. Real-world operational amplifier limits, offset voltages, PSRR, GBW etc.
4. Instrumentation amplifiers.
5. Introduction to discrete time systems with sampling and filtering in the digital domain.

Typical signals and systems courses do not include an experimental portion, as it is not obvious how to integrate the mathematical concepts with hardware demonstrations. We gave special attention to this problem, and were able to seamlessly incorporate continuous-time signals and systems concepts within the analog circuits in *Fundamentals 1*, *2*, and *3*. The discrete-time concepts proved more difficult. To illustrate sampling and aliasing we used a simple A/D converter followed by a D/A converter, driven by a sinusoid, where the students could note at what input frequency the output frequencies began to differ. The experimental hardware, Figure 17, is also used in a sequence of experiments in our *Embedded Systems* course, further strengthening the tie between these two important topics. The purely discrete-time notions were explored using Matlab-based in-class experiments. For example, students took a stored biological signal from the Physionet database and used a finite-impulse-response filter to remove some noise. They compared the effect in the time and frequency domains to using an analog filter on the same input signal using the VirtualBench.

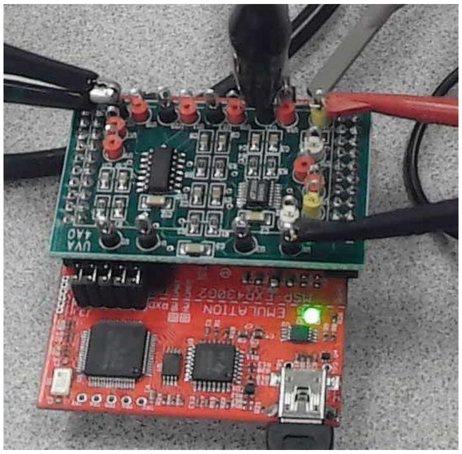


Figure 17 Sampling experiment hardware

As with our other *Fundamentals* classes, there is a final project that encompasses system specifications, analysis, design, and printed circuit layout, fabrication, and testing.

For this class the project is an EKG amplifier with an interface to a myRIO from National Instruments.[20] The block diagram is shown in Figure 18.

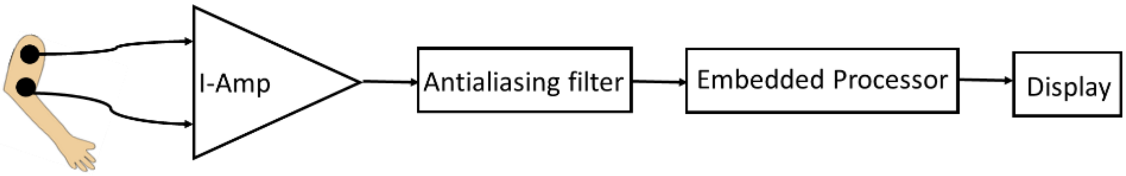


Figure 18 Block diagram of Fundamentals 3 project

The antialiasing filter is realized using a 4th order Butterworth filter. This provides an excellent opportunity to revisit the Sallen-Key topology and to explore the implications of pole placement for higher order filters, which provides additional reinforcement of concepts related to the Laplace transform. The instrumentation amplifier had already been studied in detail both through the lecture and experimental portions of the course and we were able to test preliminary designs of the circuit using actual EKG signal recordings from the Physionet database. We were able to exploit these signals both in simulation as well as through the arbitrary waveform abilities of the VirtualBench. A typical student layout of the resultant 2 layer board is shown in Figure 19.

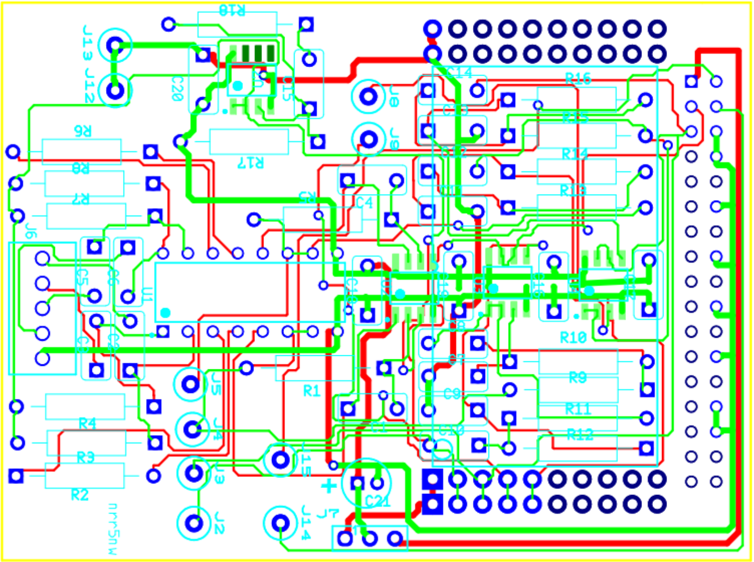


Figure 19 Typical student layout - EKG board

The students tested their assembled boards with signals from Physionet and also with electrodes on their arms. A sample of the testing, with electrode connections and the myRIO is shown in Figure 20. In this project students not only had experience in the design of the analog section of the overall system, but also had exposure to concepts of sampling and quantization using the myRIO.

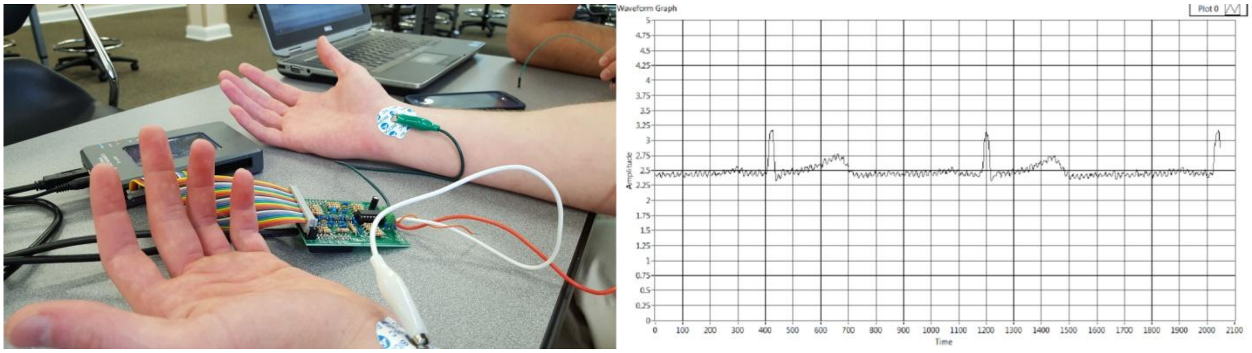


Figure 20 EKG Project Testing

As part of the final lab report submission process, students were asked to write an opinion of what they learned from the project. The following is a typical response:

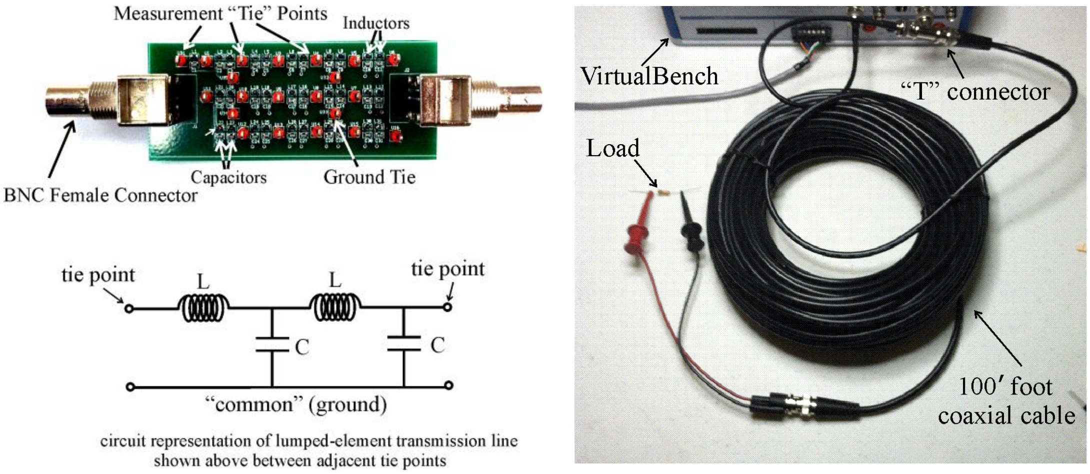
"It was exciting to be able to get a functional, graduate-level project put together in a span of a few weeks. Especially since the material we learned in the Fundamentals courses played directly into the project. In other words, linking frequency domain topics like aliasing to circuit topologies like the Sallen-Key filter made the course come together."

Electromagnetic Fields

The studio model that has been implemented for *ECE Fundamentals 1, 2* and *3* at the University of Virginia is being adopted by a broader range of courses in the undergraduate curriculum, notably our junior-level one-semester course on *Electromagnetic Fields (ECE 3209).* Traditionally, courses in *Fields* have been taught in a standard lecture format with no experiential component. The foundation of electromagnetic field theory is founded on sophisticated mathematical techniques (vector calculus and differential equations) which are topics that do not lend themselves readily to direct hands-on experiments. Moreover, the nature of the experiments and measurements usually employed to study fields and explore phenomena associated with them are difficult to transition to a classroom setting without specialized or dedicated experimental apparatus. We feel that our development of simple and inexpensive devices and projects is a major hurdle that we are overcoming in this course.

The studio version of *ECE 3209* at the University of Virginia addresses these issues and builds upon the infrastructure already in place for the *Fundamentals* courses. While beginning a fields course with transmission lines is not novel, we have found that this approach allows a direct connection to be made to the foundation in circuit analysis with which students are familiar from *Fundamentals.* This revision of the course material permits hands-on projects to be readily incorporated into the class and paves the way for new phenomena such as wave propagation and reflection at discontinuities to be introduced; this provides a firm foundation for a full study of electromagnetic waves later in the curriculum.

In keeping with the experiential nature of our approach, the second half of the class meeting period is dedicated to a sequence of “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. By way of example, typical "mini-projects" for transmission lines include measuring characteristic impedance, propagation delay, standing waves, and the determination of unknown loads by observing reflections, and the design and construction of impedance matching circuits and power splitters. A sampling of our experimental hardware is shown in Figure 21 : (a) shows an image of an “artificial transmission line” (consisting of series of surface mount inductors and capacitors) that allows students to sample the voltage waveform at discrete tie points along the line. This simulated transmission line was designed at the University of Virginia, and we can make the plans and manufacturing documents available to other universities. This experimental platform was used for a wide variety of mini-projects that explored standing waves. Figure 21 (b) shows the set-up for characterizing loads by observing the reflection on a 100 foot long 50 Ω coaxial cable.



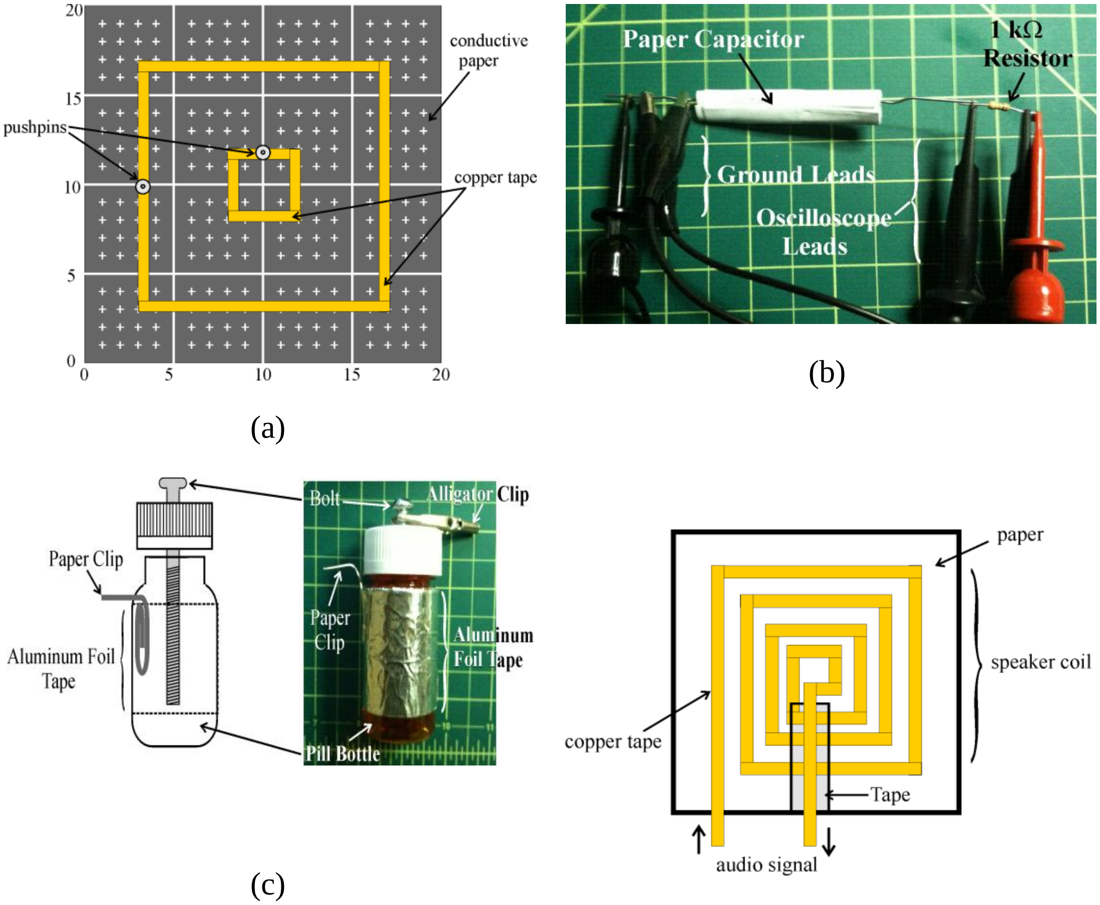
(a) (b)

Figure 21 (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 mini-experiments 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 22 shows images of a number of the electromagnetic-based structures implemented by the students including (a) copper tape-based electrodes for mapping equipotential contours, (b) a paper capacitor, (c) a “pill bottle” coaxial capacitor, and (d) a paper audio speaker.



(a)

(b)

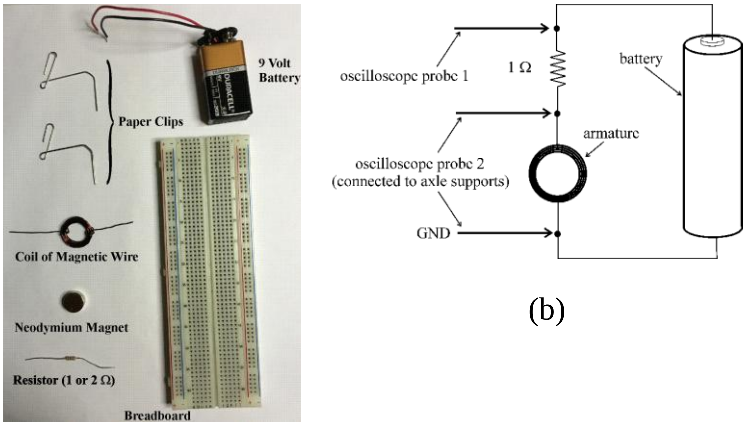
(c)

(d)

Figure 22 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, and (d) a paper audio speaker

The final portion of *ECE 3209* focuses on time-varying electromagnetic fields, including Faraday's Law and the fundamentals of electromagnetic waves. An illustrative project for this portion of the class is given below and involves an experimental study of electromagnetic induction and motors. This project follows a classroom lecture on the Lorentz force law, induced emf and the torque experienced by a current loop in the presence of a magnetic field. Moreover, the project also serves as an introduction to concepts that students learn in greater detail in *ECE 3250*, *Electromagnetic Energy Conversion*. As with all the mini-projects for *ECE 3209*, a portion of the lecture material is reviewed in a background section and is followed by a hands-on experiment that demonstrates the principle, or a mini-project in which students are asked to apply the concept. For this project, the students construct a simple "table-top" motor using magnet wire, a neodymium magnet and a battery. Using the VirtualBench, students monitor the current drawn by the motor armature to measure the frequency of rotation and investigate the effects of changing the current supply and magnetic field strength.

The materials and connections are shown in Figure 23. As can be seen in (a), the required materials are very simple and inexpensive, and plans for construction of a motor of this sort are widely available as student projects and on the internet. However, when we add the connections and instrumentation in (b), this simple project becomes a valuable tool for measuring the actual performance of the motor, including wave shapes of the current consumption and back emf generated by the armature as well as the rotational speed. Students are now able to estimate the flux density seen by the coil and experiment with various combinations of magnets. The fully assembled motor is shown in Figure 24.



(b)

(a)

Figure 23 (a) Parts used to construct the tabletop DC motor showing the motor armature made of coiled magnetic wire. (b) Electrical connections for monitoring the motor performance.

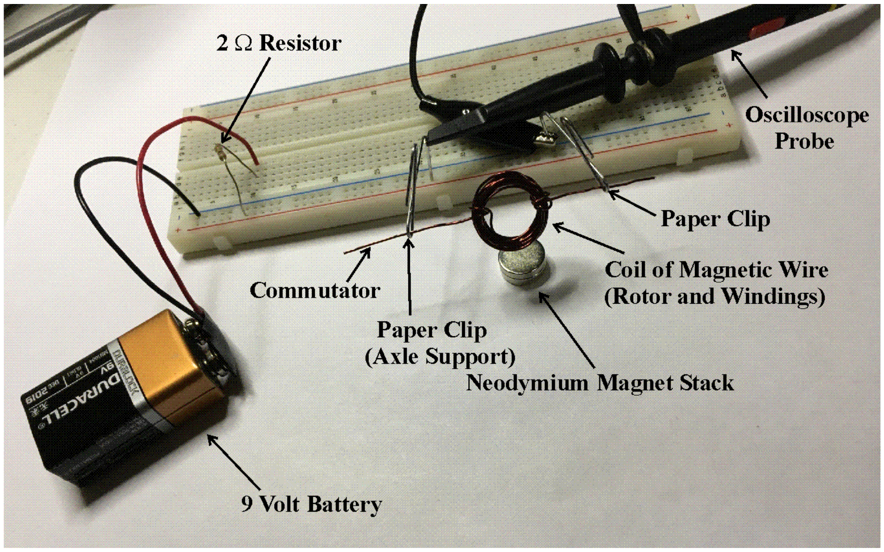


Figure 24 Fully constructed DC tabletop electric motor

By means of these simple experiments, we have been able to take a course that undergraduates usually consider to be a "weed-out" one that is purely a course in vector calculus, and convert it to an experiential based classroom scenario that makes these difficult concepts both real and approachable. We also impress upon the students that measurements that seem difficult may frequently be performed with simple hardware if one has a fundamental understanding of the concepts involved.

Assessment of Outcomes

The curriculum updates that we have undertaken have involved an enormous amount of work on our part and at the end of the sequence we must ask ourselves if we have improved outcomes for our students. At present, we are in the process of considering several metrics.

The first metric that we undertaking is a sequence of testing involving concept inventories.[21,22] These tests focus on concept understanding and not on memorization of equations or circuit topologies. Our final cohort of 4th year students, i.e. those who went through the curriculum in the previous lecture-based approach, is currently being tested with these inventories and the results will be used as a basis of comparison. The rising cohort of Fall 2016 is the first to go through under the new sequence and they will be tested in the coming academic year. Our transitions were planned with multiple sections such there is a clean break between cohorts. Also, we are beginning to develop our own concept inventories as a better test of integrated understanding than is provided by the current inventories which still tent to be oriented towards single subject tests. We plan to implement a system of continuous testing and feedback as a mechanism for continuous improvement of our program, reporting on these results in future publications.

The second metric is that of student satisfaction. At the end of *Fundamentals 3*, we conducted a poll with "Likert-style" questions focusing on how the students perceived their understanding of this material, over the extent of all 3 courses. Results from this survey are shown in Figure 25.

	Poll Question	Percent agree or strongly agree
1	Combining the class and the lab enhanced my learning.	89
2	The hands-on activities helped me understand the concepts more deeply	91
3	The physical arrangement of the classroom enhanced my ability to learn	68
4	The quizzes enhanced my understanding of the material	68
5	Doing the labs during the class helped me clarify my understanding of the topics	84
6	The relationships between the various topics was reasonably clear	77
7	Having the electronics and signals & systems material interwoven helped me see the big picture	82
8	The class enhanced my lab skills	89

Figure 25 Poll results of student satisfaction

This poll was conducted as an add-on to the final examination and we went to great lengths to encourage the students to give honest answers that would in no way affect their grade; we were seeking blunt feedback that would enable us to improve our program. The results were overwhelmingly positive, and the distribution was such that we feel the answers were thought out and not just simply "checked off". We especially observe that we should endeavor towards improvement in areas related to the physical facilities, a process already underway; our current room had a physical offset resulting in an "L" shape that limited visibility as well as mobility for both students and instructors. Renovations are planned for the summer of 2016. We are also in the process of revising our quiz concepts. However we draw special satisfaction from the results of the other questions, especially questions 1, 2, and 7. It is this breadth of understanding that was one of our major goals.

A further assessment that we consider is admittedly anecdotal, but real nevertheless. Most students in *Fundamentals 3* are in the middle of their 3rd year. At this point they are able to perform both a sophisticated analysis of concepts that encompass circuitry, electronics, and signals and systems as well actually use those concepts to perform synthesis of a difficult and involved project. Taking a real-world noisy signal in the microvolt range, amplifying it, filtering it, and performing basic digitization is certainly a daunting project for any engineer. That we are seeing students do this a little over half-way through their undergraduate program is indeed rewarding.

Future Plans

We are in the process of considering methods to apply our concepts to other courses in the curriculum that are currently electives. We feel that simple experimental devices can be designed that will allow us to conduct our *Introduction to Linear Controls* course in a studio fashion. This course is frequently taught as a math based lecture course at many Universities and we feel that converting to a studio format would of great value to the community. This would apply as well to the typical follow-on digital controls course also frequently taught using the same approach.

Another course that would greatly benefit is *Electromagnetic Energy Conversion.* This course which is very heavily associated with hardware, i.e. transformers and motors, would tie critical concepts together. This is especially urgent as a broad understanding of power systems will be crucial to any implementation of alternate energy systems in the future.

Reflections and Conclusions

At the time of this work, we are just finishing our first complete sequence of the *Fundamentals Series*. The development of these courses has involved considerable effort and it is our desire to form collaborations with other universities to expand these concepts for the benefit of all. As we ponder pedagogy and considerations of "problem-based learning" or "project-based learning" it is clear to us that student involvement in the process is key, and we view the "experiential classroom" as a strong first step towards that goal.

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