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# Work in Progress: Synergy of Visualization and Experiment in Undergraduate Engineering Electromagnetics Course

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## Abstract

Electromagnetics (EM) course is traditionally viewed as a “difficult” discipline due to its highly mathematical and relatively abstract nature. A hybrid visualization and class experiments method has been developed in assisting student learning EM concepts. The topics of demonstrations include static EM theory, Maxwell’s equations, wave propagation, and transmission line theory. The purpose of the in-class experiments and simulation demonstrations is to provide a stronger connection between abstract theory and their physical meanings. By connecting the mathematical concepts and engineering applications to the physical world, it generates more interests and in-depth learning, and reinforces the understanding of the underlying EM theory.

## I. Introduction

The classical electromagnetic (EM) theory guided by Maxwell’s Equations has been around for over 150 years. It has an incredible impact on many modern technologies such as antennas and wireless communication, integrated circuits and computer technologies, remote sensing, lasers and optoelectronics, and more. Nowadays, with the exponential growth in computing power, machine intelligence and data revolution, quantum technologies and materials, there are enormous opportunities to continue advancing fundamental EM theories towards next-generation technology developments and applications.

On the other hand, electromagnetics course is considered to be one of the most difficult and heavy mathematics involved courses. Students lacking pre-knowledge of mathematics and physics complain about not able to follow the course [1]. Traditionally in many engineering curricula, the EM course is taught in a standard format using notes and mathematical derivation of equations. As a result, many students find the course difficult and less attractive due to its highly mathematical and relatively abstract nature [2]. Part of the difficulties stem from the lack of hands-on or laboratory components in many electromagnetics courses [3]. Even where the courses include lab components, the laboratory assignments or demonstrations are often non-comprehensive, for example, course in [4] has a lab component for transmission line and resonator, but the topics in the lab do not cover most of the course syllabus. Other courses may contain simulations or MATLAB demos on limited topics, [5] but lack physical demonstrations or assignments.

In our university, EM theory has been separated into a two-sequence course, a required fundamental course and an advanced selective course. The fundamental course focus on static fields, dynamic field and wave propagation. The advanced course focus on antennas, radiation theory, waveguides and resonant cavities etc. In recent years, only 15-25% of the students who have took the fundamental course are willing to enroll in the advanced course. This have arisen a warning for instructors because both courses are essential for engineering students to better prepare for senior technical elective courses including microwave circuits, antenna, power electronics, communications, imaging etc. Hence, it becomes necessary to develop new teaching methods to foster students’ greater awareness and interest in engineering EM discipline.

A hybrid visualization and class experiments/demonstration method has been developed in assisting student learning EM field and theory in the fundamental course. In order to help students to relate the EM content with the physics insights, we adopt in-class experiments and simulation demonstrations to enhance students learning. By connecting the mathematical and engineering applications to the physical world, it generates more interests and in-depth learning than only presenting equations and concepts. In order to help students 'visualize' the invisible EM waves, we utilize several interactive EM simulation software to visualize various EM sources, fields, waves, and their interactions with environments. The approach of utilizing Computer-aided design (CAD) tools in teaching EM has been reported in [6-9], which promotes students learning and provides a deeper understanding of engineering concepts. Figure 1 shows the interaction between theory, experiments, simulation, and applications.

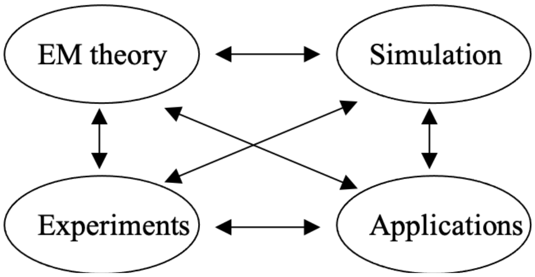


**Figure 1. Synergy between theory, experiments, simulation, and engineering applications.**

The purpose of the proposed method is to provide a tight integration between mathematics theory, physical meaning, and EM applications. Under this framework, the instructors may show the elegance and beauty of the basic EM theories and concepts, and demonstrate the significance of these fundamentals by applying them to real-world applications. The method proposed in this paper has been implemented for two semesters. The preliminary feedbacks show growth in students' interests, enhanced understanding of EM concepts, and improved know-how of applying EM theory to engineering applications.

## II. Course Description

The fundamental EM course ECE3xx is offered to Junior students for every semester. The course is organized in 13 weeks, 3 times a week. The topics start with the static fields, including electrostatics and magnetostatics, then turn to the dynamic fields, followed by the transmission line theory. Mathematical components, such as vector operations and integral operations are introduced at the beginning of the static fields as needed. Introducing simpler scalar field first helps students gets well prepared for the following dynamic contents [10].

We designed several experimental and simulation demonstrations along the various topics in the course. For each topic covered in one week, there is a paired in-class experiment and/or simulation example corresponding to the topic. The outline and the associated in-class demonstration are depicted in Table 1.

**Table 1. Weekly course schedule and associated in-class demonstration.**

| # of Week | Topics | Experimental Demonstration | Simulation Demonstration |
|---|---|---|---|
| **Module 1: Electrostatics** | | | |
| 1 | Lorentz Force and Gauss's Laws | Point source, line charge, and surface charge | Electric field from point charges by Mathematica [12] |
| 2 | Electrostatic Potential and Boundary Conditions | Electrostatic potentials using neon lamp | Electric field and potential distribution from line charge |
| 3 | Poisson's and Laplace's Equations | | Laplace's equation solver by Excel [11] |
| 4 | Capacitance and Conductance | Electric field from parallel plates | Electric field from parallel plates |
| **Module 2: Magnetostatics and Maxwell Equations** | | | |
| 5 | Ampere's Law and Faraday's Law | Magnetic force demonstration | Magnetic field of a Finite solenoid with ferrite core |
| 6 | Maxwell's Equations | Lenz's Law demonstration | Planewave propagation in free space and wave velocity |
| 7 | Wave Equation and Solutions | Induced EMF | Wave propagation in material medium |
| 8 | Wave Solutions in Conducting Media | Visualization of magnetic fields | Damped wave in conducting media |
| **Module 3: Transmission Line Theory** | | | |
| 9 | Wave polarization and Reflections | | Wave reflection due to impedance mismatch |
| 10 | Transient Response and Bounce Diagram | Transmission line reflection measurements | Transient time domain response with different termination schemes |
| 11 | Input Impedance | Source and load termination schemes on transmission lines | Input Impedance by LTspice [13] AC analysis |
| 12 | Line Impedance | Transmission line input impedance | Half- and Quarter-wave transformer |
| **Module 4: Transmission Lines and Smith Chart** | | | |
| 13 | Smith Chart and Impedance Matching | | Impedance matching examples by LTspice |

## III. In-class Demonstrations

### A. Module 1 – Electrostatics

In this module, we have designed several experiments and simulation to help students gain more insight into electrostatic equations and underline electrostatics physics. Through this endeavor, the students will learn the fundamental concepts of practical application including the Van de Graaff generator, laser printer, electrostatic painting, and electrostatic air filters, etc.

**Point source and Coulomb's Law:** We use a Van de Graaff generator as source to demonstrate the inverse square distance rule and electrostatic repulsion. We hang a small balloon through a thread to a stick. After the Van de Graaff generator is turned on, we use the balloon to touch the Van de Graaff generator, so that the balloon has the same charge polarity. Then we move the balloon about twenty centimeters away from the Van de Graaff generator. Due to the electrostatic repulsion, the balloon is trying to move away from the generator. But since the balloon is hanging on the stick, it forms an angle between the balloon thread and stick. Then we move to about forty centimeters away from the Van de Graaff generator, the angle between the thread and stick goes up. As the distance between the balloon and the Van de Graaff generator increases, the angle goes up quickly. When the balloon moves to more than a meter from the Van de Graaff generator, the balloon doesn't appear to have electrostatic repulsion anymore and the angle is at its maximum of 90°. This phenomenon is corresponding to the inverse square distance rule of the electric field generated by point charge.

**Line charge, surface charge, and Gauss's Law:** In the lecture, we use Gauss's Law to calculate the electric field due to a line charge and an infinity surface charge. Next, we will demonstrate the electric field by using the Van de Graaff generator. For the line charge, we connect the Van de Graaff generator with a metal rod. Then we use the same balloon hang on the stick. For the line charge, when we move the balloon away from the metal rod, the angle between the balloon thread and stick decrease, which is corresponding to the inverse distance rule. Then for the surface charge, we connect the Van de Graaff generator to a foil sheet with the size of 80 by 160 centimeters. When we place the balloon 10 centimeters and 20 centimeters away from the sheet, the balloon is having almost the same force, and the angles between the balloon thread and stick remain constant. At these close distances, we can approximate the foil sheet as infinite charge sheet. Then we move the balloon a little further away at 60 centimeters, the angle goes up a little bit. That's when the infinite charge sheet assumption becomes not valid.

**Electric field in between parallel plates:** We use parallel plates to demonstrate the electric field lines inside and the fringe field. A Wimshurst machine is used to charge the parallel plates with opposite charges on each plate as shown in Figure 2. Then we use a conductive ball and let it bounce inside the parallel plates. When the ball is bouncing between the parallel plates, it follows a straight-line trajectory and bouncing in a very fast speed – exactly as the straight electric field lines inside a capacitor. The fast-bouncing speed indicate the electric field lines inside are strong in magnitude. Every time the ball is bouncing on one plate, it takes the charge off the plate. So each time the ball hits the plates, it changes polarity. Then if we bring the ball all the way across the edge to the outside in the close proximity to the gap of the plates, the ball follows an arc type of movement in a slower speed. Because the plates are not infinite, the ball is following the weaker fringe field which is leaking from the gap. From the movement of the ball inside and on the edge of the parallel plates, students can view the electric field lines inside parallel plates as well as the fringe field due to the fact that the plates have finite size.

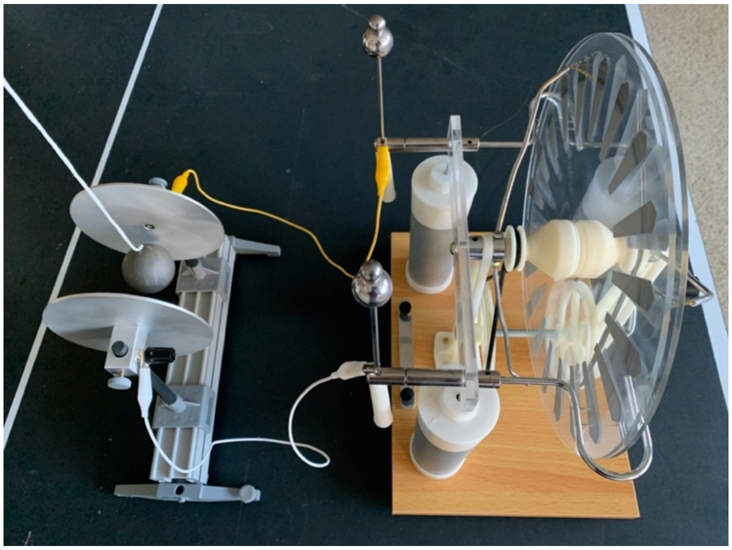


**Figure 2. Experiment setup on electric field in between parallel plates**

**Electrostatic potentials with a fluorescent tube:** To illustrate the electrostatic potentials, we will use the Van de Graaff generator again. The Van de Graaff generator is charged to 325 kV, so its outer surface will take about ten micro-Coulombs. The electric field will be radially pointing outwards from the generator. When a 30-cm long fluorescent tube is brought to the generator in the radial direction, there will be a large potential difference between the two ends of the tube. Then the tube will light up. The light in the tube means that electrons are moving through the gap inside, so charge or current is moving without any external wires. If I touch one end of the tube with my finger, the current will go straight through my body to the earth, which will increase the light of the tube. If the fluorescent tube is in the azimuth direction, the two ends of the tube will be at the same electrostatic potential, thus there's zero potential difference. Then the tube will have no light at all.

**Simulation demonstration:** In addition to various in-class experiments to invoke the students' interest in learning EM physics, we further consolidate their understanding by performing interactive simulation examples. For electrostatic problems with point charge, line charge, and sheet charges, we utilize Wolfram Mathematica [12], which can help students 'visualize' the 3-D electric field and electrostatic potential for the entire system, as well as examine and tailor the detailed components for various charge distributions. With such visual illustration of electrostatic field distribution, the students will gain more insight between the electrostatic equations and the physics behind.

### B. Module 2 – Magnetostatics and Maxwell's equation

From Nuclear magnetic resonance (NMR) to magnetic storage devices in computer memory, magnetostatics is another essential building block for engineering electromagnetics. Several experiments are designed with the goal of best understanding the physics of the basic laws. On the electrodynamics regime, the emphasis is placed on the wave propagation phenomenon through simulation demonstrations.

**Magnetic force:** We repeat Ampere's experiment on magnetic force between two wires. We dispose two parallel long wires and connect the wires to a DC source. If the currents on the two wires are in the same direction, the experiment shows that the wires will attract each other. If the currents are in the opposite direction, the wires will repel.

**Lenz's Law demonstration:** We demonstrate Lenz's law by using two light copper rings and a bar magnet. Copper is paramagnetic material, so the copper rings are non-magnetic. The first copper ring is a close circle, while the second copper ring has a cut on one side. We hang the two rings and start moving the magnet towards and away through the rings. The first ring starts to swing back and forth. However, when we move the same magnet through the second copper ring, it has no effect. This is due to the magnetism that created in the copper ring fights the change of magnetism from the bar magnet. When the bar magnet is approaching the closed copper ring, the magnetic field inside the copper ring is increasing, which is going to induce a current. The induced current will create a magnetic field to oppose the increasing field, so the copper ring will get pushed away. When the bar magnet is being pulled away, the magnetic field inside the copper ring is decreasing, and so there will be a current induced to try to maintain that magnetic field. So it will pull the copper gasket towards it. That's why this first copper ring will start swinging when we move the bar magnet back and forth. Then with the second copper ring with a cut on it, there's no current flow on the ring. Then no magnetic field will set up inside the copper ring in response to the changing magnetic field due to the movement of the bar magnet. That is the reason the second copper ring with a cut has no response.

**Induced electromotive force (EMF):** We repeat Faraday's experiment by connecting a coil with a sensitive amp meter – a galvanometer. Then we take a bar magnet to approach the conducting coil loop. At first, when the magnet is stationary, the galvanometer is at the center position. Then when the bar magnet is approaching the loop, the needle of galvanometer shows current running in one direction. When the bar magnet is holding still, the galvanometer returns back to zero position. When the bar magnet is pulling out from the loop, the galvanometer deflects in the opposite direction. If the bar magnet moves faster, so that the change of the magnetic field per unit time is stronger, then galvanometer shows more current is running in the conducting loop. If the bar magnet moves very slowly, then the current is almost nothing. clearly the change of the magnetic field will matter the induced EMF or voltage in the coil. The same thing happens if we hold the bar magnet still but move the coil loop instead. From this demonstration, the students can see there's a relationship between the relative motion between conducting coil and the magnetic field from the bar magnet. The change of the magnetic flux linkage with the coil induces a voltage across the coil.

### Linear hall effect sensor demonstration

**Measurement and calibration of hall effect sensor using solenoid:** Using a linear hall effect (common E49 type) sensor and an Arduino, students measure magnetic fields from both permanent magnets and electromagnets. The hall effect sensor will output a voltage corresponding to magnetic flux density, which is read by the Arduino A/D converter and then converted to mT units and plotted via the serial plotter. The following configuration is used for the circuit configuration (in this example using the STEMTera Arduino compatible board shown in Figure 3):

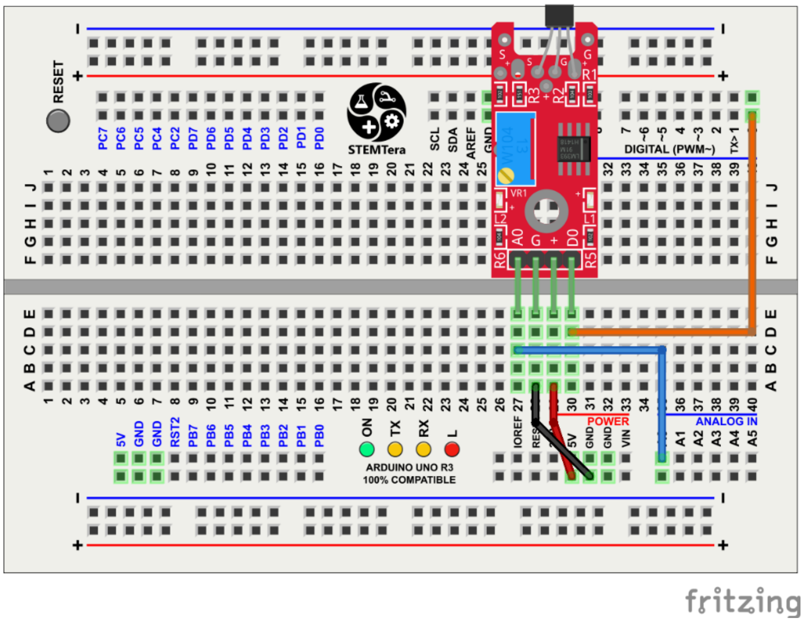


**Figure 3. Experiment setup on visualization of magnetic fields**

The following Code 1 are used to convert the Arduino analog inputs to magnetic field strength units in mT according to the E49 datasheet:

```
int analogPin = A0; // linear Hall magnetic sensor analog interface
int analogVal; // analog readings
float flux;

void setup ()
{
  pinMode (digitalPin, INPUT);
  Serial.begin(115200);
}

void loop ()
{
  // Read the analog interface
  analogVal = analogRead(analogPin);
  flux = ((float)analogVal/1024.0)*5000.0;
  flux -= 2500.0;
  flux /= 14.0;
  Serial.println(flux);

  delay(50);
}
```

**Code 1. Arduino code for reading and plotting magnetic field strength**

**Magnetic field strength of solenoid winding:** Using an iron nail and insulated wire, we can wind a solenoid of a small number of turns (for example, 50 turns) and compute the theoretical field strength using the equation:

$$B = \mu \frac{N}{L} I$$

Where $\mu$ is the relative permeability, N is the number of turns, L is the length of the solenoid and I is the current. We can then use a current limited power bench power unit to supply current I to the solenoid (the current should be limited to a small number of Amps, to avoid overheating the solenoid wires). We can then measure the magnetic field strength using the setup of the previous module, and compare our results to the theoretical solenoid results.

**Simulation demonstration**: At the beginning of module 2, the topics are magnetostatic problems. We use a numerical demonstration of a finite solenoid and ferrite core to illustrate the magnetic flux density distribution. This solenoid example has many practical applications in electromagnets, including magnetic relays, loudspeaker, doorbell, etc. The topic then moves from static field to dynamic field and Maxwell's equation. For the electrodynamic phenomenon, the simulation examples are focused on the wave propagation behavior. We use Mathematica [12] to simulate planewave distribution in free space, material medium and damped wave in conducting medium. When we change the permittivity of material medium or the conductivity of conducting medium, the student immediately observes the consequences on the propagation phenomenon. Problems of wave propagation are especially suitable using simulation demonstrations [10]. The plane wave propagation has applications including antennas used in communication system, radar. The practical applications of damping wave used widely are RF shielding against external EM sources.

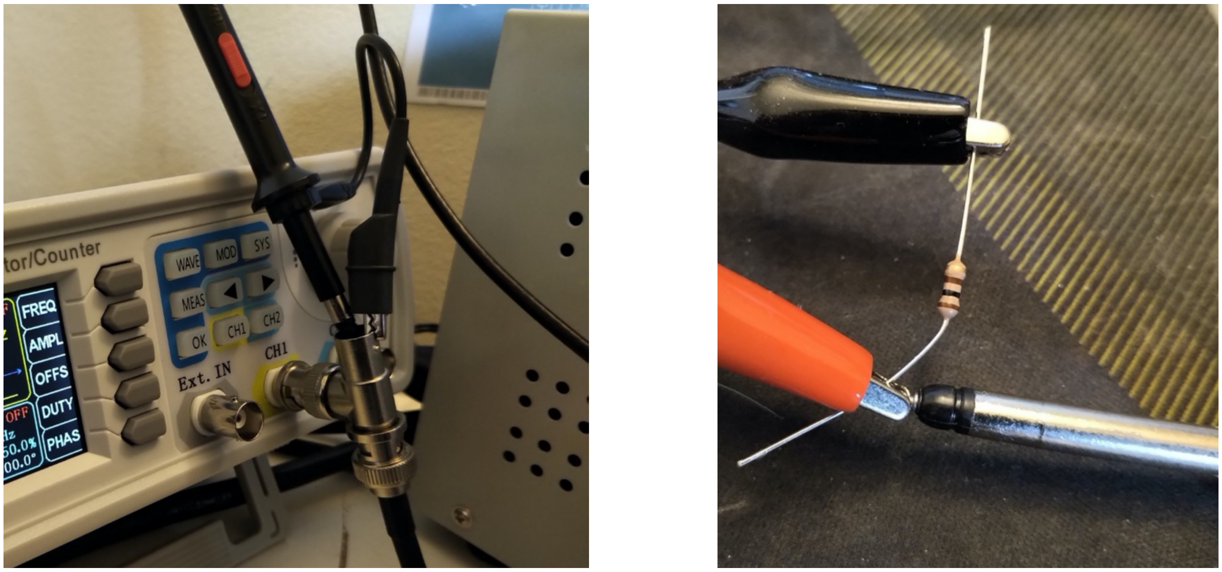
### C. Module 3 – Transmission line theory

Transmission line theory is another fundamental concept in electric engineering. It will also play an important role in future courses such as circuits, power and energy systems, communications, optics, etc. We have designed a few transmission line experiments that help students understand the guided wave propagation. The students are expected to learn the wave reflection, attenuation, and dispersion from both frequency and time domain viewpoints.

**Transmission line source and load termination experiments**: This experiment will require an oscilloscope and a function generator connected with standard 50 Ω coaxial cable. The experiment setup is illustrated in Figure 4. First, the function generator should be set to "High-Z" mode if the device allows. The function generation should be set to 1 MHz sinusoidal, with 5V amplitude and 0 offset. The oscilloscope input should be set to "High-Z/1MΩ" mode. The student should note that at this frequency, the oscilloscope shows the correct amplitude level (for example, by using the measure function of the oscilloscope). Then we slowly increase the frequency of the function generator, while observing the change in the measured amplitude on the oscilloscope. The student should observe that as the frequency increases, the amplitude measured on the oscilloscope decreases, and note the frequency at the 3 dB point. Swap the coaxial cable with a different length of coaxial cable and observe the difference in amplitudes.

At this point, students should be able to answer:

- *What is the cause of this amplitude difference between the sinusoidal waveform at 1 MHz versus higher frequencies?*
- *Does the relationship between the amplitude difference at higher frequencies depend on the length of cable and is the relationship easily characterized?*



(a) (b)

**Figure 4. Experiment setup on transmission line impedance matching and various termination scheme (a) Tee-connection on source end (b) Termination with 100 Ω on load end**

Then we turn the waveform to 1 MHz and change the oscilloscope termination to 50 Ω. The student should observe that the amplitude measured drops to 2.5 V, even if the function generator shows a 5 V output. The student should then repeat the experiment as previously described; however, the student will now observe different behavior at high frequencies. The students should now answer:

- *Why does the oscilloscope now measure only half of the amplitude reported by the function generator?*

- *Why is the amplitude of the oscilloscope measured waveform now (mostly) constant even as the frequency is increased?*

Repeat the experiment with different cable lengths to observe that the cable length no longer has a significant effect on the amplitude behavior.

**Transmission line experiments and bounce diagrams:** This experiment will require an oscilloscope and function generator, with various lengths of 50Ω coaxial cable, Tee junctions, alligator to BNC adapters, and various resistor values. Configure the function generator for 50 Ω mode and set the oscilloscope to “High-Z/1MΩ” mode. Connect a Tee-junction to the function generator and a passive oscilloscope probe to the inner conductor and connect the third junction in the Tee to the coaxial cable. This probe will be used to measure the voltage at the source. Connect the other end of the coaxial cable to an alligator clip adaptor and connect a resistor across the clips. Connect the other oscilloscope probe to the clip which corresponds to the inner conductor. Configure the function generator for a slow (e.g., 10 kHz) square wave with 10 V amplitude and 5 V offset. The student should be able to answer:

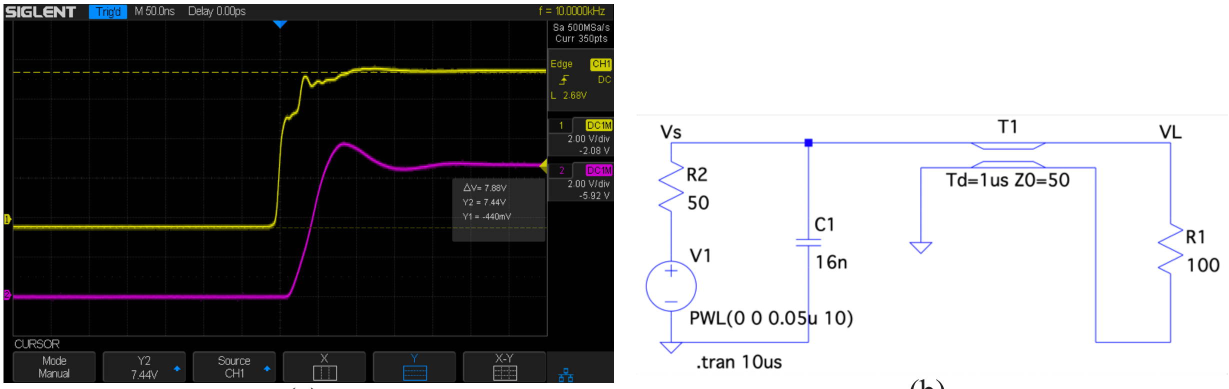
- *Find the steady state value of the voltage level, using the equation:*

$$V_{SS} = V_S \frac{R_L}{R_S + R_L}$$

- *For example, if* $R_L = 100\Omega$*, then:*

$$V_{SS} = 10 \frac{100}{50 + 100} = 6.67\ V$$

The circuit diagram of the measurement setup as well as the measurement result is depicted in Figure 5. Students can then observe the steady state voltage, as well as compute the reflection coefficients at both the source and the load using the characteristic impedance of the coaxial cable, as well as the values for the source and load impedance, and see the value of the voltage at the source and load prior to the steady state value. Students can then repeat the experiment with a different coaxial cable with different characteristic impedance, for example, 75 **Ω** coaxial cable. In the case where the coaxial cable has a characteristic impedance which differs from the source impedance, students will need to create a full bounce diagram to explain the results. Students can create the bounce diagram for this situation and compare the bounce diagram to the plot of the voltage at both the source and the load.



(a) (b)

**Figure 5. Transmission line bounce diagram results. (a) Measured bounce diagram with $R_s$ = 50 Ω, $R_L$= 100 Ω, and $Z_c$=50 Ω (b) System circuit diagram for simulation**

**Simulation demonstration:** When we provide in-class simulation for the transmission line problems, we use LTspice [13] to demonstrate wave reflection, various termination scheme, input impedance, as well as half-wavelength and quarter-wavelength transformer. LTspice is a free SPICE simulation software, which is easy to use with its schematic editor and waveform viewer. We used to spend a lot of class time deriving the bounce diagram for one single problem. With the help of LTspice demonstration on wave reflection due to impedance mismatch, students can get the big picture of how various parameters will affect the transient response of transmission lines, for example, by changing the source/load impedance and transmission line delay time.

## IV. Conclusion

In this paper, a hybrid visualization and class experiments/demonstration method has been discussed. We have created a website for the students to access the experiments and simulation models [14]. From the early feedback, it has shown the proposed method increases the students' interest and promotes in-depth learning of the concepts. Furthermore, the proposed method establishes the link between the theory and physics with in-class experiments. Meanwhile, the method inspires students to explore more practical applications through simulation demonstrations. The proposed method is work-in-progress. We will discuss the student evaluation and feedback for the spring semester in the ASEE conference.

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