Restructuring an Electrical and Computer Engineering Curriculum: a Vertically Integrated Laboratory/Lecture Approach

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Abstract

In most Electrical and Computer Engineering curricula, the core 2nd and 3rd year course material is typically divided into 3 distinct courses – Linear Circuits, Electronics, and Signals and Systems. As part of our curriculum overhaul, we are developing an innovative vertically integrated course structure for the core of Electrical and Computer Engineering. Each course, now referred to as Fundamentals 1, Fundamentals 2, and Fundamentals 3 encompasses material from each of the 3 courses in our previous sequence. Additionally, we have dissolved the laboratory-lecture dichotomy. Lecture material is covered within an extended laboratory environment and short compact experiments are performed in concert with the lecture. This is facilitated by integrated compact test equipment that allows a full laboratory suite of instruments accessible on each desktop. A highlight of the course work is a physical design project at the end of each semester, including printed circuit design and assembly.

Keywords

Curriculum, problem-based learning, course restructuring

Background

Nationwide, universities are facing declining enrollment in Electrical and Computer Engineering Curricula and there have been a number of reasons cited[1]. Our experience at the University of Virginia (UVa) with informal surveys indicates that many students feel that the current curriculum is too abstract and hence too difficult. Other students feel that perhaps it will not prepare them for a job after graduation[2]. Another persistent issue is that students do not see the relevance of Electrical and Computer Engineering to everyday life; the ubiquitous and pervasive nature of the contributions of electrical and computer engineering also cause them to fade into the background of our daily existence.

The problems associated with decreasing enrollment are further aggravated by the relatively static nature of a typical curriculum, especially at the core levels seen in the second and early third year levels. While the knowledge required in the field of electrical and computer engineering is expanding rapidly, the core material and the way it is covered has not changed in any appreciable way, and the normal sequence of courses leaves students with little sense of connection between the many concepts that must be mastered[3].

There have been a number of pedagogical approaches taken to enhance the understanding level of students in introductory electrical and computer engineering courses. Some universities have worked with studio approaches for a number of years, and Carlson et al.[4] have shown good results, especially with improving student satisfaction. Another approach is the so-called "flipped classroom" that has been employed in several formats[5,6,7]. This approach focuses on moving the lecture component outside of the traditional classroom and into on-line delivery methods. The classroom time is then used more as a problem-solving session; this approach has shown considerable promise. It is useful to note that in many alternative approaches the methodology includes reduction or elimination of the traditional lecture as a means of imparting understanding.

Perhaps the most persistent shortcoming of a traditional sequence of courses that we have observed is the tendency for students to place knowledge from each course into its own "box" never to be needed again. Students for example perceive traditional linear circuits as bearing little relation to electronics, or electronics to signals and systems. We have begun to address that issue through our embedded systems course at the third year level. In that course we combine lectures with laboratory experiments, studio-style, and structure each experiment such that it contains knowledge from embedded computing in concert with concepts from across the rest of the electrical and computer engineering curriculum[8,9]. A typical experiment might be pulse-width modulation (PWM) control of a small direct current motor with encoder feedback, shown in Figure 1. This combines the embedded computing concept of PWM generation along with electronic concepts of transistors as switching elements, fundamentals of motor operation and basic principles of feedback control, keeping several parts of the larger picture in mind at all times. This course has been extremely well received and is one of the most popular courses in our department.

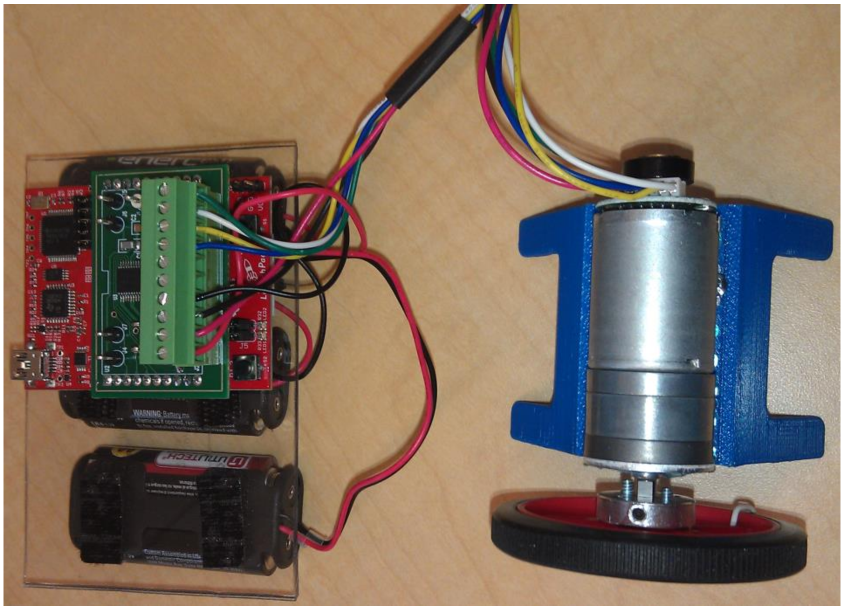


Figure 1 : Example Multi-Concept Embedded Experiment

In order to address the problems in electrical engineering education, we are undergoing a major curriculum overhaul. Our previous curriculum was one that is typical of many U.S. universities. Our first year program is general in nature, and majors are declared late in the Spring semester. Actual work within the major starts in the second year.

In the first semester of second year, our students took a very standard course in linear circuits with 3 hours of lecture per week, and a laboratory section that met every other week. Heavy emphasis was placed on fundamental circuit analysis techniques, i.e. Kirchhoff's laws and nodal analysis. There was no exposure to devices other than the three basic passive elements, resistance, capacitance, and inductance. Also, there was little exposure to signal analysis in the frequency domain.

The second course in the sequence was on electronic devices, and the course format was much the same as in the first semester, with the exception that the laboratories met every week. This course covered operational amplifiers, diodes, MOSFETs, and bipolar junction transistors. The final course in the sequence was signals and systems, meeting for lecture 3 hours per week and having no laboratory section. This course covers all of the basic transforms for working in the frequency domain including Fourier and Laplace.

There are a number of drawbacks inherent in this approach, both from a pedagogical perspective as well as the overall student experience. For example, in the first semester, students gather the sense that all of electrical engineering is circuit analysis, wrapped up in large sets of simultaneous equations. In the second semester, when active devices were introduced, the use of capacitors for bypassing and interstage coupling required ad hoc explanations of frequency domain concepts normally introduced in the third semester. In signals and systems, there were so many concepts to be covered that students were frequently unsure of what the actual applications were. A comment heard all too frequently was "this is a math course for which there will be little need once I graduate"!

Our curriculum overhaul intends to address these limitations and shortcomings going to a breadth first approach, in which each semester students are exposed to most of the concepts studied in the previous 3 semester sequence. Each semester reiterates the previous sequence with a progressive deepening of detail and understanding at each level. This pedagogical approach has been demonstrated as an effective means to achieving both depth and breadth of understanding and concept retention[10,11,12]. We are combining this approach with studio instruction techniques and now are employing this in a combined laboratory-lecture approach in which each class session has both a hands-on component as well as interspersed lectures.

We have now re-sequenced our course names to "ECE Fundamentals 1, ECE Fundamentals 2, and ECE Fundamentals 3" in order to reflect the broad nature of each course. The rest of this paper will describe our classroom setup and approach in implementing ECE Fundamentals 1 over the course of the Fall 2014 semester, and a sketch of what is envisioned for the sequels. This course sequence is in an emergent state; Fundamentals 2 will be first offered in Spring of 2015 and Fundamentals 3 in the Fall of 2015. We are in the process of gathering concept inventory style test results from current 3rd and 4th year students who went through our previous sequence of courses as a mechanism for the comparison of content retention as our current students move through the program.

In the following sections, we discuss the basic classroom physical setup and organization. Due to section and scheduling constraints we had 2 class sections, one that met 3 days per week for 2 hours per session, and another that met 2 days a week for approximately 3 hours per session. The strategies for dealing with the constraints of timing and classroom management are discussed in the following sections, followed by a discussion of limitations of current approaches to teaching Signals and Systems and how we are addressing that in the Fundamentals courses. Students are presented with basic frequency domain concepts in Fundamentals 1, and we discuss further the inclusion of more advanced frequency and time domain concepts in Fundamentals 2.

Classroom Organization and Equipment

Our classroom is organized in such a way as to comfortably handle approximately 45 students arranged in groups of 3, with a total of 9 students grouped at triangular based work stations, shown in Figure 2. There are projector screens located at each end of the room, allowing easy visibility to the instructor's lecture materials and demonstrations from anywhere within the room.

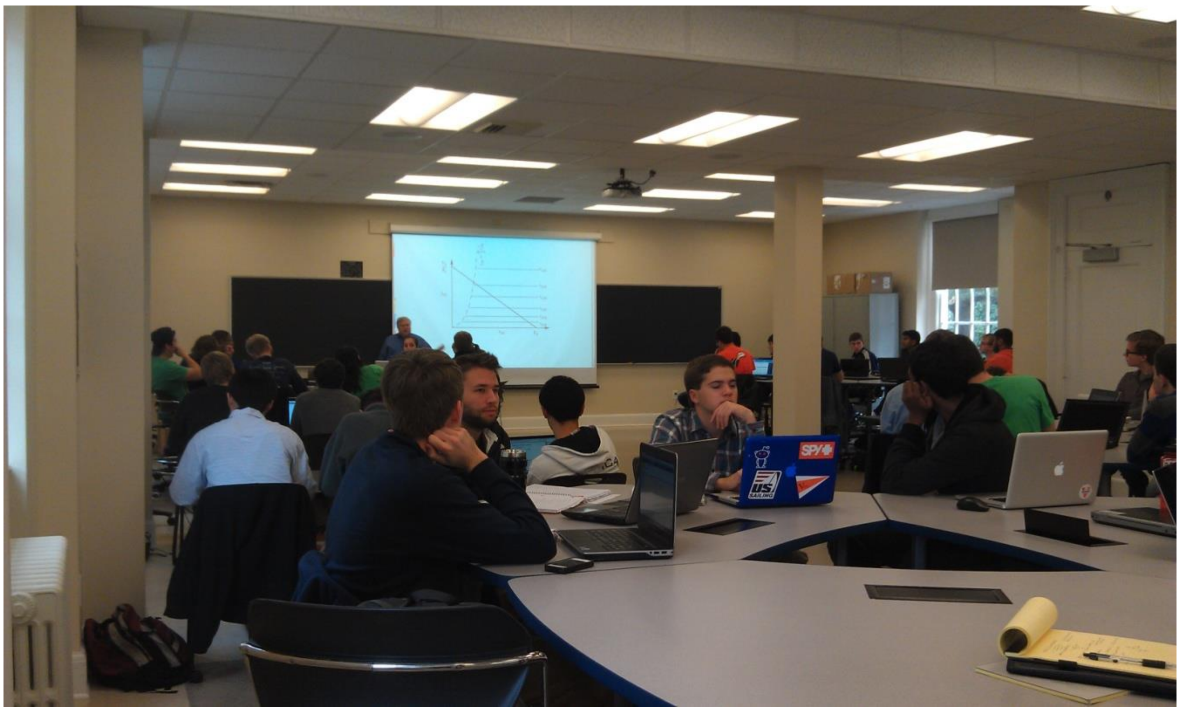


Figure 2 : Basic classroom arrangement

A challenge to this arrangement lies in making all of the required equipment available to the students in a compact fashion and without obstructing the view of the screens or the instructor. A full suite of test equipment is required including power supplies, signal generator, multimeter, and oscilloscope. These requirements led us to consider integrated instrumentation and our final selection was the *VirtualBench*™ from National Instruments Inc[13], shown in Figure 3. This equipment facilitates both in-class exercises and has the ability to upload experimental data to the students' laptop computers for post lab analysis. This data is in a format that may be imported into math software or circuit simulators, which facilitates more extensive analytical experiments, and gives students a broad exposure to other software tools, i.e. MATLab™ and how such tools might be employed in electrical engineering problem solutions.

In addition we created several accessories to facilitate ready setup and teardown within the classroom time frame. This also reduced unnecessarily repetitive actives, especially connecting and disconnecting power supplies from solderless breadboards.

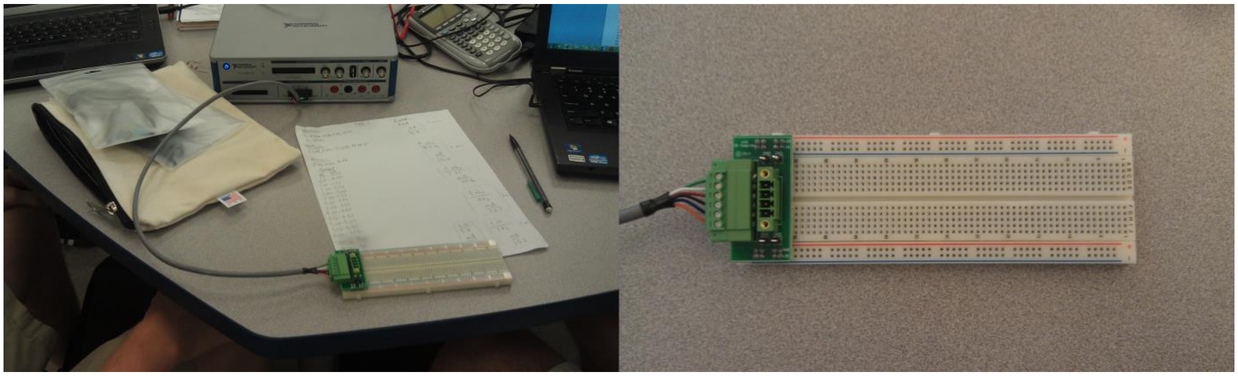
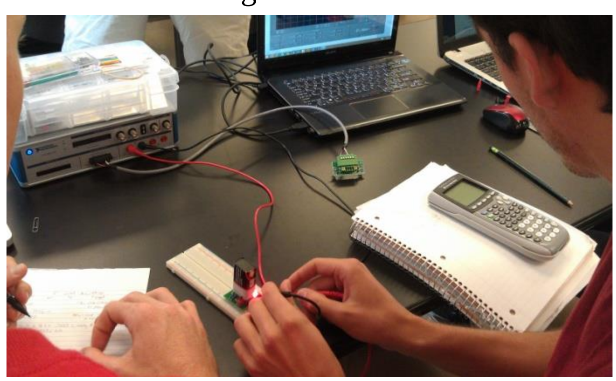


Figure 3 : Typical *VirtualBench* setup

We created the cable accessory at the right to accomplish several goals. The first was to correctly distribute power and ground from the power supplies in a logical manner with convenient test points for ground connections of oscilloscope and signal generator probes. A second goal was to eliminate the necessity of having students constantly screw wires into the instrument at the start of each period, which would inevitably lead to early wear and failure of the connections. The adapter was designed such that it would readily plug into either end of a standard solderless breadboard such as is commonly used in undergraduate laboratories.

Class Session Scenarios for Short Section Times

One section of this class met for one hour and fifty minutes three times each week. Each class period included some time for lecture and discussion, brief assessments of student understanding, and practical exercises. The lecture and discussion time rarely occupied more than half of the total class period. The brief assessments were in the form of quizzes administered on-line and time-limited to a range from 5 to 10 minutes. All of the remaining time was dedicated to the practical exercises. The organization of these times varied between class periods. Some classes started with the short quiz followed by lecture and discussion and ended with the practical exercises. Other classes started with the practical exercises followed by the quiz and ended with the lecture and discussion. A few class periods interspersed practical exercises with lecture and discussion, and this format might have been the most effective but it was the most difficult to manage. Most class periods started with the lecture and discussion followed by the short quiz providing a transition to the practical exercises.



The class period organization that appeared to be most practical started with the lecture and discussion, transitioned with the short quiz, and ended with the practical exercises. This organization was most practical because it enabled the natural allocation of different amounts of time to practical exercises based on the needs and abilities of the individual students. Those students who found the practical exercises to be easy completed those exercises quickly and could simply leave the class early. Those students who found the practical exercises to be more challenging could take more time and get more help. A few students needed even more time for some of the practical exercises than could reasonably be allocated within the class period, and additional outside help sessions were made available to accommodate the needs of those students.

All practical exercises were coordinated closely with the lecture and discussion topics. The tightest coordination occurred during the class periods when lecture, discussion, and practical exercises were interspersed. During these classes, each part of the practical exercise was revealed as the related topic was discussed. The students immediately undertook the appropriate part of the exercise to illustrate or confirm the phenomenon discussed; a typical exercise is shown in Figure 4. This may have provided the most effective teaching and learning, but it was the most difficult to manage because of differing practical capabilities among the different students. Time was provided to accommodate the needs of all students, and many students had to wait after they had quickly finished the assigned task. This imbalance might have been improved by better assignments of group members with the more practically capable students paired with the more practically challenged students.

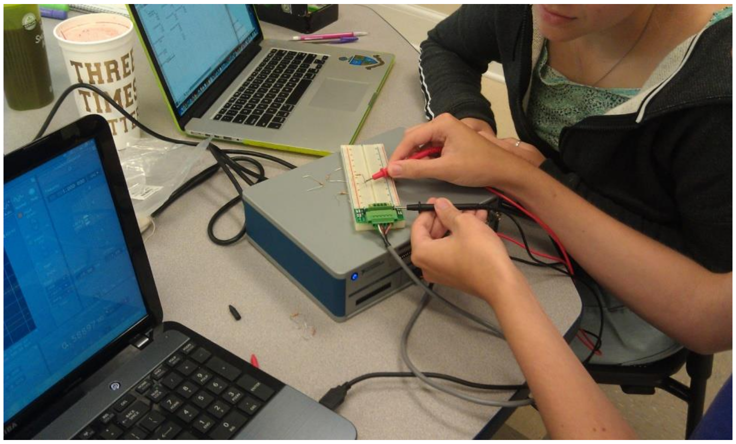


Figure 4 Typical practical exercise

The integration of practical experience within every class period appeared to simplify and accelerate student learning. Abstract concepts and mathematics were immediately given practical context, validation, and justification. The students asked good questions while working on their practical assignments, and it was typically appropriate to respond to the questions with reference to the topics of the lecture and discussion. As the semester progressed, the discussions became lengthier and often included more advanced questions. Student performance on formal assessments and in informal discussions suggested reasonably deep understanding of the concepts covered.

The practical exercises were greatly enhanced by the employment of undergraduate teaching assistants. While this was a new class that varied both in content and presentation style from earlier classes, undergraduate students who had performed well in earlier classes covering the content of this class were hired to help the instructor to manage the practical experience parts of each class. This was necessary to accommodate the enrollment while also providing timely support for students who generally did not have prior circuits lab experience. Many of these undergraduate teaching assistants have commented that they believe students in this class have had an easier time learning the material than the teaching assistants experienced in the traditional classes separating traditional lectures from labs.

It may be useful to consider a specific example class period to illustrate the approach. First, it will be useful to know the preparation leading up to the example class period. The topic of non-linear devices was introduced after the first test was administered about one third of the way into the semester. The diode was discussed as a simple example non-linear device. Its current-voltage characteristic curve was presented, and various techniques were offered for analysis of circuits including a non-linear element in general and a diode in particular.

The specific example class revisited the concept of superposition and evaluated the applicability of the superposition concept to circuits that include a non-linear element. Earlier classes had experimented with superposition using two constant sources in linear circuits composed of resistors, so the students were already familiar with the superposition concept and how they might proceed to test its applicability to the new circuit containing a non-linear element. One of the practical experience tasks assigned during this period was to build the circuit shown in Figure 5 and determine whether superposition appeared to apply to this circuit.

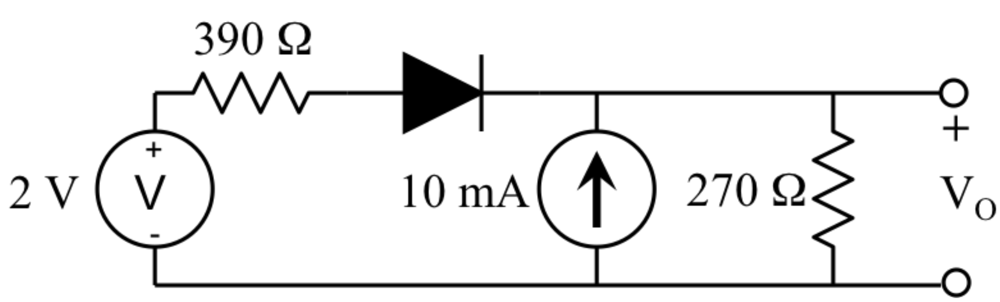


Figure 5 Typical Superposition Experiment

The students built the circuit and performed tests to determine the output voltages resulting from the activation of each source alone and from both sources together. They discovered that superposition did not hold for this circuit. This discovery was followed by lecture and discussion of the general inapplicability of superposition to circuits including non-linear elements. The students experimented further with different voltages for the voltage source to see that superposition might appear to apply for some combination of source values, but they were now aware that it does not apply in general.

We have also included a section of the coursework in which students gain practical CAD and circuit assembly skills at an introductory level. Students designed and simulated a simple single-stage MOSFET amplifier. They then created a printed circuit board layout for their design, and a board for each student was sent out for manufacture. Students were required to assemble the parts, gaining skills in soldering components.

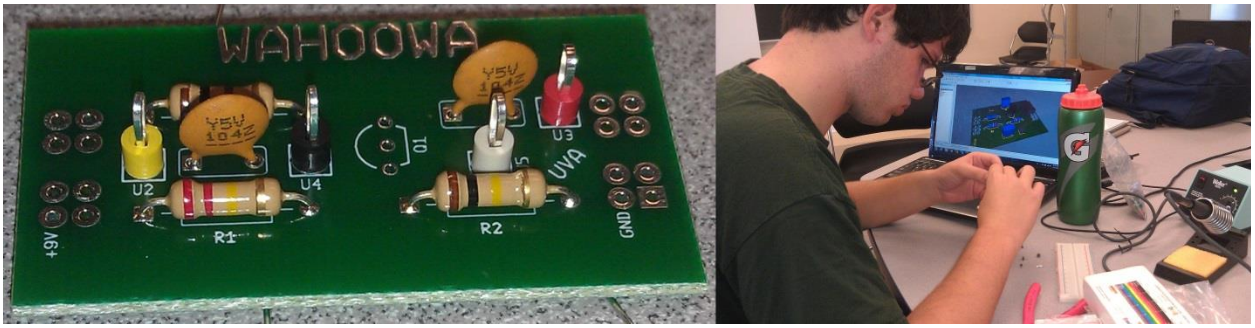


Figure 6 MOSFET Amplifier and Assembly

The left side of Figure 6 is a sample of the circuit board to be assembled. The amplifier stage employed capacitive coupling, which allowed the students to explore frequency response issues as well as isolating the D.C. bias conditions. In the right side of Figure 6, the student is loading parts on the board, using the CAD layout as a guide.

Students also soldered together the components, and tested their designs using previous simulations as a basis of comparison (Figure 7).

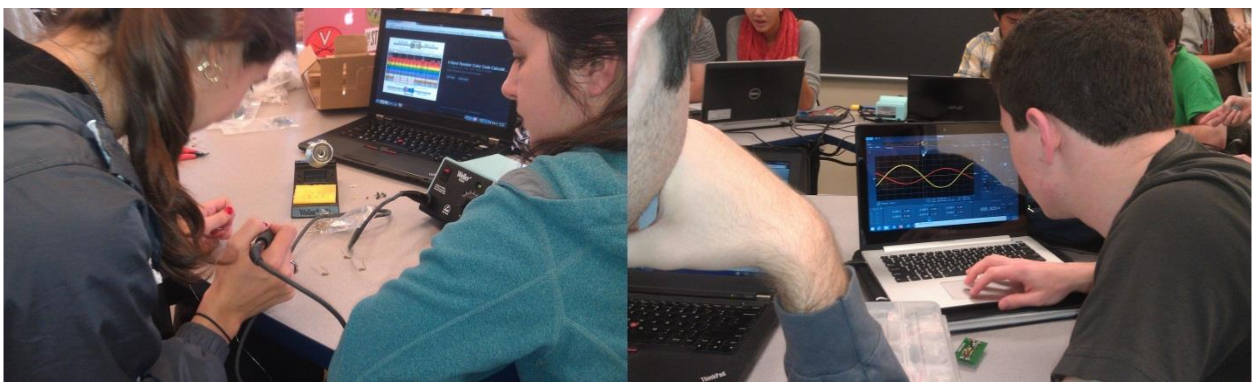


Figure 7 Assemble, Solder, and Test

A number of students also used this exercise as an opportunity to explore their circuits in open-ended sense. For example some students looked at the effect of varying power supply voltages on gain and bias conditions. Others drove their circuit well into distortion, Figure 8, which was instructional from several standpoints. Students were able to directly observe the limitations of the small signal models, and gain an intuitive sense of how the circuit behaved as transitions were made from the small signal region into a more non-linear area of operation. Additionally students were able to observe the effects of distortion in the frequency domain, using the FFT ability of the ***VirtualBench*** to observe spectra of both the input and output signals. Although the concept of frequency domain and Fourier analysis were introduced in the lecture sessions, the impact of actually seeing it on a circuit which the students had designed and assembled themselves had a much more visceral impact on their qualitative understanding. The musicians in the class were also pleased to note this sort of distortion is applied in guitar effects!

We envision the board design process as having a ripple effect throughout our curriculum. In Fundamentals 2, when students become involved in active filter design we intend for the students to have several additional design projects and we anticipate that this will continue with Fundamentals 3 as well. Additionally, this will amortize the learning curve for the CAD tools over several semesters, and enable the students to have a more fulfilling experience when designing their 4th year Capstone projects, at which point they will have already mastered the required skills for assembly and test.

Class Session Scenarios for Long Section Times

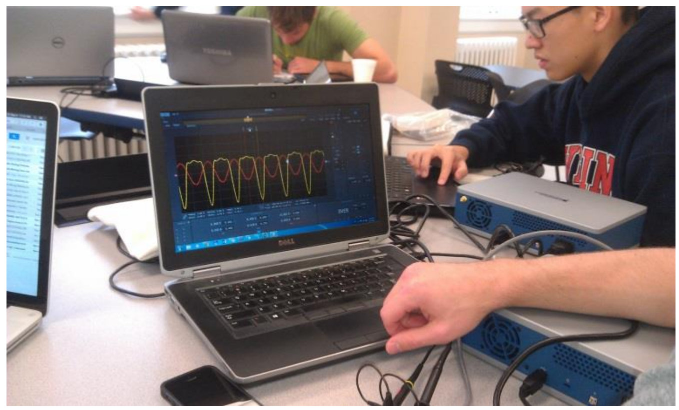


Figure 8 Observing Distortion

The second section of this class met twice a week, with each class two hours and forty-five minutes. As with the first section, each class period was partitioned into lecture/discussion, an in-class activity (quiz or short group assignment), and laboratory exercises. A typical class began with a lecture/discussion period in which homework problems would be discussed and solutions presented, usually leading to or motivating the development new topical material. The use of the *VirtualBench* provided a convenient vehicle for using lecture demonstration to illustrate the concepts being taught by permitting the response of various circuits and experiments to be displayed to the class.

Following the lecture/discussion period, a quiz or team assignment would be assigned (typically lasting 15 minutes) to test the students' comprehension/understanding of the concepts and allowing them to discuss the topics in small groups. The final portion of the class, often followed by a short break, consisted of laboratory exercises and project that focused on illustrating, exploring, and applying the concepts discussed in lecture. As with the first section of the class, this organizational structure proved most practical as it permitted different groups of students to work at their natural pace and minimized set-up time and disruption for the laboratory exercises. Critical to implementing the integrated laboratory exercises was the availability of significant support from undergraduate teaching assistants who could roam the classroom to assess progress and be available to assist students with questions or experiencing difficulties with their circuit construction, debugging, or measurements.

The combination of lecture/discussion with immediate reinforcement through practical and direct hands-on demonstrations/experiments by the students in small groups (consisting of no more than three students each) appeared to reinforce understanding and was effective in breaking down the reluctance students often have in interrupting formal lectures to ask questions and initiate discussion.

One focus of the laboratory exercises was not only to illustrate/support material discussed in the class, but to reinforce and connect that material with that from other courses in the ECE curriculum. As an example, in discussing MOSFETs, part of the laboratory exercises assigned included construction and characterization of some basic CMOS logic gates (illustrated in Figure 9 and Figure 10). This exercise was included to help connect the course material the ECE course in digital logic design, which many of the students take concurrently. Following this exercise, students were challenged to apply their understanding of MOSFETs to design and demonstrate a logic gate of their own (for example, an XOR gate).

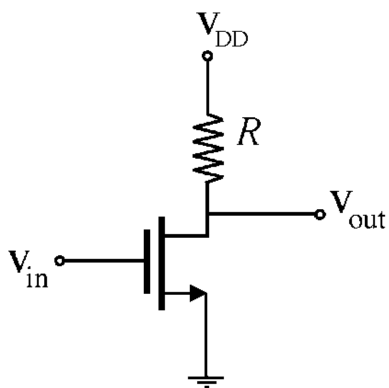


Figure 9 Simple Inverter

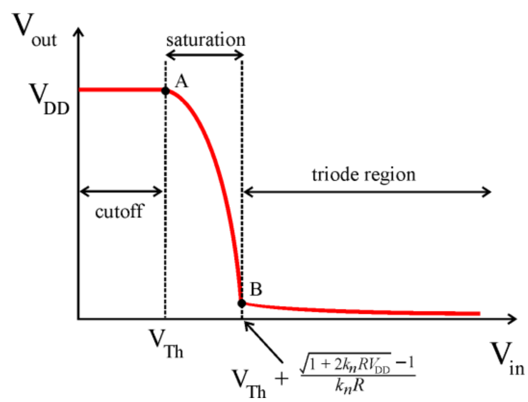


Figure 10 Transfer Characteristic

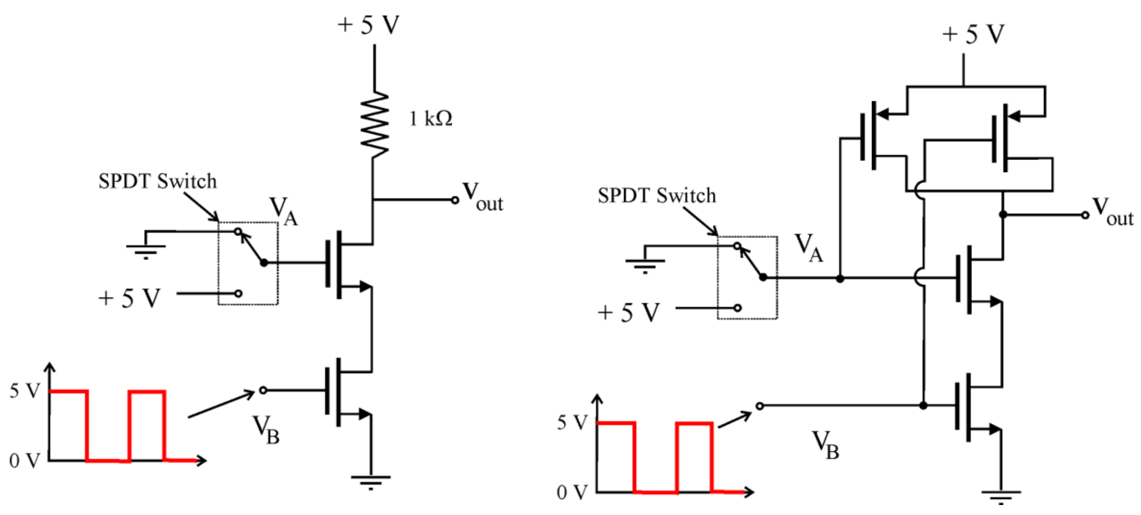


Figure 11 RTL NAND Gate and CMOS NAND Gate

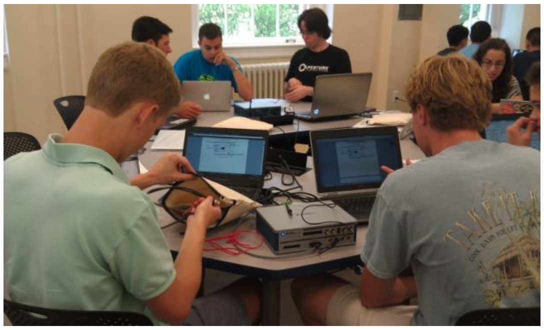
Examples of MOSFET logic gates circuits constructed and characterized by students in the class are shown in Figure 11. The circuit on the left is a resistor-transistor NAND gate design and the right is a CMOS NAND gate design. Students were asked to verify the gate truth tables and use an oscilloscope to measure the gate propagation delay. Afterwards, students were challenged to design, construct, and characterize an exclusive OR gate.

Signals and Systems Methodology

The ECE curriculum at UVa, as it has evolved over the last 20 years, has reduced the number of credit hours allocated to core subjects to make room for more advanced, newer, and presumably more applicable topics. The Signals & Systems portion of the curriculum thus transitioned from a two-semester required sequence, to one required plus one elective, to simply a one-semester-long course. In the resulting lecture-based course, over the 14 weeks the students were expected to learn seven transforms, three in continuous time and four in discrete-time. Because of the packed curriculum, there was no time to explore any applications of the concepts, with but occasional reference to what they will use the knowledge for in the future.

At the beginning of the semester the students had barely had any exposure to manipulating signals in time or frequency, with similarly scant experience with complex-valued functions. The course began with time-domain manipulation of signals, where differential equations were used to solve for complete solutions of circuit problems with initial conditions. Even after having had a first circuits course, the students found it difficult to understand this material. They could solve a circuit problem, they could solve a differential equation problem, and they knew the voltage-current relationships for the various passive elements in the circuit. Yet this was the first time the pieces have been brought together as one topic. This should have been a eureka-moment for them, but it was not: it was a sterile cookbook process resulting in a meaningless mathematical expression, devoid of applicability or significance. Learning the process of convolution and its relation to the impulse response of a linear time-invariant system was equally abstract.

The course then progressed through the Fourier series, Fourier Transform, and the Laplace transform. The sampling theorem lead to discrete time analysis, including the discrete-time Fourier Series, the discrete-time Fourier transform, and the Z-transform. The discrete Fourier Transform (DFT), and its computationally efficient implementation, the fast Fourier transform (FFT), were briefly discussed. For each topic two aspects were emphasized: the mechanics of how to compute the transform, and the purpose of the transform. Yet this purpose remained abstract. Most examples started mathematically and finished that way. The occasional real example, however, did help. We explored harmonics emanating from guitar chords, filtered noisy voice signals, watched wagon wheels look as they are rolling backwards due to aliasing. However, these short respites from the rigor of the material were woefully insufficient to engage students.



In the new ECE Fundamental 1, 2, and 3 classes, all of the same material is being covered, with absolutely no sacrifice in depth or rigor. The difference is in the motivation. The topics are woven into the curriculum, placing each within a circuit or electronics experiment that makes direct use of the theoretical concepts. When possible, a preliminary experiment is designed to familiarize the students with a device or concept. This experiment raises questions that require a short lecture and exercises to understand some Signals and Systems theory. This is then followed by a more sophisticated experiment or design project that directly uses and illustrates the theory presented.

Let us consider an example planned for early within ECE Fundamentals 2, in which an opamp is used to implement a filter. The week-long module would proceed as follows:

> Experiment 1: (Noise Reduction) Build a simple passive analog low-pass filter to review circuits concepts. Listen to the effect of passing a voice or music clip through the filter. Analyze the signal before/after in both the time and frequency domains. This involves using the Virtual Bench to capture the filtered audio and send it to the computer for playback.
>
> Lecture: (Fourier transform) Introduce the frequency domain in terms of pitch. Give definition, examples, and properties of the Fourier transform. Explore *Matlab*™ symbolic and numeric functions to compute the FT. Learn how to design real-pole filters using Bode plots.
>
> Experiment 2: Build an opamp low pass 1st-order filter. Cascade two opamp filters to show effect of higher order. Analyze the signal before/after in both the time and frequency domains. Verify linearity abstraction still holds. Compare output of analog filter to *Matlab* simulation of filter.

Each of the Signals & Systems concepts will be addressed is a similar fashion. Convolution and the impulse response will be understood by generating a short pulse and exploring a system's output. Aliasing will be learned by experimenting with undersampled A/D conversion followed by D/A conversions. Instability will be invoked through positive feedback, and simple control notions will then be explored via negative feedback. The approach of inserting short as-needed lectures within experiments is consistently applied, over the course of the three semesters, effectively covering all the material from the three individual classes.

Summary and Conclusions

We have described a major and innovative curriculum reform effort currently underway in Electrical and Computer Engineering at UVa. Our preliminary results with Fundamentals 1 are very encouraging and we plan on an ongoing standardized "concept inventory" style of assessment for comparison with student outcomes in our earlier more conventional course sequence. Students are grasping basic concepts well and we attribute this in large part to the tightly integrated laboratory and lecture experience. Interest in the course material remains very high, and we believe that this is primarily due to the breadth- first approach giving students exposure to and experience with active components as well as the basic passive ones normally encountered in a first course. Student comments are strongly in favor of the hands-on components of the classroom experience, and have expressed the opinion that this has enhanced learning.

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