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Mini-Laboratory Activities to Reinforce Counter-Intuitive Principles in a Senior-Undergraduate Course on Electromagnetic Compatibility

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Abstract

Few institutions teach techniques of electromagnetic compatibility at the undergraduate level. Even fewer institutions offer hands-on activities to accompany their EMC course. In this paper, an extensive literature review of college curricula which include EMC is summarized. Adding to the existing library of hands-on activities developed for EMC-interested seniors, three hardware-based “mini-labs” are presented. Each activity can be performed using equipment that is part of a standard undergraduate electronics laboratory.

Keywords

electromagnetic, compatibility, interference, device, hands-on, laboratory, activity, non-ideal, impedance, common-mode, choke, crosstalk, coupling

Motivations for This Work

The primary objective of an electromagnetic compatibility (EMC) engineer is to design digital devices such that they do not produce electromagnetic interference nor are they susceptible to interference which originates from other digital devices. In electrical or computer engineering undergraduate programs which offer radio-frequency coursework, EMC techniques are presented in a senior-year elective. EMC practice extends from principles introduced during a theory-heavy course in Electromagnetic Fields (typically taken in the junior year).

Many concepts central to EM Fields are counter-intuitive (e.g. why wires carrying current in the same direction attract each other; why a magnet moved across a conductor induces a voltage difference from one end of that conductor to the other). Not surprisingly then, many concepts central to EM Compatibility are also counter-intuitive (e.g. why circuit elements self-resonate and reverse their reactance-vs-frequency trend beyond that point; why signals carried along circuit-board traces appear along other traces on the board when there is no metallically conductive path between them).

To mitigate the confusion produced by EM physics and to provide opportunities for students to practice interference-control techniques, the author designed three “mini-lab” exercises and recently included them as part of his undergraduate course in EMC. 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 presents all three exercises -- objectives, equipment required, procedures, sample data, and student feedback -- and suggests additional activities which can be developed to further enhance an undergraduate course in EMC.

EM Compatibility Courses at Other Institutions

The history of education regarding electromagnetic compatibility can be traced back at least as far as the 1970s when the United States Federal Communications Commission (FCC) began regulating "unintentional radiators that use timing pulses at a rate in excess of 9000 pulses per second and use digital techniques" [1]. In practical terms, this means that, for the last 50 years, the FCC has imposed legal limits on emissions, both conducted and radiated, from all devices which generate clock signals at 9 kHz or faster. Thus, nearly all commercially-available microcontroller-based electronics (e.g. computers, cell phones) fall under the jurisdiction of the FCC [2, 3]. Academic conferences for aspiring EMC-focused engineers sprouted in the 1980s, and practitioners created short-courses for folks already working in industry [4]. Until the 1990s, the field of EMC lacked rigorous theoretical analysis [5], until Henry Ott and Clayton Paul published the seminal textbooks in this field [6, 7].

EMC is considered an advanced application of EM theory; therefore, historically, EMC has not been taught to undergraduates. Paralleling the growth of digital electronics, however, schools around the world began to offer courses in EMC [8, 9, 10, 11, 12, 13, 14]. Some schools opted to teach EMC without calculus to practitioners [15, 16, 17, 18, 19]; others opted to de-emphasize EM theory to make their course more accessible to computer engineers [20, 21, 22]. An EMC-focused course can be the backstop of a multi-semester sequence in electromagnetics [23, 24] or it can be delivered at the Master's level [25, 26, 27] or as a post-graduate lecture series [28]. Some educators have meshed EMC awareness with industry as part of a co-op program [29]; others have tailored EMC techniques to biomedical applications [30] or power conversion [31].

EM Compatibility Curricula and Hands-On Activities

The topics which are typically discussed in an EMC course, surveyed across the few-dozen schools which currently offer such a course at the undergraduate level, are largely uniform [32, 33, 34, 35, 36, 37, 38, 39]:

- history & terminology -- the origins of EMC stemming from governmental regulation,
- standards & laws -- particular regulations which exist inside and outside of one's country,
- equipment & testing -- instruments which can test devices for EMC and how to use them,
- transmission-line theory -- the wave nature of signals traveling along a printed circuit board (PCB) or along wires/cables at high frequencies,
- antennas -- how electrically-long runs of traces on PCBs and unshielded wires emit wave-radiation and captures it from other electronics in the "far field",
- coupling -- how those same PCBs and wires emit field energy and capture it from other electronics (or subsystems within the same device) in the "near field",
- filtering -- how passive elements may be added to electronic devices to minimize emissions and susceptibility to other devices, and
- shielding & grounding -- how signal-carrying and return-wires can be arranged to confine field energy to a device, and how metal structures can be added to prevent excess radiation from leaking in or out of a device.

In the absence of a laboratory with instruments to directly observe EMC phenomena, educators have incorporated simulations into their courses. Exercises in PSpice and Advanced Design System can demonstrate the frequency content of trapezoidal waveforms, the non-ideal behavior of passive components, crosstalk analysis in the time domain, and emissions radiated from a transmission line [40]. Calculations performed in MATLAB and LabView can reinforce transmission-line theory [41]. Full-wave simulators can illustrate the true paths of return currents and determine the shielding effectiveness of metallic enclosures [42, 43].

A small library of hands-on EMC-related activities has been amassed:

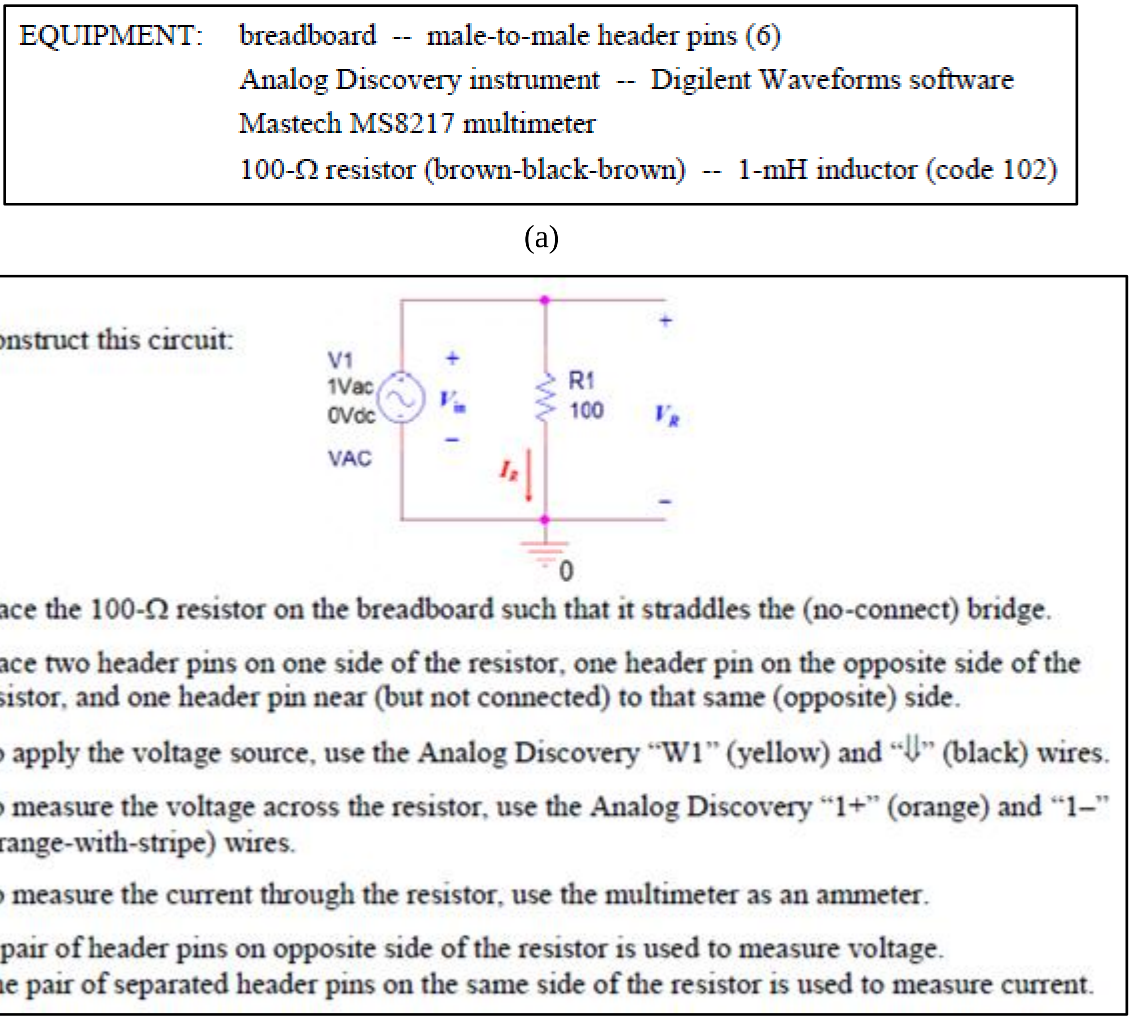
- measurement of magnetic-field coupling, noise in digital circuits, and coupling via ground-return wires -- using nearby (unshielded) cables [44],
- demonstration of the susceptibility of devices to electric and magnetic waves -- using a Gigahertz Transverse Electromagnetic cell [45],
- observation of near-field coupling -- using loop antennas [46] and nearby PCBs [47],
- comparison of device performance with and without consideration of EMC -- using a haphazardly-designed PCB contrasted against one designed with EMC in mind [48],
- measurement of insertion and return loss -- using a network analyzer [49],
- reduction of radiated emissions -- using off-the-shelf shunt capacitors [50],
- demonstration of counter-intuitive sources of EM interference -- using a small-scale model of a house containing motors, lights, and relay coils [51], and
- observation of emissions radiated and conducted from power electronics -- using hand-made magnetic-field “sniffer” probes [52].

At least one course has required its students to design a functional circuit (e.g. a DC-voltage “buck” converter) to achieve minimum emissions [53]. This paper presents another three “mini-labs” for students to observe EMC concepts first-hand; it adds to the aforementioned library of activities which may be implemented in an EMC course using equipment which is either readily available in an undergraduate-educational laboratory or is easily affordable by an undergraduate-focused engineering school.

Laboratory Exercise #1: Non-Ideal Behavior of Electronic Components

In this first experiment, students determine the true impedances of two bread-boarded through-hole components when they are excited by voltages at high frequencies: a 100-Ω resistor and a 1-mH inductor. Figure 1 contains segments of the lab procedure: a list-of-equipment is provided, along with the measurement setup for the resistor.

The students activate the AC voltage across the resistor, set the amplitude to 1 V_{RMS} and the frequency of the voltage to 100 Hz, measure the AC current through the resistor, and compute the magnitude of the resistor’s impedance using $|Z| = V_{RMS} / I_{RMS}$. At 100 Hz, the resistor impedance is approximately equal to the expected nominal value of 100 Ω. The students then repeat their measurements at higher frequencies, up to 50 kHz, at the same 1 V_{RMS} amplitude. After plotting |Z|-vs.-frequency logarithmically, the data resembles Figure 2(a).



EQUIPMENT: breadboard -- male-to-male header pins (6)
Analog Discovery instrument -- Digilent Waveforms software
Mastech MS8217 multimeter
100-Ω resistor (brown-black-brown) -- 1-mH inductor (code 102)

(a)

Construct this circuit:

Place the 100-Ω resistor on the breadboard such that it straddles the (no-connect) bridge.

Place two header pins on one side of the resistor, one header pin on the opposite side of the resistor, and one header pin near (but not connected) to that same (opposite) side.

To apply the voltage source, use the Analog Discovery "W1" (yellow) and "⇓" (black) wires.

To measure the voltage across the resistor, use the Analog Discovery "1+" (orange) and "1–" (orange-with-stripe) wires.

To measure the current through the resistor, use the multimeter as an ammeter.

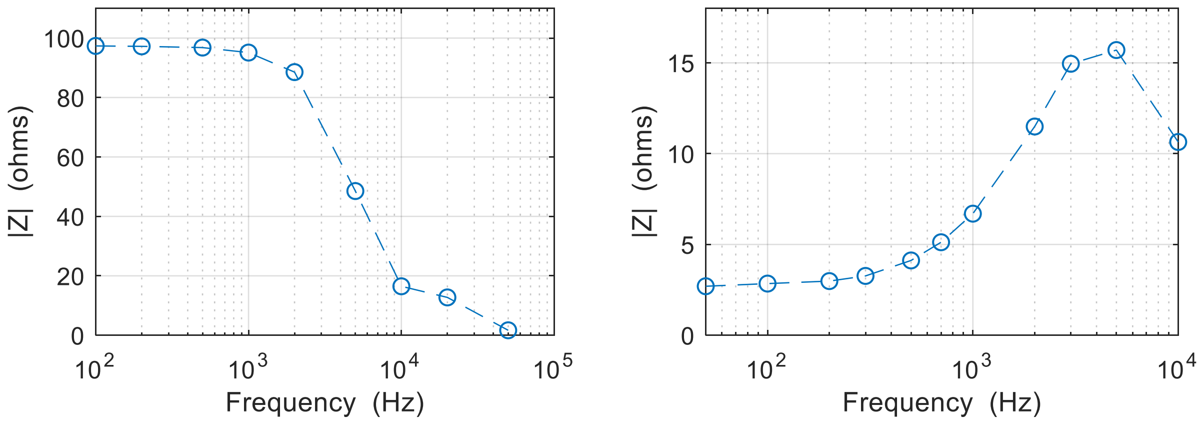
A pair of header pins on opposite side of the resistor is used to measure voltage.
The pair of separated header pins on the same side of the resistor is used to measure current.

(b)

Figure 1. "Non-ideal" experiment: (a) equipment and (b) a snippet of the lab procedure.

The standard low-frequency model of a resistor is a pure resistance whose impedance is independent of frequency. In reality, however, the leads on the sides of the resistor form a capacitance which provides a non-negligible path for current to be diverted at frequencies above 1 kHz [6, 7]. Students begin to "see" this otherwise "hidden" (parasitic) path when, at high frequencies, measured current increases while the applied voltage remains constant.

A similar effect appears when the students perform the same measurements on a 1-mH inductor. The data resembles Figure 2(b). For this experiment, between 5 kHz and 10 kHz, the reactance of the lead-capacitance equals the reactance of the nominal-inductance, and thereafter the overall impedance of the manufactured inductor *decreases* at higher frequencies (i.e. the inductor's |Z|-vs.-frequency curve follows the theoretical trend of a *capacitor*).



(a) (b)

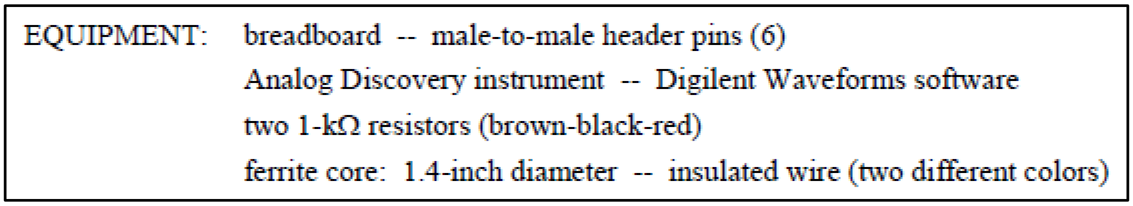
Figure 2. Measured impedances: (a) 100-Ω resistor, (b) 1-mH inductor.

In this manner, students realize the importance of "self-resonant frequency" as reported on the datasheet for a packaged component. Effectively, above this frequency, an inductor's impedance no longer increases (and a capacitor's impedance no longer decreases). This physical limit helps EMC engineers to more carefully select (or re-design) components to accomplish passive filtering and mitigate emissions from components which generate quickly-varying signals (e.g. a computer's central processing unit which uses a GHz clock).

Laboratory Exercise #2: Common-Mode Choke

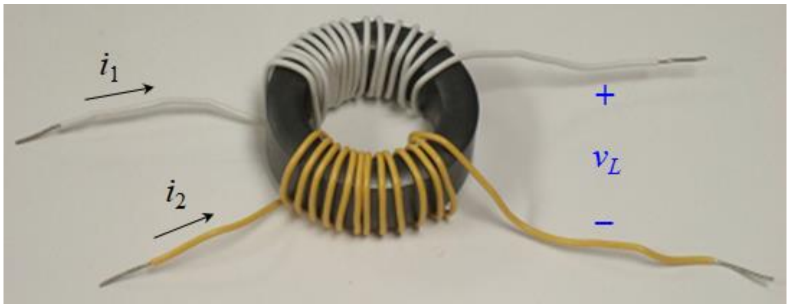
In the second experiment, students fabricate a radio-frequency choke by winding insulated wire in two sets of coils around a single ring-shaped ferrite core. Then the students evaluate the performance of the choke in different (but related) scenarios. Provided in Figure 3 is the equipment list for the activity and a picture of one such choke.

The students apply 2-V square waves to two different circuits with the choke inserted between the source(s) and load(s), in two different arrangements. In the first circuit, shown in Figure 4(a), the voltages are applied to identical 1-kΩ loads with the ferrite carrying magnetic flux in the *opposite* direction through each inductor. In this *differential* mode, the magnetic field of one inductor tends to cancel the magnetic field of the other inductor. Ideally, $i_2 = -i_1$, the magnetic fields completely cancel each other, and the impedance seen by the voltage source is the 1-kΩ resistance alone. In reality, across v_L, the students observe a 2-V step-voltage with a rise time under 300 ns.



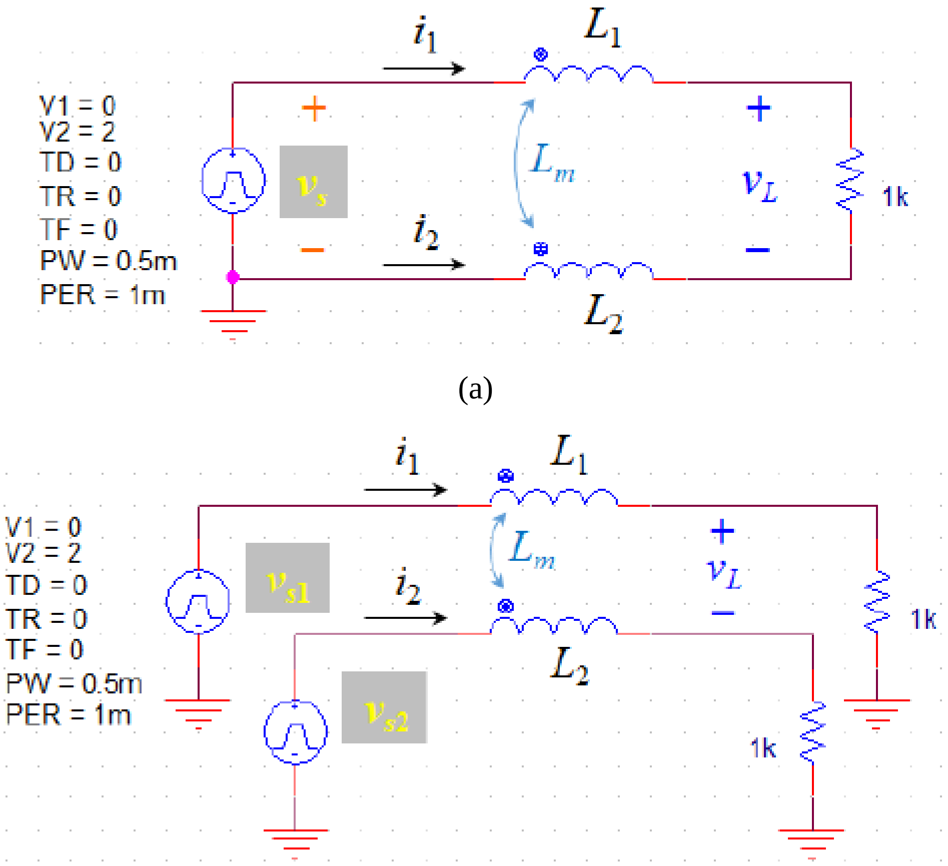
EQUIPMENT: breadboard -- male-to-male header pins (6)
Analog Discovery instrument -- Digilent Waveforms software
two 1-kΩ resistors (brown-black-red)
ferrite core: 1.4-inch diameter -- insulated wire (two different colors)

(a)



(b)

Figure 3. Common-mode choke experiment: (a) equipment, (b) example choke.



(a)

(b)

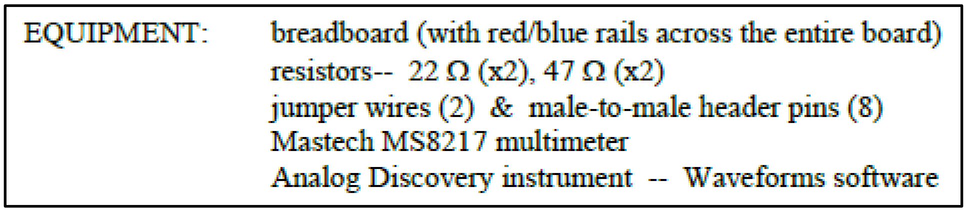
Figure 4. Comparison of currents: (a) differential-mode, (b) common-mode.

In the second circuit, shown in Figure 4(b), the ferrite carries magnetic flux in the *same* direction through each inductor. In this *common* mode, the magnetic field of one inductor tends to reinforce the magnetic field of the other inductor. The impedance seen by each voltage source is 1 kΩ *plus* the impedance of *both* wound inductors. Across v_L , the students observe a 2-V step-voltage with a rise time of approximately 3 μs. Because the settling time of the common-mode circuit is an order-of-magnitude longer than the settling time of the differential-mode circuit, the students observe that the impedance seen by common-mode currents passing through the choke is significantly greater than the impedance seen by differential-mode currents passing through the same part.

Common-mode currents which couple to power lines are notorious for causing devices to exceed FCC radiated-emissions limits. Thus, common-mode chokes are an integral part of passive filters used to block conducted emissions before they exit from a power supply [6, 7].

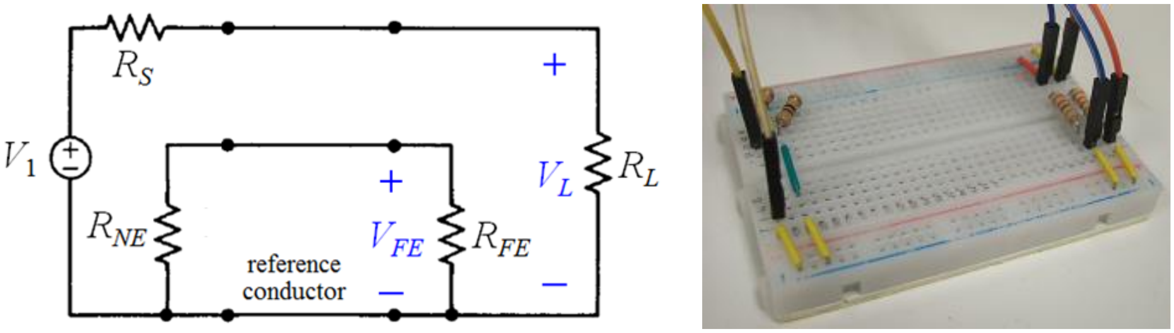
Laboratory Exercise #3: Crosstalk

For the third experiment, the students build a simple structure on a breadboard: two signal-carrying lines running along the top of the board (each terminated by a single resistor) and a single common-reference return path along the bottom of the board. The equipment list, a schematic, and a picture of the constructed breadboard circuit are shown in Figure 5. A portion of the lab procedure directing the students to build the circuit is reproduced in Figure 6.



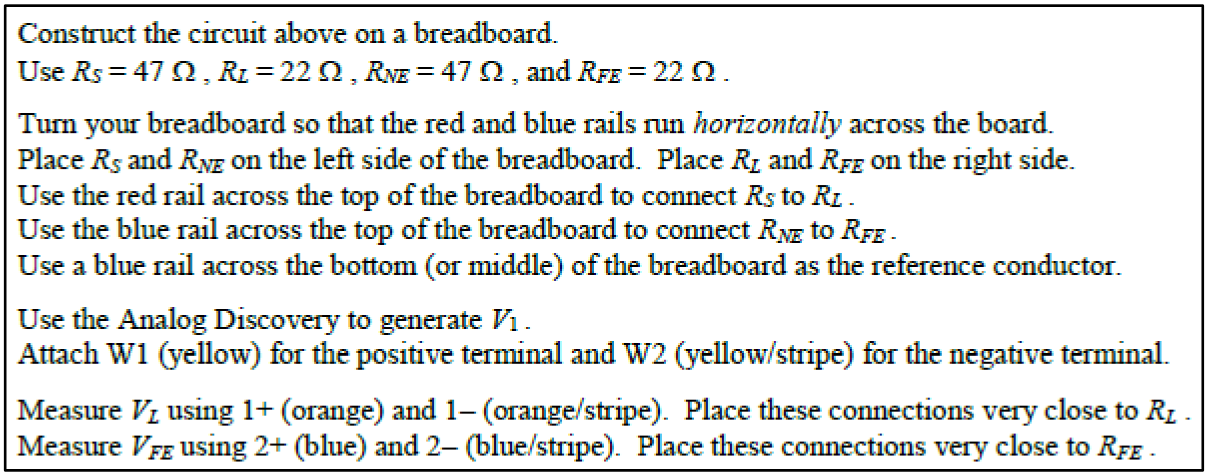
EQUIPMENT:	breadboard (with red/blue rails across the entire board) resistors-- 22 Ω (x2), 47 Ω (x2) jumper wires (2) & male-to-male header pins (8) Mastech MS8217 multimeter Analog Discovery instrument -- Waveforms software

(a)



(b) (c)

Figure 5. Crosstalk experiment: (a) equipment, (b) schematic, (c) picture of the circuit.



Construct the circuit above on a breadboard.
Use $R_S = 47\ \Omega$, $R_L = 22\ \Omega$, $R_{NE} = 47\ \Omega$, and $R_{FE} = 22\ \Omega$.

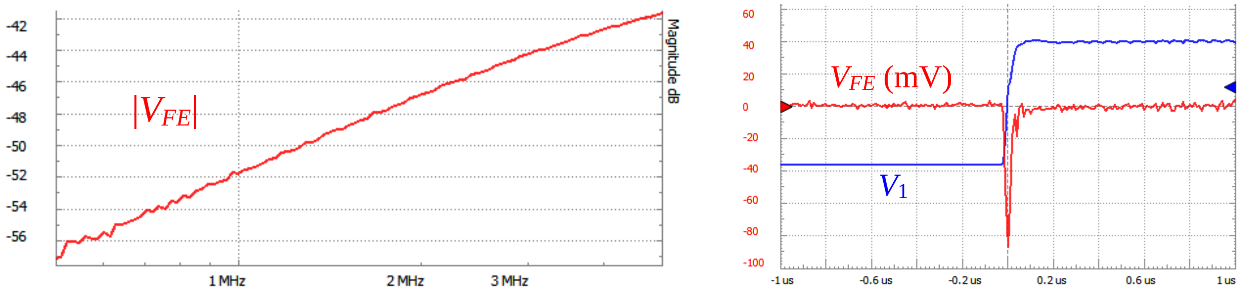
Turn your breadboard so that the red and blue rails run *horizontally* across the board.
Place R_S and R_{NE} on the left side of the breadboard. Place R_L and R_{FE} on the right side.
Use the red rail across the top of the breadboard to connect R_S to R_L .
Use the blue rail across the top of the breadboard to connect R_{NE} to R_{FE} .
Use a blue rail across the bottom (or middle) of the breadboard as the reference conductor.

Use the Analog Discovery to generate V_1 .
Attach W1 (yellow) for the positive terminal and W2 (yellow/stripe) for the negative terminal.

Measure V_L using 1+ (orange) and 1– (orange/stripe). Place these connections very close to R_L .
Measure V_{FE} using 2+ (blue) and 2– (blue/stripe). Place these connections very close to R_{FE} .

Figure 6. Crosstalk experiment: a snippet of the lab procedure.

The students apply a source voltage V_1 (which produces current through R_S and R_L), and they measure the voltage across R_{NE}. Not only is this voltage *not* zero (counter to expectations, because there is no conductive connection between the R_S/R_L and R_{NE}/R_{FE} circuits), but V_{FE} increases as the frequency of V_1 increases. Sample data of a frequency sweep (with $|V_1| = 0$ dBV) is given in Figure 7(a). The students change the source voltage to a square wave and record V_{FE} in the time domain also. A sample transient trace, recorded near the rising edge of V_1, is given in Figure 7(b).



(a) (b)

Figure 7. Measured voltage V_{FE}: (a) in the frequency domain, (b) in the time domain.

Two mechanisms by which energy from the active circuit (V_1-R_S-R_L) appears in the neighboring inactive circuit (R_{NE}-R_{FE}-V_{FE}) are capacitive and inductive coupling, also known as electric and magnetic near-field coupling. Voltage produced in an otherwise inactive circuit by a nearby active circuit is called "crosstalk".

Theory states that capacitive/inductive crosstalk happens only during transient periods of the signal on the active line [6]; this phenomenon is confirmed by Figure 7(b). Theory also states that this crosstalk is linearly proportional to frequency [7]; this phenomenon is confirmed by Figure 7(a). Observation of these effects reminds EMC engineers to take care when laying out signal-carrying lines for subsystems within an electronic device: a general rule-of-thumb is to minimize (or avoid entirely) long & nearby parallel runs of interconnect which use similar frequencies or whose digital data could be corrupted by sharp edges in the digital data of neighboring circuits.

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 *Interference Control in Electronics* course (taught 6 times since Fall 2016 but offered for the first time with all 3 of these activities in Spring 2023):

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

- "The labs."
- "[The professor] bringing the lab equipment to class to show the concepts actually working as described in the text and lectures."
- "The demonstrations… provide a real-world understanding of the topics being covered."
- "I loved the real life examples, props, and in-class demos…"
- "All 3 labs were helpful…"
- "…learning the reasoning behind certain industry practices that I have never fully understood (such as installing ferrites)."
- "The demos and the way material was presented… Also being able to rent out lab equipment to do hands-on demos was nice."
- "In-class demonstrations and projects…"
- "Lab activities…"

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

- measurement of the degree of filtering achieved by shunt capacitors, using a network analyzer -- to emphasize that, above its self-resonant frequency, a capacitor no longer diverts high-frequency current as intended, and
- capture of harmonics produced by a full-wave bridge rectifier, using an oscilloscope and the Fast Fourier Transform algorithm to display the spectrum of the "DC" output -- to demonstrate that nonlinear elements generate significant harmonics within the "ripple" of a power converter.

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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