AC 2011-1846: A PROJECT-BASED INTRODUCTION TO ELECTRONICS

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A Project-Based Introduction to Electronics

Abstract

We have created a laboratory subject that gives a hands-on introduction to electronics, aimed at undergraduate and first-year graduate students with no background in electronics. The initial experiments are aimed at getting the students working with a limited range of test equipment (digital multi-meters and power supplies) by building circuits that give them a tangible result. These experiments include driving LEDs and building simple audio amplifiers that they can drive from their MP3 players. By the fourth week (meeting for one three-hour session each week) they can design, build, debug, and demonstrate their first substantial project -- an LED-based night-light circuit. Then, we introduce the function generator and oscilloscope as tools for viewing frequencies too fast to view by the unaided eye. These tools are used to analyze RC circuits, and students observe how the performance of these circuits can be tailored by changing the values of select components.

All 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 sensors (e.g., photocells and thermistors) and actuators (e.g., solenoids and motors). The subject concludes with a design project applying the material learned. Recent examples include an analog optical communication link and a color organ. Our goal is to engage students in building and hacking simple circuits that give immediate satisfaction, then use those circuits to illustrate a rule-of-thumb approach to the theory behind them. Our expectation is that, having engaged the students in electronics, some of them will be motivated to enroll in more advanced courses to learn how to use circuit theory to develop their circuit design skills.

Rationale and Goals

This subject was inspired by the recognition that high-school students with little formal training in electronic circuit theory can (and do) build fairly sophisticated electronic circuits[1]. They do so through simple models of how devices operate and rule-of-thumb design practices. Therefore we have adopted our previous seminar-style electronics lab (described[2] in 2004) and revised it to emphasize designing, building, and debugging a series of projects through the application of simple models of components and devices.

Our subject is an attempt to meet the needs of two groups of students, i) freshmen interested in exploring electronics as a field of study, and ii) upperclassmen and new graduate students from other departments who want to learn rudimentary electronics to fill a perceived gap in their education. These students generally come into the subject with an intuitive notion of electrical current, a poor concept of voltage, and essentially no experience with either the test equipment or 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 with 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 become familiar with many of the fundamental concepts of electronics (e.g., voltage, resistance, capacitance) and gain 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 more detailed theory required to make their circuits work.

Relation to Other Project-Based Efforts

This approach clearly has significant overlap with the ongoing efforts in project-based learning within ECE. However, there are also some substantial differences as well. In particular, the project-based ECE programs we are aware of tend to be focus on upper-class majors[3], on particular sub-fields (e.g., embedded controls[4]), or on having students work in interdisciplinary teams on large-scale design projects[5]. Some use remote, mixed-reality, or virtual projects[6], in contrast to our hands-on approach. All ultimately employ project-based learning to impart knowledge with a rather high degree of rigor. Our goal, in contrast, is to engage students in the joy of creating engaging circuits, and evoke in them the drive to seek out the rigor other courses offer.

Overview of the Subject

As much as possible, we open each 3-hour class meeting with a lab exercise. Some 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, overlaying the results for the different component values. (E.g., plotting the attenuation of an RC filter for different RC values.)

We discuss their results in class and present the simple model that we will apply to the component or device under study. The instructor works out a design problem on the board applying the simple model, and we note any intuitive relationships that can be extracted from the model. The students are given a small homework assignment and (every 2-3 weeks) a design problem to solve, both requiring application of the model just presented. The homework is due in class the following week, as is the completed circuit for the design problem. We give the students the combination required to enter the lab, so they have access to the lab off hours.

The subject has been offered three times in this format, teaching a total of 36 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. The class is included in MIT's standard assessment process, and the results are summarized at the end of the paper.

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 3 or 4 weeks long. The first focuses on giving students success with some simple design projects and introducing a few key components. The only items of test equipment used are a triple-output power supply and a digital multi-meter (DMM). The second section goes into more depth in both theory (e.g., AC instead of DC, capacitors) and tools (the function generator and oscilloscope are introduced). The final section of the subject is the final project.

The pace is kept fast, and we try to maximize the time spent building circuits while allowing enough time for reflection and discussion. We now present the material covered each week for the first two sections of the term.

Section 1: Let's Build!

Week 1. On the first evening of class the students are shown the instructor's first-generation iPod, which has no external volume control. We connect the iPod to external speakers (e.g., those for a desktop computer) and draw the connections on the board. The instructor then takes a stick of graphite and draws heavy streak (~1-inch-wide and ~6-inches-long) down a sheet of paper. The iPod output is connected across the ends of the streak. One speaker lead is attached to one end of the graphite streak, while the other is slid along the graphite, causing the sound level of the speaker to rise and fall (Figure 1). These connections are then sketched on the board, and students (typically working in pairs) are given graphite and paper and asked to draw their own lines, of whatever size or shape they wish. For the next 30- to 45-minutes, there is much excitement (and sound) as students explore their designs. We spend about 10 minutes reviewing what we have discovered.

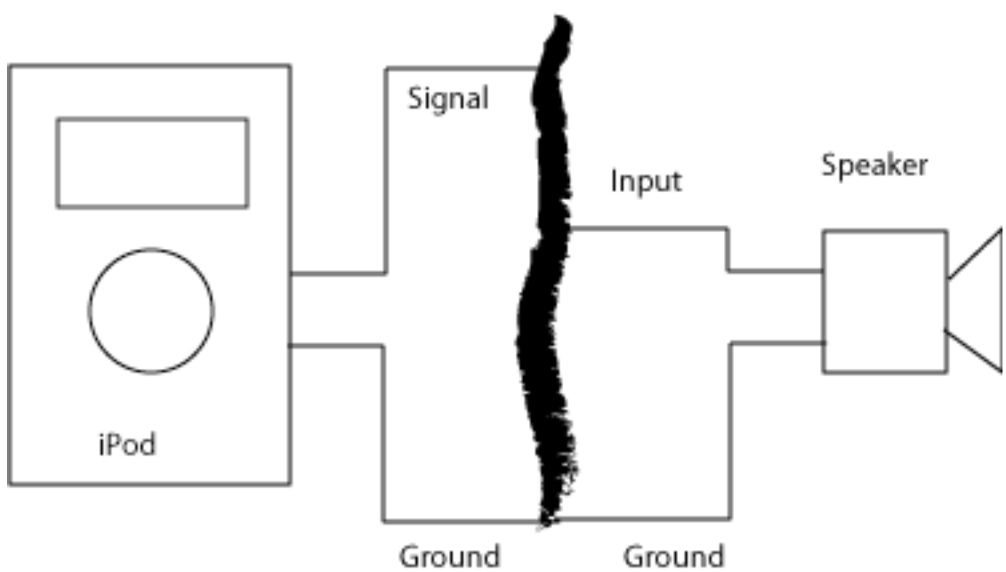

Figure 1. Diagram showing connections to the graphite streak used as a crude potentiometer. The iPod output is connected to the ends of the streak (irregular line down the middle). The powered speaker shares the ground connection, but students pick off the

signal by sliding an alligator clip down the streak.

The instructor then sets forth our working concepts of current (the flow of charge) and voltage (by analogy to gravitational potential energy) as the electrostatic potential energy of a charge one point in our circuit as measured relative to a reference point in our circuit (called either *common* or *ground*). We show how the power relationship $P = VI$ flows directly from our definitions of voltage and current.

Next, Ohm's law is presented as $\Delta V = IR$, where we use ΔV to emphasize the fact that there is no absolute potential, so devices can only respond to potential differences. We define a resistor as *a two-terminal device that obeys Ohm's law*. This introduces our convention of defining devices by their constitutive equations.

The students learn the operation of the triple-output power supplies (+5 V and ±12 V) that they will use during the term. They learn how to measure DC voltage and resistance with the DMMs we provide. There is a brief aside on cables and connectors (e.g., banana plugs and alligator clips), and then 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!

For homework they are given an independent exercise to construct a voltage divider and measure its output under different loads, as well as a paper problem exploring voltage dividers.

The remaining three class meetings in the first section of the subject are similar in pace and structure. The topics covered are listed in the syllabus (presented in the Appendix), we will highlight the main features of them in the balance of this section.

Week 2. The second week opens with the students being handed a lab exercise, a prototyping board, and an op-amp (powered from the ±12 V supplies). The exercise explains the connections within the prototyping board, the convention on pin numbers, and has them build an inverting op-amp. They test their circuits with a variable voltage source, which they build as a voltage divider with two 1-k resistors and a 1-k potentiometer between the ±12V supplies, creating a ±4 V source. Each team of students uses different values for input and feedback resistors. After they have built and tested their circuits, they compare data and discover:

1. The gain is $-(R_F/R_I)$.
2. The op-amp outputs can become saturated.
3. The gain relation does not apply when the outputs are saturated.

We note the etymology of "op amp" (operational amplifier, i.e., an amplifier that performs a mathematical operation). The instructor then presents the "golden rules" of op-amps (i.e., the inputs draw no current and, with negative feedback, the output tries to swing the inputs to be at the same voltage). We tell the students that these are, in fact, false, but note the typical magnitudes of the input current and voltage difference required for operation. The instructor warns the students that much of what we tell them are, in fact, lies, albeit useful ones!

We also present Kirchhoff's circuit laws, and use them (along with the golden rules) to derive the performance of the inverting amplifier they have just built, as well as a voltage follower. For their homework they must analyze the circuits of the voltage follower, a summing amplifier, a differential amplifier, and a non-inverting amplifier. Additionally, as homework the students design a circuit that conditions a DC signal. A typical assignment might read:

> *A pressure sensor outputs 2 V for 5 psi, 1 V at 0 psi, and is linear in between. Build a circuit -- using as many op-amps as you need -- that takes the sensor's voltage as an input and outputs 0 V at 0 psi and 5 V at 5 psi.*

Students are encouraged to work out a mathematical expression for the desired op-amp performance first, and then design the circuit to perform the desired operations.

Week 3. Now we introduce diodes and LEDs. The students use a handful of current-limiting resistors to map out the I-V curve of the diode. We then present our model of a diode: No current flows until ΔV across the diode (ΔV_{DIODE}) reached V_F, at which point *any* positive current can flow without increasing ΔV_{DIODE} in the least. And, this too, we tell them, is a lie. We sketch the actual I-V curve on the board and note that it is an exponential, but also note that our model is generally easier to apply and it usually works well enough.

One question that often arises is, "What is the resistance of a diode?" We respond by asking the student our definition of a resistor, to which they reply "a two-terminal device that obeys Ohm's law." We then ask if a diode obeys Ohm's law, and they recognize that it doesn't and thus we note that the notion of resistance doesn't apply to the diode. (We note that this too, is a bit of a lie, and in later classes they will discover the notion of differential resistance, but that is a notion that does not exist in our subject.)

We derive the expression for determining the value of current-limiting resistor required for safer operation of an LED. We then have them discover how parallel, reversed LEDs can indicate the direction of current flow (Figure 2).

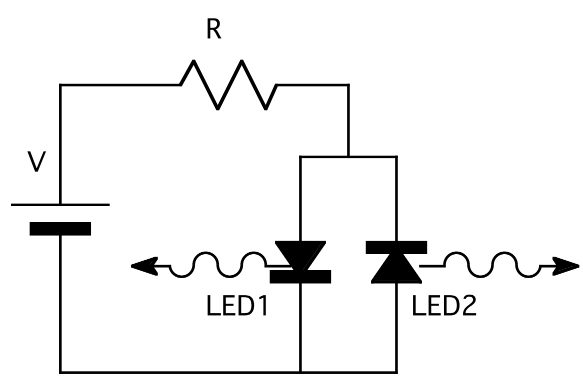

Figure 2. Using two LEDs to indicate the direction of current flow through a resistor.

The homework set has problems that require sizing current-limiting resistors as well as using diodes as voltage clamps. We also give them a design problem to build outside of class. They are given an LM34 temperature sensor (output of 10 mV/degree F) and instructed to build a circuit that dimly lights a red LED when the temperature reaches approximately 70 C, and makes the LED glow bright and brighter as the temperature approaches 80 C. This circuit is easy to test by simply holding the sensor in a tightly closed hand, where body temperature will heat the sensor.

Week 4. We open by giving each team a CdS photocell and having them find its light and dark resistances. We then return to the op-amp, but configured as a comparator this time. The students discover what a comparator does by varying the voltage on first one input and then the other. We note that with the comparator they now have the ability to build circuits that make decisions. Their homework assignment is to design, build, and debug an LED nightlight circuit. Once they succeed they are asked to find as many ways as they can to:

1. Have the LED work with the desired logic (one variant is, e.g., to swap the inputs and set up the comparator output as a current sink rather than a current source).
2. Reverse the logic of the circuit (i.e., make the LED turn on when the room is bright and off when the room is dark)

There is a real sense of delight from the students when, four weeks into the term, they have built an LED thermometer and a nightlight, and both work!

Section 2–Going Deeper
The goal of the middle four weeks is to build on the sense of success gained from the first design efforts to lay a deeper understanding of circuits, components, and devices.

Week 5. Now 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 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 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 3). 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 the pair of LEDs that light up 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.

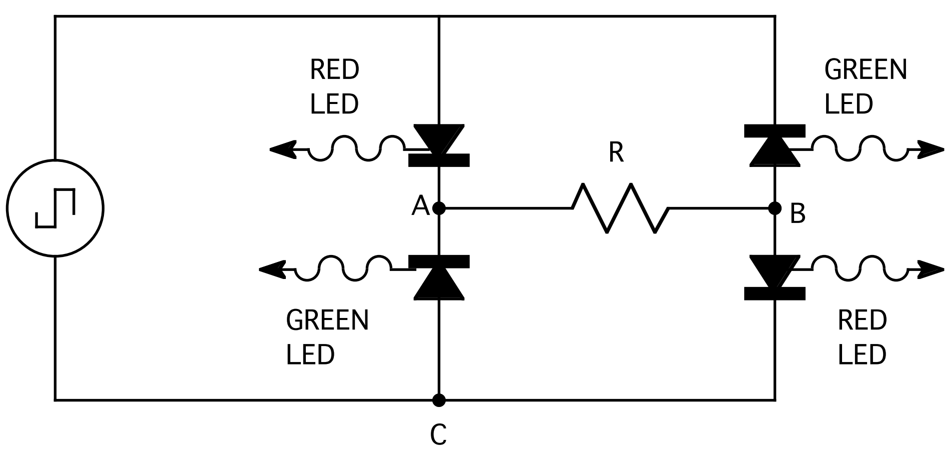

Figure 3. LED-based circuit illustrating the operation of a bridge rectifier. Some time is spent with this circuit, as it offers the opportunity to solidify the students' concept of voltage and its relative nature. In particular, they first measure the voltage drop across load for both polarities, that 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.

Then we provide 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 3. 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 (constant, that is, if the forward voltage drops of the diodes are matched).

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 open the last hour of the session by asking them generate the highest-frequency AC waveform they can with their switches. The knife switch, of course, limits them 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. We note that, by carefully studying the light out put of the LEDs at low frequencies (~0.5 Hz), they can detect the difference between the square wave, triangle wave, and sine wave driving functions. With that preparation, we have them use the light output from the LED bridge to observe the effects of changes in duty cycle and from adding DC offsets, again at low frequencies.

<u>Week 6.</u>The sixth week starts with a more lecture-oriented approach, beginning with a review of the function generator and an introduction to the oscilloscope. It takes a solid hour to walk through the settings on the oscilloscope. We describe the oscilloscope as a device that creates graphs of voltage as a function of time, and then note how the controls (in our case, of our analog scopes) group into controls for the vertical (voltage) axis, for the horizontal (time) axis, and for triggering. We call out triggering as "telling the scope when to start plotting", and assure them that, if they master the scope's trigger section, they will appear to have magical power to the uninitiated. By the end of the hour we can alter the function generators settings, scramble the oscilloscopes controls, and the students can recover the signal (albeit with some guidance from a cheat sheet).

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 $V = q/C$, and draw the parallel to Ohm's law, where I is replaced by q and R by 1/C. We briefly touch on the analogous constitutive equation for inductors as well.

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 3dB 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 with their experiments, the instructor writes the differential equation for the RC circuit on the whiteboard, showing that the waveforms seen are exponentials and sinusoids. This analysis reinforces the treatment of the RC circuit they have seen (or will see) in the E-M section of their freshman physics curriculum. We state the rule of thumb that a capacitor acts like a large resistance at low frequencies and a low resistance at high frequencies (another lie, of course, as capacitors are not resistors). We then note that this way of looking at capacitors turns the RC filters into frequency-dependant voltage dividers, where the time scale RC determines what is a low- or high-frequency. Students generally find this to be an intuitive way of viewing the filters.

Week 7. 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 (both NPN and PNP) to interface switches and the function generator to LEDs and motors.

We hand out a short take-home midterm. We assure the students that our primary goal is to see what they have learned and where their knowledge needs refreshment. It includes problems addressing the transistors they have just learned that week. It is due 9 AM of the day of the next class, so that we can identify topics that the class as a whole needs help with.

Week 8. This is a review week. We prompt students in class to tell us what they have learned about the various components and devices we have covered. We cover all topics, but pay particular attention to those areas that the midterm identified as areas of weakness across the class.

We lay out a formal design process:

Specification leads to block diagram leads to a circuit for each block

We also lay out a formal debugging process:

Synthesize the input signal and use it to debug the first block. Synthesize its output and use that to debug the second block. Plug the second block into the first; drive the first with the synthesized input signal and see if the blocks work together. Once they work together, repeat the process for third, fourth, fifth, etc. blocks.

Week 9. This section of the subject closes with the 555 timer. The students build and characterize the 555 timer IC; 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 Project
For the final third of the subject students design, build, test, and debug an electronic project. For the last two semesters the project has been to build a color organ. This is a circuit that takes an audio input, assesses the signal strength in the bass, mid-range, and treble frequency bands, and (for each band) drives an LED with brightness proportional to the in-band signal strength.

One feature of this design problem is that the passive RC filters we have taught them have poor performance for this task. This is by design -- we ensure that the students have realized this (sometimes with substantial prompting) by the end of their second week. We give them a short review of the types of filters and send them off looking for circuit diagrams for active filters on the Internet. Our goal is to help them realize that:

1. The Internet can be an extraordinary source of useful circuits
2. You have to know what you seek and know key terms of the art (i.e., the right jargon)
3. It still helps to have a solid understanding of how circuits and devices work!

They end up with color organs that work, whose performance they can -- mostly -- explain, and sense of rudimentary skill with electronic components and text equipment. This, we believe, is the limit of what can be accomplished through three hours a week of lab and lecture, along with one to three hours a week of effort outside of class time.

Results to Date and Conclusions

The course has been taught three times, to date, with a total of 36 students 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 these groups (many students listed more than one):

1) The hands-on nature of the subject and delight in building interesting projects
2) A sense of a need to learn rudimentary skills in electronics
3) A desire to explore the field of electronics to decide if they want to invest more time and effort into learning it.

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. They find it one of the more demanding subjects for the credit received, but did not recommend cutting back on the material covered or the pace.

Clearly, the number of students who have taken the subject is too small for significant statistical analysis. However, we do have the results of MIT's regular assessment for the Spring 2010 term (with 12 responses from 14 students), from which we draw the following results.

Overall satisfaction was quite high, with students rating the class at 6.8 out of 7.0. The students felt that they had "a good understanding of the concepts learned (6.3 out 7.0) and could apply them (6.5 out of 7.0).

Critical comments were:

- A bit disjointed at times, probably ... due to the open nature of the lecture and discussion.
- Would have liked to see more digital and inductors.
- I would have liked more instruction on 555 timers.
- I know it is a hand-wavey class, but just a little more going into deeper explanations if possible?
- A second meeting per week might be very beneficial, to add some content and depth.
- Lectures could be better organized.
- Handouts could use some proofreading and clarification.

There were several generally positive comments (e.g., "Great job, keep doing the same thing"), as well as two highlighting the "practical approach" and "learning ... how to apply" the concepts covered.

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

- Has a strong appeal 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).
- Requires a lab space equipped with several sets of lab instruments (DMM, function generator, and oscilloscope).

Acknowledgments

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References

[1] The success of, e.g., *Make* magazine (http://www.makezine.com) and the *Instructables* web site (http://www.instructables.com), among many related sites, is a testimony to the power of a less formal introduction to electronics.

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