A "Hands-On" Module to Introduce Freshmen to Electrical Engineering

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Abstract

Freshman engineering courses are being widely implemented so that students can make an informed decision about their major. Module-based approaches that trade depth for the sake of breadth are often used to present each of the varied disciplines separately. Electrical engineering, an abstract and mathematically intense discipline, is particularly challenging to distill into a few hours. This paper describes a four-hour electrical engineering module that examines the role of electrical engineering in the manipulation of audio signals, developed for a new introductory engineering course at the United States Naval Academy.

In the first hour, students were given a short presentation on biometrics (signals that can be used to identify a person) and participated in demonstrations of iris, face, and fingerprint recognition systems. They then completed a laboratory experiment in which they analyzed plots of speech (audio) signals, measured pitch frequencies, and identified male and female voices using that information. During the following hour, after a brief overview of A/D and D/A conversion, the students captured their own voices and viewed the quantized voice signals as oscilloscope images. They used a Matlab script to manipulate the sampling rate and quantization and to play back the modified signals, illustrating aurally the effects of changing these parameters.

The last two hours of the module were spent on a small electronics project involving a "light organ." This discrete circuit consists of a microphone, an amplifier, and a series of band pass filters tuned to different frequency ranges. The filters drive LEDs that flash with an audio signal. Circuit boards were prefabricated with all components except for the band pass filter resistors in place. The students engaged in the design process by first identifying the desired frequency ranges for their filters using function generators and speakers, and then choosing resistor values using an Excel spreadsheet programmed with the filter's design equations. Finally, the students soldered their resistors into place and tested their circuits.

Thus, within four hours, the students were exposed to digital systems, digital signal processing, electronics, frequency response and communications—all tied around the central and concrete theme of audio signals.

Introduction

The United States Naval Academy is unique in many ways. For one, we hire all of our graduates. While they may choose different areas of the service upon graduation, they are all Navy or

Marine Corps officers in a military that is as technologically complex as it ever has been. It is with this in mind that the Naval Academy has endeavored to become one of the best undergraduate engineering schools in the country. The facilities, the faculty, and the focus on undergraduate education are keys to the success of the institution. In addition, the Naval Academy is the primary source of engineering majors for the Navy and Marine Corps.

Our students enter the Naval Academy as undesignated majors. As such, all of them, no matter which major they may eventually choose, take an identical course load during their first year. This includes two semesters of calculus, two semesters of chemistry, and potentially advanced math or physics if they "test out" of the entry-level courses, a process we call validation. Until the late 1980s, the mechanical engineering department taught a course known as introduction to engineering. The course was primarily aimed at preparing students to understand the basic steam cycle and other naval engineering applications so they would be equipped to work in the engineering plant during their summer training. It was eliminated for many reasons and was never a traditional freshman engineering course. For the last 15 years, there has been no freshman engineering course and no exposure to engineering as a field of study or a discipline prior to the students declaring a major in the spring of their first year.

The Naval Academy has five engineering departments offering six majors. These are: Ocean Engineering, Naval Architecture, Aeronautical Engineering, Mechanical Engineering, Systems Engineering and Electrical Engineering. The five departments comprise about 40% of all majors at USNA, which are approximately 1200 students in the upper three classes. Electrical engineering is typically one of the smaller majors but all of the majors continually strive to increase enrollment from a fixed number of freshmen in a class.

Students go through the process of choosing a major in two phases; they make a preliminary choice of up to four majors in January followed by a final selection in March. The reason why this selection is more critical at the Naval Academy than at other schools is that there is little chance to change major at a later date because of the high professional course load and the requirement that students graduate in four years. The Naval Academy provides "fall back" majors for those students who decide to change but cannot meet the requirements of a new major. In engineering, this fall back is general engineering, a non-ABET accredited major.

Many reasons exist for offering a freshman engineering course, among these is to expose students to the engineering profession and to the many facets of its varied disciplines. These courses contain topics relating to the engineering design process, ethics, math, and critical thinking skills to introduce them to what will follow in the next three years in their chosen major [1]. Our problem is that our students do not declare majors until late in the freshman year, so we chose to offer an elective course with these elements to students that may have a proclivity for engineering.

The students we recruited to register for our experimental introduction to engineering course were those who had not validated any introductory courses but had scored high enough on the placement exams to warrant an advanced introductory calculus course. We chose to stay away from the high validators who are more likely to choose engineering anyway and go after the academic "middle" of our freshman class. Using these criteria, we decided on 60 students for the first iteration. The notification of approval to teach this course came late in the summer, so we had little time to put a two-hour, one credit class together by the beginning of the fall semester. Since working in an interdisciplinary fashion, while desirable, was not realistic in these time constraints, we broke the students up into groups of ten. Each of the six engineering majors was given two weeks with each group. This "module-based" approach did not allow for the development of a semester-long freshman electrical engineering course, such as those developed at other schools [2-5]. We therefore faced a challenge in distilling an abstract discipline into a short period of time. Our choice was to make the experience as hands-on as possible.

The hands-on approach used in this course was designed around the fact that all of our courses contain a laboratory. In addition, we make a concerted effort in almost every lab-based course to include some element of design. Finally, we wanted the course to be enjoyable and for the students to take something that they had made away from the course. It was with these principles in mind that we approached the design of the electrical engineering module.

Electrical engineering is a diverse subject. Our goal was to present several facets of the major with a unifying theme. We chose audio signal manipulation as this theme because audio signals are a tangible way to tie the abstract concepts of electrical signals to something with which the students already have familiarity. This approach uses the method of using signal processing as an introduction to electrical engineering as illustrated by the popular text *DSP First* [6]. We therefore divided our four-hour module up into three sub-modules. The sub-modules explore biometrics, A/D and D/A conversion, and the design and construction of a small electronics project called a "light organ."

Biometrics Sub-module

Students were first given a short presentation on the types of physical characteristics that are unique enough to use for identification, with an emphasis on iris recognition, face recognition, fingerprint recognition, and voice recognition. We played video clips from movies that use biometrics, including Minority Report, Boondock Saints, and Sneakers. In these movies, a biometric system is spoofed with a false biometric, such as a severed finger or eyeball. After showing the film clips, we then talked about current commercial biometric systems, and the safeguards designed into them that have "liveness" testing. For example, some fingerprint systems have the ability to look at changes in sweat pores in the finger, while some iris recognition systems look for changes in the pupil due to variations in the light around the iris collection system.

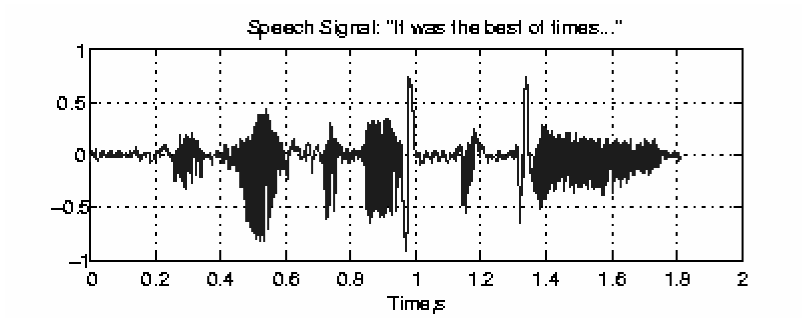

Figure 1: Speech sample signal

For a hands-on exercise, the students collected speech signals and plotted them using prewritten MATLAB software. An example speech signal is shown in Figure 1, and contains the utterance "It was the best of times..." We discussed the two main categories of speech - voiced and unvoiced. Voiced sounds are those in which the vocal cords are vibrating (the "e" sound in "the") and unvoiced sounds are those in which the vocal cords are not vibrating (the "th" sound in "the"). (Put your hand on your throat over the vocal cords and say "the" to see the difference.) We then discussed the fact that the frequency with which the vocal cords vibrate (also called the pitch frequency) is a biometric - but it is not a good one to use to identify someone because it is not easy to measure with enough accuracy. However, the pitch frequency can be used to generally distinguish male and female voices. Pitch frequencies range from 60 to 300 Hz (cycles per second), with male voices in the lower range and female voices in the upper range. After this discussion we then used MATLAB to isolate a word from our speech signal, such as the word "best" shown in Figure 2. We then selected a piece of the voiced sound (such as the "e" in "best"), and plotted it as shown in Figure 3. Using the plot in Figure 3, we then measured the pitch period in seconds, where the pitch period is the interval between the periodic minimum values in the plot. In this case the pitch is roughly 0.005 seconds. The frequency is equal to 1/pitch, or 200 Hz. This frequency is near the higher end of pitch frequencies, and is thus likely a female voice. (Actually, it is the voice of one of the co-authors - Delores Etter.) Students were then given a set of "unknown" speech signals, and asked to separate them into male and female voices by measuring the pitch frequencies.

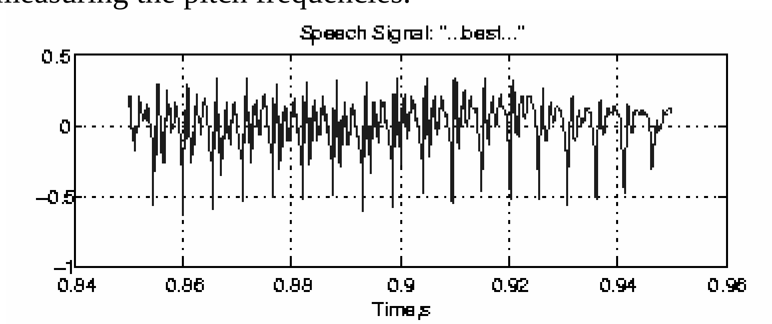

Figure 2: Isolated word from speech sample

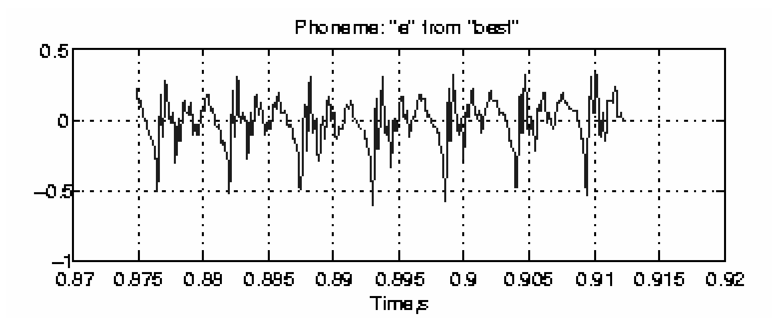

Figure 3: Single phoneme used for identifying gender of speaker

Analog/Digital Conversion Sub-module

After an hour in the biometrics laboratory, the students were provided a short lecture describing the basic principles underlying digitization of sound signals. The lecture began with a description of a simplistic digital communication system depicted in Figure 4. The example architecture consisted of a microphone, an analog-to-digital (A/D) conversion block, a storage/transmission block, a digital-to-analog (D/A) conversion block and a speaker. The A/D, storage/transmission, and D/A blocks were discussed only in terms of their conceptual function, and it was found that this discussion could be accomplished in a simplistic way that did not introduce substantial technical detail. Additionally, most students have sufficient background such that rudimentary discussions of sound waves and the operation of microphones and speakers are appropriate.

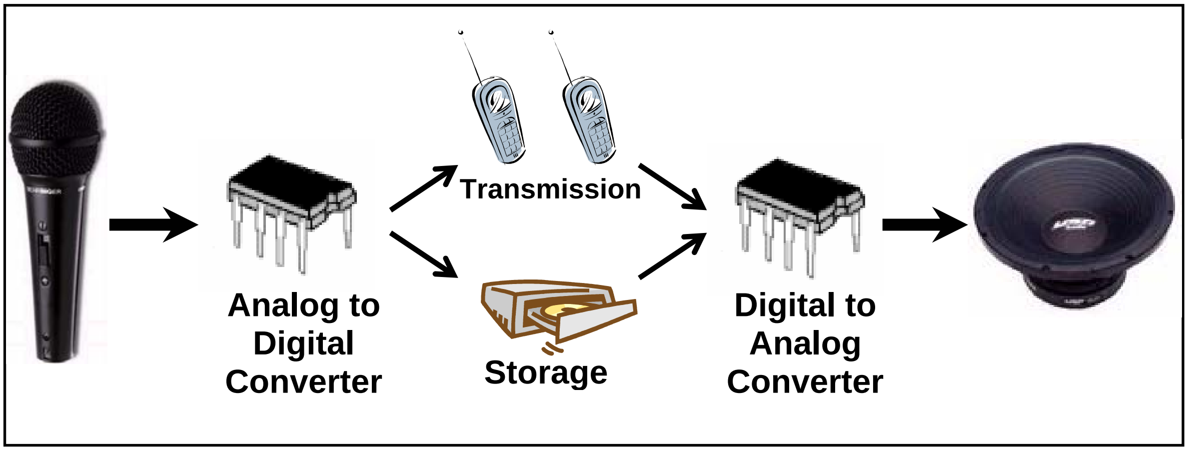

Figure 4: Digital Communications Framework

After introducing the framework, some of the advantages of digital communication systems were discussed. Students learned about its relative noise-resistance over analog transmission and storage and that computer-based signal processing enables compression and encryption of digitized information. Generally, students were familiar with compression in MP3 files, and this example was provided further meaning through a discussion of the size of CD-quality files verses their MP3 derivatives.

The fundamentals of Pulse Code Modulation (PCM) were then presented using Figure 5. The example depicts an input voice signal (in blue) and the sampled and quantized version (in red) that results from the A/D conversion process. Three sample intervals are detailed during which a small segment of the analog voice signal is encoded as three 4-bit binary words and appended to form the PCM data stream.

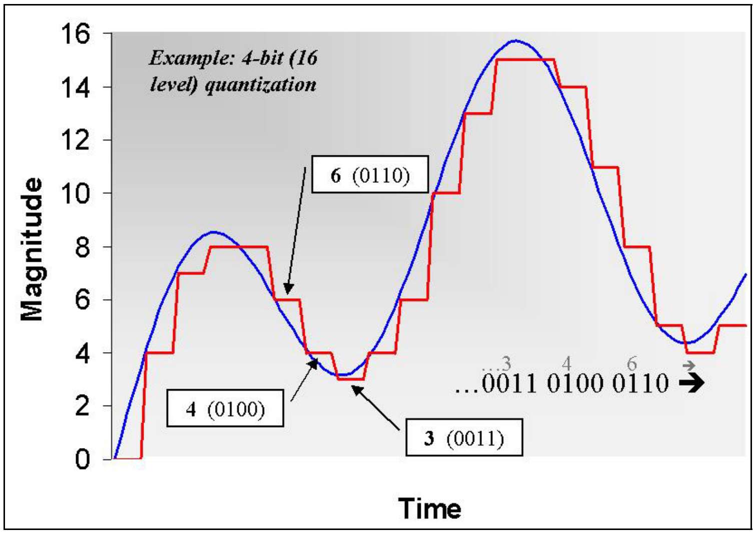

Figure 5: Pulse Code Modulation (PCM)

This graphic also provided a basis for discussing the fundamental trade-offs of digitization. A slower sampling rate limits the maximum frequency that can be captured in the A/D conversion process, and lower quantization results in greater error because the sampled value must be rounded to one of the increasingly discrete levels – an effect called "quantization noise". Therefore, as the sample rate and the number of quantization levels are increased, digital systems approach perfection. This gain in quality comes with an important disadvantage, however. By examining the equation below, students recognized that a higher bit rate ultimately places greater demands on the communications system or the storage medium.

$$\left(\frac{bits}{\sec ond}\right)=\left(\frac{bits}{sample}\right)\cdot\left(\frac{samples}{\sec ond}\right)$$

To further illustrate this trade-off, an audiovisual demonstration was presented. A short piece of popular music was re-quantized from CD-quality resolution (16-bit) to 8-, 4-, and 2-bit resolution using a MATLAB script discussed later in this section [7]. Each clip was played in the classroom using Windows Media® player with the *scope* visualization enabled. The music was paused during each clip, and the students were asked whether they could hear or see a difference in the re-quantized clips. Visual plots similar to the ones in Figure 6 resulted when the music was paused revealing the effects of quantization. Most students responded that they could not aurally or visually distinguish between the original clip and the clip re-quantized to 8-bit resolution. However, the 4-bit and 2-bit clips had noticeable quantization noise and visual "stair-stepping."

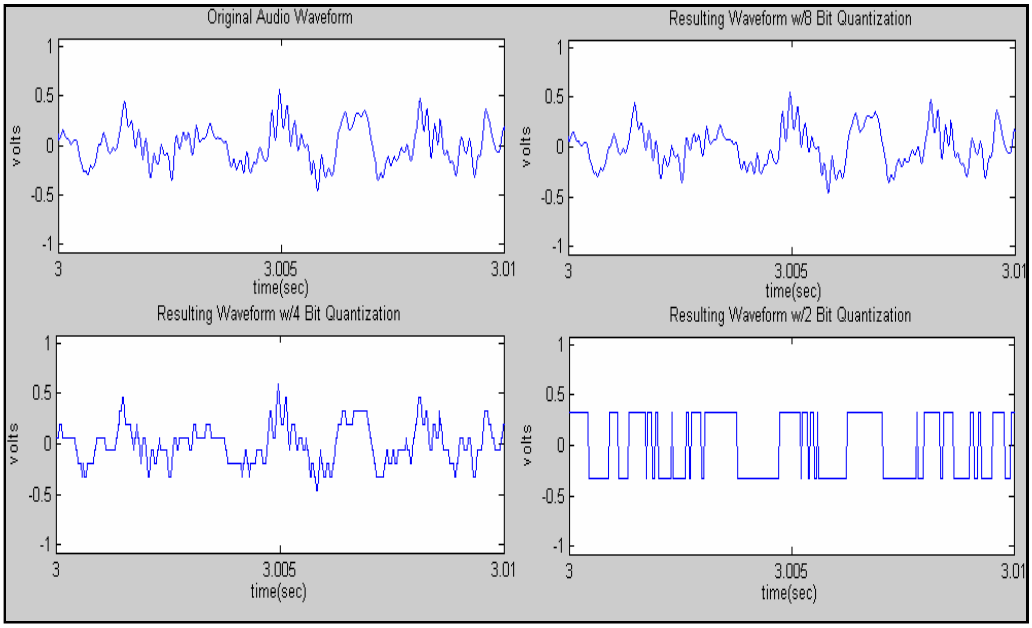

Figure 6: Visible Effects of Reducing Quantization

Subsequently, another short piece of music was played at its original CD-quality sampling rate (44,100 samples/second). A re-sampled version of the same clip (4,000 samples/second, pre-filtered to avoid *aliasing*) was then played. This second clip sounded duller and muffled because frequencies above 2 kHz were not captured in accordance with the sampling theorem. Without discussing too much technical detail, this demonstration revealed that a lower sampling rate will not capture higher frequency content.

While no mention of aliasing or the Nyquist criterion was made during this module, in future offerings of the course the authors might consider discussing the importance of pre-filtering sampled signals to prevent aliasing. Such a discussion could begin by playing two identical, under-sampled sound clips – one that was pre-filtered and another that was not. The students will hear the effects of aliasing in the unfiltered clip. Further, Java applets exist that visually illustrate aliasing using under-sampled rotating wheels and sinusoids [8, 9]. However, due to time constraints upon this module, the topic was not addressed.

Digital Music Exercise

Following the introduction, the students performed a thirty-minute computer based practical exercise. They first recorded a five second clip of their voice as an 8-bit PCM ".wav" file using the Microsoft® Sound Recorder. After playing and viewing this clip using the Windows Media® Player "scope" visualization, the students were directed to read the file into MATLAB using the *wavread* command, i.e. ***[a , fs, nbits] = wavread('filename.wav');***, where **a** is the quantized voltage waveform, **fs** is the sample rate, and **nbits** is the number of bits per sample.

Using the *wavplay* command, the students first played the clip at MATLAB's default sample rate – 11,025 samples/sec, or half the recording speed. After a brief explanation, they were then told how to play the clip at the original or any other desired playback speed using ***wavplay(a, A*fs);***

where ***A*** is a multiple of the original sample rate. This exercise illustrated the importance of the application knowing the correct sampling rate when determining playback speed.

Finally, the students were instructed to adjust the quantization of their voice signals using a pre-scripted MATLAB m-file function named ***audio***. By entering ***b*** = ***audio(a , B);*** where **B** is the number of bits, the resulting variable **b** contained the re-quantized voice signal that the students played using the wavplay command. The function ***audio*** also provided two plots – the original 8-bit waveform and the re-quantized waveform. Some examples of plots produced using this function were shown previously in Figure 6.

Light Organ Sub-module

The following week, we explored an electronics project called a "light organ." A light organ is an electronic circuit that responds to audio signals by illuminating a light [10], in this case a light emitting diode (LED). After capturing sound with a small microphone, the circuit utilizes three electronic band-pass filters to process the audio signal and illuminate one of three LED pairs. Thus, high-range audio frequencies illuminate a green LED, mid-range frequencies illuminate a yellow LED, and low-range audio signals illuminate a red LED. The block diagram for the light organ is illustrated in Figure 7. This project introduced the students to basic electronic components and to circuit board assembly, and provided the students a little design experience.

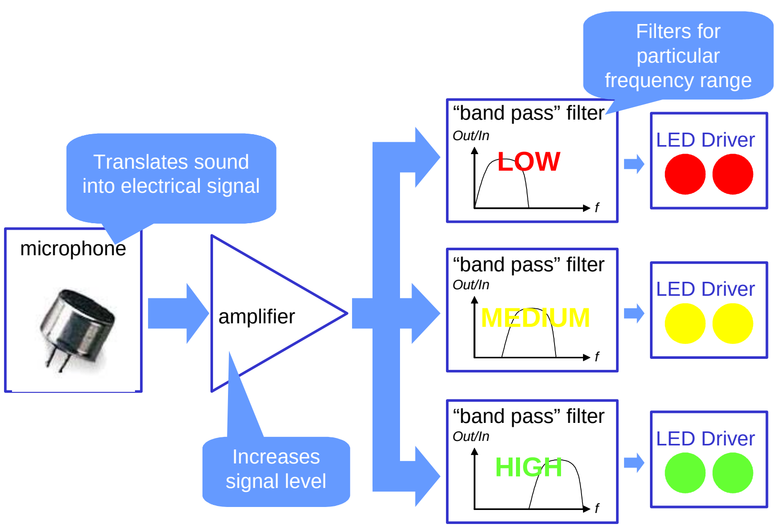

Figure 7: Light Organ Block Diagram

Circuit design and preparation

The schematic for the light organ is shown in Figure 8 and consists of a microphone, a two-stage amplifier with adjustable gain, three separate band-pass filters and three pairs of LEDs. The bandpass filters are active Butterworth filters, with pre-determined capacitor values. A complete circuit board layout was designed based on the schematic and was populated with all of the components except for the band-pass filter resistors, which were to be chosen and installed by the students.

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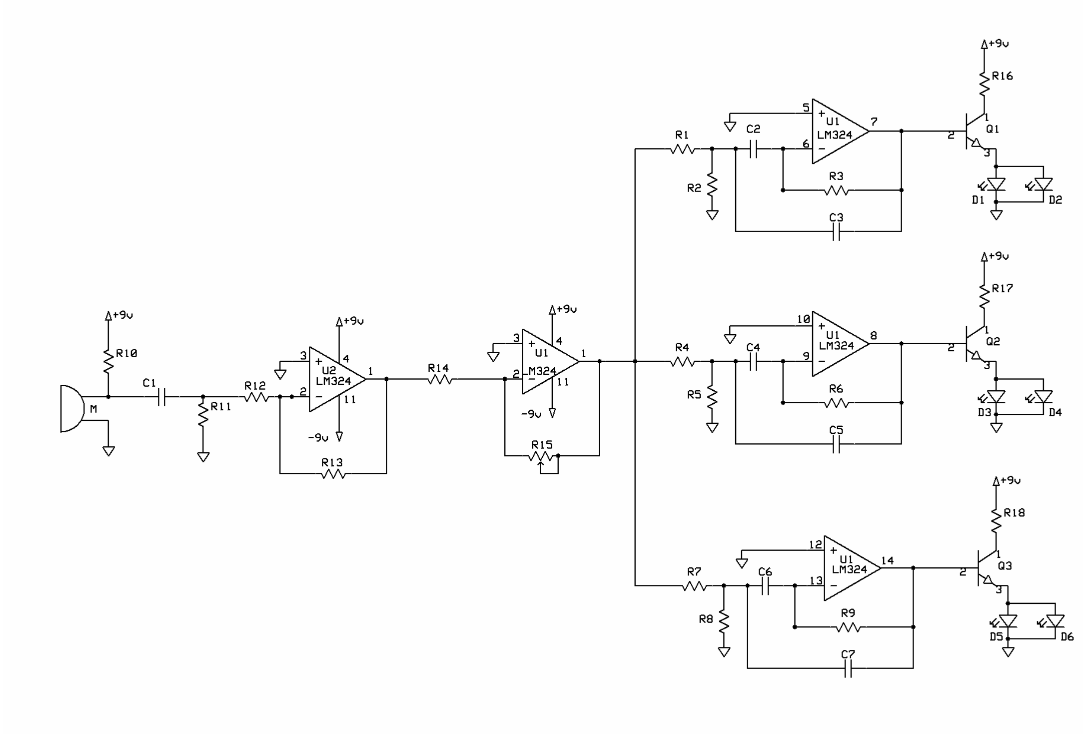

Figure 8: Schematic for Light Organ

Student Work

At the start of the sub-module, the students were given an overview on the circuit's functionality and on the operation of band-pass filters. By experimenting with a speaker connected to a function generator, they were able to define the approximate desired center frequencies for their three filters. They were then assigned the task of selecting appropriate resistor values (R_1 – R_9 in the schematic) to create the required frequency response. To assist in their design effort, a spreadsheet was developed (shown in Figure 9) with the design equations for the Butterworth filters pre-programmed. This spreadsheet enabled students to rapidly assess the gain and frequency range of the filters as they changed resistor values.

After an introduction to soldering and a little time practicing on old circuit boards, the students then collected their resistors (using the resistor color chart to confirm value) and soldered the resistors in place. Finally, the students tested their designs using function generators and speakers. Figure 10 shows a completed light organ.

Every student left the class with a functioning light organ, which they were encouraged to take back to their rooms, where the project could also serve as a subtle advertisement for electrical engineering as a major.

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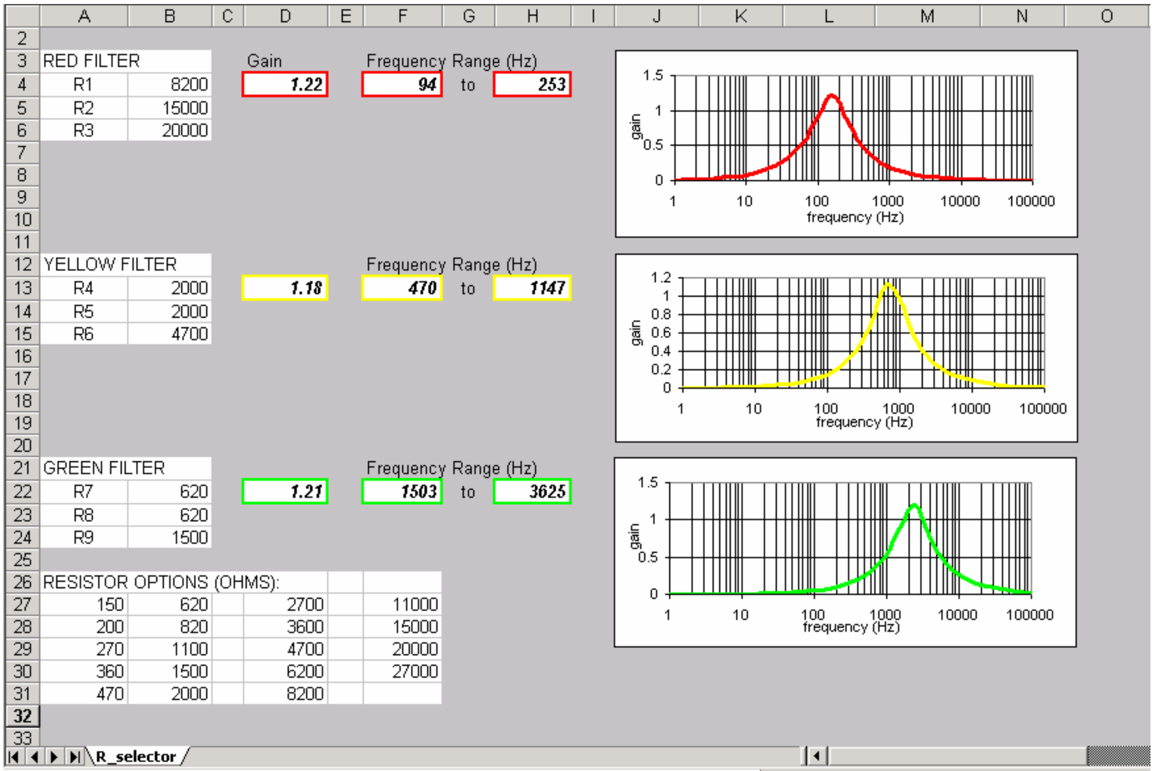

Figure 9: Spreadsheet for student design of band pass filters

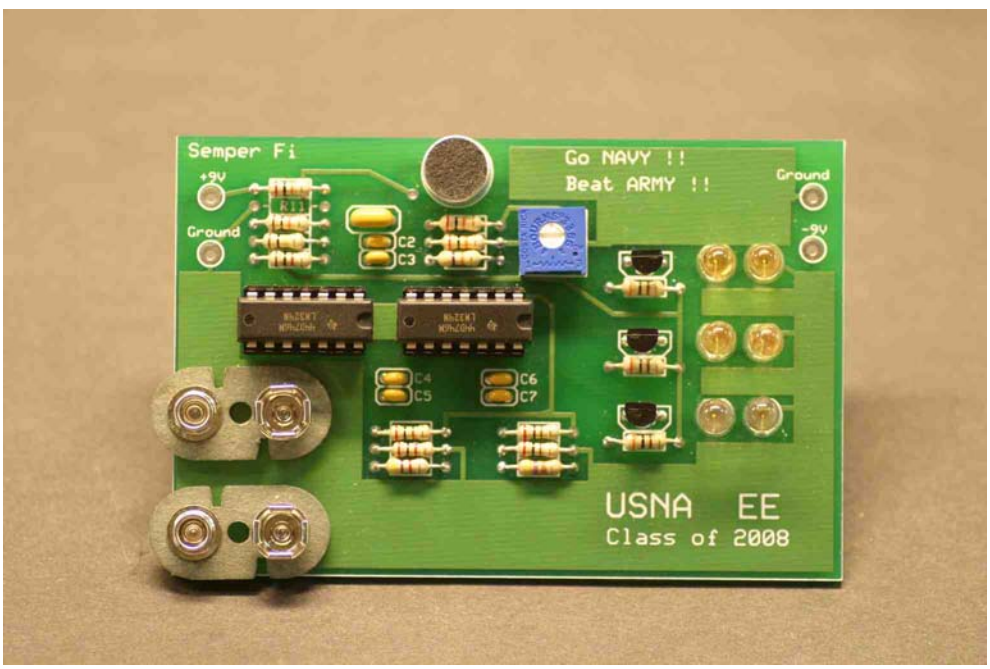

Figure 10: Photograph of Completed Light Organ

Assessment and Student Response

A weakness with this module was the lack of a means for generating a meaningful grade for the participants. Student grades were based on the successful completion of the light organ. Since every student was able to complete their project, all participants received A's for this module. The future addition of a short multiple choice quiz, testing the major concepts introduced by the module could be used to resolve this problem in the future. Students were given a questionnaire during the course to solicit feedback on their experience with the new class. The survey asked broad, open-ended questions that afforded students the opportunity to provide individualistic responses. In particular, the students were asked "Was the project beneficial to you for making a decision in selecting an engineering discipline?" Of the 43 students surveyed, 72% responded to this question as it pertained to the electrical engineering portion of the freshman engineering class. Of those who responded, 94% had a favorable experience with the project. Numerous comments were gleaned that indicate the students both enjoyed and benefited from the exposure to electrical engineering that they received in our four-hour module. A representative sampling follows:

> "Making circuits was challenging but would love to do it again"
> "Making the circuit board was really interesting and I understand the major better now"
> "Very informative and fun"
> "The project was a lot of fun and gave me just a small taste of EE - enough to know that I don't want to choose it for a major"
> "It was really interesting and the light organ was the coolest thing since the academic year has started"
> "The project was awesome!"
> "Very good to have a product to take with you."
> "I liked making the circuits and it was very informative."
> "The project was lots of fun"

Conclusions

Based on the student responses and faculty experiences, this module was successful in introducing electrical engineering as a discipline. However, the freshman engineering course as a whole was judged to be too fragmented and not conducive to an adequate level of depth. Each of the six majors only had two weeks with each group of students and due to shortness of preparation time, no integration of modules was attempted. This left the course appearing disjointed to the students. Therefore, the format for this course will likely change for the next year from a module approach to a more integrated approach among the disciplines. The new approach will still integrate some kind of longer design project, and we are considering expanding parts of the electrical engineering module developed this year into one such project.

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