

Implementation of a Lab Section for Electricity and Magnetism with Transmission Lines

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Abstract:

This paper focuses on the implementation of a laboratory section for an undergraduate course in engineering electromagnetics. In Fall 2018, both Klamath Falls and Portland-Metro campuses of the Oregon Institute of Technology adopted a laboratory section for EE 341: Electricity & Magnetism with Transmission lines, which is a required class for all electrical engineering students. This paper will discuss the laboratory activities, outline the challenges we faced when altering a well-established class to include a laboratory section, and report initial outcomes. The application of electromagnetic phenomena drives a long list of technologies and applications – to name a few: WiFi, Bluetooth, GPS, electric guitar pick-ups, fiber-optic communications, microwave ovens, radar, antennas, sensors, circuits, and power transmission and distribution. As such, engineering electromagnetics is a required class for the majority of undergraduate electrical engineering programs. However, this course is commonly viewed by students as impractically abstract and mathematical. This is not helped by the fact that the class is typically offered without a laboratory component. We have seen that including hands-on activities motivates students and helps them better visualize and understand concepts. Given the central importance of electromagnetics, we believe a meaningful, hands-on experience in this area is crucial for the success of undergraduate electrical engineering students.

Introduction:

Unless you are reading this on a handwritten scroll in a cave by candlelight, there is a good chance the following equations are directly impacting your life this very moment:

$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \partial \mathbf{D} / \partial t.$$

These are known as Maxwell's equations, which were described by James Clerk Maxwell in the 1860's and form the foundation of the classical electromagnetics. They describe how electric and magnetic fields are produced by charges and currents and evolve over time.

The motivation to study electromagnetics is all around us. All technologies and applications of electrical and computer engineering operate on the principles of electromagnetics. Every time you switch on a light, surf the web, send a text, or microwave a slice of pizza you are making electromagnetics work for you. Richard Feynman famously wrote

[1]: “From a long view of the history of mankind, seen from, say, ten thousand years from now, there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics. The American Civil War will pale into provincial insignificance in comparison with this important scientific event of the same decade.” An excellent introductory chapter of the Indian Edition of *Elements of Engineering Electromagnetics, Sixth Edition* [2] called “Why Study Electromagnetics” offers an additional 18 engaging and diverse answers from engineering faculty (mostly from UIUC) to this question. One would think that electrical engineering students would be flocking to electromagnetics classes, but they are not. What is going on?

Most students perceive electromagnetics difficult, abstract, and overly mathematical (just take a look at Maxwell’s equations above to understand the plight of the student studying electromagnetics). This is a well-documented phenomenon [3,4] that we have observed first-hand. On top of that, the physical quantities and fields in electromagnetics are generally hidden or invisible. The average person simply does not experience electromagnetic fields and charges in every-day life directly (lightning storms, sparks, and permanent magnets aside). Undertaking the study of electromagnetics therefore requires imagination and accepting an unfamiliar and somewhat unintuitive model of reality.

At Oregon Tech, our packed Electrical Engineering (EE) curriculum includes only one course in engineering electromagnetics that students take in their senior year – *EE 341 Electricity and Magnetism with Transmission Lines*. Compared to other EE courses in the curriculum like electronics, digital signal processing, and microcontrollers, our students regard EE 341 as comparably difficult and abstract. This leads to low interest and motivation in the class, which negatively impacts student learning.

Like so many other universities, we traditionally taught our electromagnetic engineering course without a lab. Specifically, the course was primarily taught through lectures, reading and homework assignments, and exams. This seemed out of place given our hands-on curriculum. Furthermore, by looking at the positive impacts of lab activities to electromagnetic courses at other universities (e.g., [3,4]), we have identified that a laboratory section could boost our instruction and increase learning. We therefore decided to create and pilot a set of lab activities that would serve our unique student body, which includes many non-traditional students who are older, hands-on, and career-motivated.

During the 2018-2019 academic year, we implemented a laboratory section for EE 341. While developing these labs, we operated with the following five goals in mind.

1. The lab activities should be engaging, interesting, and motivate students to learn the more abstract concepts.
2. The lab activities should complement the material learned in lecture and homework.
3. The lab activities should not be too “cookbook”, meaning that there should be a chance for students to explore and interpret the results and think about how to apply the results.

4. The lab activities should not duplicate what the students learn in physics. While EE 341 does review fundamentals that are covered in physics (e.g., Coulombs law, Faraday's law, etc.), the course is not a physics class.
5. The lab activities must be implemented with a tight budget and without expensive lab equipment.

With our goals established, the lab activities and initial results are presented below.

Lab Assignment Summary:

Math Review - For practical reasons, it made sense to set up the first lab of the quarter as a math review. Concepts covered included basic vector concepts and a review of Matlab. This is the only lab which does not involve a hands-on activity.

Electric Fields & Charges – When someone thinks about electrostatic electricity experiments, perhaps what comes to mind are images of sparks and Van der Graaf generators and hair standing on end. In developing our lab activities in electrostatics, we focused more on exploring foundational concepts and applications. Standard classes in electromagnetics start the discussion of electric fields by covering electrostatic topics, including Coulomb's Law and Gauss's Law. In an introductory lab activity, students begin by performing calculations involving Coulomb's Law and Gauss's Law. Then, MATLAB is used to create simple electric field plots. Then, for the hands-on portion, students perform a simple observation of electric charge by charging a small piece of metal hanging from a string and observing repelling/attractive behavior with a plastic rod. Next, students construct a simple electroscope (simple electrostatic observation device where two metal 'fins' repel each other when charged). Finally, students use this electroscope to perform Faraday's Ice Pail experiment. Here, students use a small metal cup and a charged device, where the cup is attached to the electroscope, to make observations about how the charged device interacts with the cup. Discussion questions are used to tie their observations from this experiment to the better known Faraday cage and the frequently used Faraday bag, better known as the silver bags used for shipping electrical components. [5]



Fig 1 – Faraday's Ice Pail

An Electrician's Best Friend –The Fluke VoltAlert is little battery powered non-contact voltage detector used by electricians and adventurous homeowners to detect live AC voltage. In this experiment, we commandeer this handy device to explore the concept of shielding. If you place the plastic tip of the detector near a normal insulated wire with a live AC voltage, the meter will glow and beep to warn you that the wire is hot. Interestingly, if you keep the meter and live insulated wire in exactly the same position, but physically do not touch the barrel of the meter, the meter may go silent. Students are asked to explore this curious behavior by (safely) probing standard three-prong outlets and power cords with and without holding the meter. Students are then asked to use their findings to explain how the meter works. Next, students wrap a standard power cord in aluminum foil and probe the foil. To some students' surprise, the meter detects the foil as hot, even though the foil is not actually touching a hot wire. Students are asked to explain this false positive. Next the aluminum foil is grounded (or effectively grounded by having a lab partner touch the foil with a finger). Upon probing the foil again, the students will find – again, to some surprise – that the meter does not detect a live voltage. Students are asked to explain this observation using the principles of capacitance and shielding learned in class.

How Do We Get Current Anyway? – In this lab activity, students explore some simple concepts of electrical power generation. Calculations involve the current density vector, which is covered in class prior to this lab activity. Then, students perform a calculation using Matlab. Next, for the hands-on portion of the lab activity, students start by creating a simple 'penny' battery, which they use to light an LED. Next, students use a simple generator (made of a nail, 2 magnets, a cardboard 'frame', a string, and magnet wire) in order to light an LED (in next year's version, students will construct their own generator instead of using a pre-made one). These two activities are especially useful in contrast to each other because these are very visual demonstrations of DC versus AC power generation. Supporting questions involve basic concepts of generators and batteries. [6]



Fig 2 – Simple 'Penny' Battery

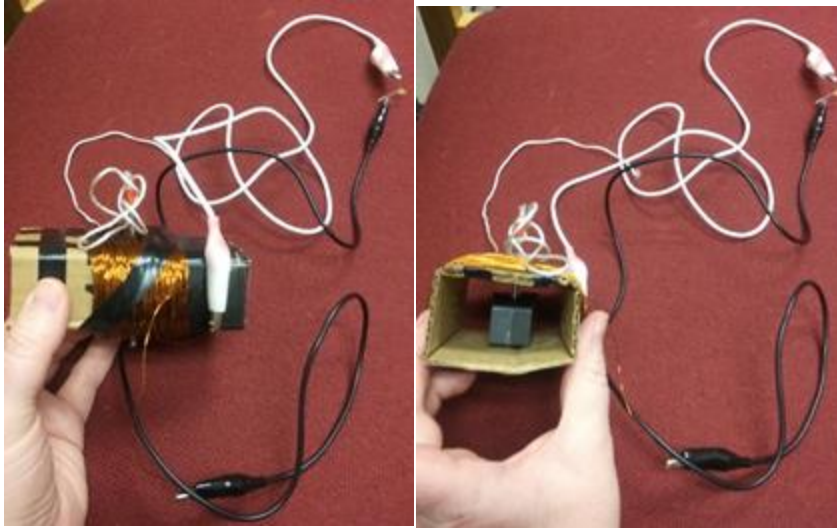


Fig. 3 – Simple Generator

Capacitors – In this lab activity, students focus on solidifying basic concepts of capacitance. Calculations focused on basic boundary value problems (these concepts should be discussed in class prior to the lab activity) as well as basic calculations for capacitors as presented in an introductory electromagnetics class. Next, students use Matlab to determine how the capacitance of a homogeneous capacitor should change as basic parameters are altered. For the hands-on part of the lab activity, students construct basic capacitors using metal and dielectric materials and use LCR meters to measure the resulting capacitance of the capacitors. It should be noted that the design values and measured values do not have very good agreement for this activity; however, students can get a relative understanding of how various changes impact the value of capacitance. Lastly, students use an Arduino and a small piece of metal to create a touch capacitor system; students are able to then turn on an LED by touching the piece of metal. Supporting questions explore uses for capacitive touch sensors as well as the concept of parasitic capacitance. [7]

Resistors – In this lab activity, students focus on solidifying basic concepts of resistance. Calculations focus on using Poisson's Equation and Laplace's Equation to solve boundary value problems in order to determine the resistance of sections of material. Then, Matlab is used to create some plots in order to increase student understanding of how changing basic parameters of a homogeneous resistor will alter its resistance value. For the hands-on portion of this lab activity, students create and measure some simple resistors (graphite and wirewound). It should be noted that the design values and measured values do not have very good agreement for this activity; however, students can get a relative understanding of how various changes impact the value of resistance. Additionally, while creating the wirewound resistors, students measure values of inductance and capacitance in addition to resistance; this continues student awareness and understanding of parasitic effects, as well as introducing basic ideas for minimizing them. Finally, students use an Arduino to measure the voltage across and resistance of an attached resistor. Supporting questions explore additional uses for

graphite/graphene (such as for super capacitors) as well as additional concepts involving parasitic effects.[8][9]

Magnetism – In this lab activity, students explore basic concepts of magnetism. Students start with basic calculations involving Ampere’s Law and the Biot-Savart Law; these laws will have been introduced in class prior to the lab activity. For the hands-on portion of this laboratory activity, students begin by making basic observations about magnetic fields using iron filings and two magnets. Then, students use a compass to map out the magnetic field of a magnet. Next, students are introduced to two simple magnetic devices: the reed switch and the Hall Effect sensor. Students use a magnet and basic circuits involving these two devices to turn an LED on and off; the Arduino board is used again in this lab for the circuit involving the Hall Effect sensor. Supporting questions explore the uses of magnets in electrical systems. [15]

Inductors – In this lab activity, students explore basic concepts of inductors and coils. This lab begins with students answering questions regarding how they expect inductance to change as parameters of a simple inductor are altered. For the hands-on portion of this laboratory activity, students create a number of simple inductors using different gauges of wire and dowel supports. The students measure the inductance and resistance of these inductors, and verify their understanding of how changing parameters effected these values. Next, students use a battery, tape, nail, and magnet wire to create a simple electromagnet; they are able to verify that it works by using it to pick up small pieces of metal. Supporting questions explore the use of inductors and coils in electrical systems.

Basic Motors – In this lab activity, students explore concepts of magnetic force and torque. Students begin by using concepts covered in class to analyze the forces and torque acting on a simple loop in a magnetic field. For the hands-on portion of this laboratory activity, students use a battery, a magnet, magnet wire and a screw to create a simple homopolar motor (single loop motor) and then a more complicated simple motor (standard simple motor demonstration) which uses a battery, a magnet, magnet wire and tape. Supporting questions explore basic motor concepts. [6][15]

Wireless Power Transfer - Resonant inductive power transfer (IPT) is not only a promising technology for wirelessly charging electric vehicles, robots, and kitchen appliances, but it also makes for an engaging lab activity that supports the teaching of electromagnetic induction. In this activity, students wind their own transmit and receive coils by wrapping magnet wire around a non-conductive material (we have found a 12-inch diameter wooden sewing hoop is an ideal winding core). These coils act as air-core inductors, which can wirelessly couple energy from one to the other through electromagnetic induction. In order to increase the range of the system, each inductive coil is connected to a capacitor to form a simple LC resonator. If the resonant frequency of these two coils matches the driving frequency – in our lab, we operate the system around 1 MHz – then enough power can be wirelessly transferred to drive a bright colorful LED at the receiver, which may be positioned several feet away from the transmitter. Even in the modern world, where we are accustomed to near-instant wireless communication, some students are still amazed that with only some wire and simple circuitry they can

prototype a system that can transmit enough power through empty space – or across walls and other objects – to power an LED. The system transmits relatively low power and the load draws about 50 to 100 mW. Discussing the amount of power transferred has led to good discussions about EMC and magnetic field safety. This has also led to interesting anecdotes, such as from one former military radar tech in the class who entertained fellow students with stories of cooking foods with high powered military radars. This lab activity supports student understanding of the following concepts: resonance, quality factor, Faraday's law of induction, self-inductance, and mutual inductance. As a bonus, if students put a metal object near one the coils, they will see that this detunes the corresponding resonator (visually, the LED will dim). In effect, the students have also made a metal detector.

Challenges:

We had three main challenges in implementing these labs. As a group, students at our institution tend to enjoy hands-on activities; the school's catch-phrase is 'Hands-on education for real-world achievement'. Consequently, student perception of adding a lab section to a class without one is that it's an improvement; that attitude helped get the labs off to a good start. Overall, the challenges that we experienced were in three categories.

First, the lab fee for the class should have been set higher. We set the initial lab fee at \$20 per student. That amount of money didn't cover enough magnet wire for students to individually create their own simple generators; there were a few other lab activities where having additional funds available for lab supplies would have improved the student experience. For example, some activities involved using an Arduino for measurements. To keep costs low, we purchased knock-off Arduinos for the student kits; however, the ones that were purchased ended up having a couple small differences from name brand Arduinos. This was enough to introduce a few small problems in a couple labs. To address this, we've requested a lab fee increase for next year.

Secondly, the labs took too long for students to complete. With a combination of calculations and hands-on activities, many groups needed more than the standard 2hr 50min lab period to complete the lab. Although students didn't express a lot of concern about this during the term, a number of students mentioned this in the end of quarter evaluations. It's worth noting that, because this lab was added to the existing schedule, it extended until the comparatively late time of 6:50pm in the evening; this may have added to student irritation when the labs ran long. To address this, we'll assign the calculation portion of the labs as part of the weekly homework, next year.

Thirdly, lack of good simulation software. Ideally, good engineering labs should follow a calculate -> simulate -> construct -> design format. Although both instructors have done some Matlab activities for this class, including useful student assignments with numerical analysis techniques, it's not quite the same educational value as having an industry standard electromagnetic simulation package. Recently, we were fortunate enough to receive a donation

of ANSYS Designer classroom licenses; we plan to include simple simulation activities during the next academic year to address this concern.

Conclusions:

Overall, the student experience of the labs appears to have been generally positive; however, there were multiple comments that the labs were too long (6 on this topic in the lab section reviews). Comments from this year's teaching evaluations, the first year that we've run the labs in full, included the following positive comments: "The labs were super awesome and I learned about stuff that wasn't covered in the course material but did pertain to electromagnetism", "I really enjoyed the labs", "The material helped me in the class and was high quality", and "I was able to understand the text material deeper as a result of the labs."

In running this lab section next year, we'll continue to work on improving the experience that students have working through these assignments. Based on student comments, we plan to slightly restructure the labs in order to help students complete them within the standard lab section time period; this may involve streamlining some activities and assigning some calculations as 'prelabs' or as part of the weekly homework assignments for the lecture section. It will be interesting to read student comments following next year's sections.

We also plan on continuing to improve the labs overall. One additional plan not mentioned previously is to introduce a couple of activities focusing on topics of interest in the area of renewable energy; we think that projects in this area would be of particular interest to students and quite reasonable given the topics covered in the class.

References

[1] R. Feynman, *The Feynman Lectures on Physics, Volume 2: Mainly Electromagnetism and Matter*, Reading, Ma, Addison-Wesley, 1964.

[2] N. N. Rao, *Elements of Engineering Electromagnetics, Sixth Edition*, Delhi, Pearson Education India, 2006. Article *Why Study Electromagnetics?* available online:

http://faculty.ece.illinois.edu/rao/EM/Why_Study_EM.pdf

[3] H. Roussel, M. Hélier, "Difficulties in teaching electromagnetism: an eight year experience at Pierre and Marie Curie University", *Advanced Electromagnetics*, Vol. 1, No. 1, May 2012.

[4] L. E. Donohoe, J. Urbina, T. Kane, and S. G. Bilén, "Developments in the Teaching of Engineering Electromagnetics for Improvement in Student Interest and Understanding", ASEE Annual Conference & Exposition, New Orleans, LA, 2016.

[5] 'Faraday's ice pail experiment', Wikipedia, https://en.wikipedia.org/wiki/Faraday%27s_ice_pail_experiment, Feb. 2019.

- [6] M. De Vinck, "Making a Penny-Powered Flashlight, A Flying LED Copter, And More!", Maker Media, 2017.
- [7] D. Keefe, "Make: Family Projects for Smart Objects", Maker Media, 2016.
- [8] D. Cheng, *Fundamentals of Engineering Electromagnetics*, Addison-Wesley Publishing Company, Inc., 1993. pg 165.
- [9] M. Thakur and R. Manoj, *Measurement Made Simple with Arduino: 21 different measurements covers all physical and electrical parameter with code and circuit* (Kindle Locations 207-233). Kindle Edition.
- [10] N. Anderson and M. Nina, "A new approach in teaching electromagnetism: How to teach EM to all levels from freshmen to graduate and advanced-level students," in Proc. 2003 American Society for Engineering Education Annu. Conf. & Expo.
- [11] J.F. Hoburg "Can computers really help students understand electromagnetics education?," *IEEE Trans. Education*, vol. 36, no.1, pp. 119–122, Feb 1993.
- [12] X. M. Zhang, S. L. Zheng, Y. Du, X. F. Ye and K. S. Chen, "Perspective of Electromagnetics Education," *Proc. Progress in Electromagnetics Research Symp.*, Xi'an, China, March, 2010.
- [13] S. Field, G. Quellen, *Gizmos: Projects & Devices to Channel Your Inner Geek*, Chicago Review Press, Chicago, Illinois, 2002.
- [14] F. M. Mims, III, *Science and Communication Circuits and Projects*, Niles, Illinois: Master Publishing, 1986.
- [15] Leeb, Steven. "The Simple DC Motor: A Teacher's Guide." MIT Center for Materials Science and Engineering. Aug. 2003. Web. 2 Mar. 2016.