A Studio-Based Electromagnetics Course for the Undergraduate Electrical Engineering Curriculum

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Abstract

Advances in the RF and wireless communications and systems should be reflected in the undergraduate electrical engineering curriculum. Although electromagnetics is fundamental to this and most other subjects taught in electrical engineering — encompassing a wide range of topics, ranging from semiconductor physics to communication systems —its place in undergraduate education is constantly being debated as newer topics are integrated into an already crowded curriculum. Furthermore, students usually want to see the immediate relevance of the subject to practical engineering problems. However, the applications of electromagnetic principles often seem remote or abstract.

Over the past three years, the University of Virginia has restructured its core curriculum in electrical engineering, with a primary goal to merge traditional lectures with practical hands-on projects within a studio-style class model. This studio model currently is being applied to a revised version of our required one-semester course on Electromagnetic Fields (ECE 3209) as described in this paper.

Keywords

Electromagnetics, Studio course, experiential learning

Background

In 2013, the Department of Electrical and Computer Engineering at the University of Virginia began a thorough restructuring of our undergraduate core curriculum. Our original courses in *Circuits*, *Electronics*, and *Signals and Systems* were delivered in a conventional lecture format, with separate laboratory sections for *Circuits* and *Electronics*; there was no laboratory content for *Signals and Systems*. We had consistently observed that students exhibited a strong tendency to "silo" this coursework, and the retention of material from one semester to the next was adversely affected. Students could not readily perceive the overall subject breadth of electrical engineering and critical links necessary for the profession were not being made.[1,2]

Among our goals in the restructuring process, we elected to dramatically increase the hands-on component of these courses as experience has shown the efficacy of problem and project-based learning as a mechanism for increasing concept retention.[3,4] Furthermore research has indicated that a progressive deepening of understanding improves concept comprehension, i.e. a breadth-first approach.[5]

With these goals in mind, we modified our original 3-course sequence of disparate topics into a cohesive sequence, *Fundamentals 1,2* and *3*.[6] This new course sequence is taught in a studio style with combined lecture and laboratory components in each class session. Each course has a similar syllabus, covering the breadth of all of the topics from our previous course sequence, but with a progressive deepening of understanding of the material with each iteration.

The studio model that has been implemented for the ECE *Fundamentals* sequence is being adopted by a broader range of courses in the undergraduate curriculum, notably our 3rd-year one-semester course, *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 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 (for example, 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 primary motivation for moving from a lecture to studio format for ECE 3209 was to enhance the retention of key concepts that form the foundations for many other parts of electrical engineering. For example, a clear conceptual understanding of these concepts is important in understanding the operation of motors, generators, transformers, field effect transistors, and even basics such as Kirchhoff's laws — particularly with regard to their application to RF and microwave circuit design. Ultimately, hands-on demonstrations of these key concepts in the context of the advanced mathematical descriptions (Maxwell's equations) can avoid the common lament of students: "It was a lot of math. I got an A in the class but really didn't learn much that related to the rest of electrical engineering". The transition to the studio format was gradual over two offerings of the class. It started initially with instructor demonstrations using very simple materials and equipment done in a small class format (12 students in the initial offering). This laid the foundations for developing the hands-on experiments and demonstrations for the full studio version. The demonstrations included a qualitative reproduction of Coulomb's experiment, the artificial transmission line (described below), magnetic force, induction, polarization, and others.

Electromagnetic Fields Studio

The studio version of ECE 3209 at the University of Virginia addresses the issues described above and builds upon the infrastructure already in place for the ECE Fundamentals courses. 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. Introducing transmission lines at the beginning of the class allows a direct connection to be 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 curriculum. 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.[7]

To implement the studio portion of the class, the second half of the class meeting period is dedicated to a set of "mini-projects." Our studio space is shown in Figure 1. 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 and 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 construct a set of impedance matching circuits, including a 50 Ω power splitter. As an example, Figure 2 shows our "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.

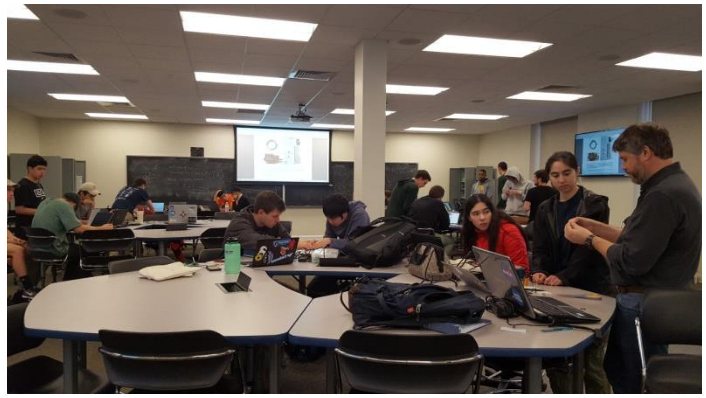


Figure 1 Typical Studio Class space

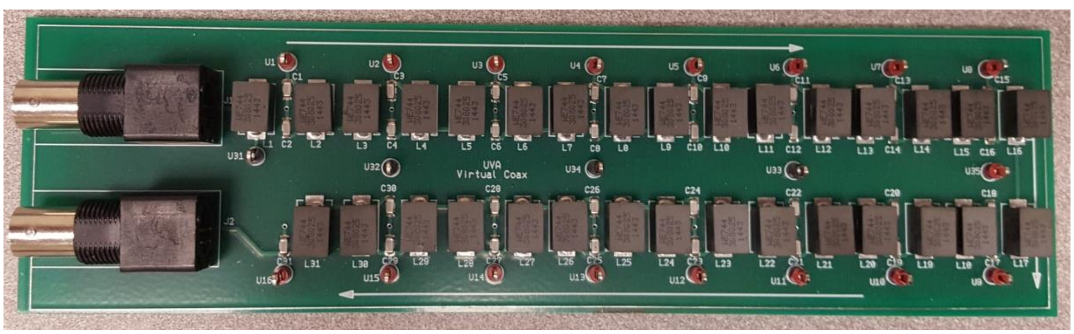


Figure 2 Artificial Transmission Line

The line is designed to simulate a 50 Ω coaxial cable using a lumped-model approximation. Test points are inserted between pairs of the inductors and capacitors, allowing experimental setups to "tap" the equivalent of increments of 2 meters of cable, and the entire board can simulate 64 meters of cable. An equivalent line of this length allows the experiments listed above to be performed at

Figure 3 Typical Lab Setup for transmission line experiment

modest frequencies using non-critical benchtop setups as shown in Figure 3 Note that these designs and all fabrication files are open source and are available on request from the authors.

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.

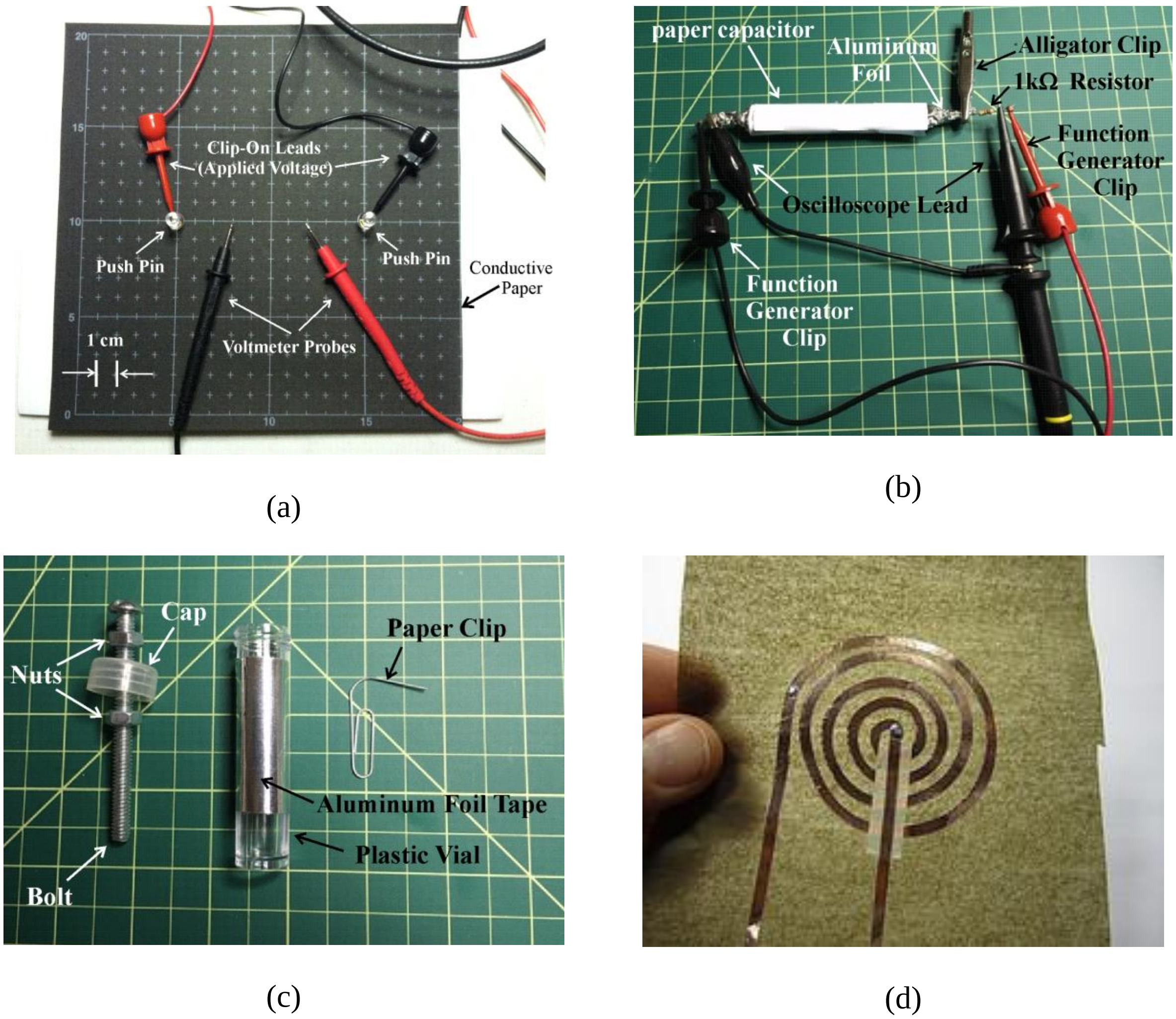
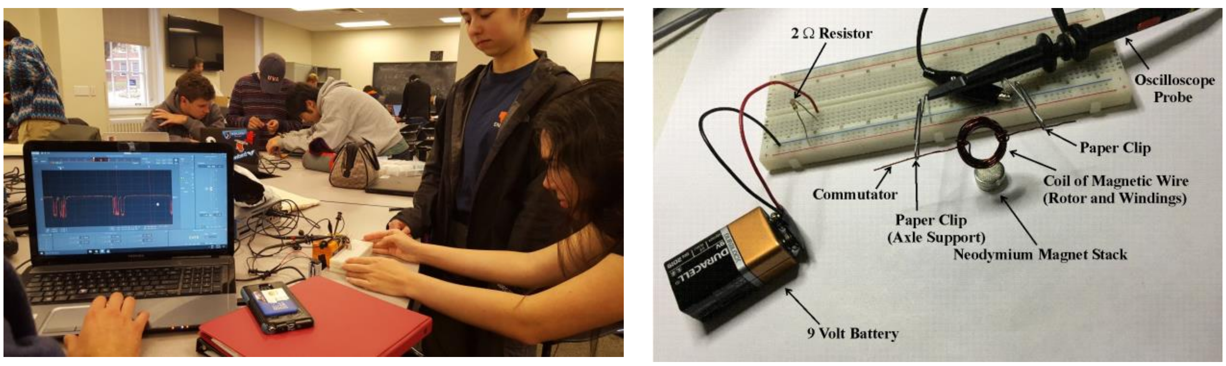


Figure 4 (a) Field mapping and equipotential project, (b) Paper capacitor project, (c) Dielectric constant measurement using a pill-bottle capacitor, and (d) A paper speaker project to illustrate magnetic forces

Among the projects associated with this material are (a) two-dimension field mapping using conductive paper and copper tape, (b) design and characterization of "paper capacitors", (c) measuring dielectric constants using a "Pill Bottle" capacitor, and (d) demonstrating magnetic forces by building a paper audio speaker.

A set of images illustrating the experiments performed by the students during these mini-projects is shown in Figure 4.

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 (Figure 5). 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.



(a) (b)

Figure 5 (a) Electric Motor Mini-project. (b) Motor details

Student Feedback

We have conducted surveys of our students to assess the value of the experimental portion of the material. Students were very enthusiastic about the laboratory activities as evidenced by a sample of the comments below:

"Some of the measurements were tedious, but they really helped me understand the material."

"I could do the math, but without the experiments I would not have understood what it meant."

"The transmission line experiments were awesome. I never believed reflections really existed until I saw them first-hand."

Conversely, several topics were discussed that did not have a laboratory component: transformers, antennas, and solenoids. Students reported not being as comfortable with these topics, compared to those for which there was an experiential element.

Conclusions

Through our *Fundamentals* courses, we have come to realize the power and effectiveness of experiential learning. We consistently receive student comments that testify to the power of making concepts come alive through experiment and visualization. With our *Electromagnetics* course we have completed the transition of our entire central required curriculum to studio-based instruction. We are seeing an increasingly positive response to this class as we have moved from a traditional "math-only" model to a hands-on approach, and in our 4th-year Capstone course, we are observing increased retention of concepts as students undertake the real task of engineering: turning ideas into reality.

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