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Introduction to Electrical Engineering: Empowering and Motivating Students through Laboratory-Focused Teaching

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Introduction to Electrical Engineering: Empowering and Motivating Students through Laboratory-Focused Teaching

Abstract

A new curriculum for Introduction to Electrical Engineering has been developed, with the goal of making it more of a hands-on, laboratory-focused approach. The stated goals are to empower each student to be a maker after taking the class, and to expose students to the broad topics of electrical engineering. To this end, nine new laboratory assignments were created, with each one building on the preceding ones. In class, the material is closely tied to the ongoing laboratory assignment. To assess the stated goals, four surveys were administered throughout the quarter. Each time, students were asked to evaluate their comfort with their electronics skills and knowledge, as well as how much understanding of electrical engineering they are gaining from the course. Additionally, the results of university-administered surveys that rank various aspects of the course were also included in the assessment. Overall, the findings support the fulfillment of the stated goals of creating makers out of students and showing the breadth of electrical engineering.

1 Introduction

We find ourselves in a very interesting point in history, where electronics and electrical engineering are ubiquitous to a fault. Every modern device, with exceedingly few exceptions, contains at least one, if not many, aspects of electrical engineering. Because of this, electrical education has proliferated greatly. At Northwestern University, many departments have their own version of an introduction to electrical engineering, with a focus on their own discipline. For example, mechanical engineering has a circuits course to prepare for mechatronics. Biomedical engineering has a circuits course and a signal processing course to prepare for biomedical devices. But while these courses may prepare students for usage of electrical engineering in their respective departments, they do not show a "grand picture" of electrical engineering that allows students to extrapolate upon their knowledge and become independent makers. And while it may be a sufficient goal in many cases for students to become independent makers, an added expectation of an introductory course to electrical engineering is to also stay true to the other goal of showing students all aspects of the very broad discipline that is electrical engineering.

This creates a very challenging task, as the course must simultaneously provide a very broad education in the classroom, while also creating engaging laboratory assignments to solidify these concepts. Not only that, but in the author's opinion it is much more valuable to have a single, long-lasting project than to have many disparate laboratory assignments throughout the term. This means that the laboratory assignments have to all be related to each other while reinforcing the plethora of topics taught in the classroom.

Even though the goals are twofold, the ultimate decision was to focus more heavily on the laboratory aspect. This is because in the author's opinion, intuition is built from tinkering more than from lecture. Of course, this is not a novel realization. Bales [1] describes a laboratory-first course whose main purpose is to get students excited about building circuits first and foremost, and to have the technical rigor filled in by higher level classes. Song and Dow [2] describe their efforts in introducing project-based learning to lower level electronics classes, in their case focusing on digital electronics. Sterian et al [3] describe their work in integrating projects into introductory electronics courses, focusing on analog electronics. Bell and Horowitz [4] describe their integration of projects into a non-major circuits course, dividing the laboratories into four projects. Indeed, Chen et al [5] reviewed 108 papers on implementing project-based learning across engineering.

The novelty in the proposed approach is the creation of as unified of a project as possible, in order to show students that even in an introductory course, they could gain enough knowledge to develop a very complex device using all aspects of electrical engineering. At the same time, the course does not compromise on the detail presented, making it a fully-fledged introduction to most aspects of electrical engineering. In summary, there were two goals:

- To empower students, as so many tasks in life can be handled with basic electrical knowledge.
  - Approach: create a multi-week laboratory project that engages all aspects of electrical engineering.
- To show students the many facets of electrical engineering so they can choose whether it is something they want to pursue further.

- Approach: create a curriculum that addresses most facets of electrical engineering while still tying to the underlying laboratory project.

The rest of the paper will show how these goals were accomplished. Sec 2 will present the structure of the laboratories and lectures. Sec 3 will present the results from surveys regarding this new class structure, as well as some discussion around the findings. And Sec 4 will summarize the findings and present next steps.

2 Class Design

At Northwestern University, this course is a mandatory course for electrical and computer engineering students, and optional for other engineering majors, many of which have their own versions as stated in Sec 1. Even so, for the past three offerings of the course, 55% of students have been electrical and computer engineering majors, and the rest from other departments. This made the stated goals even more pertinent, as so many students were from outside the department, in order to give them a skillset to take back to their own studies and to show them exactly what electrical engineering is and entails.

Since the main goal is to empower students, the focus was put heavily on laboratory work when designing the curriculum. In past versions of the course, laboratory assignments served to reinforce class concepts, but otherwise stood on their own. There was a laboratory assignment on operational amplifiers, on wireless power transfer, on feedback control, etc. In contrast, the goal of the new curriculum was to show students that they could build a complex system using only introductory tools. In order to do this, the laboratory assignments must build on each other, as will be detailed in Sec 2.1.

At the same time, the main learning of new concepts did not happen in laboratory, but rather in lecture. Therefore, the lectures had to be synchronized to the laboratory work, which made a very interesting order to the class topics, which will be seen in Sec 2.2.

Finally, in the same spirit of empowerment, traditional exams were eschewed. Instead, the class used take-home assessments in the form of “deep dives”, where students could pick among a set of topics and explore them at a deep level. More details about this will be presented in Sec 2.3.

2.1 Laboratory Work

As laboratory assignments are the focal point of the course, the goal was to make sure that students had ample time to perform them. To make them as accessible as possible, the following measures were taken.

- Take-home kits were created for the laboratory work, containing everything except soldering equipment.
- 24/7 access to the laboratory space was granted, which contained more hand tools and soldering equipment.
- A full week was given to complete each laboratory assignment.

- At least 20 staffed laboratory hours were provided each week (split between teaching assistants and peer mentors).

For each laboratory assignment, the desired outcome is first and foremost to create something. Therefore, less emphasis was placed on the laboratory report than on the building process. The laboratory report contained mostly photographs and brief explanations of the various steps in the project. Additionally, students were asked to reflect on the entire experience for each assignment, which allowed students to exercise some metacognition, and also gave the course staff an idea of where the main challenges lie. Finally, for each assignment, students showed either a recorded or a live demo of the working product.

An essential component of the laboratory assignments was the opportunity for students to both synthesize and analyze electronics. In most laboratory assignments that the author encountered as a student, the emphasis was heavily on analysis. Students were given a circuit, asked to build it, and then to analyze its properties. In the opinion of the author, this is insufficient. Therefore, in this class, students are asked to synthesize circuits as well as to analyze them. They are given the operating principles, but the actual circuit design is left open-ended. This is a necessity to allow students to extend their knowledge beyond the classroom setting.

2.1.1 Laboratory Assignment 1: Introduction

The first laboratory assignment is about learning the instrumentation that students will use throughout the term. This involves

- Using the Analog Discovery 2 [6], which is a compact all-in-one tool. Students learn to use it as
  - an oscilloscope,
  - a power supply,
  - a waveform generator,
  - a logic analyzer.
- Using a breadboard for both series and parallel connections,
- Using a soldering iron to solder proto board and printed circuit boards.

Even in this introductory laboratory assignment, students are asked to synthesize a simple circuit to turn on a couple of parallel LEDs. The goal is to get students thinking of circuit design, as opposed to simply analysis, as early as possible.

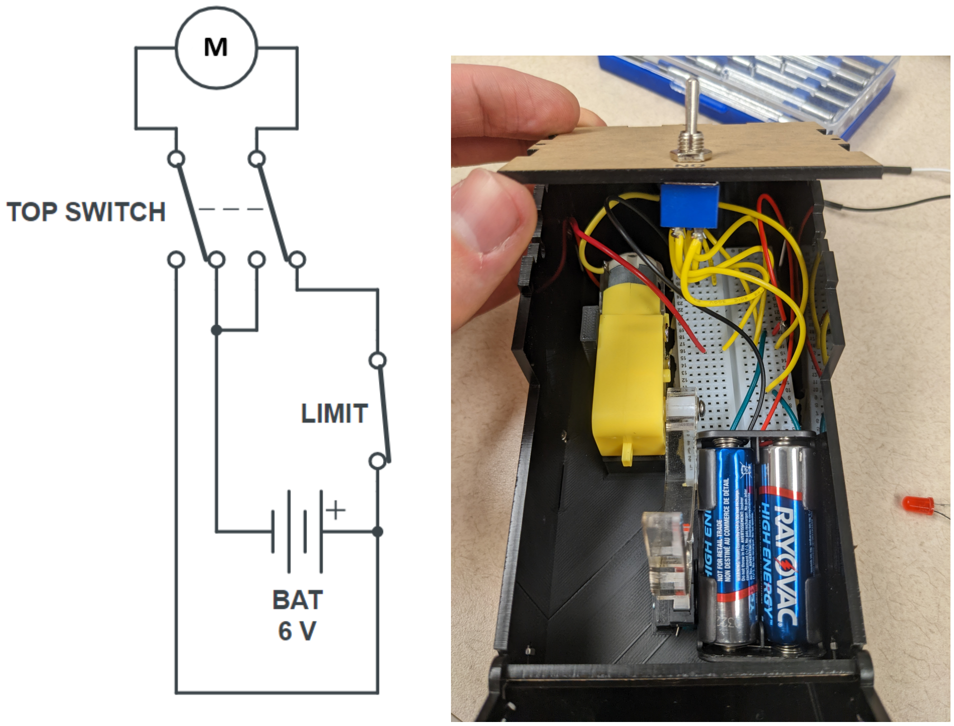
2.1.2 Laboratory Assignment 2: Useless box

The second laboratory assignment involves designing and building a "useless box", which was inspired by the work of Bell and Horowitz [4]. This is a device consisting of a box with a switch on top. When the switch is flipped, an arm comes out of the box and flips the switch back, after which it retracts back into the box.

Even though the name of the device is apt, the learning is anything but useless. This project requires no digital components, and is only made of switches and a motor. The reason this project is so great is that it really gets students to think critically of circuit synthesis and electricity flow.

Working through 4 stages, students learn about DPDT switches, limit switches, and ultimately synthesize the final circuit, shown in Fig. 1(a).

Then, students use a provided kit to house all of their components, which they solder and connect by hand. With a little finagling, everything fits into the box and they have a final product, the insides of which are shown in Fig. 1(b).



(a) (b)

Figure 1: (a) Schematic of useless box, (b) physical implementation of useless box.

2.1.3 Laboratory Assignment 3: 3 × 3 LED matrix

The third laboratory project involves building a manually-controlled, 3 × 3 LED matrix. This is the start of the extended project for the term. In this assignment, students learn about persistence of vision, how large LED matrix displays work, how to use shift registers, and how to use n-type and p-type transistors. Given some scaffolding, students ultimately synthesize the circuit shown in Fig. 2.

For this assignment, the shift registers are controlled by pushbuttons, so students get to see exactly how such devices work before they relegate their control to microcontrollers. As a culmination of the assignment, students are asked to create a specific pattern of lights on the LED matrix.

2.1.4 Laboratory Assignment 4: Smart useless box

The fourth laboratory assignment involves modifying the useless box built in Laboratory Assignment 2 (Sec 2.1.2) to give it some personality. This, like Laboratory Assignment 2, was also inspired by Bell and Horowitz [4]. This modification involves replacing the purely analog

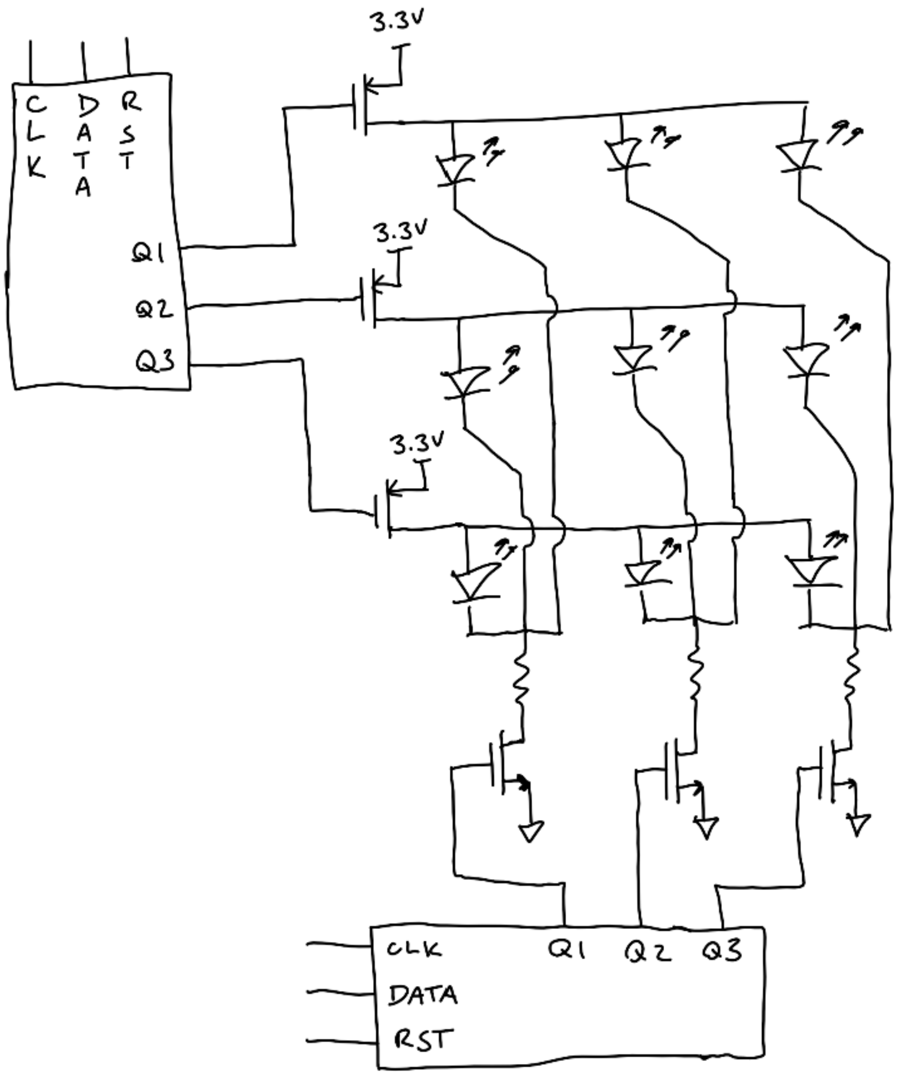


Figure 2: Schematic of 3 × 3 LED matrix. The shift register inputs can be controlled either by buttons or a microcontroller.

circuitry in the original useless box with a microcontroller and using the switches as inputs to it. Students again have to think about electricity flow and circuit synthesis as the wiring of the switches changes significantly. Additionally, since the motor is no longer being controlled directly from the power rails but rather from the microcontroller, students have to implement an H-bridge from discrete transistors.

After all of the wiring is complete, students program their microcontrollers to sense the switches and react accordingly. The "personality" that students program can be anything, such as making the arm more lazy by slowing it down using PWM.

2.1.5 Laboratory Assignment 5: Microcontroller-controlled LED matrix

The fifth laboratory assignment involves modifying the LED matrix built in Laboratory Assignment 3 (Sec 2.1.3) to control it from a microcontroller instead of using pushbuttons. The reset, data, and clock lines of each shift register are connected to a microcontroller, and students program the microcontroller to replace the pushbuttons.

The final goal is again to display a given pattern, but this time using persistence of vision. Students start by scrolling through the rows of the LED matrix slowly, and speed it up until the transitions are no longer visible.

In the process, students learn more extensively about programming embedded systems, and specifically about using hardware timer peripherals. Students write most of the code independently, provided light scaffolding.

2.1.6 Laboratory Assignment 6: Audio spectrum visualizer part 1 - prep

The sixth laboratory assignment involves creating a filter bank for audio input. This is in preparation for displaying an audio spectrum visualization using a larger version of the LED matrix built in Laboratory Assignment 5 (Sec 2.1.5).

In the assignment, students build a filter bank of four passive RC bandpass filters. They first test the filters by inputting a signal created by the waveform generator, and then substitute in an analog microphone. Students view the inputs and outputs on an oscilloscope to fine-tune their designs.

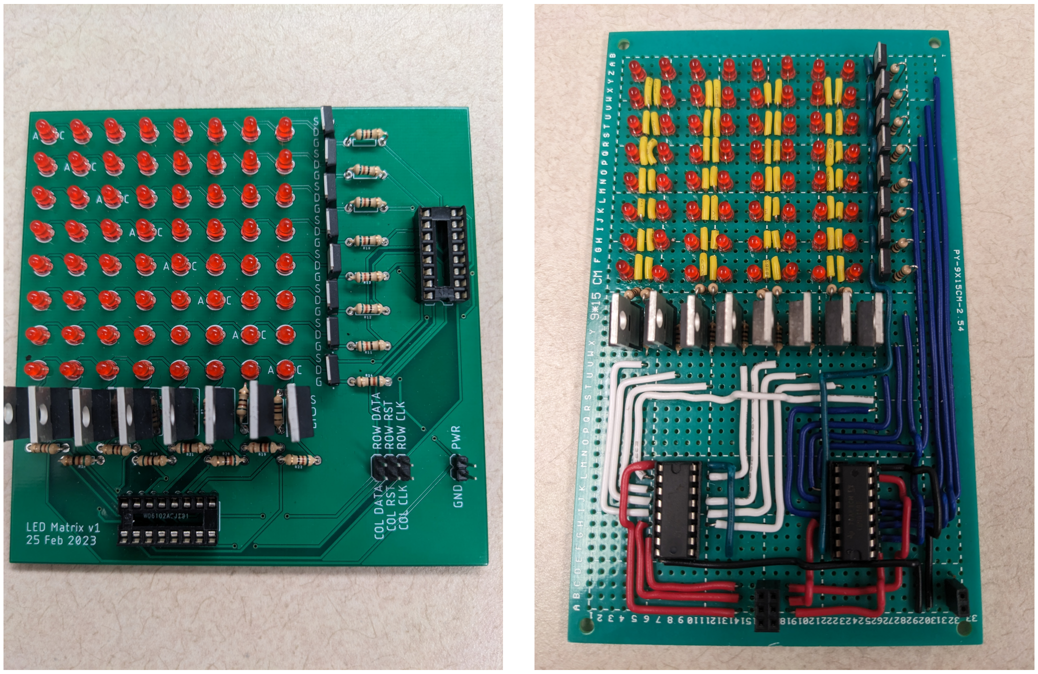
2.1.7 Laboratory Assignment 7: Audio spectrum visualizer part 2 - analog

The seventh laboratory assignment involves creating a fully functional audio spectrum visualization. This is one of the most involved projects of the term and consists of two parts.

First, students construct an 8×8 LED matrix. This uses all of the same principles from Laboratory Assignment 5 (Sec 2.1.5), and shows students how their knowledge can theoretically be scaled to any size LED matrix, or even to more sophisticated technologies like LCD monitors and OLED displays. For the construction, they have two choices: use a PCB, or use a proto board. The PCB option, an example of which is shown in Fig. 3(a), is the easier option, but is still quite soldering-intensive. The proto board option, an example of which is shown in Fig. 3(b), is a much harder option but also comes with some extra credit. A couple of enterprising students attempt this every term.

After the LED matrix is constructed, students modify their code from Laboratory Assignment 5 (Sec 2.1.5) to account for the fact that there are now 8 LEDs in each column and row instead of 3. This can be a trivial affair for some students, but others quickly learn that writing scalable code is important. At this point, they can display arbitrary patterns on the LED matrix.

Finally, students connect their circuits from Laboratory Assignment 6 (Sec 2.1.6) to gather the audio data in four discrete frequency bins. They implement a moving average filter in their code to smooth out the data, and plot the magnitude of each frequency bin as the height of each bar on the LED matrix. Since there are four frequency bins and eight columns, each frequency bin is



(a) (b)

Figure 3: (a) PCB version of 8 × 8 LED matrix, (b) proto board version of 8 × 8 LED matrix.

plotted on two columns (mostly because the author felt bad asking students to build eight RC filters).

2.1.8 Laboratory Assignment 8: Audio spectrum visualizer part 3 - digital

The eighth laboratory assignment involves creating the same audio spectrum visualization, but instead using professional tools. Instead of the hand-made LED matrix, students are given a professional 64 × 32 RGB LED matrix. Instead of an analog microphone and our microcontroller's 12-bit ADC, students are given an I2S 24-bit MEMS microphone. And instead of using discrete RC filters, the students use FFT-based filtering implemented on the microcontroller.

This assignment is an easier one than Laboratory Assignment 7 (Sec 2.1.7), and is more of an avenue to learn about how the work they have performed this term translates to the professional world. Students get to appreciate how even though these tools are much better, they are really no different than what they created by hand. Upon careful inspection of the LED matrix, they realize that it is nothing more than just very tiny LEDs and lots and lots of shift registers. And the FFT is implemented for them, so all they have to decide are the cutoff frequencies for the bins. Upon inspection, they realize that this is really no different than picking values of resistors and capacitors for RC filters.

When everything is wired and programmed, students get a visualization like in Fig. 4. They then spend some time customizing it and testing it with various songs until they get a display that makes them happy.

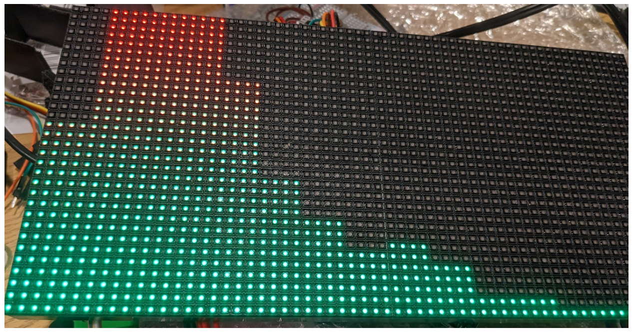


Figure 4: 64 $\times$ 32 LED matrix showing demo of audio spectrum visualization.

2.1.9 Laboratory Assignment 9: Embedded machine learning

The ninth laboratory assignment involves embedded machine learning. Depending on the pace of the class, the class sometimes gets to this project and other times it does not. The goal of the project is to create a keyword spotting algorithm, where students train a custom keyword.

To facilitate this assignment, students use a service called Edge Impulse [7], which is an online tool to create embedded machine learning models. They go through a workflow to train a model to respond to their keyword, and the tool exports a library that can be included in the microcontroller code. Then, new data is acquired using the same microphone as in Laboratory Assignment 8 (Sec 2.1.8), and processed using this model. If the keyword is spotted, the LED matrix from Laboratory Assignment 8 displays a custom message.

2.2 Lectures

In order to support the laboratory assignments, lectures had to be presented in a non-traditional order. At first it seemed that this order would seem unnatural, but it actually worked much better than initially feared. Following the content of the laboratory assignments allowed for strong continuity even with disjoint topics. This is the order that was used:

1. Circuit theory
    - Ohm's Law
    - Kirchhoff's voltage and current laws
    - Electronic network simplification (i.e. series and parallel)
    - Capacitors and inductors (in the time domain)
2. Semiconductors
    - Intrinsic and extrinsic semiconductors
    - PN junctions
    - Diodes and LEDs
    - Bipolar junction transistors
    - Metal oxide semiconductor field effect transistors
3. Microcontrollers
    - Generic programming in C
    - Embedded-specific programming (e.g. interrupts, timers, PWM)
4. AC circuit analysis

- Phasor analysis
- Impedance
- RLC filters
- Transfer functions

5. Signal processing
   - Fourier series and transform
   - Sampling and aliasing
   - Signal reconstruction
6. Operational amplifiers
   - Ideal op-amps
   - Op-amp circuits (e.g. amplifier, buffer, summer, integrator)
   - Non-ideal effects (e.g. gain-bandwidth product, slew rate)
7. Machine learning
   - Linear regression
   - Logistic regression
   - Gradient descent
   - Neural networks and backpropagation
   - Reinforcement learning
8. Signal compression (extra topic, if time)

Learning about circuit theory at the start is very important, as it lends to comprehension of every circuit that was synthesized and analyzed in the laboratory. This becomes very evident in Laboratory Assignment 2 (Sec 2.1.2) as students have to think critically about voltages and currents throughout their useless box circuits. Circuit analysis is also on full display in Laboratory Assignment 3 (Sec 2.1.3) as students come up with an architecture for a 3×3 LED matrix. Of course, the knowledge from circuit theory pervades every laboratory project from thereon out.

Learning about semiconductors second allows the class to dive quickly into Laboratory Assignments 3 (Sec 2.1.3) and 4 (Sec 2.1.4). In Laboratory Assignment 3, it is of course nice to know how the LEDs that the students are using actually work, but the main purpose of semiconductor theory is to learn to use MOSFETs. Laboratory Assignment 3 uses both p-type and n-type MOSFETs, so it is critical that students understand how to control them and when to use each type. Likewise, in Laboratory Assignment 4, students build a discrete H-bridge, where again knowledge of n- and p-type MOSFETs is paramount.

Following semiconductors with microcontrollers is necessary to allow for Laboratory Assignments 4 (Sec 2.1.4) and 5 (Sec 2.1.5). In Laboratory Assignment 4, the useless box is controlled entirely with a microcontroller. In this case, the coding is rather light, so it is a good introduction to coding a practical application. In Laboratory Assignment 5, the LED matrix from Laboratory Assignment 3 is automated using a microcontroller, and here the coding gets more intense.

After microcontrollers, the class gets back into circuits with AC analysis. This allows the lectures to establish the theory for Laboratory Assignments 6 (Sec 2.1.6) and 7 (Sec 2.1.7), where students build and utilize an RC bandpass filter bank to create an audio spectrum visualization. This also allows students to start thinking about the frequency domain in general, which informs the following section on signal processing.

Then, the class learns about signal processing in order to facilitate Laboratory Assignment 8 (Sec 2.1.8), where students create a digital audio spectrum visualization. In the assignment, students must understand the limitations of sampling audio at a particular frequency, as well as how the frequency domain looks for the sampled signal. Additionally, signal processing theory adds comprehension to Laboratory Assignments 5, 6, and 7. One of the most interesting discussions comes every term when students are shown the LED matrix through a camera. The refresh rate is tuned just right to create a strong aliasing effect. This usually leads to a lot of confused looks, as the LED matrix is shown operating as expected without the camera and very strangely with. Through sufficient discussion, students reason through what is happening and gain a deeper insight into both circuitry and signal processing.

Following signal processing, the class learns about operational amplifiers. Though this topic does not directly support a laboratory assignment, it fits in the curriculum here nicely as it leverages everything that has been covered in circuit theory and AC circuit analysis. Originally, there actually was a laboratory assignment that this would be paired with, where students create an electrocardiogram monitor, but it was ultimately not used for the sake of time. The decision was made to keep the lecture topic, though, as it shows a very useful application of circuit theory. If the academic terms at Northwestern University were longer than 10 weeks, the class would definitely run the proposed assignment. If other institutions have longer terms, the author highly recommends using this assignment, as students have a lot of fun with it. Even though the complete assignment did not fit within the confines of the academic term, it was rolled into one of the course's deep dives, presented in Sec 2.3.

As the last big topic, the class covers machine learning. This ties directly into Laboratory Assignment 9 (Sec 2.1.9), where students build a keyword spotting algorithm using their equipment from Laboratory Assignment 8. Even though there is only time for a few classes, lectures get to a very decent amount of depth, where students come away hungry to learn more.

Finally, time-permitting, the class covers some extra topics, such as signal compression or analog communications. There is no laboratory work pertaining to this, but there are options in one of the course's deep dives (Sec 2.3) using these extra topics.

2.3 Deep Dives

Instead of traditional exams, the class uses a different approach. To go along with the stated goal of empowerment, students explore topics of their choosing in much greater detail than can be done in class. In order to constrain the scope a little, a few choices were given for each deep dive. For example, here are the choices that were given for the second deep dive.

- Build an electrocardiogram monitor using discrete op-amps.
- Analyze and characterize the non-ideal properties of an op-amp.
- Write code to perform backpropagation on a simple neural network.
- Write a children's book on a class topic.
- Argue with ChatGPT [8] and find a fundamental misunderstanding in its response.

In addition to allowing students to explore interesting topics in greater detail, this method of assessment uses the Universal Design for Learning (UDL) [9] principle of "multiple means of expression". Since not everyone expresses their knowledge and interests best through a written examination, the deep dives provided different ways to express students' knowledge. The first option emphasizes circuit synthesis and hands-on work. The second option emphasizes more traditional analytical skills. The third option is similar to the first, but is better suited to those more comfortable with software than hardware. The fourth option is for students who want to use their creative sides to express their learning. And the fifth option is a mix of creativity and analysis.

Each time these options are offered, there is not a clear preference, which is exactly what is desired. The distribution is actually rather uniform. If clustering was observed, that would indicate that either one option was much easier than the others, or that the options are not representative of the multiple means of expression that were intended. However, the uniform distribution shows that students do in fact gravitate toward a given mode of expression, and once they choose it, they come up with great work.

As part of the assessment, students are asked how long they spent on their work. The typical times are around 6 hours. When pressed further, students often say that they spent that long because they were interested in the work. Each term, after the first deep dive, the class is polled to see if they prefer this form of assessment or a traditional paper exam for their second assessment. Each time, the results have been identical: around 95% of students prefer this, even though a traditional exam would take exactly one hour. This shows that students really enjoy the freedom and flexibility of such assessments, even though they are a greater time commitment.

3 Results and Discussion

To evaluate the efficacy of the new curriculum, data was gathered in two modalities: four surveys throughout the course of the academic term (administered by the course instructor), discussed in Sec 3.1, and post-term course evaluations (administered by the university), discussed in Sec 3.2. Both forms of assessment were anonymized.

In addition to the results of the surveys, it is also important to discuss how the course helped students achieve the desired ABET outcomes for such a course. This discussion is in Sec 3.3.

3.1 Surveys

In the surveys that the course instructor administered, the focus was on measurable metrics that students could think about throughout the term. As is unfortunately the case with most such research, these questions were not asked in the old version of the class, nor are these questions asked in other universities to the author's knowledge. However, even as standalone metrics, there are interesting observations and conclusions to draw.

3.1.1 Confidence in electrical skills

In all four surveys, students were asked how they felt about their electrical skills. The phrasing was kept broad intentionally to avoid bias, such as focusing only on circuitry or signal processing. The results, which can be seen in Fig 5, are very heartening.

In Fig 5(a), there is a clear push toward confidence. The fact that very few students ranked themselves as "very confident" is very positive, as it shows that students have learned enough to understand just how much they do not yet know. Additionally, seeing that fewer than 3% of students still find themselves "unconfident" after the course is a great outcome.

In Fig 5(b), it is clear that students are gaining confidence through their work in the course. This is consistent with the findings in Fig 5(a). Additionally, seeing that fewer than 1% of students felt less confident throughout the term is a great outcome. Furthermore, greater than 97% of students felt that their electrical skills improved as a result of the course.

3.1.2 Interest in electrical engineering

In the first and last surveys, students were asked about their level of interest in electrical engineering. This was separated into two questions, to gauge interest in the topic and in the major individually. The results can be seen in Fig 6.

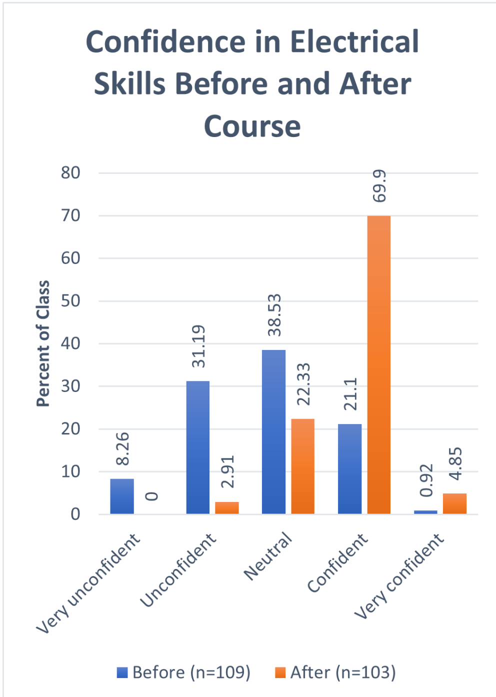
In Fig 6(a), it can be seen that the course is polarizing. The Neutral and High categories dropped, while the Very Low, Low, and Very High categories increased. This is the desired outcome, as it shows that students are getting a good understanding of what electrical engineering entails. And of course, it is not for everyone. This fulfills the goal of the course to show students what the various facets of electrical engineering are.

In Fig 6(b), it can be seen that students' perception of the major increased after learning what electrical engineering is all about. This may be due to a misunderstanding of what electrical engineering is by those who are not familiar with it. Once students understand what can be done using electrical engineering, the interest in the major naturally increases.

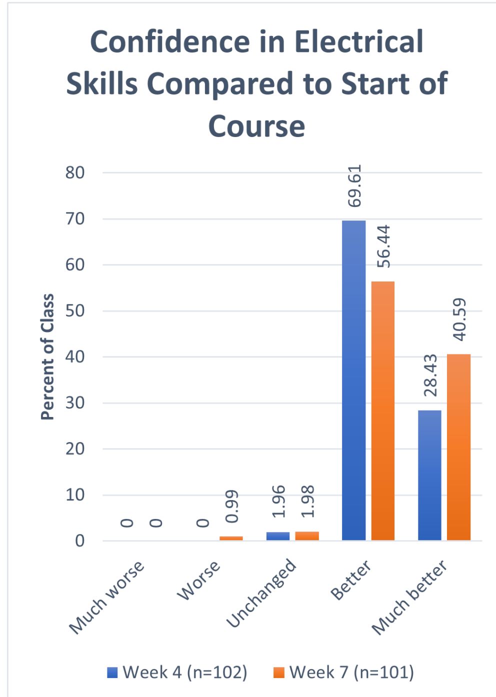
However, it should be noted that the movements in Fig 6 are very small. This is not surprising as 96.6% of students went into the course with a declared major. It would be unreasonable to expect one course to change students' minds significantly.

3.1.3 Learning throughout the course

In the second and third surveys, students were asked if they were learning what they hoped to in this course so far. The results can be seen in Fig 7. This goes hand in hand with Sec 3.1.2, as it once again reinforces the idea that students do not really understand what electrical engineering entails prior to taking such a course. This result also joins nicely with Sec 3.1.1, as it shows that the amount learned in the class correlates strongly with the confidence that students gain in their electrical skills.

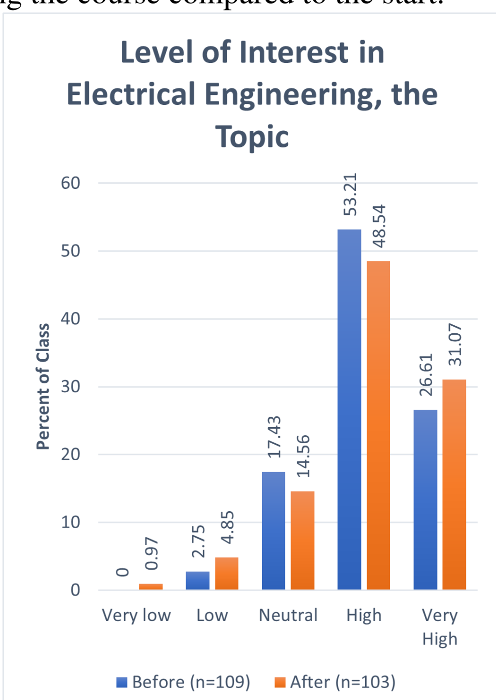


(a)

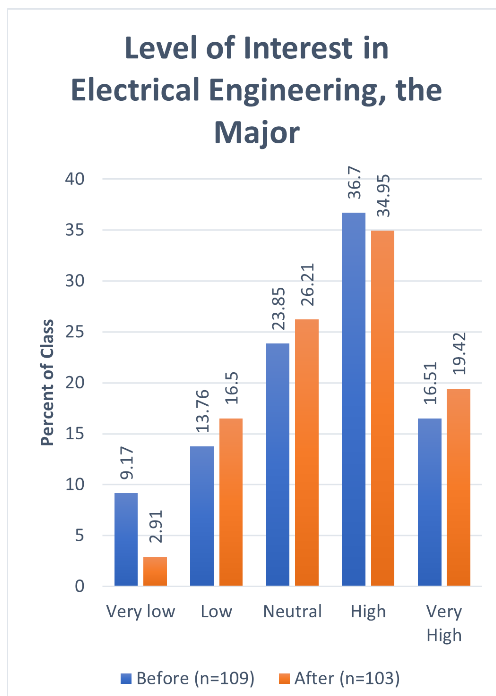


(b)

Figure 5: Survey results about confidence in electrical skills (a) before and after the course, and (b) during the course compared to the start.



(a)



(b)

Figure 6: Survey results about level of interest in electrical engineering, specifically (a) the topic, and (b) the major.

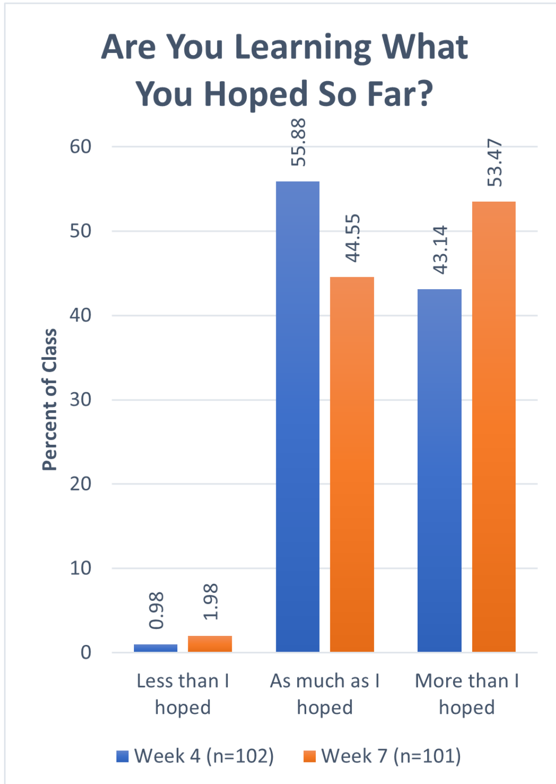


Figure 7: Survey results about whether students are learning what they hoped at two points in the course.

3.1.4 Post-course thoughts

In the last survey of the course, students were asked to reflect on some of their specific learnings. The results of this survey can be seen in Fig 8. These results fit perfectly with the stated goals in the Introduction (Sec 1).

Fig 8(a) shows that students are empowered to pursue their own projects. An aspect that stands out is that very few students felt confident in their skills before the course started. This shows that students truly did gain these skills as a result of taking the class.

Figs 8(b) and 8(c) show that students have indeed gained an appreciation for what electrical engineering is, both in the classroom and in the broader context of general impact. This goes nicely with Secs 3.1.2 and 3.1.3 as it shows that there is true learning happening that allows the students to grow throughout the course. It is fascinating that zero students indicated that they understood what electrical engineering was prior to the course. Just this finding alone is evidence enough for why such classes are so greatly important.

3.2 Course evaluations

University-administered course evaluations contain both numerical and qualitative responses. For both of these, the focus will be on recent offerings of the course, comparing the three times that the new course has been run versus the ten offerings before that, going back to 2018. The

(a) (b) (c)

Figure 8: Survey results regarding reflections on the course after its conclusion.

Table 1: Anonymous course evaluation results.

Prompt	Fall 2018 - Spring 2022 10 offerings	Fall 2022 - Fall 2023 3 offerings
Provide an overall rating of the course	4.9	5.2
Estimate how much you learned in the course	5.2	5.5
Rate the effectiveness of the course in challenging you intellectually	5.2	5.6

numerical ratings are on a scale of 1 to 6, where 1 is the lowest score and 6 is the highest. The results can be seen in Table 1.

Even though there is not much data yet, the course evaluations seem to suggest that although the course has become more challenging, it is also more enjoyable and a better learning experience. This shows that students are happy to put in the effort if they feel they are getting something out of it. And combined with the results in Sec 3.1, this provides even more confidence that the initial two goals are getting fulfilled.

The unstructured responses in the course evaluations told a similar story. The most prevalent comment was that the laboratory work take a significant amount of time, but that the time commitment is worth the investment because students learn so much. It should be mentioned that this was not always stated in the most positive light, as it was the top compliment and complaint. Also prevalent was the comment that the laboratory assignments directly reinforced the classroom concepts, which is very encouraging because of the unconventional teaching order that was followed to make this happen.

3.3 ABET Outcomes

ABET provides guidelines [10] for desired student outcomes in engineering courses, summarized as seven criteria. This course allows students to demonstrate proficiency in three of these.

Outcome 1 is an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics. This is demonstrated both in homework assignments and in the laboratory. On homework assignments, students must use their new knowledge to identify the method to solve the question at hand. In the laboratory, students must understand the necessary approach to build the system described.

Outcome 5 is an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives. While the teams are not large, students do work in pairs on each laboratory assignment. This creates an opportunity for group dynamics to evolve, with some students taking a natural lead and each group member collaborating in order to complete the tasks.

Outcome 6 is an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions. This outcome is the most applicable to a laboratory-first educational setting. From the very first laboratory assignment, students are conducting experiments and analyzing the results. Since the goal of the projects is to build a complex system throughout the academic term, there is no “right answer” for any given experiment. Therefore, students must become proficient in interpreting their own results and using their judgment to draw conclusions. This is even further emphasized in the deep dives that students undertake during the term. Especially in the “analysis” and ”synthesis” options, there are no right answers and everyone’s work leads to unique results. This tests students’ abilities to use all aspects of this ABET outcome.

Altogether, the results seen in Sec 3.1 and Sec 3.2 demonstrate the ability of students to attain the ABET outcomes, especially outcome 6. As students’ skills increase throughout the term, they become better and better at identifying and solving complex engineering problems by setting up appropriate experiments and analyzing the results. This empowerment allows students to gain a skill they can continue their education with and take directly into the industry or further studies.

4 Conclusion

After working through the course laboratory assignments, students end up building a fully functional audio spectrum visualizer, with a keyword spotting device as an extension thereof. Along the learning journey, they also create a smart “useless box”. These are no small feats for an introductory class. Indeed, these are very time consuming, and a fear as this course started running was that students would give up because of the difficulty of the laboratory projects. Instead, the complete opposite proved to be true. Even though the difficulty of the course increased in all metrics, students have been happier with their work and learning. This means that students must be becoming intrinsically motivated, since pure extrinsic motivation would lead to an inverse relationship between time spent and course satisfaction [11]. This fits very nicely with the findings in Sec 3.1, as students gain electrical skills and realize the impact that learning these skills can have in their careers and on the world.

One reason that seems responsible for this development is the complexity of and emphasis on the laboratory work. Students seem to take ownership of their projects, and are genuinely proud of the results they achieve. This shift from "do a laboratory assignment and characterize some aspects of electrical engineering" to "build a real-world, complex device" makes students realize that they are capable of much more than a traditional course in electrical engineering would have them believe. And this makes all the difference. Anecdotally, the author has seen students who are barely able to wire a simple circuit in Laboratory Assignment 1, undertaking (and even enjoying) the construction of Laboratory Assignment 8. The transformation, both in terms of abilities and attitude, is tangible.

This alone, however, fulfills only half of the stated goals. The other half, besides empowering students as makers, is to introduce the full spectrum of electrical engineering. The results of the deep dives (Sec 2.3) and surveys (Sec 3.1) show that the other goal is getting fulfilled. The diversity of work on the deep dives, in addition to the *voluntary* amount of time spent on them, show that students have had the opportunity to take in the full gamut of topics and are actively engaging with them. The polarization of interest in electrical engineering in the surveys also shows that students can more fully comprehend the topics that comprise electrical engineering.

Overall, it seems that the proposed class structure fulfills the goals of an introductory class in electrical engineering, while giving everyone involved the skills to be an independent maker. Whether or not a given student ends up pursuing electrical engineering, they will have gained a life skill and something to take to their chosen major. Additionally, for non-majors, having taken a class whose topics are as broad as this one allows them to go back to their own major with a deeper understanding of electrical systems that can inform their education in a way that a more narrowly focused class may not offer.

However, no course is ever perfect, and this one is no exception. In the future, the plan is to keep innovating the laboratory experience to keep introducing the most modern and useful tools. Additionally, the laboratory assignments will be modified as new technologies become prevalent. For example, the author is still thinking of how to better incorporate large language models into the course, beyond just the deep dives, in order to help students gain an even deeper understanding.

Additionally, due to the structure of the course, the course has no textbook. The author plans to address this shortcoming by writing a textbook as an open educational resource (OER) [12]. With an OER, two goals will be fulfilled. First, students will have access to supplemental course content free of charge, decreasing financial burdens. Second, the work can remain a living document, which will create less friction as the course is updated over the years.

Finally, to serve the stated course goals even better, the author wants to update the class model to one of ungrading [13, 14], specifically standards-based grading [15]. As the top goal is for students to fully engage with the laboratory work and to become independent makers, giving them multiple chances to make a functional product, along with formative feedback to push them toward mastery, makes a lot of sense. The current class structure is already amenable to this approach, so it will be the next experiment that is attempted.

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