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Mini-Laboratory Activities for Observing Electromagnetic Fields in a Required Undergraduate Course for Electrical Engineers

Dr. Gregory J. Mazzaro, The Citadel

Dr. Mazzaro earned a Bachelor of Science in Electrical Engineering from Boston University in 2004, a Master of Science from the State University of New York at Binghamton in 2006, and a Ph.D. from North Carolina State University in 2009. From 2009 to 2013, he worked as an Electronics Engineer for the United States Army Research Laboratory in Adelphi, Maryland. For his technical research, Dr. Mazzaro studies the unintended behaviors of radio frequency electronics illuminated by electromagnetic waves and he develops radars for the remote detection and characterization of those electronics. In the Fall of 2013, Dr. Mazzaro joined the faculty of the Department of Electrical & Computer Engineering at The Citadel. There, he is the primary instructor for Electromagnetic Fields, Interference Control in Electronics, Antennas & Propagation, and Electrical Laboratory courses.

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Abstract

Few institutions offer hands-on activities to accompany their introductory courses in Electromagnetic Fields. Adding to the existing library of experiments and projects developed for basic-EM undergraduate courses, in this paper, three hardware-based “mini-lab” activities are presented. These activities enliven a heavy physics- and calculus-based theory course, and they help students to more intuitively grasp EM principles. Each activity can be performed using equipment that is part of a standard undergraduate electronics laboratory.

Keywords

electromagnetic, fields, physics, electronic, electrical, device, hands-on, laboratory, activity, waves, sensor, magnet

Motivations for This Work

The science upon which all designs for electrical and electronic devices are based is electromagnetic theory. For this reason, most undergraduates majoring in electrical engineering are required to pass at least one course in Electromagnetic (EM) Fields. A single-semester EM Fields course introduces Maxwell’s Equations and generally focuses on static electric and magnetic fields; it is usually taken during the junior year. Aspiring engineers who intend to work with radio or optical frequencies will typically complete follow-on courses which focus on dynamic fields with applications to high-frequency circuits, free-space waves, antennas, waveguides, or electromagnetic interference/compatibility; these advanced courses are usually taken as senior-year electives.

Many concepts central to EM Fields are counter-intuitive: wires carrying current in the same direction attract each other; magnets moved across a conductor induce a voltage difference from one end of that conductor to the other; field oscillations moving through each other can either cancel or reinforce each other. To mitigate the confusion produced by EM physics, the author designed three “mini-lab” exercises and recently included them as part of his required undergraduate EM Fields course. Each exercise can be performed using equipment that is part of a standard undergraduate electronics lab, and each exercise can be completed by an undergraduate student in under an hour. This paper will present all three exercises -- objectives, equipment required, procedures, and student feedback -- and the paper will suggest additional activities which can be developed to further enhance an EM Fields course.

Hands-On Activities in Electromagnetics Courses at Other Institutions

The electrical-engineering curricula at many research-oriented universities favor EM courses which are heavy in theory; most hands-on lab activities do not fit within the scope or the time available [1]. Electromagnetic experiments are usually reserved for graduate courses, specialized in high-frequency circuit analysis and/or wireless technologies. Some schools offer advanced-EM courses as electives; there, circuit design software can be used to draw and simulate EM structures (e.g. microstrip circuits). Schools equipped with a milling machine can export those drawings and etch radio-frequency (RF) and millimeter-wave designs (e.g. amplifiers, couplers) [2]. In a dedicated lab course, students can fabricate microstrip structures on printed circuit boards [3, 4, 5]; designs which do not compensate for parasitic effects may be compared against those which use matching networks so that the students appreciate the need for transmission-line theory. In a lecture-lab hybrid course, experiments may be performed which focus on wireless communications [6]. Departments which conduct radio-frequency research might assemble student lab stations with network analyzers, spectrum analyzers, and digitizing oscilloscopes [4]; experiments focus on RF filtering, frequency conversion for wireless transceivers, and planar antennas. Instructors can fabricate microstrip PCBs for the students (e.g. before the course begins); the students can then measure (a) impedance-mismatch caused by discontinuities in transmission-line width, (b) crosstalk from neighboring transmission-lines caused by coupled magnetic fields, and (c) parasitic reactances inherent to passive elements which are observed at radio frequencies [5].

For schools with minimal RF capabilities, a 5.8-GHz transceiver pair can be assembled from an off-the-shelf voltage-controlled oscillator, connectorized amplifiers, an RF power detector, and planar antennas [7]. At a distance of only several feet between transmitter and receiver (and not requiring an anechoic chamber or an open-air test site), students are able to record antenna patterns including signal nulls. A radar-assembly project can be added to a junior-year Electronics course: with multiple (planar) antennas and digital capture instruments, students can accomplish synthetic-aperture radar and generate 2-dimensional images of their environments [8]. Depending on equipment available at-hand (possibly borrowed from a nearby Physics Department), students might conduct experiments such as matching impedances with transmission-line stubs, measuring the wavelength of a laser using an interferometer, or estimating the permeability of free space [9]. Capstone projects in the senior year might include the design, construction, and testing of an electronically steerable antenna array, a microwave FM communication link, or an optical AM communication link.

Textbooks can include case studies, to merge fundamentals with engineering practice and place engineering within a great societal context [10]. Examples of such case studies include (a) evaluating field strengths at a school near a high-voltage transmission line, (b) locating faults in underground power cables using transmission-line theory, and (c) determining safe exposure standards for RF and microwave radiation.

Computer-aided tools using finite-difference methods can be used to simulate fields and demonstrate the conditions under which analytic approximations (e.g. parallel-plate capacitance) are no longer valid [11]. Students can even use computer-based tools to design surge arrestors, micro-motors, and waveguides [12]. An entire EM laboratory can be simulated: students control radio-frequency equipment while a graphical-user-interface presents readouts from instruments as if the students were present in the lab, and videos demonstrate field measurements, wave propagation, and transmission-line theory [13].

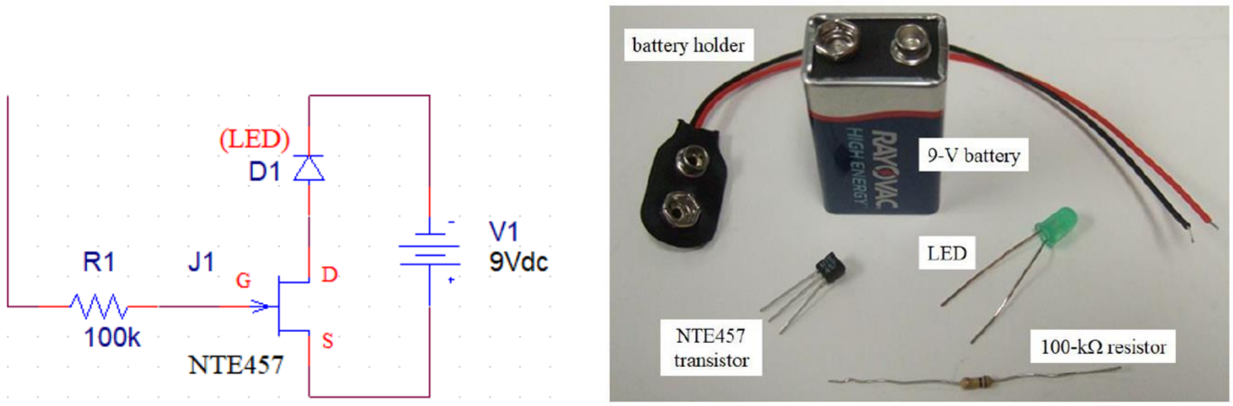
In the same spirit as the "junk" generator capable of powering a light bulb constructed from items found around-the-house [14] and planar antennas made by laying copper tape on fiberglass [2], three (quick, low-cost) experiments have been developed which are easily incorporated into a single-semester course in basic Electromagnetic Field theory. The experiments might be particularly useful to undergraduate-focused institutions whose budgets typically do not permit the purchase of EM demonstration units or RF/microwave instruments. These three activities are detailed in the following sections.

Laboratory Exercise #1: Build an Electric-Field Sensor

The first activity is the construction of a static-electric-field sensor. The students will typically build this E-field sensor after they have been introduced to Coulomb's Law and Gauss' Law. In Figure 1(a) is a schematic of the sensor circuit which includes a resistor ("R1"), a light-emitting diode ("D1"), a 9-V battery ("V1") and a depletion-mode PMOS transistor ("NTE457"). Figure 1(b) is a picture of the components required to assemble the circuit.

The transistor is normally conducting (with positive current from source to drain) without an applied electric field (i.e. without a negative voltage at the gate to exceed a threshold difference from-source-to-gate). When the transistor is conducting, the LED is on. However, if a negative charge is introduced to the gate (through the resistor) such that the source-to-gate voltage exceeds the PMOS threshold voltage, the transistor will not conduct. When the transistor is not conducting, the LED is off. In this configuration, the LED turning off indicates that a negative charge was introduced to the circuit.

In Figure 2 is the procedure given to the students to construct the sensor and demonstrate its functionality. The open-circuited side of the resistor acts as the antenna. Excess electrons introduced near to the "antenna" bias the transistor such that it no longer conducts. Thus, if the students run a comb through dry hair and bring it near to the resistor, they will see the LED turn off; when they take the comb away from the resistor, the LED turns on again. In this manner, the students are able to detect the presence of a static electric field that they themselves generated.



(a) (b)

Figure 1. E-field sensor: (a) schematic; (b) materials required for assembly.

1. With the help of your instructor, acquire the following equipment:

9-V battery	NTE457 transistor	100-kΩ resistor
9-V battery holder	light-emitting diode	metal project enclosure
breadboard: 2" x 3"		

2. Construct the circuit of Figure 1 on the breadboard.

   Leave the end of the resistor opposite the transistor-gate unattached.
   Bend the resistor leads so that the free end points upward (away from the breadboard).

3. If, after attaching the 9-V battery to the circuit (without introducing a source of charge), the LED turns *off*, place the entire breadboarded circuit into an open metal project enclosure.

4. Place a source of charge near the resistor (e.g. rub a pen or a plastic card through your hair). Observe that the LED turns *off* when a negatively-charged body is placed nearby.

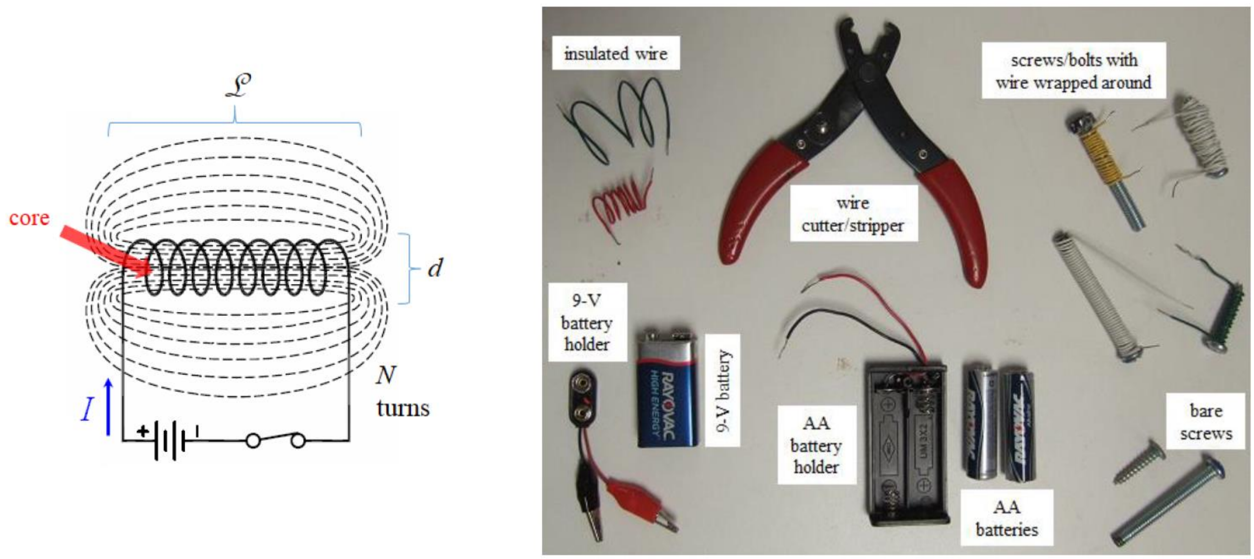
5. After your electric-field sensor is functional,
   show it to your instructor to obtain his signature: ____________________

Figure 2. Procedure for detecting the presence of a static electric field using the circuit given in Figure 1.

Laboratory Exercise #2: Build an Electromagnet

The second activity is the construction of an electromagnet. The students will typically build their magnet after they have been introduced to Ampere's Law and the Biot-Savart Law. In Figure 3(a) is a drawing of an electromagnet: wires wrapped (typically around a magnetic core) into loops that are insulated from each other. The number of loops is N, the length of the structure is $\mathscr{L}$, its diameter is d, and the current that passes through the loops is I. Figure 3(b) is a picture of the components required to assemble the magnet.

Students wrap insulated wire around a long screw/bolt. A couple of partially-completed magnets are visible in the upper-right corner of Figure 3(b). Once the ends of the wire are connected to a battery (the 9-V generates the strongest field), the magnet is capable of attaching (weakly) to small screws/nuts. A stronger magnet may be fabricated by winding additional turns around the core (in the same orientation) and/or by powering the structure using a battery with a higher voltage. As with Lab Exercise #1, the students themselves generate the field -- this time *magnetic* instead of *electric*. The students observe the presence of their field via the attraction of their magnet to small pieces of metal, which experience a temporary magnetic induction due to the applied field.



(a) (b)

Figure 3. Electromagnet: (a) diagram; (b) materials required for assembly.

1. With the help of your instructor, acquire the following equipment:

battery (9-V, AA, C, or D)	insulated wire	wire cutter/stripper
battery holder	screws/bolts	multimeter

2. Wrap at least 15 turns of wire around a screw/bolt. Cut the wire with enough extra length (beyond the screw/bolt) so that its ends may be attached to the battery holder.

3. Strip a half-inch of insulation away from both ends of the wire. Attach the insulated wire to the battery holder (by twisting the bare ends of the wires together, or by opening/closing alligator clips on the battery holder).

4. Insert your battery/batteries into the holder. The electromagnet is now active.

   Use your magnet to pick up small screws or pieces of scrap metal.
   Show your functional electromagnet to your instructor. ____________________

5. Redesign and reconstruct your electromagnet so that it picks up more pieces of metal (and/or holds those pieces more tightly).

6. For your final design, estimate the magnetic field intensity (H) and the magnetic flux density (B). Use the multimeter to measure the current flowing through your circuit.

   Show your results to your instructor. ____________________

Figure 4. Procedure for constructing and testing
the electromagnet depicted in Figure 3.

Laboratory Exercise #3: Build a Radio-Frequency Energy-Harvester Circuit

The third activity is the construction of an RF energy-harvester circuit. The students will typically build their RF harvester after they have been introduced to dynamic fields and electromagnetic waves. Figure 5 is the schematic. The circuit captures ambient RF and stores it as static voltage. The RF energy arrives at the insulated-wire antenna, passes through the 1-µF capacitors, is rectified from alternating-current to direct-current by the diodes, and charges the 3.3-mF capacitors. The output voltage v_{out} is measured and (if it is high enough) is able to activate an LED (for a fraction of a second).

Each pair of students is given a handheld radio as the RF source. After the students construct the circuit and as they transmit using the radio, the capacitors charge, usually at about 0.2 V per second up to a maximum of just below 3 V. An LED placed across v_{out} discharges the capacitors and the light shines briefly. Time permitting, the students are challenged to (a) increase the rate at which v_{out} charges and (b) increase the maximum voltage to which v_{out} can be charged. These results may be achieved with a more efficient (e.g. longer) antenna and/or different-sized capacitors.

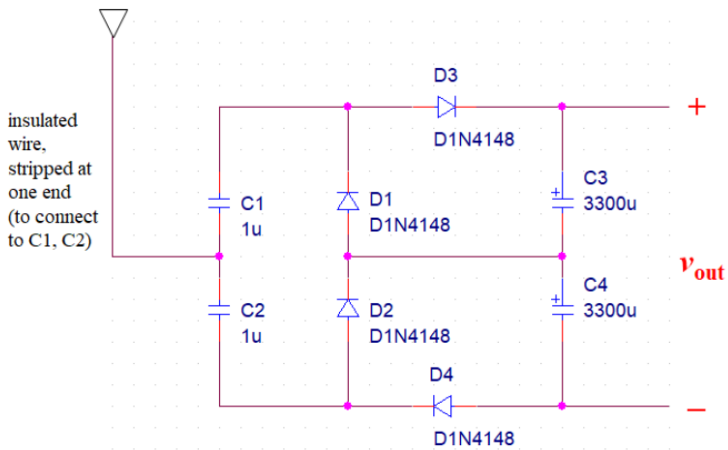


Figure 5. RF energy-harvester circuit.

1. With the help of your instructor, acquire the following equipment:

two 1-µF capacitors	light-emitting diode (LED)	insulated wire
two 3.3-mF capacitors	voltmeter	wire cutter/stripper
four 1N4148 diodes	handheld radio	

2. Construct the circuit of Figure 1. For the antenna, cut a piece of insulated wire to a length of approximately 8 inches. Strip a few millimeters of insulation away from one end so that you can plug that end into the breadboard (between C_1 and C_2).

3. With a voltmeter (e.g. Keysight 34460A), measure the (DC) voltage v_{out}.
   After connecting the voltmeter, short out capacitors C_3 and C_4 (i.e. connect a jumper wire across $v_{out}+$ and $v_{out}-$) so that the voltage measurement begins at 0.000 V.

4. Observe that v_{out} slowly charges (at approximately 10 mV per second).
   → If your capacitors are not charging, notify your instructor.

5. Bend the leads of the LED so that it may be attached across v_{out}
   (i.e. straight, away from each other -- max distance between the ends of the leads).

6. Turn on the handheld radio. (Do not change its channel/frequency settings.)
   Place the radio near your circuit. Press and hold the "push-to-talk" button.
   Observe that v_{out} charges more rapidly than before (up to 200 mV per second).
   Release the "push-to-talk" button to stop (rapidly) charging.

7. Charge the capacitors to approximately 2.0 V (or slightly more).

8. Hold the LED by its plastic bulb (i.e. do not touch its leads), place its leads across v_{out} (e.g. nudge it, simultaneously, against the + side of C_3 and – side of C_4).
   The notch of the LED denotes its 'negative' side. The opposite side is 'positive'.
   The LED polarity must align with the polarity of v_{out} .
   Observe that the LED produces light (very briefly).
   The capacitors will discharge such that v_{out} is reduced below 2.0 V.

Figure 6. Procedure for constructing and testing the circuit depicted in Figure 5.

Student Feedback & Conclusion

While a comparison of student outcomes before and after inclusion of these activities has not yet been performed, student feedback regarding the activities has been strongly positive. Below are excerpts of comments from surveys administered at the end of the author's undergraduate *Electromagnetic Fields* course:

Responses to "What did you like most about this course?"

- "the demonstrations and labs"
- "variety, e.g. lectures, demos, and labs"
- "the labs and demonstrations"
- "in-class examples and labs"
- "the labs"

Building on this positive feedback, for future offerings of his required-EM course or advanced-EM electives, the author is developing additional hands-on activities:

- generation of induced voltage from (60-Hz AC) extension cords, and minimization of that induced voltage using EM principles,
- measurement of harmonics generated by diode (e.g. rectifier) circuits, and
- observation of parasitic inductance and capacitance in otherwise purely resistive/capacitive/inductive elements, at high frequencies.

All of the "mini-labs" discussed in this paper (including the activities currently under development) may be implemented using instruments and components available to an undergraduate electrical (and/or computer) engineering department.

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