Battery-Powered Tactile-Input Speaker in a Box

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1 Introduction

This paper discusses the design and development of a battery-powered speaker with a touch-sensitive interface to control the speaker's volume. The speaker, powered via a single 1.5 V battery rather than a wall wart, includes a meter of LEDs that indicate both the amplitude of the music and the volume that the music is currently set to. The speaker, LED display, and subsequent circuitry are mounted and contained in an acrylic box machined in the MIT Cypress Engineering Design Studio. This project is exciting because it is visually, tactilely, and auditorily stimulating, and challenging because the entire project must be power efficient to run off of a single AA battery. The project was a success as we were able to integrate all of the subcomponents designed into one cohesive system that performs all of the goals we set out to meet to make it "exciting". A more comprehensive list of our goals for this project is listed in Section 2.

2 Functional Requirements

Baseline Goals

1. Power Module
    a. Achieve ±5 V from a fully charged, 1.5 V D cell battery.
2. Tactile Volume Control:
    a. Volume control voltage: controlled by two touchpads to increase/decrease
    b. Use control voltage used to change audio output volume level, without expectation that volume remains stable over time
3. Amplifier and Filter
    a. Functioning amplifier with limited distortion
    b. Passband filter to eliminate noise
4. All parts function separately.

Expected Goals

1. Power Module
    a. Achieve ±5 V from a fully charged, 1.5 V D cell battery.
    b. Achieve at least 60% efficiency of the boost converter, with the rest of the circuit as the load.
2. Tactile Volume Control:
    a. Achieve stable volume control:
        i. volume control voltage stored on capacitor remains stable for the duration of at least one song; audio volume does not change audibly in the absence of user input for the duration of one song
    b. Single LED indicating indicating DC volume voltage
3. Amplifier and Filter
    a. Alter amplifier to limit noise distortions further. Add feedback (Bootstrapping and negative feedback)
    b. Added a “fun filters” effect

   c. LED Output of baseline volume
4. All parts function together.

Stretch Goals

1. Overall
   a. Manufacture a PCB or design PCB on CAD if not enough shipping time
   b. Machined box for speaker
2. Power Module
   a. Achieve ±5 V from a AA battery
   b. Achieve at least 80% efficiency of the boost converter, with the rest of the circuit as the load.
3. Tactile Volume Control:
   a. Add linear soft potentiometer to select volume directly, in addition to the ability to increase and decrease the volume monotonically
   b. Discrete LED display to show DC volume voltage; number of lit LEDs is proportional to the volume control voltage of the musics
4. Amplifier and Filter
   a. Echo Filter
   b. More Speakers

All baseline and expected goals were met, as were all of the stretch goals with the exception of an echo filter and a linear soft potentiometer volume control.

3 System Block Diagram

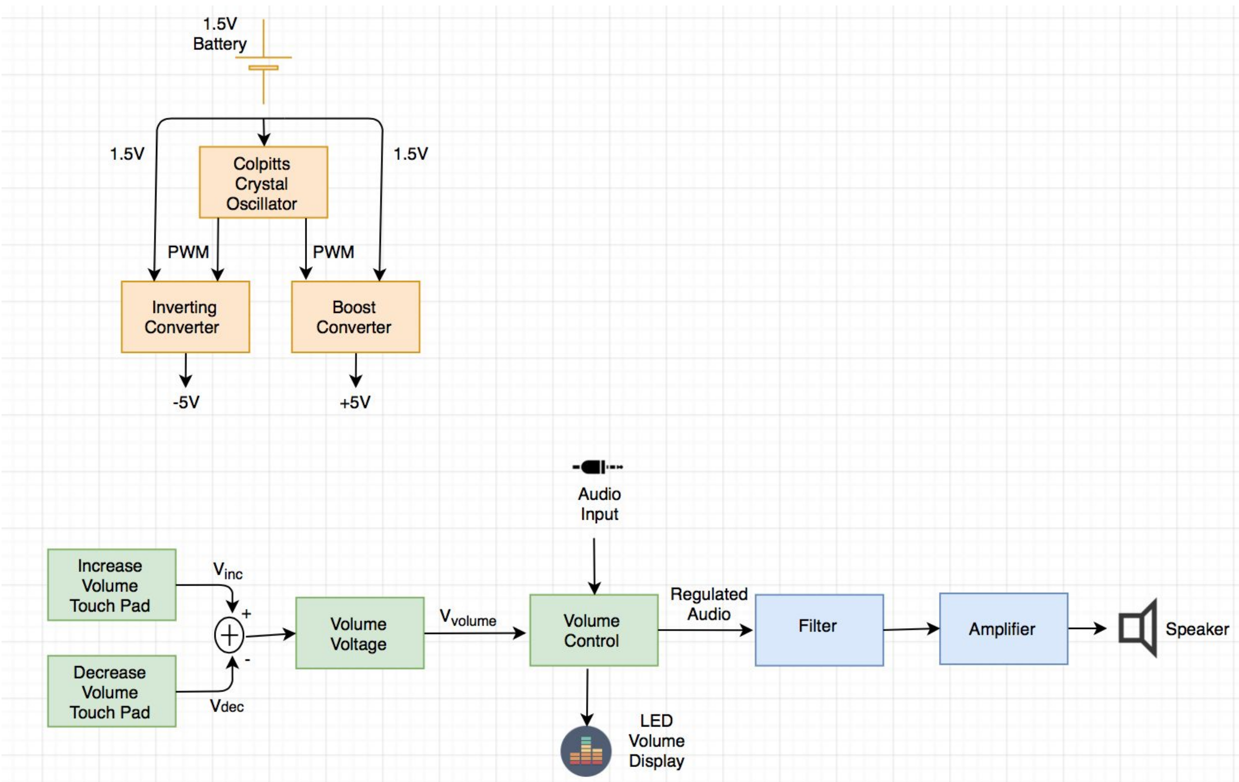

Figure 1: High-Level Block Diagram

4 System Schematics

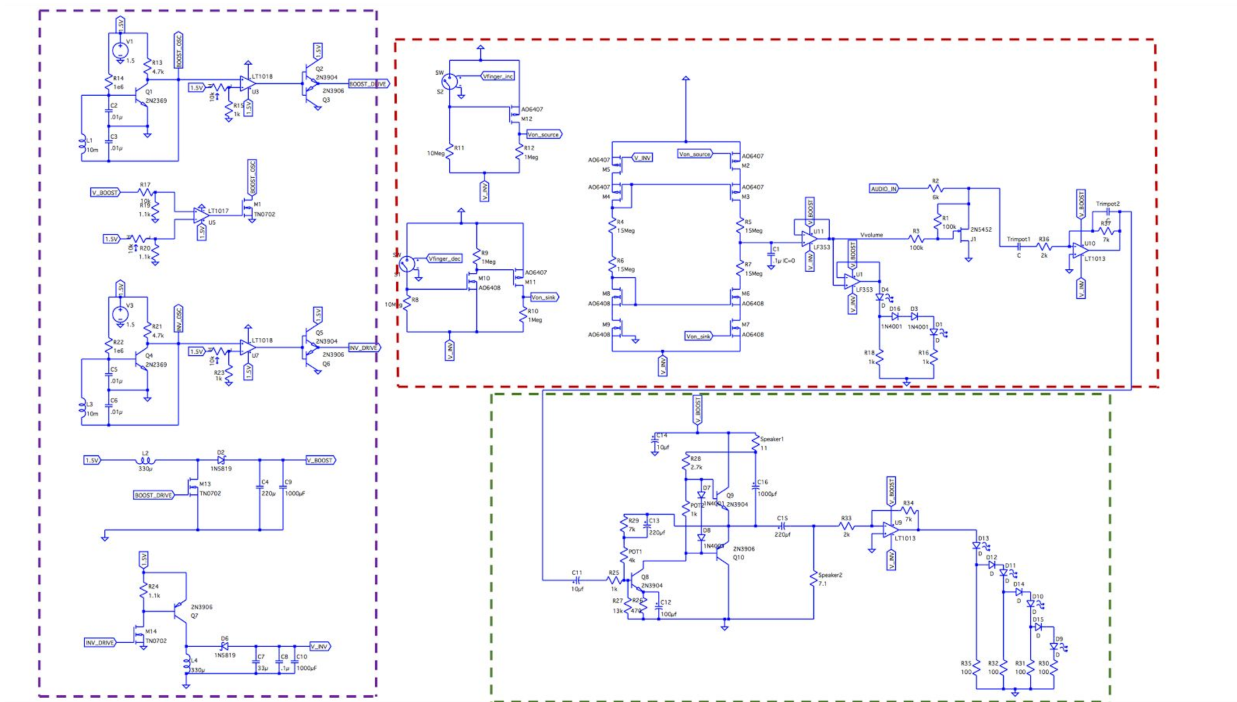

Figure 2: Complete System Schematic

Shown above is the circuit schematic for the entire system, broken down into its 3 main functional blocks - elements outlined in purple make up the power module, in red the volume control, and in green the audio amplifier and filter. The two LED displays presenting the volume and amplitude of the music are located in the red and green sections of the schematic respectively. The design of each of these sections in the schematic is discussed further in section 5.

We divided the project into these three main functional blocks, completed in parallel by each of the three team members: power supply, volume control, and amplifier stage. The power supply stage converts the 1.5 V battery to ±5 V rails that power the speaker and volume control. The volume control has two pads that sense touch - one to increase and the other to decrease volume at a continuous rate when in contact with the user's finger. When neither pad detects touch, the speaker maintains the current volume. The audio amplifier and LED display compose the final portion of the project. The LED display uses diodes and LEDs to present a discrete volume display, and the audio amplifier is class AB with positive and negative feedback. All elements of this project are designed to run off of low power, as the entire project runs off of a single 1.5 AA battery.

5 Subsytems

5.0 Power Module - Natalie

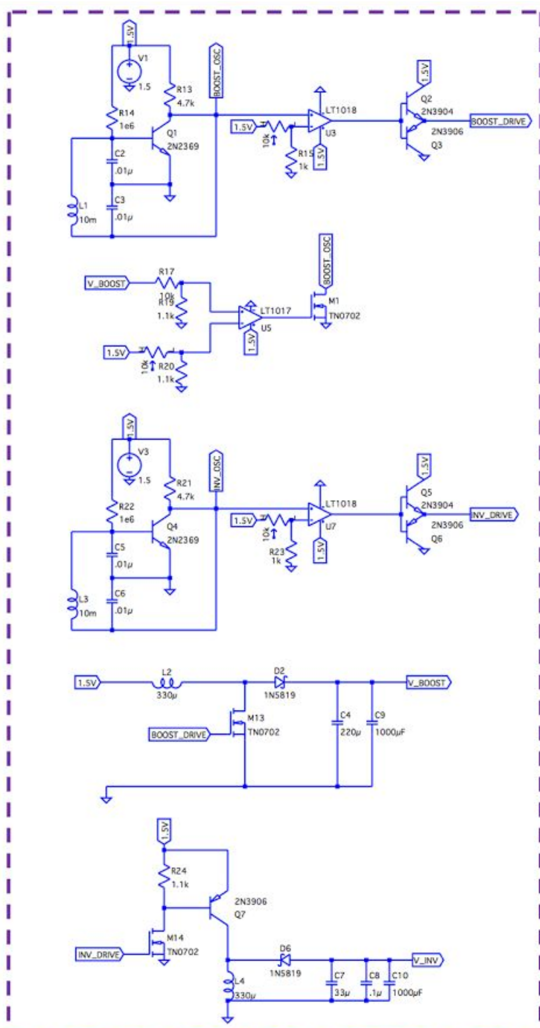

Figure 3: Power Module Schematic

The power module in Figure 3 creates the dual-supply voltage rails that supply the rest of the circuit. The input into this module is the 1.5 V AA battery, and the output is ±5 V rails. To create the positive voltage rail, a boost converter is used, and to create the negative voltage rail, an inverting converter is used.

Both the boost and inverting converter need a PWM signal to drive the gate of the MOSFETs. Two identical colpitts oscillators, one for the inverting and one for the boost, provide the initial oscillation signals. The frequency of the colpitts oscillator is set by its LC tank and the following equation: $f = \frac{1}{2\pi\sqrt{LC_T}}$ where $C_T = \frac{C_1 C_2}{C_1 + C_2}$. The frequency of operation for both colpitts oscillators is about 22 kHz, which is achieved with a 10mH inductor and two .01 μF capacitors. A 2N2369 transistor is used because it has a faster turn on/off time than a 2N3904, which increases efficiency, since transistors dissipate the most power when switching. The sine wave output of the colpitts oscillators then go into the non-inverting terminals of LT1018 comparator chips. The LT1018s compare the sine waves to a set reference voltage, which is tunable via a 10 $k\Omega$ potentiometer. When the sine wave is a greater voltage than the reference voltage, the LT1018 outputs roughly its positive rail voltage, which is 1.5 V. When the reference voltage is higher than the sine wave voltage, the comparator outputs 0 V. The LT1018 thus generates a square wave output. By adjusting the potentiometer, the reference voltage at the inverting terminals of the LT1018s is changed. This changes the duty cycle of the square wave output. The square waves are then wired to the input of a simple push-pull amplifier consisting of a 2N3904 and 2N3906. The push-pull amplifier is used to ensure that these square wave signals can supply enough current necessary to drive the boost and inverting converters.

One of the square wave signals is wired to the base of the TN0702 in the boost converter. The boost converter is composed of a 330 μH inductor, a 1N5819 schottky diode, and two capacitors of values 220 μF and 1000 μF in parallel. When the TN0702 is turned on, the inductor draws current and charges up. When the square wave is low and the TN0702 is off, the inductor current cannot change instantaneously, and the only path for the inductor current is through the schottky diode. The ideal output voltage of the boost converter with duty cycle D is $Vout = Vin * \frac{1}{1-D}$. However, with variable load resistances on the output of the boost converter, the output voltage fluctuated from the ideal calculated value. Some feedback is used to help control the output voltage and prevent it from rising too high. The output voltage of the boost converter is scaled down by a voltage divider and then fed into the non-inverting terminal of a LT1017 op amp. The LT1017 acts as a comparator, and compares the scaled boost converter voltage to a reference voltage which can be adjusted with a 10kΩ potentiometer. When the output of the boost converter rises, the voltage at the non-inverting terminal of the LT1017 will rise above the voltage at the inverting terminal, causing the LT1017 to rail to 1.5 V. The output of the LT1017 is wired to the base of a TN0702 MOSFET, and when the LT1017 outputs 1.5 V, the TN0702 turns on, which pulls the boost converter oscillator signal to ground, effectively terminating the oscillation. With no oscillation, the boost converter is no longer driven with a switching PWM signal, and the output voltage of the boost converter drops. Once the boost converter output has dropped to a lower voltage, the LT1017 comparator will see a higher voltage at from the reference voltage at the inverting input, causing it to output 0 V. This will turn off the TN0702 which will allow oscillations to begin again. By changing the potentiometer on the inverting input, the reference voltage can be changed. Changing the reference voltage effectively changes the maximum voltage that the boost converter can achieve before being limited by feedback.

Although the boost converter was designed to create ±5 V rails, it did not output this voltage level exactly. The boost converter outputs approximately 5.5 V when the rest of the project's circuitry is attached as the load and no music is playing. When music is played at max volume, more current is drawn from the 5.5 V rail, and the voltage drops, to around a 3.5 V minimum. At this supply voltage, the sound quality of the music is compromised slightly, but the distortion is not significant.

A multimeter and current probe were used to measure the efficiency of the boost converter. The results of the efficiency measurements are displayed in the table below.

No Music				Max Volume Music			
	Voltage	Current	Power		Voltage	Current	Power
Input	1.5 V	49 mA	.0735 W	Input	1.5 V	50.5 mA	.076 W
Output	5.4 V	10 mA	.054 W	Output	3.4 V	19 mA	.065 W
Efficiency	73%			Efficiency	85%		

Table 1: Power Efficiency

The inverting converter works very similarly to the boost converter. The sine wave output of a colpitts oscillator at 22 kHz is fed into a LT1018 comparator and push-pull amplifier. This square wave with an adjustable duty cycle is used to drive the inverting converter. The square wave is fed into the base of the TN0702. The drain of the TN0702 is connected to the base of a 2N3906 PNP and a 1.1 kΩ pull up resistor. When the TN0702 is on, the base of the PNP is pulled to roughly 0 V, which turns the PNP on. When the PNP is on, the inductor draws current through the PNP. When the TN0702 is off, the base of the PNP is pulled to 1.5 V, which turns the PNP off. The inductor draws current through the 1N5819, which creates a negative voltage across the output of the inverting converter. The output voltage achieved is about -5.5 V constantly, regardless of whether music is being played or not.

5.1 Tactile Volume Control - Madeleine

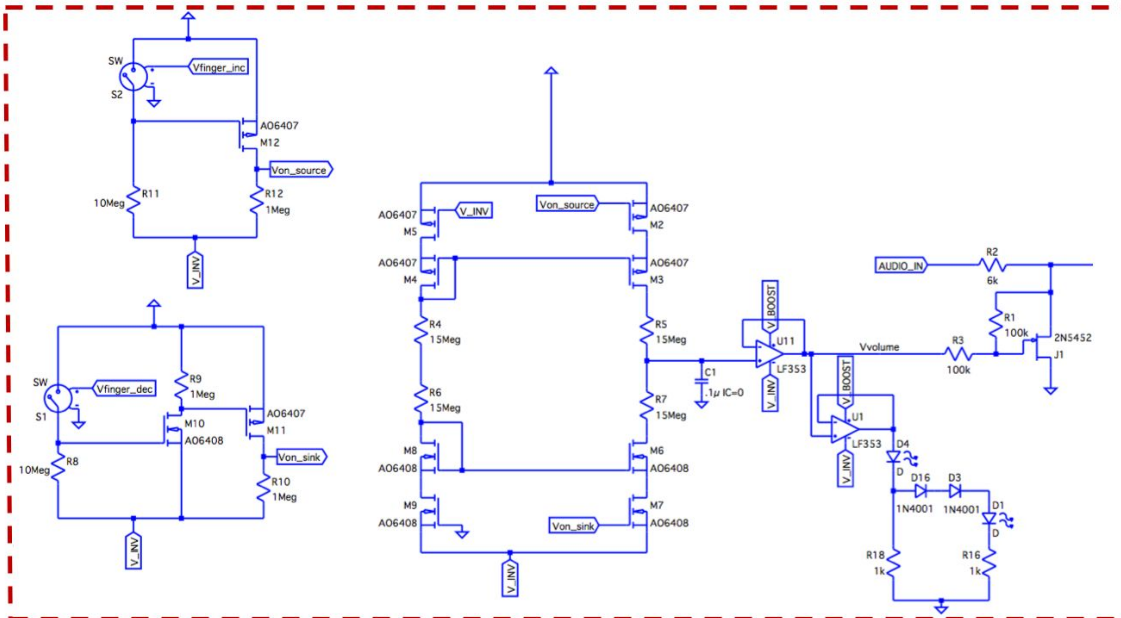

Figure 4: Tactile Volume Control Schematic with Volume LED display

The tactile volume control module allows the user to control the volume of the speaker through two touch-sensitive pads. When the user is touching a single pad, the volume increases/decreases at a continuous rate; when neither pad is touched, the volume remains stable. The module has three inputs: ±5 V rails from the power converter stage, an audio signal from a phone/laptop, and tactile input to control volume. It outputs a volume-controlled audio signal to the amplifier stage of the speaker system. The module itself consists of 4 primary stages: user input to detect a desired increase/decrease in volume, memory stage that maintains and updates the current volume control voltage, voltage controlled regulation of audio volume, and discrete LED volume display for user feedback (discussed further in section 5.3).

The touch sensing stage has two touchpads - simple wires running parallel to each other, connected when the user touches their finger to them. These feed into a series of NMOS and PMOS transistors that output constant voltages when the user's finger connects the increase/ decrease volume circuitry, as shown in the circuit schematic. The increase volume circuitry outputs 0 V when off and -5 V when on to control a PMOS current source. The decrease volume touchpad outputs -5 V when off and 0 V when on to control an NMOS current sink. The voltage output from these two pads control current source and current sink circuitry respectively, which are used to charge and discharge a capacitor at a monotonic rate.

The DC voltage stored on this capacitor represents the current volume of the speaker system, and can range between 0 V to -4 V. Connecting any circuitry directly to the capacitor causes it to discharge and reduce the volume; to prevent unintentional discharging, the capacitor feeds directly into an LF353 voltage buffer, whose input bias current is very low, approximately 50 pA. This setup provides stable volume control - no measurable voltage drop after 10 minutes of measuring.

The third section of this module - the voltage controlled regulation of audio volume - receives the volume control voltage from the voltage buffer and feeds it directly into the gate of an nJFET. The nJFET acts as a variable resistor in a voltage divider, varying the magnitude of audio voltage connected to its drain as its resistance changes with its gate voltage. This audio signal is passed into the amplifying stage of the speaker system.

5.2 Amplifier and Filter - Lorenzo

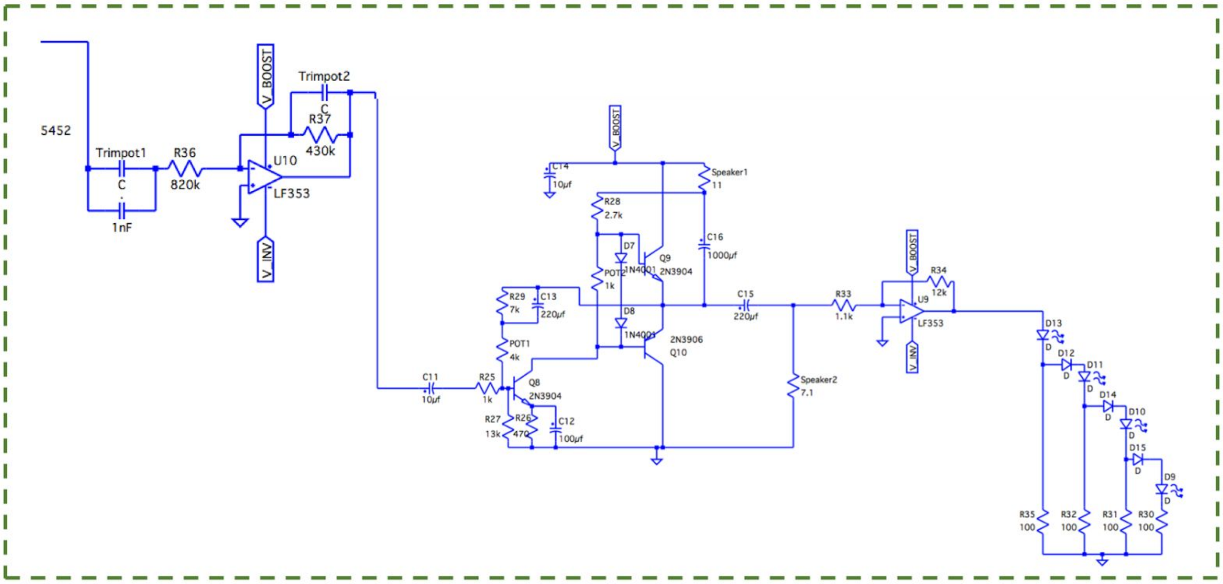

Figure 5: Amplifier, Filter, and Baseline Volume LED Schematic

This section of the project includes the majority of the outputs. They are in the form of audio, through a speaker, and lights, through LEDs. Coming from Madeleine's sections, a volume modified signal is received as the input. After this stage, the signal moves into a filtering stage, then to the amplifier, and finally to the LED display.

Due to power restrictions, the filter is simply a passband filter. Using an inverting op amp passband configuration, the signal is filtered and preamplified before the amplifier. In order to make the filter more adjustable and user friendly, the user has the option to easily move the passband portion of the filter. By using two trim caps in place of regular capacitors, the user is able to adjust both the high and low frequency poles of the filter. The values of the trimmer caps range from 12 pF to 100 pF and with the resistor values fixed at 430 kΩ and 820 kΩ for the low pass filter and high pass filter respectively. The ranges of human hearing/music is 100 Hz to 25 kHz so the filter was designed to operate around this range. The limits of the cutoff frequency for the low frequency portion are 1.9 kHz to 16 kHz, while the limits for the high frequency section are 370 Hz and 3 kHz. So by shifting the poles, the user can add unique effects to their favorite songs. After the signal has been filtered, it is wired to input of the amplifier

Drawing on inspiration from amplifiers described in lab, this amplifier was built to minimize distortion as much as possible, while being power efficient. A class AB amplifier is driven by a class A amplifier. With the addition of a bootstrapping (positive feedback) configuration and a negative feedback path, the circuit has minimal crossover distortion and is more efficient than a class AB without the feedback paths.

First, the signal goes through a bypass capacitor in order to remove DC bias. Then, a portion of the signal flows into the base of the first BJT. The top rail of the input bias resistors is set by the feedback path. This feedback helps to pre-distort this signal slightly so after it goes through the amplifier it is more smooth and has less distortion. After being amplified, the signal is fed the the input of the class AB push-pull configuration. The two diodes help with thermal stabilization as well as biasing. The output from the BJTs is passed through a bypass capacitor and then through to the speaker where the signal becomes music.

5.3 LED Volume Displays - Madeleine, Lorenzo

There are two LED displays within the entire system. One LED display shows the current volume of the song being played while the other displays what the user has set the volume to be. The same circuit layout was used for both displays. In the LED display for the current song volume, the input comes from the same signal that is fed to the speaker. In order to prevent drawing current away from the speaker, the signal is put through an op amp in a current buffer configuration. After this the signal goes to a LED which then splits, one branch takes a resistor through to ground while the other goes to a diode and then to another LED. This formation is repeated until the user decides they have enough LEDs. For this project, it was determined that four LED was sufficient for baseline volume display, and two LEDs was sufficient for user selected volume display. The voltage drop across the diodes creates a difference in light emitted by the LEDs. The LED requires only minimal stimulation to light up while the furthest will only light up when the song is very loud.

6 Design Decisions

6.0 Power Module - Natalie

The colpitts topology was chosen to create the oscillating signals because this topology allows for easy manipulation of output frequency. Another initially considered design involved the use of crystals, which are limited to outputting a single frequency which is usually in the MHz range. Crystals are not ideal for this application because they are unadjustable and operate at too high a frequency. The colpitts topology is attractive because it can be easily tuned across a wide array of frequencies and understood with a few simple equations.

The colpitts oscillator was designed to produce a relatively low frequency of 22 kHz. This was one of the lowest frequencies achievable given the selection of components in lab. A lower frequency of oscillation is desirable because lower frequencies produce a more perfect square wave on the output of the LT1018 comparator. This is because the 320 V/ms slew rate of the LT1018 is fast enough to ramp up voltage within the period of lower frequencies, but cannot ramp up fast enough when the frequency is too high. Even though the LT1018 has a very high slew rate of 320 V/ms, this was still a limiting factor in deciding the colpitts frequency of operation. During testing, a frequency of 160 kHz caused the output of the LT1018 to be a distorted triangle wave, as opposed to a square wave. This happened because the LT1018 could not switch from positive to negative supply rails fast enough, because it was limited by its slew rate. At a frequency of 22 kHz, the LT1018 slew rate of 320 V/ms can ramp up voltage fast enough within the frequency period to create a decent square wave.

The 2N904 and 2N3906 push-pull amplifier is used to supply more current to the boost and inverting converters. To ensure that the gates of the switching MOSFETs are supplied with enough current, push-pull amplifiers follow the outputs of the LT1018s.

In both the boost and inverting converters, TN0702s are used because they has a very low V_{GS} of 1.0 V. A n-channel MOSFET is used for the switching device rather than a BJT because MOSFETs generally have faster switching times and are thus more efficient.

Both the boost and inverting converters also each have a 1000µF capacitor on their outputs. This large capacitor serves to help stabilize the rail voltages, and prevent them from excess fluctuations during the course of a song. With these capacitors, the voltage rail fluctuation is at most 2 V, but without these capacitors, it is more. Whenever a song gets louder, the voltage rails tend to drop, since the load circuitry is drawing more current. The large 1000 µF capacitors help mitigate this fluctuation by smoothing the rail voltage changes.

Furthermore, both the boost and inverting converter have their own colpitts oscillator. This further separates the two voltage rails and removes any interdependencies that they otherwise may have had. Two separate colpitts oscillators also allow for the boost and inverting converters to be driven from different frequencies, making the circuit more modular and adjustable.

6.1 Tactile Volume Control - Madeleine

Power and stable volume control were the principal considerations of this module. To obtain stable volume control, care was taken to select a capacitor with low leakage current, as electrolytic and ceramic capacitors leaked away their voltage significantly in less than a minute. A 0.1 uF capacitor with a dielectric of air was deemed the best candidate to store the volume, as it functioned most similarly to an ideal capacitor and could hold the volume stable for many minutes when fed directly into an LF353 op amp with extremely low bias current, thereby minimizing undesired voltage discharge over time.

Power was taken into account in the design the nJFET audio volume control. The circuit attenuates rather than amplifies, as amplifying would require an additional op-amp, demanding power that we did not have as we were right at the limit of the power module's power output capability. Similarly, it is important to note that the two LF353s shown in the volume control circuit schematic are simply two sides of a single, dual-port LF353, further saving power as we did not have the power to control two separate LF353 chips when all three sections of this project were integrated.

6.2 Amplifier and Filter - Lorenzo

Power was the main consideration for the majority of the design designs made for the filter and the amplifier. The amplifier was built out of BJTs as opposed to op amps for this reason. Careful biasing of the BJTs was also necessary for achieving low power consumption.

Originally, more interesting filters were considered for implementation, but power limitations prevented this. For example, if an echo filter were implemented, the signal would have to be delayed a second or so, which in the analog domain is quite long. This delaying would mostly like have been done by passing the signal throw a bucket brigade configuration. This, unfortunately, is very power hungry. Therefore, a more simple and adjustable passband filter was built. This way the user could still have a cool filter to tinker with, but the circuit would still function.

6.3 LED Volume Displays - Madeleine, Lorenzo

Power was considered in choosing what LEDs to use for the displays. LEDs typically require around 10-20 mA of current to turn on. Low-power red LEDs were chosen for this speaker system, as they require only 2-3 mA to operate, thus minimizing the power required to operate these displays.

7 Challenges Encountered

7.0 Power Module - Natalie

Most of the design problems encountered in the power module were concerned with controlling the output voltage of the boost and inverting converters. These output voltages varied wildly with load resistance. For example, with zero load resistance and no feedback network, the boost converter achieved an output voltage of around 40 V. Clearly, this voltage was much too high for the application, and needed to be somehow constrained. However, the rail voltage also needed to refrain from falling too low when a large resistive load was applied. To keep the rail voltages as close to the desired values of ±5 V as possible, feedback and adjustable potentiometers were used. The feedback on the boost converter prevents the boost voltage from rising too high, while the potentiometers can be adjusted to increase the duty cycle, and prevent the output voltages from falling too low. To prevent the boost converter output voltage from going too high, feedback in the form of a LT1017 comparator is used (Figure 3). The boost converter voltage is reduced via a resistor network, and compared to a reference value which can be changed with a potentiometer. When the boost voltage gets too high, the comparator will turn on a TN0702, which will pull the colpitts oscillations to ground. Without an oscillating input signal, the boost converter voltage will drop to an acceptable level of 5.5 V. To prevent the boost voltage from dropping too low, the 10 kΩ potentiometer on the inverting terminal of the LT1018 can be adjusted, which effectively changes the duty cycle of the square wave signal to the boost. By increasing this duty cycle, the boost voltage can be raised. These two methods corralled the voltage rails into acceptable ranges.

Measuring the efficiency of the boost converter was also a challenging aspect of the power module. Measurements of the boost input power and output power are necessary to calculate the efficiency of the boost converter. To measure the input power, a multimeter set to measure current can be placed in series with the inductor of the boost converter. Placement of the multimeter caused the voltage at the inductor to drop below 1.5 V, because the multimeter has some internal resistance. So, the input voltage to the multimeter was increased until the voltage at the inductor was 1.5 V. The multimeter then showed an accurate measurement of the input current into the boost converter. A few different methods were explored to measure the output current. First, a large resistor was placed across the output of the boost converter. Power could theoretically be measured by calculating V^2/R, where V is the output voltage of the boost. However, this method of calculating output power was not accurate for this application. In this case, the load on the boost converter is the rest of the circuit, which has many types of impedances, and is not purely resistive. Therefore, using a single resistor gave unreasonable values for the output power. Instead, a current probe was used to measure the current in the wire connecting the boost output voltage to the rest of the project. The current probe initially gave some unreliable measurements, but taking many data points eventually produced valid results.

7.1 Tactile Volume Control - Madeleine

While power was a consideration in the design of the volume control, it was not a limiting challenge. There were two main challenges with this subsection: minimizing discharge of the capacitor storing the volume voltage and developing a symmetric volume control method that did not jeopardize the signal. Regarding a stable capacitor, many different capacitors were tested to see which one held voltage the longest. The solution was unintuitive, as a small 0.1 uF capacitor worked the best since it used air as its dielectric and thus behaved most like an ideal capacitor. The act of measuring the capacitors complicated matters initially, as the DMM and oscilloscope themselves caused the capacitors discharge until we connected an LF353 to the capacitor and measured the output of the voltage buffer instead.

Additionally, the capacitor volume circuit was initially designed to store 0 V to 5 V rather than 0 V to -5 V, under the assumption that an NMOS transistor would be operated in its triode to act as a variable transistor. This set up worked in LTspice using ideal components, but it was highly unsymmetric when real devices were used and ruined the audio signal. It took time to come to the conclusion of using an nJFET as a variable resistor to attenuate the volume instead of MOSFETs, and implementing it was time consuming as the entire current source/sink circuit to control the voltage on the capacitor had to be rewired to supply from 0 V to -5 V rather than 0 V to 5 V. Additionally, an nJFET with the specific threshold voltage of -2.5 V had to be used, as discovered through trial and error. An nJFET with too high of a threshold (around -4 V) never turned on since the capacitor could only reach -3.8 V due to the LF353 op amp buffer, yielding an extremely quiet output from the speaker. An nJFET with too low of a threshold (around -2.1 V) caused circuitry to draw too much power from the rails since we were right at our power limit, thus resulting in clipping of the audio signal as the power rails moved closer toward zero from the ±5 V designed.

7.2 Amplifier and Filter - Lorenzo

There were two main challenges within this subsection: power limitations and modeling feedback paths. Because the filter was the last thing added to the circuit, the power converter was already at the edge of it limitations. After adding the filter to the rest of the circuit, the power rails crashed. This was obviously a problem and created cause for redesigning the filter. After considering other designs, it was determined that a low power op amp configuration was plausible but rewiring needed to be done. At this time the baseline volume LED display used a 741 op amp, but by using a dual JFET 353 op amp, both the filter and the LED display could operate off of a single chip. This simple solution took a while to arrive at, but it helped pinpoint exactly what the limitations of the circuit was.

Computations became complicated quickly within the amplifier, as keeping track of the effects of both positive and negative feedback was challenging. The positive feedback heavily influenced the biasing of the BJTs in the AB amplifier, while the negative feedback acted as the top rail for the resistor combination that biased the BJT in the class A amplifier. This was difficult because these two feedback signals were essentially the same signal, simply wired to different sections. Decoupling these equations proved to be nearly impossible in terms of mathematical computations by hand. By making the assumption that the output, and therefore, feedback path would mostly stay within a certain range once music was playing, it was then possible to create a simplified model for how this system worked. Simulations in LTSpice and experiments helped to further narrow down and specify part values that minimized crossover-distortion while still providing an acceptable gain.

7.3 LED Volume Displays - Madeleine, Lorenzo

This section was fairly straightforward, with only one small hiccup. We discovered that connecting the LED displays directly to the volume control and audio output voltages distorted the signals by adding unanticipated impedance, quickly solved by buffering the inputs of these displays to separate them from the rest of the circuitry.

8 Reflections

8.0 Natalie

This project provided my first meaningful experience with power electronics. One of the most difficult aspects of designing the power module was understanding the system requirements, and designing the boost and inverting converters to work appropriately with the rest of the system. In the past, I have only ever built power converters as part of a lab or assignment, where the specifications were well defined. I found the design process to be much more challenging when the specifications are not predetermined, and actually may change over the course of a project. In future projects, I will make sure to adjust the specifications of my work as necessary throughout the design process. Checking design specifications often should help me create accurate designs, even when some applications or usages of the technology are unclear. Designing power converters for a speaker, which naturally has a variable resistance as the volume changes, was even more difficult. However, I think this difficulty mimics real world design challenges, where problems are not clearly defined. This project was a great lesson in the importance of communication, as our team members needed to understand the requirements of each other's modules. Effective and persistent communication between our team allowed our individual modules to be integrated successfully.

8.1 Madeleine

I thoroughly enjoyed working on this project, as it is the first time I've had the opportunity to use circuitry theory I've learned over the years at MIT and actually build from scratch a physical working system that I conceived. My team worked really well together, and, having learned from past projects, all of us put time into the project early so that the final week leading up to the due date all we had to do was machine a box and work on aesthetics for our project. A timeline as such was fun and exciting rather than stressful and exhausting. Additionally, this was a learning experience for me in the domain of specifications. As a course 6-2 major, I'm well familiar with the importance of specifications in software, but this is the first time I've ever had to think about and design to meet certain power requirements, or how to come up with clever alternatives to a variety of circuit elements in order to stay under a certain power limit.

8.2 Lorenzo

This project has been a wonderful experience for me. Though there was a ton of hard work and a lot hours put in, I feel that every second was worth it. It was great to see the final project working and to be able to listen to some of our favorite songs being played. It was frustrating at times dealing with the complicated nature of both positive and negative feedback in the amplifier. The math became complicated at times, but I learned a lot in the process, and now that I am done and looking back, I am very happy that I worked with them. I developed important skills for interfacing with complicated system that are sometimes best abstracted as black boxes. I wish that I had made certain assumptions and realizations earlier, like how sometimes imperfections in the real world actually help some circuits perform better in real life than in simulation. but overall I am very happy with how the project went and I am proud of how much I learned and accomplished.

9 Conclusion

Overall this has been a very successful project, as we met all of our baseline and expected goals, and even a number of our stretch goals. Our team followed two main strategic approaches to ensure our success. Primarily, our team recognized the importance of continuous and effective communication. Before starting the project, we decided on set methods of communication to discuss ideas and problems. We decided that verbal communication and group text were the most effective ways for our team to communicate. Having decided on particular channels of communication lessened response times and made our communications more efficient. Effective communication was paramount to understanding each other's work, and ensuring that all our modules could be integrated successfully. Our other strategic approach to this project was to begin working early. We recognized that starting our project earlier would reduce stress, and allow for more time to handle unforeseen issues. Having more time towards the end of the project also allowed us to make our designs more thoughtful and robust. For future students of 6.101, we recommend working with people who have similar work styles, and starting the project as early as possible. All of the members on our team are punctual and take initiative to start new projects. This shared work style helped our team stay on schedule and work better together. We recommend that future students in the class also try to work with people who share similar work styles. We also recommend that regardless of their preferred work style, students begin their projects early. Oftentimes, project ideas turn out to be more complex and challenging than students may initially think. Starting the project early will provide some buffer to overcome these unforeseen obstacles, and may even provide time to complete some stretch goals.

10 Acknowledgments

Our team would like to thank Professor Gim Hom for inspiring our project idea and helping us throughout the design process. Our TA, Yanni Coroneos, also provided assistance and advice when we ran into bugs in our designs. We'd like to thank EDS for providing us with the space, materials, and guidance to build our circuits and mechanical structures. Thank you to Dave Custer for providing feedback and advice on the communications portion of this project. Lastly, a huge thank you to the entire teaching staff for a wonderful semester!

11 System Usage

First, the user should ensure the AA battery is fully charged. The ground of the battery should connect to the ground of the circuit, and the power of the battery should connect to one side of the switch. To turn on the speaker, simply flip up the switch at the back of the box. To play music, connect the audio jack to a computer, phone, or other device. Once the switch is on and the audio jack is connected, the user can play music.

Volume is controlled at the back of the box. When the user wishes to increase the volume, one simply touches a finger to the exposed set of wires on the right hand side of the figure.

Likewise, touching the exposed set of wires on the left decreases the volume monotonically as long as a finger is kept in contact with it.

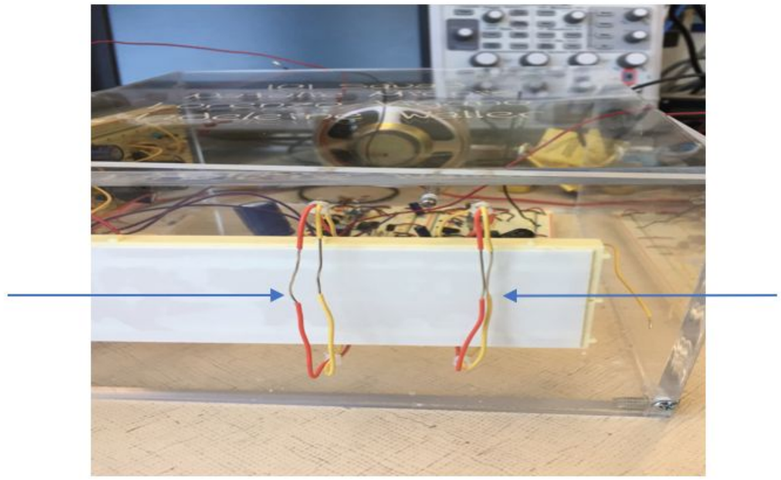

Figure 6: Volume Control Panel

The filter is an optional feature and to add or remove simply involves moving two wires as shown in Figure 7 below (feed the circled part of the purple wire to where the circled part of the orange wire is, and then unplug the orange wire). The amplifier does not need to be adjusted, nor the speaker setup.

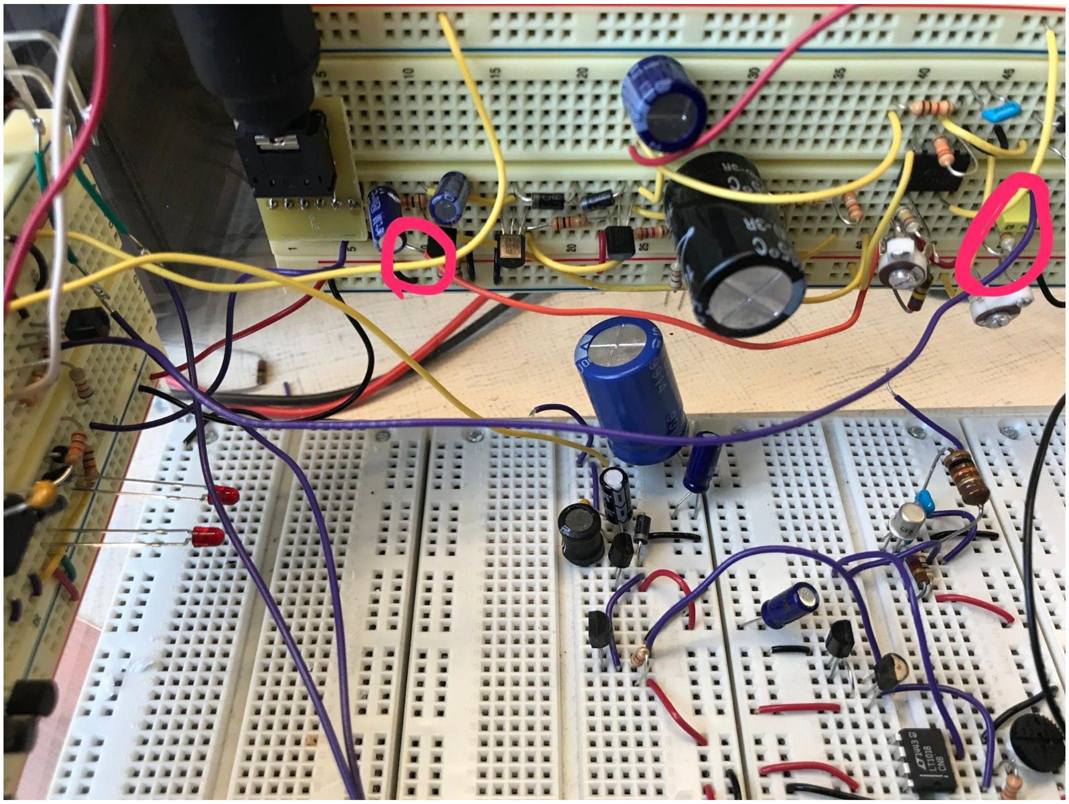

Figure 7: Optional Filter

12 References

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