A Hands-on Introduction to Electronics

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Abstract

We have created a seminar subject (primarily for freshmen) that gives a hands-on introduction to electronics. Initially, the test instruments are limited to a voltmeter and LEDs used to indicate the presence and direction of current in a circuit. Concepts presented this way include voltage dividers, bridge rectifiers and RC charge/discharge. Then, we introduce the function generator and oscilloscope as tools for viewing frequencies too fast to view by the unaided eye. The middle section of the subject is spent building and testing circuits, and observing how their performance can be tailored by changing the values of select components. These experiments are followed by in-class discussion to solidify understanding, with additional explanatory material presented as needed. Active components are covered in a "black-box" fashion, along with discussion of how to read data sheets. Devices covered include transistor switches, comparators, operational amplifiers and elementary timing circuits. Most experiments include indicators, sensors, and/or actuators (e.g., solenoids and motors). The subject concludes with a service-learning design project applying the material learned. A recent example involved adding a solid-state on/off timer to electronic toys used to teach autistic children. We believe that this approach helps students gain an intuitive understanding of current and voltage, as well as giving them the satisfaction of immediately visible results. Our expectation is that some of our students will continue building and hacking circuits on their own, and will encounter situations where the simple rules they know fail. Some of these students (we believe) will be motivated to enroll in more advanced courses to learn the more detailed theory required to make more complex circuits work.

Rationale and Goals

We recognized a need at MIT for a subject offering students a pragmatic, hands-on introduction to electronics. The pool of students for the subject includes

- Freshmen who wish to experience enough electronics to decide if they wish to major in EE.
- Freshmen with no prior electronics experience who intend to major in EE, and feel that some familiarity with circuits and test equipment will help them in their sophomore EE subjects.
- Upperclassmen and new graduate students from other departments who want to learn rudimentary electronics to fill a perceived gap in their education.

Our subject, titled "Practical Electronics," is an attempt to meet the needs of these three groups of students, in a seminar format. These students generally come into the subject with an intuitive notion of electrical current, a poor concept of voltage, and essentially no experience with the test equipment and hand tools used for electronics. They also arrive with an interest in the subject, a desire to learn, a familiarity with mathematics through integral calculus (or beyond) and some understanding of electricity and magnetism from high-school physics classes. The subject meets for one three-hour-long session each week.

Therefore we have taken the approach of presenting concepts in the simplest and most direct manner possible, and then having the students build, test, debug, and appreciate as many circuits as possible. Along the way, they gain familiarity with both many of the fundamental concepts of electronics (e.g., voltage, resistance, capacitance) as well as facility with the standard test equipment. Our expectation is that by getting students building and hacking simple circuits (both in-class and on their own), some of them will encounter situations where the simple rules they know fail. Some of these students (we believe) will be motivated to enroll in more advanced courses to learn the detailed theory required to make complex circuits work.

Overview of the Subject

All students receive a lab notebook at the start of the term, and instruction in its use. The students work in teams of one or two, as they prefer. As much as possible, we open each class meeting with a lab exercise. Most lab exercises have each team building and measuring the same circuit, but with different component values. The teams swap their results, and plot the performance of the circuit for variations in the key parameter values. The instructor creates the same plot on the whiteboard in the lab. They are given one to three simple homework problems each week to help consolidate what they see in class. We encourage them to work together and to consult the course staff for help as needed, and we distribute solutions to the homework at the following week's class session.

The final third of the subject is devoted to a project that requires students to design, build, test, and debug a circuit for use by others. We work with MIT's Service Learning Initiative[1] to select the projects. For example, one term the project was to create a solid-state timer for inexpensive toy pianos used by autistic children at a school in the Boston area.

The autistic students are allowed, at times, to play with the toy pianos for a-20-minute-long period. This raises two problems for their teachers. First, a teacher has to remember when a child's time with a piano is over. Second, a teacher then has to get the child to relinquish the toy (often the child is deeply engaged with it). The teachers believed that if the piano could be easily activated, run for 20 minutes, and then shut off of its on accord, they would be relieved of two burdens. We selected this project as it can be addressed with a simple 555 timer circuit.

The subject has been offered four times, teaching a total of 42 students. Our results and conclusions are derived from informal surveys, observations, and discussions with the students, as the small number of students taking the subject does not provide a good statistical basis for assessment surveys.

In the next section we present the 3-part structure of the course, and discuss each part in turn. We then describe our preliminary findings, and make recommendations for further work.

Structure of the Subject

Conceptually, the subject can be broken into three sections, each four or five weeks long. The first section introduces fundamental concepts in electronics and the use of the test equipment. The second section introduces selected sensors, actuators, and ICs to give the students a small, but flexible, toolkit of components that they know how to use. The final section of the subject is the service-learning-based final project.

Section 1–Fundamentals

During the first section of the subject we introduce the following fundamental concepts

- Voltage and current.
- Ohm's Law
- Circuits and Kirchhoff's Laws.
- RC time constants.

The following components and items of test equipment were also presented

- Resistors, Capacitors, and LEDs.
- Protoboards
- DPDT knife switches.
- Digital Multimeters (DMMs).
- Function Generators.
- Oscilloscpes
- Three-terminal, linear voltage regulator (e.g., 78xx)

The pace is fast, and we try to maximize the time spent building circuits while allowing enough time for reflection and discussion. As an example, here is the material for the first 3-hour session.

Week 1. On the first day of class the students learn the operation of the triple-output power supplies (+5 V and ±15 V) that they will use during the term. They also learn how to measure a DC voltage and a resistance with the DMMs we provide. There is a brief aside on cables and connectors (e.g.. banana plugs and alligator clips) as they measure the voltages at the outputs of their power supply to verify that the supply is working. They also discover that the voltage specifications are not precise!

A discussion of the concept of current as the flow of electrons follows. In it we note the analogy to the flow of water, and we state the sign convention of current (i.e., that the direction of current flow assumes that the carriers have positive charge). We then discuss the concept of voltage. At this stage we simply assert that voltage is a measure of the energy that each electron has available to do work when it is at a given point in the circuit. We make the analogy to water systems and to the concept of gravitational potential energy which they have learned in their HS physics curriculum. The latter allows us to introduce the notion of a reference point for potential, as the students have seen it in the context of gravitational potential energy.

From here we move on resistors and review Ohm's law. We present Kirchoff's voltage and current laws, and use them to analyze a simple resistive voltage divider circuit. The students build the circuit using test-leads with alligator clips, and measure the output voltage. Each team uses a different pair of values for the divider, but all pairs are chosen to give the same output voltage. The teams compare their results.

Finally, each team uses their divider to drive a set of seven load resistors. These resistors are chosen to ensure that each divider will loaded (and its output voltage begin to sag) by at least one of the load resistors. The students measure the output voltage for each load resistor, and each team plots its results on a single graph on the lab whiteboard. Thus, they discover that the load resistance must be much greater than the resistances selected for the divider.

The remaining three class meetings in the first section of the subject are similar in pace and structure. We will highlight the main features of them in the balance of this section.

Week 2.In the second week we introduce diodes and LEDs, and the students investigate the ability of an diode to act as a simple voltage regulator. Also in the second week, we present the three-terminal linear voltage regulator (e.g., 7805) as a method of creating a stable voltage source. The students also explore how parallel, reversed LEDs can indicate the direction of current flow (Figure 1). Their understanding of the performance of LEDs is critical to their understanding of the bridge circuit presented in the third week.

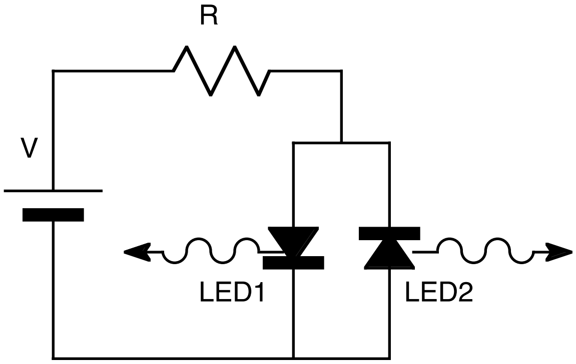

Figure 1. Using two LEDs to indicate the direction of current flow through a resistor.

Week 3.In the third week our students make the conceptual transition from DC to AC. This is a two step process. First we have them wire a 9-volt cell and DPDT knife switch to give a +9 V or a -9 V output, depending upon the direction the switch is thrown. The knife switch is preferred because its the connections are exposed for the students to see. The students use the DMM to verify that the output from the knife switch behaves as expected. We take a few minutes to note that with this apparatus they can create an AC voltage source that provides a crude approximation of a square wave.

Next they build a bridge rectifier circuit using LEDs for the rectifiers (Figure 2). The schematic requires that LEDs which are on during a given half-cycle have the same color. We have them power the bridge from a 9-volt cell, first in one polarity, and then the opposite, and they see that which pair of LEDs is lit changes with the polarity of the input voltage. The students are quick to recognize that the change in which LEDs light up tells them that path the current follows depends upon the polarity, and the workings of the bridge are now readily apparent.

Then we begin a brief lecture on the behavior of the bridge rectifier under quasi-static inputs. Some time is spent with this circuit, as it offers the opportunity to solidify the students' concept of voltage and its relative nature. In particular, they first measure the voltage drop across load for both polarities, that is, the voltage drop between points A and B in Figure 2. This does not change with polarity (except for differences in the turn-on voltage of the LEDs used), and the students recognize that the circuit rectifies an AC square wave into a constant DC voltage drop across the resistor.

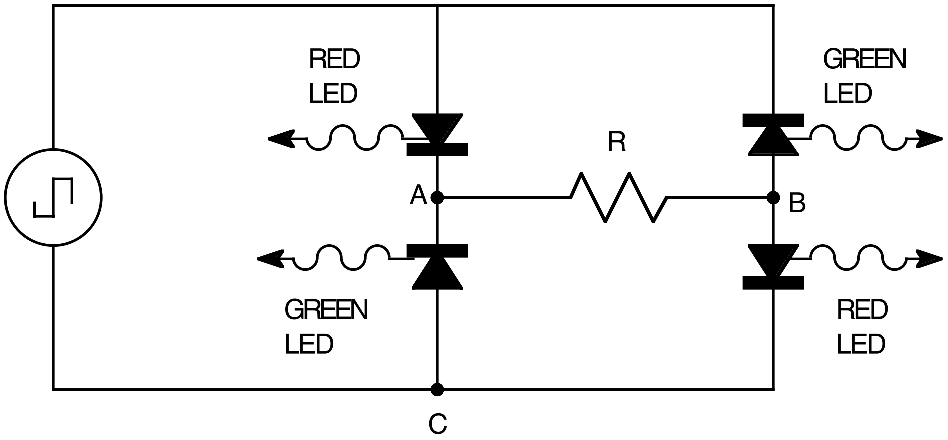

Figure 2. LED-based circuit illustrating the operation of a bridge rectifier. Some time is spent with this circuit, as it offers the opportunity to solidify the students' concept of voltage and its relative nature. In particular, they first measure the voltage drop across load for both polarities, that is, the voltage drop between points A and B. Next, they measure the voltage at each end of load with respect to the negative terminal of the 9V battery for both polarities (i.e., the drop between points A and C, and between points B and C). The first is essentially constant, while the second varies with the polarity of the voltage applied to the bridge.

Next, they measure the voltage at each end of load with respect to the negative terminal of the 9V battery for both polarities (i.e., the drop between points A and C, and between points B and C). These, of course, vary significantly depending upon the polarity of the input, and shows that the voltage at each end of the resistor is an AC waveform with respect to the source, but that the voltage drop across the resistor is fixed.

We close the session by asking them generate the highest-frequency AC waveform they can by rapidly flipping their DPDT switches. They are, of course, limited to rates low enough that the flicker of the LEDs in the bridge is quite visible. We then introduce the function generator as a tool for generating waveforms of arbitrary speed. The students find the frequency (as shown by the dial of the function generator) at which the LEDs cease to flicker, and appear to be always on.

Week 4.The fourth week starts with a more lecture-oriented approach, beginning with a review of the function generator and an introduction to the oscilloscope. We then present two ways of considering capacitors. First, we present the physical model as a device that stores charge, and draw the corresponding analogy from hydraulics (water stored in a tank or bucket). We then give a more abstract definition that a capacitor is a device that obeys the equation $V = qC$, and draw the parallel to Ohm's law, (i.e., the R in Ohm's law is replaced by C, and I by its integral q).

Next the students construct a simple low-pass filter. Each team uses different RC time constants, and all teams use the function generator and oscilloscope to find the 3 dB point and the general shape of the response curve of the circuit. Again, the teams swap data and plot the performance of the circuits. The process is repeated for the high-pass filter configuration. When the students have finished, the instructor writes the differential equation for the RC circuit on the whiteboard and shows that the waveforms seen are, in fact, exponentials. This analysis reinforces the treatment of the RC circuit they have seen (or will see) in the E-M section of their high school or freshman physics curriculum.

Section 2–Building a Toolkit of Components

The goal of the middle four weeks is to equip the students with a small toolkit of components, sensors, and actuators that they can use for the final project, and for other projects of their own devising (robots are particularly popular). We chose to present sensors and actuators to the class next, as they help spark interest in projects that the students might pursue on their own initiative.

Week 5. Students begin by studying an electromagnetic relay to determine how it works. They then use the relay to drive a simple 12-V DC motor. We note both the strengths of mechanical relays (e.g., isolation, current capacity on the load side) and their limitations (e.g., low switching speed, high power requirements on the drive side), and use those limitations to motivate the introduction of the bipolar transistor as a switch. The students then build a range of circuits using bipolar transistors to interface switches and the function generator to LEDs and motors.

Week 6. Next the students examine the performance of CdS photocells as light sensors. We note the difficulty in directly interfacing a CdS cell to a relay or a transistor, leading us to the need for a comparator. We use the venerable 741 op-amp for this role, because of its ubiquity. The description of the comparator is kept to a minimum, focusing on the digital nature of its output (we note that is it is a 1-bit A/D converter), and the inability of the 741 to operate rail-to-rail. The rest of the lab is spent building a variety of circuits that use the components and circuit fragments introduced to date, concluding with a circuit that uses a photocell to detect a change in the ambient lighting, and then drives a motor for a brief period after each change.

Week 7. The students return to the 741 op-amp, this time as an amplifier. They first build and characterize the performance of a simple inverting op-amp circuit. Then we present to them the two "golden rules" of op-amps:

1. The inputs draw no current.
2. With negative feedback (and out of saturation), the inputs are at the same voltage.

We lead the class through an analysis of the inverting op-amp using these two rules (with

Kirchoff's laws) and derive the performance they observed. Then, each team is given a different op-amp circuit (e.g., non-inverting amplifier, voltage follower, summing amplifier), which they build and characterize. They present their results to the class, as well as an analysis of their circuit using the two rules above.

Week 8. This section of the subject closes with the 555 timer. The students build and characterize the 555 timer first as an oscillator (astable mode) and then as a one-shot (monostable mode). As before, the teams build identical circuits, except for the value of the timing capacitor, and the students exchange their data and plot the output frequency (or pulse duration) against the value of the timing capacitor.

At this point, the students have a limited (but sufficient) grounding in the fundamentals of electronics, and the ability to use a small set of components, sensors, and actuators. With these, they are ready to tackle a final project.

Section 3–Final Projects

The final third of the subject is devoted to a project that requires students to design, build, test, and debug a circuit for use by others. As described above, one term's project was devising a circuit for a school teaching autistic children. Again, the teachers there wanted a toy piano (or electric keyboard) that could be easily activated, run for 20 minutes, and then shut itself off.

The course staff obtained a collection of toy pianos and electric keyboards of different styles from area toy stores. Each team of students was given one of the toys to modify. The teams figured out how to open up their keyboards, and some time was spent as a group inter-comparing the different devices, which varied widely in cost, number of components, and internal layout. They were consistent in using 4 AA alkaline cells for power (at nominally 6 V).

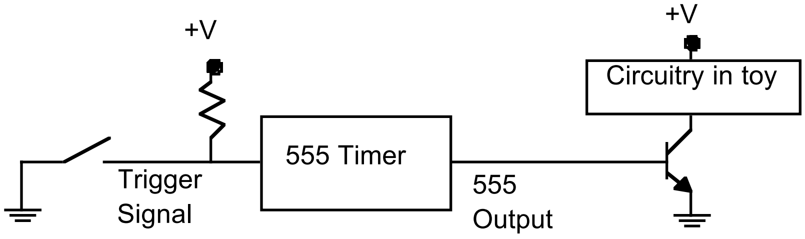

Figure 3. Block diagram of the circuit used by the students for their final project.

Each team spent some time (inside and outside of class) devising the timing circuitry, and each group chose the same basic approach (a block diagram is presented in Figure 3). All used a 555 timer configured as a one-shot with a 20-minute pulse width, and had the 555 drive the base of an NPN power transistor. The line from the toy's circuitry to the negative terminal of the battery is cut, and the two ends are connected to the collector and emitter of the transistor, respectively. Thus, once triggered, the 555 drives the base of the transistor, applying power to the toy keyboard for 20 minutes.

The students built their circuits on protoboards and demonstrated that they worked. At this point we had the teams consult with each other, and asked the students to present to the staff their best collective design for the circuit.

Three issues remained that needed to be addressed at this point

1) How would the teacher trigger the 555 timer?
2) How would the teams fabricate their circuits and install them in the toys?
3) Would the circuit drain the toy's battery too quickly?

The circuits were constructed so that the input to the 555 was held high by a pull-up resistor. This meant that whatever the teacher did to activate the device must make a switch closure pulling the trigger input to ground. The students devised two approaches to this problem. Some keyboards had an input jack for a microphone input jack. The teams with those keyboards generally disconnected the leads from that jack, and reconnected the jack to the trigger input, then modified a microphone connect to be a shorting plug. When the connector is inserted into the jack, the trigger input of the 555 is pulled to ground, starting a 20-minute cycle. The second approach was to glue a reed switch to the inside of the case of the keyboard. Then, the teacher can pass a magnet over the outside of the case, closing the reed switch, activating the 555.

The fabrication issue was solved by having the course staff create a PCB layout of the preferred circuit. We had each team give us the spacing and diameters of the mounting holes they wished to use for their boards, so that we could include those hole patterns onto the board. In many cases the students were able to exploit existing screw-mounts in the toy. In a few cases, the students simply glued the boards into the cases using a silicone RTV adhesive.

Finally, since the circuit is constantly powered, excessive current draw would quickly run down the batteries in the toy. The subject staff selected a CMOS version of the 555 to minimize the current draw of the circuit. We had the students measure the current draw of their circuit (just under 1 mA), and they determined that, given the 2,850 mA-hr capacity of an alkaline AA cell[3], the toy could sit unused for over 2,850 hours, or approximately 4 months, before the batteries would be discharged.

Results to Date and Conclusions

The course has been taught four times, to date, with a total of 42 students. Clearly, the number of students who have taken the subject is too small for significant statistical analysis, but we found that informal surveys and anecdotes do present a consistent story.

At the start of the term we asked the students to tell why they signed up for this seminar. Most of their answers fell into two groups (many students listed more than one reason, spanning the groups):

1) The hands-on nature of the subject
2) The opportunity to get a jump start on the sophomore EE subjects.

When we asked the students at the end of the term for the strengths and weaknesses of the subject, they generally felt that it had met their expectations and given them the hands-on experience and skill-building they sought. Some liked the interdisciplinary nature of the final project, which required some mechanical modifications to the toys. They also felt that this was one of the more demanding subjects for the amount of credit received, but they did not recommend cutting back on the material covered or the pace. Several students stated that they appreciated the fact that there were people who were eager to use their final project, and that this provided extra incentive to learn the material and to perform well on the final project.

We believe that the strengths of the subject include that it:

- Has a strong appeal to both freshman considering EE as a major and to non-EE students who wish to learn more about electronics without having to digest extensive theory and math.
- Gets students building circuits from the start, with little theoretical introduction.
- Lets students experience early in their careers the non-idealities of real-world engineering, and demonstrates the utility of simple rule-of-thumb design.
- Appears to have students complete the subject with a positive impression of engineering as a field of study.
- Can be readily taught by a graduate student or an advanced undergraduate, enabling large numbers of students to take the subject without taxing a limited (and over-worked) faculty and staff.

Its weaknesses include that it:

- Is somewhat more time consuming than typical for the amount of credit received (one half that of a typical subject such as first-term calculus, physics, or chemistry).
- Appeals most to those students predisposed towards electrical engineering.
- Requires a lab space equipped with several sets of lab instruments (DMM, function generator, and oscilloscope).

Acknowledgments

This effort was sponsored by the MIT Edgerton Center. I would like to thank Professor J. Kim Vandiver, Mr. Tony Callogero, Mr. Ed Moriarty, and Mr. Chris Wilkson of the Edgerton Center, as well as Dr. Thomas Consi of the Department of Ocean Engineering, for their valuable discussions on this approach. Thanks also go to Ms. Amy Banzaert, Ms. Sally Susnowitz (MIT Public Service Center) and Ms. Amy Smith (Edgerton Center) for the opportunity to incorporate service-learning into the course, and to Ms. Amy Fitzgerald and Ms. Sandi Lipnoski (MIT Edgerton Center) for their supporting efforts. My deep thanks go to the students in the subject, whose interest and dedication was inspirational, and who were just a lot of fun to be around!

Bibliographic Information

[1] A description of the Service Learning Program at MIT can be found at http://web.mit.edu/mitpsc/servlearn/

[2] The school in question is The Learning Center of The Protestant Guild for Human Services, Inc., a not-for-profit agency based in Waltham, MA. http://www.protestantguild.org/homepage.html

[3] Battery capacity is for the Duracell Model MN1500 alkaline-manganese dioxide battery (AA-size), Duracell, Inc., Bethel, CT, Doc. No. MN1500-12/96.

Biographical Information

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Dr. Bales is the Assistant Director of the MIT Edgerton Center, where he teaches a range of hands-on subjects including "Doc" Edgerton's Strobe Project Lab. He received his Ph.D. in solid-state physics from MIT in 1991. His research interests include engineering education, high-speed imaging, and underwater robotics.