Rethinking Non-major Circuits Pedagogy for Improved Motivation

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1 Introduction

It is no secret that student motivation is critical to learning. Put succinctly, students will only apply effort to learn if they see value in learning the material or skill at hand. This value may come from a combination of one or more sources, such as the pleasure of attaining mastery of a skill, the enjoyment of the material itself, the potential for better job prospects, or simply the need to earn a particular grade to keep a scholarship [1]. Many of these value factors are influenced by the structure of our courses and the way we teach, and electrical engineering is an exciting field rich with opportunities to inspire and motivate students. Yet many introductory EE courses (ours included) have a reputation among students as being dry, boring, and even useless.

This paper describes how we transformed our rather traditional circuits course for non-EE-majors into a project-centered introduction to practical electronics. By building the course around a set of interesting projects and drawing links to real devices whenever possible, we aimed to demonstrate the value and relevance of EE to students in other fields and to those still deciding on a major. Student evaluation comments and several significant shifts in enrollment patterns suggest that we have been at least partially successful. Our goal in this work is to share our course design philosophy and some aspects of our specific implementation, in hopes that others will be able to make similar changes in their courses.

Like most universities with a sizable engineering program, Stanford's electrical engineering department offers a large introductory electronics course (known as ENGR 40) taken by students from many backgrounds and majors. Figure 1 shows the breakdown by major and class year, aggregated across four offerings of the course (Spring 2012 through Fall 2013).

As the graph suggests, there are two primary groups of students. The first are "undeclared" students who take the course in their first or second year as a way to decide which engineering discipline suits them. The second group takes the course because it is required by their chosen degree program, either explicitly or as one of a set of breadth electives. The remaining handful take it simply out of interest. Students who have already chosen electrical engineering are not required to take ENGR 40, but may elect to take it as an early introductory course.

Five years ago, ENGR 40 followed a fairly traditional pattern for introductory circuits courses: lectures on Kirchhoff's voltage and current laws, Ohm's law, techniques for solving resistive circuits, then capacitors and inductors, operational amplifiers, sinusoidal signals, and finally wrapping up with passive and active filters. In the weekly labs, students built simple circuits which embodied the lecture concepts. In the final weeks of the course, students built small audio amplifiers with op-amps and soldered their final circuits together on prototyping PCBs.

The class had a reputation for being dense and unexciting. Speaking broadly, students put up with it as a necessary evil. So did the faculty member teaching the class, who grew to resent the crowds of students who were taking the class merely as a graduation requirement and who cared for nothing other than a passing grade.

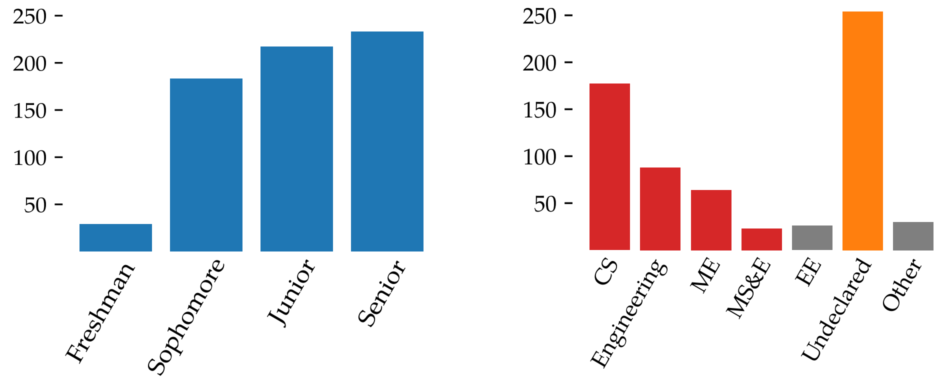


Figure 1: Total enrollment for four offerings of ENGR 40, from Spring 2012 through Fall 2013. Majors in red are required to take ENGR 40, either specifically or as an engineering breadth elective. CS: Computer Science, ME: Mechanical Engineering, MS&E: Management Science and Engineering. "Engineering" includes all other engineering disciplines. Class years are official standings based on total course credit, which may be slightly inflated due to AP or other incoming credit.

2 Student motivation

A great deal of educational research has explored the theme of student motivation, and a few recent works specifically consider motivation in introductory circuits courses such as ENGR 40. These raise two particular needs to consider when teaching students majoring outside of electrical engineering: First, students must be able to connect what they are learning to their own interests, whether by seeing links with their chosen field of study or by understanding how the material makes a difference in the real world. In a word, the course must be "relevant" to students [2]. Second, the mix of topics and depth of coverage ought to be tailored to the needs and interests of non-majors. Zekavat et al. observe that,

> The class time devoted to the details of circuit theory in a service course detracts from the time needed to study and understand the connections between electrical engineering and related engineering fields. As a result, non-EE students regularly express dissatisfaction with the traditional service course and increasingly maintain that the course should no longer be required in their programs of study. [3]

Bales argues that a project-first exploratory introduction to circuits can be effective, as evidenced by the popularity of media such as Make magazine and Instructables.com [4]. Even high school students with no formal training in circuit analysis are perfectly capable of wiring up sensors to a microcontroller and writing code to control actuators. For students who will never take another circuits class, skills like these are dramatically more useful than the ability to calculate a Thévenin equivalent circuit or find the second-order transient response of an RLC circuit.

Several projects have attempted to address this lack of motivation by better integrating theoretical content with project-based laboratories [5, 6, 7, 8]. By building complete working devices in lab (often with a small amount of open-ended design), students more readily see the connection between the theoretical work they are doing and its practical application in the "real world".

Course evaluation results, surveys of student interest in EE, statistics of final grades, and performance in subsequent classes all indicate that this approach does in fact increase motivation for non-majors and pique interest in those who might otherwise not pursue EE as a major.

As we redesigned ENGR 40 to create a new course, ENGR 40M ('M' for "making"), we also drew heavy inspiration from CS 106A, the introductory computer science class at Stanford. More than 80% of undergraduates at Stanford take CS 106A— majors from mechanical engineering to biology to history. This is partly because we live in Silicon Valley, with its unrelenting hype of software startups, and partly because the class is run by a stellar group of faculty and TAs. But CS 106A is also popular because it is empowering. Aided by appropriate scaffolding, students are able to work on interesting problems right away to build realistic applications. One author in the student newspaper observed that by the end of the 10-week quarter, students who initially knew nothing about programming feel like they could drop out of school and start the next Google or Snapchat or Instagram [9].

We believe that electrical engineering is equally empowering, but unfortunately it often takes two or three years before students get their hands on real applications and discover why their theoretical training is of value. So like CS 106A, ENGR 40M introduces students to realistic and fun applications from the beginning of the class. Where necessary, we simplify and scaffold the assignments so that our students can build real devices.

3 Course design approach

As we designed and iterated on ENGR 40M, the following criteria emerged as central guiding principles:

- *Teach introductory electronics, not linear circuits.* Non-linear components such as diodes and transistors are every bit as widespread and important as linear elements. For example, a basic electronics kit is far more likely to include a pack of LEDs than it is an incandescent lamp, and so students ought to learn the peculiars of wiring up an LED early on.
- *Integrate digital and analog electronics.* Today, nearly every consumer electronics device contains a microcontroller, meaning that every product is a mix of analog circuitry, digital circuitry, and software. Our labs reflect this by incorporating a microcontroller and software into three out of the four major projects.
- *Focus on real applications.* Real applications provide the essential motivation for students to keep learning the material, and this cannot be deferred until years later in the program. As the following sections will show, we aim to incorporate real applications not just in the labs but also in lectures, homework, and exams.
- *Use labs to teach skills, not just theoretical concepts.* Labs are valuable not primarily because they provide a second repetition of lecture concepts, but because they expose students to a different set of challenges: learning to use tools and instruments, grappling with the non-ideal behavior of the real world, making predictions and verifying their accuracy, and troubleshooting when experiments or designs do not work the first time. While students must have a solid grasp of the concepts to complete the lab work, our

primary goal is to give students practical experience building and debugging circuits. This is reflected in our feedback and grading scheme, which is detailed below.

Based on the teaching philosophy that informed the above criteria, our approach was to center everything in the course around a series of lab projects. After some early experimentation we settled on four projects, chosen to give some sense of the breadth of electrical engineering: a solar-powered cell phone charger, an electromechanical box that can switch itself off (known as a "useless box"), an LED cube, and an electrocardiograph. Each of these are described in more detail in the following sections. Each week, the lectures cover the topics students need for the following week's lab, providing an immediate utility that was lacking in the previous course structure.

This approach is not without drawbacks. Organizing the class around the projects makes a number of major demands on the pedagogical structure of the course, which we have debated and wrestled with over the last four years. First, it requires a carefully synchronized dance between lecture topics and lab exercises, as shown in Figure 2. Students begin building their solar phone chargers in the second week of the course, which means that we must introduce a whole host of topics in the first four class periods: voltage and current, Kirchhoff's voltage and current laws, Ohm's law, power, diodes, solar cells, and the basics of using a multimeter. Later sections of the course have a little more slack, but the lab sequence takes us on a somewhat unusual route from basic linear circuits to transistors and digital logic and then back to the analog domain for capacitors, inductors, op-amps, and filters.

Second, the projects demand that we teach some concepts that would typically be left out of an introductory course. The solar charger lab requires that we talk briefly about solar panels, which are normally reserved for an advanced course on silicon devices or green energy. Similarly, the electrocardiogram project uses an instrumentation amplifier, so we spend part of a class period talking about common-mode noise and the internals of an instrumentation amplifier.

However, we believe these tradeoffs are worthwhile. Because of this pedagogy, ENGR 40M is a bit like an archeology tour: we travel through many areas in electrical engineering, and at each stop everyone gets off the bus and gets their hands dirty doing real work. As tourists, we don't have time to dig as deep as we'd like, and serious archeologists might be horrified at our superficial treatment of their work. But for the tourists, the experience provides something they'd never understand from a museum.

The following section describes the lab projects in more detail, followed by a discussion of the key structures that facilitate the rest of the course.

4 Lab sections

Each week's lab contains a prelab where students analyze or design the circuit for the lab, the "in-lab" time, and a postlab with further analysis and a metacognitive reflection. Students are required to submit their prelab 24 hours before their regularly scheduled lab section, which gives lab TAs time to provide feedback and ensure that all students are on track and ready to make progress when they come into the lab. In rare cases when students are wholly unprepared, we

			Topics	Assignments
Week 1	1	Monday	Course introduction; learning to look inside stuff; voltage and current	
	2	Wednesday	Describing device behavior with an I-V curve; resistors and Ohm's Law; solving circuits the “hard way”	
	3	Friday	Introduction to the solar USB charger; calculating where power goes in a circuit; ideal diodes	HW 1 released
			Lab 0: Soldering	
Week 2	4	Monday	Real diodes; solar panels	
	5	Wednesday	Some shortcuts for solving circuits (Series/parallel, voltage/current divider, Thevenin/Norton)	
	6	Friday	Another trick for solving circuits (superposition)	HW 1 due HW 2 released
			Lab 1: Solar charger	
Week 3	7	Monday	Introduction to the useless box; state machines and digital logic; using switches to express logic	
	8	Wednesday	Breadboards; MOS transistors	
	9	Friday	MOS transistors and CMOS digital logic	HW 2 due HW 3 released
			Lab 2a: Basic useless box	
Week 4	10	Monday	Introduction to Arduino programming; how your code interfaces with the “real world”	
	11	Wednesday	Doing math with logic; how we build computers out of transistors	
	12	Friday	Introduction to the LED cube; planning and debugging; suggestions for building your cube	HW 3 due
			Lab 2b: Computerized useless box	
Week 5	13	Monday	Midterm review	
		Wednesday	Midterm (Everything through the end of week 4, including the useless box lab)	
	14	Friday	Light and diodes revisited; controlling more LEDs than you have pins	HW 4 released
			Lab 3a: Building the LED cube	
Week 6	15	Monday	Capacitors and inductors; steady-state behavior; energy storage	
	16	Wednesday	Resistor-capacitor and resistor-inductor circuits	
	17	Friday	More on RC and RL circuits	HW 4 due HW 5 released
			Lab 3b: Wiring and programming the LED cube	
Week 7	18	Monday	Signals in the frequency domain; Fourier series	
	19	Wednesday	Capacitors and inductors in the frequency domain	
	20	Friday	Passive filters; gain; Bode plots; corner frequencies and falloff	HW 5 due HW 6 released
			Lab 3c: Making the LED cube awesome	
Week 8	21	Monday	The human electrical system; introduction to the ECG	
	22	Wednesday	Ideal op-amps; building amplifiers	
	23	Friday	Making filters with op-amps	HW 6 due HW 7 released
			Lab 4a: Building the ECG frontend	
Week 9	24	Monday	How the whole ECG system fits together; electrical isolation; digital filtering	
	25	Wednesday	Using capacitors and inductors for power conversion; buck converter	
	26	Friday	Boost converter; how your charger power converter works	HW 7 due HW 8 released
			Lab 4b: Completing the ECG	
Week 10	27	Monday	Review (sometimes cut out due to holidays or quarter schedule)	
	28	Wednesday	Review (sometimes cut out due to holidays or quarter schedule)	
	29	Friday	Review; next steps in electrical engineering	HW 8 due
			Final exam	

Figure 2: Typical schedule for the course. Stanford runs on a quarter system, with three 10-week quarters per year, plus an accelerated summer term. Note that the lab listed for each week runs Tuesday-Friday, concurrent with the lectures listed above it.

encourage them to seek help in office hours and attend a later lab section, rather than come in and waste their time trying to get up to speed.

The labs are graded both on completion (finishing the lab and getting reasonable results for any measurements) and on “style”. Since one of our goals for the course is that students learn good circuit construction and debugging techniques, we explicitly evaluate and give feedback on the quality of their construction in the same way that introductory programming classes grade the style of code in addition to its functionality. As with software, the style grade is not primarily aesthetic, although projects with high style grades do tend to look good. Instead, we are concerned with the clarity of the design (such as laying out components in an orderly way and color-coding wires), with quality of construction, and with ease of debugging. Circuits with clean solder joints and color-coded wires neatly trimmed to the right length are less likely to break and easier to debug. Because style grading could easily become highly subjective and vague, we have created rubrics describing the possible range of quality for each project. One example is shared in Appendix A.

Each postlab asks one or two “analysis” questions which challenge students to analyze or extend an idea from the project in a little more depth. Students also respond to three metacognitive prompts, which are intended to spur their own thinking and to provide the teaching staff with some feedback about where the students are still struggling. The questions are the same each week:

1. What was the most valuable thing you learned, and why?
2. What skills or concepts are you still struggling with? What will you do to learn or practice these concepts?
3. If this lab took longer than the regular 3-hour allotment, what part of the lab took you the most time? What could you do in the future to improve this?

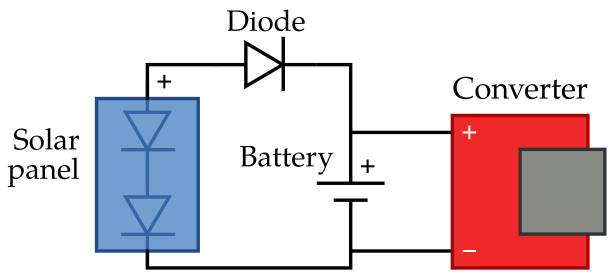
For the first couple years the course was offered we also asked, “What is something you wished you had known before you started the lab?” This initially provided a stream of suggestions for improving the lab handouts, but after a few iterations of the course the answers tended towards “I wish I had read the lab handout.” So far we have only used the responses to these results for individual feedback, but in the future we would like to do a more thorough analysis to examine students’ metacognition.

4.1 Soldering introduction

During the first week of class, we run an “introduction to soldering” lab, where students solder an AM/FM radio kit on a PCB. The kit [10] assumes zero prior experience with soldering and electronics, so students can complete it without any concepts from lecture. Our goal here is simple: to give students practice soldering and to build something tangible in a short period of time. TAs give feedback on soldering technique and quality, but the lab is only graded for completion, which gives students a chance to get practice and feedback before a “high-stakes” summative evaluation.

4.2 Lab project 1: Solar charger

The first full lab is to build a solar-powered cell phone charger using a solar panel, a LiPo battery, and a small DC-DC converter that takes 4.1 V from the battery and provides 5.0 V for the mobile device. Figure 3 shows the circuit diagram and a completed charger[1].



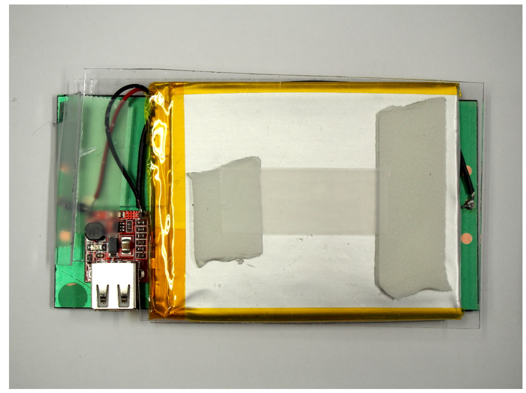


Figure 3: Solar charger project, week 2

We treat the DC-DC converter as a black box, and ask students to measure the power and efficiency as a function of the load by taking voltage and current measurements for a set of load resistances. While this gives students some experience calculating with voltage, current, resistance, and power, the real aim is for them to become comfortable using their multimeters to take measurements.

After taking the measurements, students design and build their solar charger. We provide pieces of polycarbonate plastic and tape to make a simple case for the electronics (especially the battery), but we also encourage students to build more polished cases with other materials. A handful of students have used 3D printers on campus to produce very elegant and robust designs.

4.3 Lab project 2: Useless box

The second project is to build a "useless box". The earliest such device that we are aware of is attributed to AI researcher Marvin Minsky [11], with a more recent incarnation popularized by the web retailer ThinkGeek [12]. In its simplest form, the box contains a toggle switch that when switched on causes a finger to extend out of the box and flip the switch back off. This behavior can be reproduced using a single motor and battery, a DPDT toggle switch, and an SPST limit switch, as shown in Figure 4.

In the first week of the lab, students construct a basic useless box, shown in Figure 4. We provide a snap-together set of laser-cut acrylic parts for the box, but students are responsible for designing

[1] The solar panel has a nominal power output of ~1 W at 8 V, which means the solar panel will charge the battery (albeit not at maximum efficiency) as long as it is exposed to light. The diode prevents discharge though the solar panel when light is not shining on it. The batteries we use have built-in overvoltage and undervoltage protection, which greatly simplifies the rest of the circuit.

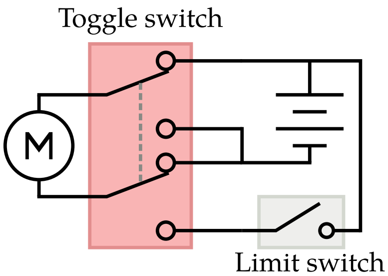
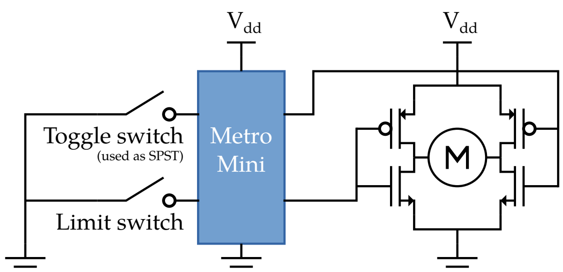


Figure 4: Useless box project part 1, week 3



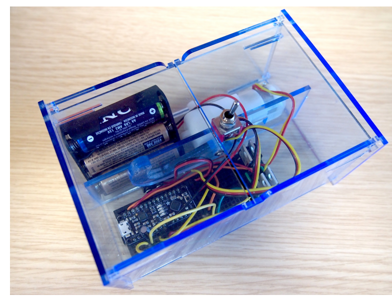


Figure 5: Useless box project part 2, week 4

the circuit, planning their wire layouts, soldering the circuit together, and assembling the box. This tends to require a certain amount of debugging, as students need to make sure the motor turns the correct way when the switch is flipped on, and that the limit switch disables the motor as the finger goes down rather than up.

In the second week, students upgrade their box to be computer-controlled using an Adafruit Metro Mini [13] (an Arduino-compatible board that can be plugged into a breadboard), as shown in Figure 5. This requires that they design and build an H-bridge with power MOSFETs to drive the motor, rewire the switches as inputs to the Metro Mini, and write software to control the motor based on the state of the switches. Once students are able to replicate the behavior of the original box, they are challenged to add "personality" to their box by writing software to make it appear hesitant, aggressive, impatient, timid, and so on. Most students make small modifications such as adding random delays before moving the finger, moving the motor more slowly with pulse width modulation, or pausing briefly after the finger pokes out of the box. A few eager students have gone farther and created multiple modes, added speakers to play sounds, added text LCDs to indicate personality, or built PC-side interactive "mood control" dashboards.

4.4 Lab project 3: LED cube

The third project is to build an "LED cube," a 4×4×4 matrix of LEDs which can be programmed to display fun patterns and respond to music, as shown in Figure 6. The key technical idea of the

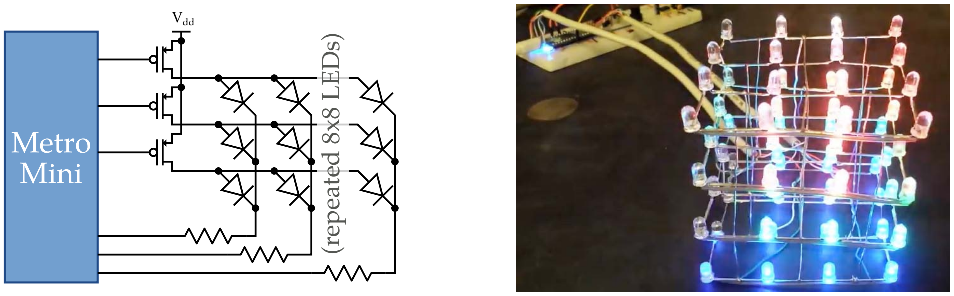


Figure 6: LED cube project, weeks 5-7

project is to control 64 LEDs with fewer than 20 I/O pins by using time multiplexing and the persistence of human vision, but the more important objective is for students to practice designing and building a circuit of modest complexity where they will have to debug mistakes.

The task for the first week of project is to solder the LED cube together. This is a relatively mindless and repetitive task, and we have debated whether the time spent on this exercise is worthwhile. However, the schedule places this lab during a week when many classes are holding midterm exams, so having a straightforward project with no prelab is a welcome relief to many students. As a compromise, we allow students to build a 6×6 plane, which takes roughly half the time to construct and less than half as long to program as the cube. Given the choice, a majority of students still choose to build a cube.

In the second week of the project, students wire their cube to a breadboard, add the resistors and transistors necessary to connect it to their Metro Mini, and write software to make the cube display arbitrary patterns represented by a 3-dimensional matrix in their Arduino code.

For the third week, we give students an open-ended challenge to "do something interesting" with their cubes. This presents a conflict between our optimistic desire to see every student launch off in their own direction and the practical realities that we must evaluate roughly a hundred projects in a fair way, and that many students would much prefer to follow a step-by-step lab to earn their grade. Over several iterations of the class, we have evolved a set of guidelines to quantify "interesting" and a rubric to help maintain fairness across projects of varying complexity. We also provide several lab outlines with varying levels of structure, which give students some ideas to start with and which provide a step-by-step path for students who simply want a clear minimum standard to meet. This solution remains imperfect, but has worked as a reasonable compromise.

4.5 Lab project 4: Electrocardiograph (ECG)

In the final project, students use what they have learned from class about filters and amplifiers to build the electrocardiograph (ECG) circuit shown in Figure 7 and measure their heartbeat. An example breadboard and heartbeat capture are shown in Figure 8.

The goal of the lab is for students to learn how to use the function generator and oscilloscope, and to construct and debug another moderately complex circuit. Unlike the LED cube, which is

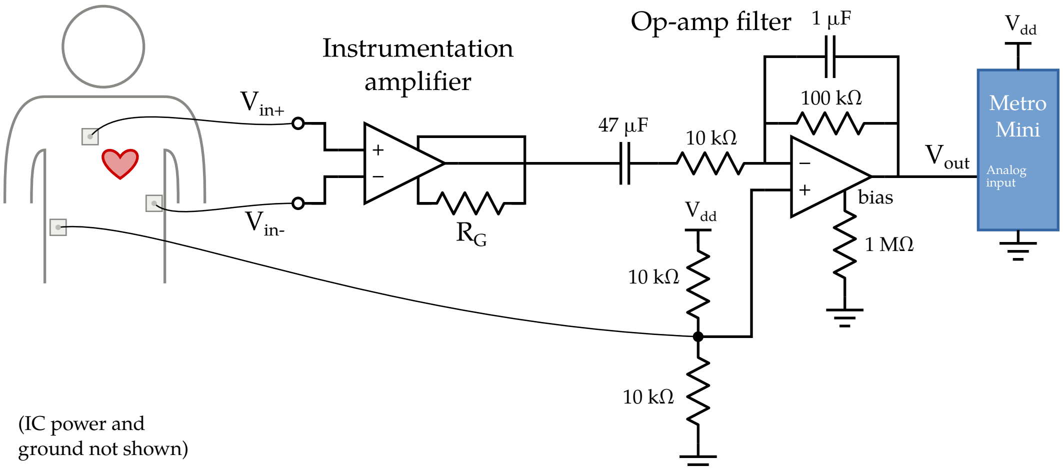


Figure 7: Schematic for electrocardiograph project, weeks 8-9

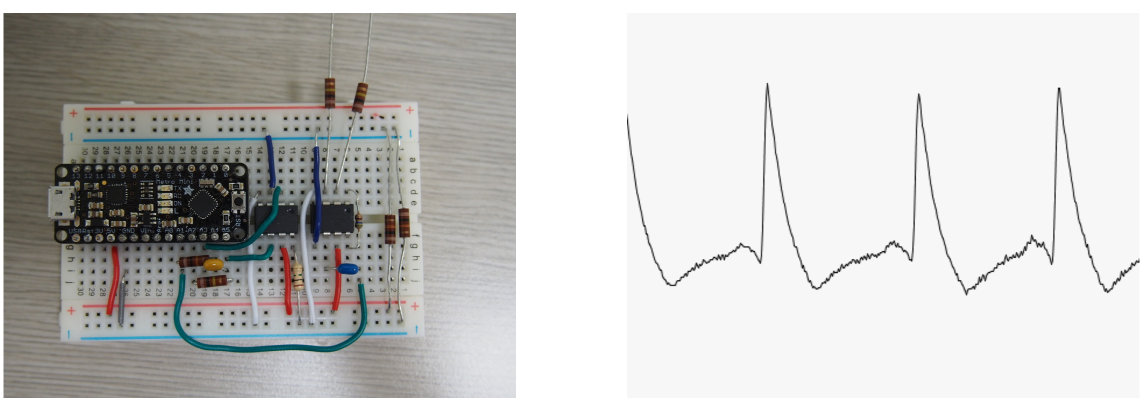


Figure 8: Electrocardiograph project, weeks 8-9

complex because it has many components in parallel, the ECG circuit is complex because it has several components in series, and failure at any point may result in distorted or missing output. Part of our intent is to help students develop a rational debugging process, so we discuss this in class and train TAs to help students think through the debugging process.

Needless to say, safety is paramount in any project that involves connecting a circuit to the human body. We discuss this extensively in class, and use three layers of isolation on the project itself. First, the circuit is isolated from the student with large ($> 100\,\mathrm{k}\Omega$) resistors. Second, rather than using an oscilloscope (which is plugged into the wall) for display, we use a laptop computer running on its battery. And third, the circuit is powered by a 5 V source (such as the solar charger) and connected via an isolation chip to the laptop.

The first week of the lab is spent building the circuit and testing it with sine waves of varying frequencies. During the second week, students connect their circuit to an analog input of the Metro Mini, and write code to sample the voltage and send the values across the virtual COM port to the laptop. We provide code (written in Processing) to plot these values on the laptop. Finally, students connect the isolation resistors and USB isolator cable, attach ECG pads to themselves, and record a snapshot of their heartbeat. This second lab is designed to be relatively short and easy, as it falls on week 9 of the quarter when the end-of-semester crunch reaches a crescendo. The shorter lab also serves as a buffer for students who are still finishing the first part of the circuit.

5 Other course structures

Not surprisingly, finding a textbook that matched our course content was a challenge. We experimented with a couple of textbooks and online resources before deciding to develop our own course reader. The current reader remains a work in progress, but is now sufficient to serve as official reference material alongside the lecture slides. It is available online at engr40m.stanford.edu/reader.html.

In order for students to be able to work on their projects outside of the lab, we give each student a lab kit containing a multimeter, two Metro Minis, breadboards, wires, and most of the circuit components necessary to build each of the projects. With the exception of soldering and using the oscilloscope, students have all the tools they need to work at home. Students pay a $100 course fee to offset the cost of their lab kit, which they keep at the conclusion of the course. The total cost of the components is slightly over $100 (especially if purchased individually) and there are there are no other course expenses such as a textbook, so we have not found this to be an undue burden for students. We replace broken, missing, or defective parts from our lab stock. This extra expense is modest[2], and easily covered by the regular lab budget. The full contents of the lab boxes are listed in appendix B.

Distributing lab kits also makes it easier for us to do in-class lab experiments. This is an area we are still exploring, but so far we have done a number of hands-on exercises during the regular

[2]Except for the year when we bought ultra-cheap Arduino clones and had a failure rate well over 50%. We moved to the Metro Mini the following quarter.

“lecture” period:

- Using multimeters to measure voltage, current, and resistance,
- Building boolean logic with switches on a breadboard,
- Measuring the on and off resistance of a transistor, and
- An introduction to programming the Metro Mini.

Due to the large enrollment, the class usually meets in a lecture hall with stadium-type seating and small fold-away desks. This makes in-class exercises a little inconvenient, but most are sufficiently simple and self-contained that they are not too troublesome. What is most hampered by the room layout is the freedom for the teaching staff to roam around and personally check in with each group.

We bring applications into lecture periods through a series of “breaking breaks”, where the lecturer disassembles an electronic device and discusses how the theoretical topics at hand are relevant in the real world. We introduced these partly as a way to partition the 80-minute class period and provide a brief mental break, and partly because we as teachers simply love taking things apart. But the breaking breaks also serve to show how the concepts students are learning apply to commercial products, grounding the abstract course topics in reality and providing essential motivation to keep going.

Breaking breaks are easy to replicate: all that is needed are some household items which use electricity (preferably broken or unwanted!) and a handful of tools. For equipment, we bring a USB webcam with autofocus and a $20 USB microscope for close-ups. Running a simple webcam viewer on our laptops enables us to quickly project the action for everyone to see. The key to implementing breaking breaks is to practice them prior to class. This ensures that the device really can be pulled apart quickly, minimizing the time in class spent removing one screw after another.

Some of our breaking breaks have included:

- A hair dryer, rice cooker, and hot water kettle,
- Cooking a hot dog with 120 V from a wall outlet,
- Tearing the packaging off diodes, capacitors, and inductors to show how they are constructed,
- Switches of various kinds,
- Keyboards and mice,
- The $5 multimeter that students receive in their lab kit,
- The filters used to remove DSL signals from phone lines,
- A laser printer and DLP projector, and
- Power supplies of all sizes.

As teachers, these are some of the most fun and delightful parts of the class. One quarter we had allocated the last day of class to reviewing for the final exam, but ended up spending thirty minutes on a breaking break, disassembling a projector and exploring its inner workings. One student reflected, “Wow, we didn’t review half the material we were going to, but that was *so cool*.”

Most recently, we have turned the breaking break over to the students themselves. Prior to discussing the multiplexing scheme for the LED cube, we gathered students in groups of 3 or 4, and gave each group a keyboard[3]. We asked each group to take their keyboard apart, figure out how it is able to read 100-odd switches with only a couple dozen wires, and write brief two page report on their findings. All of the groups figured out the essentials of the keyboard multiplexing scheme, and it formed the base for a lively discussion during the following class period.

The homework is designed to complement the labs, providing essential practice solving circuits on paper while requiring modest time and effort. Wherever possible we base the questions on real applications, including devices such as capacitive touchscreens, rectifiers for power supplies, and AM radios[4].

The more abstract homework questions are tailored to address particular misunderstandings or conceptual barriers, and we design the problems so that they emphasize circuit concepts rather than grinding through pages of algebra or calculus. Each problem set contains a 2-point reflection question that asks how long the assignment took, and what the most difficult problem or topic was. The average time to complete each assignment is around 2 hours, although some finish in as little as 45 minutes and a few may take five hours or more.

So far, we have retained a fairly conventional midterm and final exam, which together comprise 40% of the final grade. The questions are much like the homework and prelabs, which ask students to analyze various circuits, explain behavior, design a circuit for a particular function, or write a snippet of code.

6 Results

The enrollment statistics shown in Figure 9 indicate a significant shift in the demographics of students taking ENGR 40M relative to ENGR 40. Unlike ENGR 40, which was skewed toward older students, ENGR 40M quickly attracted a large number of underclassmen who would otherwise have pushed the course until their junior or senior year. These younger students are correspondingly less likely to have declared a major: 46% of ENGR 40M students are undeclared, compared to only 30% of those taking ENGR 40.

In course evaluations, students are almost universally positive about the labs, with the caveat that they are challenging and time-consuming. The most gratifying results are unstructured student comments about the course:

[3] The primary challenge here is acquiring 50 unwanted keyboards, which turns out to be quite easy if your computer science building is undergoing renovation for the first time in twenty years.

[4] We’ve also occasionally explored less familiar applications, including electric “worm getters” and electromagnetic pulse weapons.

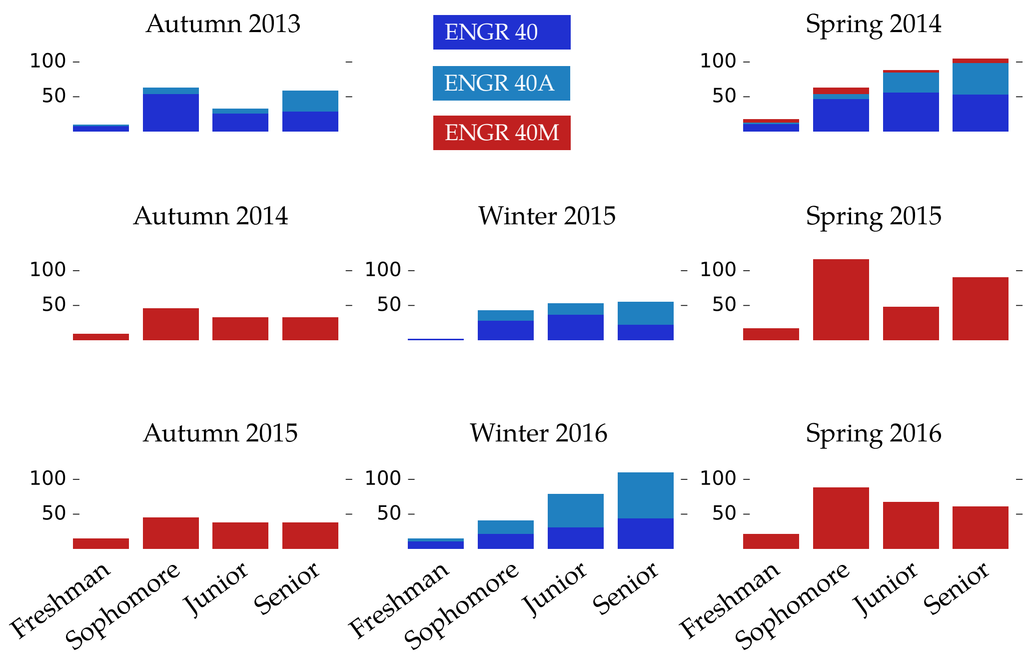


Figure 9: Total enrollment by quarter starting with the introduction of ENGR 40M. ENGR 40A is an abbreviated version of ENGR 40 that ends after the first seven weeks of class.

- “Didn’t want to take this class, but it was required. I actually enjoyed building things and I learned a lot of interesting info.”
- “I took it as one of two options for the CS major. It was surprisingly fun! I really enjoyed the labs.”
- “HUGE time commitment if you put in effort but SO much fun. Favorite class so far!”

Lastly, enrollment in the EE undergraduate program has nearly doubled since the introduction of ENGR 40M. While there are many factors for this, ENGR 40M was specifically cited by some students as a reason for choosing electrical engineering.

We still hear complaints, such as “This course is not relevant to computer science. It shouldn’t be a required course.” Moreover, as described earlier, older students are more likely to take ENGR 40 or ENGR 40A which is offered during winter quarters. The latter is an abbreviated version of ENGR 40, which is taken for three course units rather than five, and ends after the 7th week of class. The desire for a lighter workload is understandable, but this suggests there is still room to capture the interest of more students.

7 Lessons learned and future directions

To conclude, we offer a few lessons learned as advice to those who would like to implement similar methods. One of the best decisions we made was to beta-test the course with around 20 students in the spring of 2014, prior to launching it for the full enrollment of 100+ students the following autumn. During the beta quarter, we rearranged the syllabus for the second half of the course, added homework assignments, smoothed out major shortcomings in the lectures, and refined our list of lab materials. It was relatively easy to make these rapid corrections when labs were all on one day and the students knew they had opted into an experimental course; in a class of 250 such corrections would have caused widespread chaos.

A second key is to plan ahead for the labs. While low-cost overseas suppliers such as Banggood and DealsMachine offer great bargains on many of the components we need (such as LiPo batteries, solar panels, breadboards, and wire kits), items take several weeks to ship from China and clear customs. More than once, we found ourselves anxiously checking the status of a shipment of LiPo batteries or useless box parts, with labs scheduled to begin that afternoon. Likewise, the particular clear plastic bins we selected for the lab kits appeared to be commonly available at Walmart, but would go out of stock online for months at a time.

Like any course, ENGR 40M remains a work in progress, and there are multiple areas where we would like to do further work. One of these is in the way we explain particularly troublesome conceptual topics, several of which have emerged as we have iterated on the course. We experience the first conceptual hurdle when we introduce the passive sign convention and the directionality of voltage and current more generally. Students often do not grasp the purpose of sign conventions, and confuse the signs on all but the most trivial of problems. Later, a large fraction of students struggle with the idea that an open circuit can have a voltage across it, and often misapply Ohm's law to everything in a circuit ("There's no current there, so the voltage must be zero"). Similarly, students tend to think of a MOSFET as having an "output" controlled by an input, rather than thinking of it as a voltage-controlled switch. This manifests in several ways, notably in thinking that current must somehow flow from the gate through to the drain or source. While we have created some homework assignments and in-class exercises to address these, more direct and detailed research into these misconceptions and ways to approach them (such as those described by Skromme [14]) would be very valuable.

As mentioned earlier, we also plan to do more work on metacognition, particularly with respect to performance in lab. Most students who struggle with the labs — or struggle to complete them in a timely way — do not realize why they are having difficulty, and do not evaluate or adjust their approach as an expert would [1]. In addition to the postlab metacognitive questions, we have experimented with a mid-lab discussion, where students share a problem they solved or technique they figured out to make the lab easier. We have not rolled this out across the whole class, but would like to try this in the future.

Our success thus far with ENGR 40M demonstrates that it is possible to build meaningful (or at least fun) projects in an introductory circuits course. By structuring the course around these projects, we have been able to excite and motivate students studying other majors, some of whom thought they had no use for electrical engineering. And while the students who complete ENGR 40M are unlikely to immediately drop out and start a consumer electronics company, they do know enough to grab a microcontroller, wire up some sensors, and build something cool.

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A Example Lab style rubric

Your build quality grade for the ECG project is based on the quality of your breadboarding and testing setup. You should make use of the oscilloscope probe clip-tips and BNC minigrabbers, and avoid stringing together jumper wires and alligator clips.

Plus

- Testing set-up is stable and consistent
- Breadboard layout is clean and organized
- Set-up is very stable with all components fitting comfortably into the breadboard
- Wires are color-coded and easy to trace
- Wire lengths are about right
- All power supply points are cleanly connected

Check

- Testing set-up is mostly stable, although some components or cables could be connected better
- Breadboard layout is organized, but could have been improved with some more careful planning
- Wires are mostly color-coded, and can be traced with minimal difficulty
- Wires lengths are mostly right
- Most power supply points are cleanly connected

Minus

- Testing set-up is not very stable, and several components are sub-optimally placed
- Breadboard layout doesn't follow a consistent pattern
- Lack of color-coding makes wires difficult to trace
- Wires lengths are off and lead to spaghetti wiring, which may cause shorting
- Many power supply points are not very cleanly connected

B Lab kit contents

Item	Quantity	Specification/part number/source
Latch-top box	1	Sterilite 1713
Multimeter	1	
Breadboard wire kit	1	
Jumper wires	Bundle of 60	
Alligator clip wires	6	
LEDs	4	CREE 503B family
Various resistors		
Metro Mini	2	Adafruit
Micro-USB cable	2	
Solder	1 tube	
Solar panel	1	$\sim 1\,\mathrm{W}$
Lithium polymer battery	1	$\sim 2000\,\mathrm{mAh}$
5V USB converter board	1	Banggood #89326
Polycarbonate Sheet, 2.5”×4.5”	1	Cut from 1/32” sheets
Polycarbonate Sheet, 2.5”×3.5”	1	Cut from 1/32” sheets
DPDT toggle switch	1	EG2400-ND
Limit switch	1	ZMA00A150L04
Gear motor	1	Solarbotics GM3
3 AA battery holder	1	
AA Batteries	3	
Small breadboard	2	170 tie-points
P-channel MOSFET	2	NDP6020P
N-channel MOSFET	2	RFP12N10L
Large breadboard	1	830 tie-points
P-channel MOSFET	10	BS250P
Speaker	1	AR027150
Male-male audio cable	1	
3.5mm audio jack	1	
Medium breadboard	1	400 tie-points
Operational amplifier	1	LM4250C
Instrumentation amplifier	1	INA126P
Schottky diode	2	1N5819

Items provided in lab:

Useless box parts	1 set	Laser-cut acrylic or wood
#2 and #6 Plastite screws	2 each	McMaster
LEDs	64	CREE 503B family
ECG electrode pads	3	Amazon