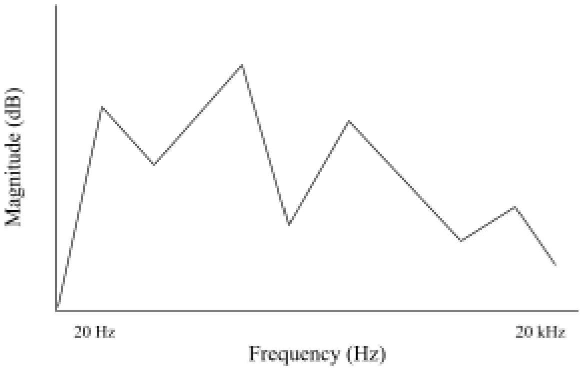
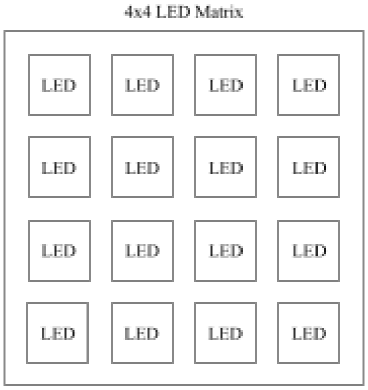
LED Spectrum Viewer

Proposal Statement

Whether it's the soft glow of a mechanical keyboard or the vibrant dance of christmas lights, there is a unique allure of the interplay of light with our environment. Our goal is to replicate this satisfaction when playing music by visualizing the ebbs and flows of audio waveforms in a colorful fashion. Our project is an LED based spectrum viewer, where multiple LEDs will light up to represent the strength of different frequencies of the sound being detected and displayed.

In general, a spectrum visualizer represents a frequency (hertz) vs sound intensity (decibels) graph. Our goal is to create this graph on an LED matrix display. Therefore, each column of LEDs will represent a range of frequencies, and the number of LEDs which light up vertically will represent the decibel of that frequency range based on the input sound.





First, we will need to use a microphone to obtain an audio input signal. This signal will be an AC signal, which we will subsequently have to amplify to increase the signal. The frequencies and magnitudes of this signal is what we will display on the LED matrix.

The average hearing frequency range of humans is about 20 Hz to 20 kHz. So, we will make band-pass filters within the 20 Hz-20 kHz range to visualize audible sound. To do this, our filters will have bandwidths of 20 Hz -112.5 Hz, 112.5 Hz - 632.5 Hz, 632.5 Hz - 3556.5 Hz, and 3556.5 Hz - 20 kHz. As indicated, these bandwidths are based on a logarithmic scale where the range of frequency increases over time, mimicking the scaling of pitch.

We decided to use band-pass Butterworth filters because the drop in gain to frequency is the steepest of all the filters, and the range is constant until the frequency drop off. This characteristic will help us maintain the original waveform the best, which is ideal for us when displaying the audio input. The other filters, for example Chebyshev and Elliptic, are variable in gain, which will make it harder to maintain the same waveform. Additionally, the Bessel filter is a good competitor, but the drop in gain is not as steep.

Using a microphone as our audio input, these filters will be connected to peak detectors which will output the maximum voltage from our filter. This maximum voltage will represent the magnitude of the frequency. The output of the peak detector will be inputted into four comparators as the input voltage. This input signal will be compared to four different reference voltages, which we will set using a voltage divider. Therefore, the comparators will light up a certain number of LEDs based on the comparison of the input voltage and the reference voltage.

Our final design will consist of a 4x4 matrix of LEDs and resistors soldered onto a perfboard. This perfboard will be connected to the comparators so it can display the audio spectrum of a sound.

Timeline

Week of September 25: Finalized project steps and circuit design
Week of October 2: Designed one bandpass filter
Week of October 9: Built one band-pass filter and tested it
Week of October 16: Finished second band-pass filter and tested it; built a peak detector and worked on implementing a comparator
Week of October 23: Continued implementing the comparator and tested one LED row
Week of October 30: Successfully tested one LED row and started designing final LED matrix
Week of November 6: Finish building/implementing filters, peak detectors, and comparators
Week of November 13: Final testing and begin finishing up
Week of November 20: Began soldering LED perfboard
Week of November 27: Finished soldering LED perfboard and began final report
Week of December 4: Finished and submitted final project

Milestones

Our first milestone was to complete the design of all of the band-pass filters. Our next milestone was to complete building and testing one of these filters on the breadboard. Following that, we sought to create and test one peak detector to check if our design would function properly. The next milestone was to successfully amplify the output of the peak detector to create a signal that could be used as a reference voltage for the comparators. The following step was to implement the comparators and LEDs to create a fully functioning row of LEDs. After we proved that one of the LED rows was working, we were then able to recreate the circuit three more times to obtain four rows of four LEDs. Up to this point, we were using the waveform generator of the oscilloscope to test the function of our filters and other circuit components. However, our final project needed a way to capture audio input. So, our next milestone was to develop a functioning microphone circuit and test the LEDs with that input instead of a generated waveform. After all of the previous components were functioning, we technically had a fully functioning project. Nevertheless, we still planned to solder the LEDs to a perfboard to create a more compact LED matrix, and our final milestone was to have a functioning LED matrix.

Verification and Operation of Milestones:

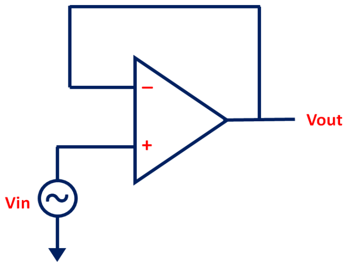
We have 3 sub-circuits that power each row of LEDs. First is the band-pass filter, which allows specific frequencies of sound from the inputted noise to pass through, second is the peak detector, which outputs the highest voltage signal of the input, and the output of the peak detector is the input to our third sub-circuit, which includes the comparator and LEDs. All of the LED rows require input from a microphone, which will take in audio.

Filters:

One of the main aspects of our project was the filters. The main function of the filters was to separate the audio input from the microphone into four different ranges of frequency so we could display the magnitudes of the different frequencies in our LED matrix. Without the filters, the LEDs would simply show how loud the input noise was, with no correlation to the frequencies. We chose the ranges based on a logarithmic scale to mimic the exponential relationship between frequency and pitch. Then, we developed band-pass filters with Sallen-Key topology with a 3 dB bandwidth that corresponded with our ranges by cascading a high pass filter with a low pass filter.

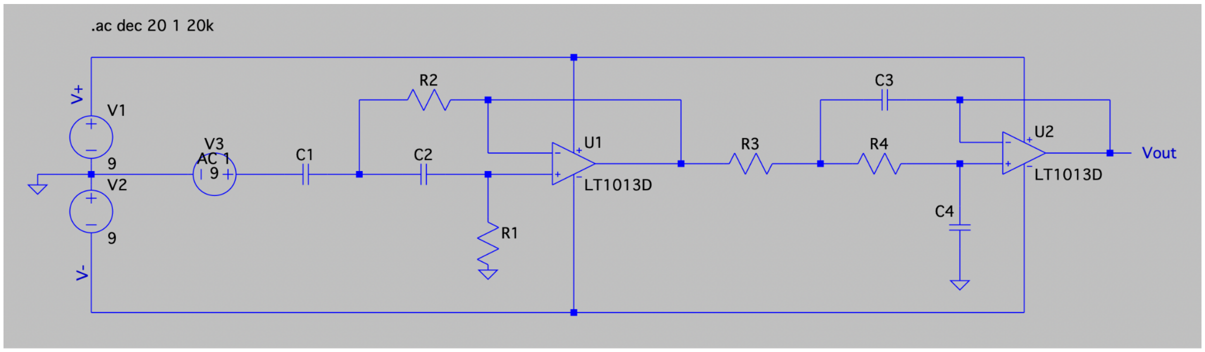
The basic physics around our filter relates to the capacitor. The reactance of a capacitor is given as $X_C = \frac{1}{\omega C}$. Therefore, for high frequencies that are sent into the circuit, the reactance of the capacitor will approach zero and for low frequencies the reactance of the capacitor will approach infinity. By designing a proper circuit that takes advantage of this fact, we could filter out certain frequencies in a threshold. We combined a high pass filter (which lets in frequencies above a certain threshold) and a low pass filter (which lets in frequencies below a certain threshold) to filter out frequencies in a certain range. Additionally, it is important to note that our filters are active, meaning that we implemented circuit elements like op amps, compared to a more traditional passive filter that uses only resistors and capacitors.

We spent some time designing and testing each filter we built. We used LTSpice to simulate the frequency response graph of the filters we designed based on the schematic below, using the specific capacitor and resistor values we chose. Then, after building the filter on our breadboard, we used the oscilloscope to input an AC signal into our filter and probed the output. When we tested our first filter, we realized that we needed to add an op-amp buffer in order to improve our input signal, so we could get a better output signal, since our output was not as consistent as we expected. The op-amp buffer acts as a voltage follower for two circuits with different impedances so the signals from the second circuit do not interact with the first circuit.

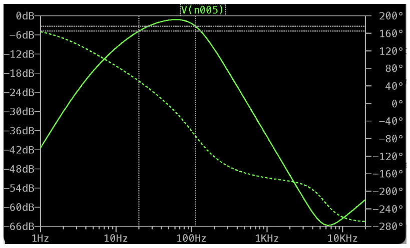
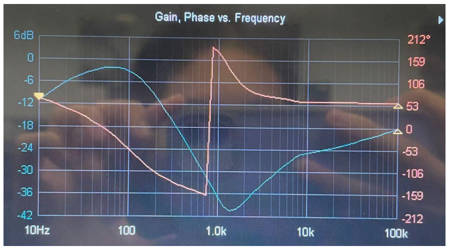


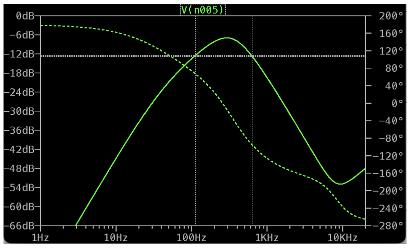
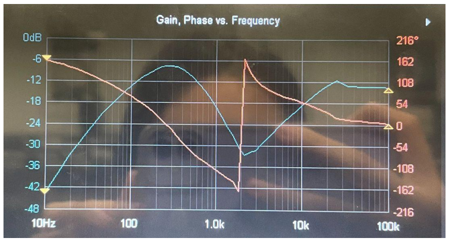
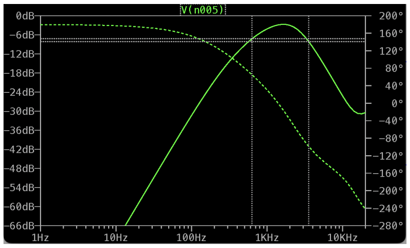
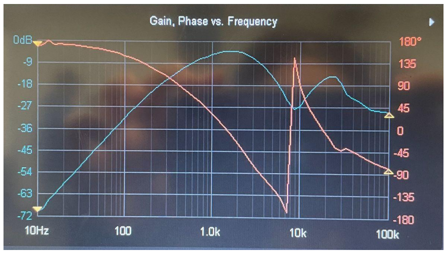
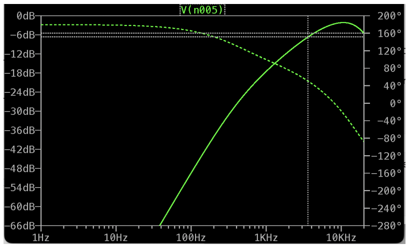
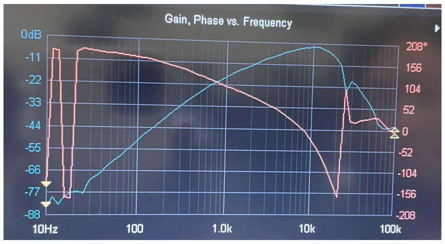
Op-Amp Buffer

After adding the op-amp buffer, we altered the frequency of the input signal, testing frequencies below the lower cutoff frequency, within the bandwidth, and above the upper cutoff frequency. We were able to see that the output changed depending on the input frequency. Additionally, we ran a frequency response analysis on the filter using the oscilloscope and compared that graph with the one we simulated in LTSpice. In general, our filters matched their predicted function.



Band-Pass Filter

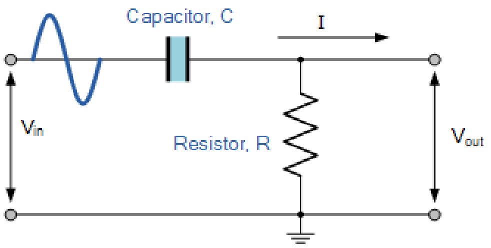
Filter Designs				
	Range	Values	Simulated	Actual
			*Simulated and Actual graphs have different x and y-axis values	
1	20 Hz - 112.5 Hz	C1: 100 µF C2: 100 µF C3: 2 µF C4: 1 µF R1: 100 Ω R2: 220 Ω R3: 1 kΩ R4: 1 kΩ		

2	112.5 Hz - 632.5 Hz	C1: 1 µF C2: 1 µF C3: 2 µF C4: 1 µF R1: 680 Ω R2: 2.2 kΩ R3: 330 Ω R4: 330 Ω		
3	632.5 Hz - 3556.5 Hz	C1: 1 µF C2: 1 µF C3: 2 µF C4: 1 µF R1: 220 Ω R2: 330 Ω R3: 47 Ω R4: 47 Ω		
4	3556.5 Hz - 20 kHz	C1: 200 nF C2: 200 nF C3: 20 nF C4: 10 nF R1: 220 Ω R2: 1 kΩ R3: 680 Ω R4: 680 Ω		

Peak Detector:

We used two slightly different designs for our peak detectors. The first design corresponded with the first filter that we built, which initially had a DC offset due to incorrect wiring of the filter. The second design is what we applied to the other three filters, without the RC high-pass filter to correct the DC offset.

Our peak detector circuit for the filter with a DC offset consists of an RC high-pass filter whose output is inputted into the peak detector, and the signal is then amplified using a non-inverting op-amp amplifier. The RC high-pass filter works since the reactance of the capacitor is very high at frequencies below the cutoff frequency, so it does not allow the signal to pass. When the input frequency is higher than the cutoff frequency, the capacitor allows the signal to pass through, making it a high-pass filter.



RC High-Pass Filter

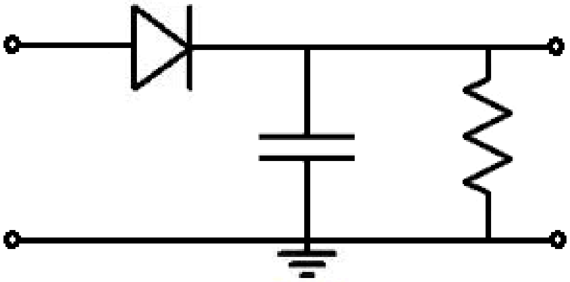
We added a RC high-pass filter because when we were testing the output of the filter, we realized that there was a DC offset. After adding this filter, we were able to see that the offset was reduced.

Before RC High-pass Filter

After RC High-pass Filter

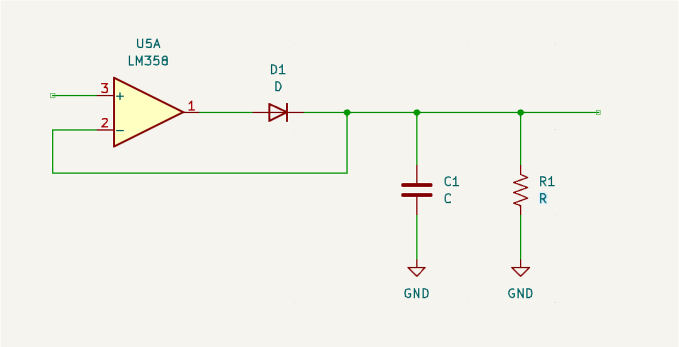
(green line represents the generated waveform, yellow line represents the filter output)

We built our first peak detector based on the schematic below, and we were able to verify its function since the output of our band-pass filter was an AC signal, but the output of the peak detector was a DC voltage. The output of the peak detector also followed the variation of peak in the waveforms that we tested. Therefore, we could use this voltage as the input to the comparator because it was no longer varying.



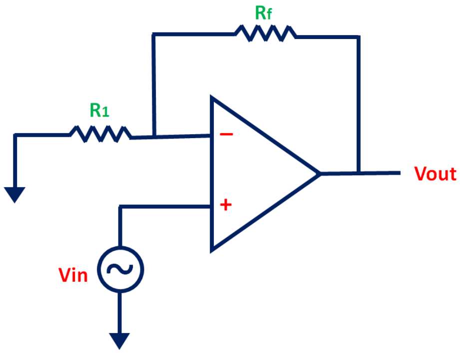
Peak Detector (Design 1)

The schematic below shows the schematic of the peak detector that we used for the rest of the filters that did not have a DC offset. For some reason, the peak detector without an op-amp did not function properly for the filters that filtered higher frequencies, but once we added the op-amp, it worked as expected. This peak detector works as follows: the op-amp is configured to be a voltage follower, and since the diode is inside the feedback loop, its nonzero turn-on voltage is compensated for. The capacitor is charged through the diode, and it gets charged to the maximum value of the signal that is inputted. As such, the capacitor "detects" the magnitude of the frequency. The capacitor then discharges through the resistor, which is connected in parallel. If or when there is a new peak, the capacitor charges again to that voltage. We varied the capacitor and resistor values based on the RC time constant to determine the charging and discharging durations.



Peak Detector (Design 2)

After we probed the output of the peak detector, we realized that the peak voltage from the filter was too small, and needed to be amplified before it could be connected to the comparator. So, we added a non-inverting op-amp amplifier to maintain the positive voltage but increased it by a gain of R_f/R_1. We were able to see this gain when comparing the input and output of the amplifier circuit. The gains differed for each filter since the highest peaks were all different, and we chose resistor values accordingly.



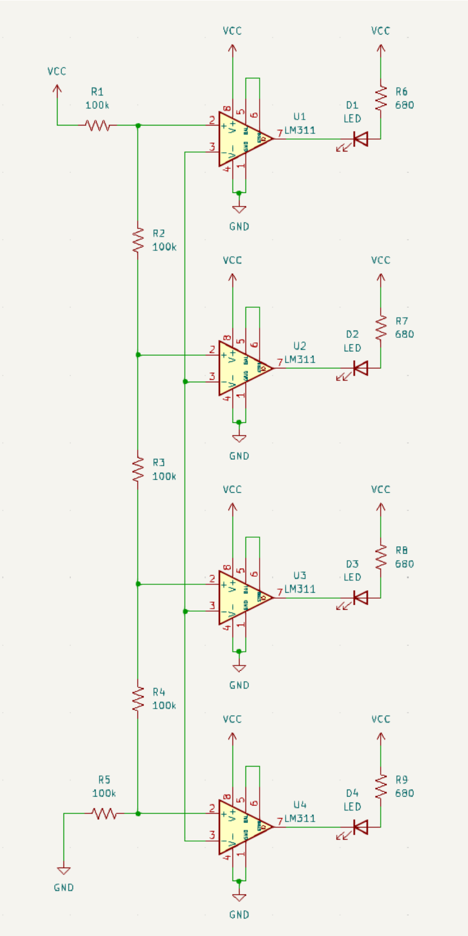
Non-Inverting Op-Amp Amplifier

Peak Detector Before Amplification Peak Detector After Amplification

(blue line represents the peak detector, green line represents the output of the filter)

Comparator and LEDs:

The comparators were connected to the amplified output of the peak detector. We wired the comparator based on the schematic below, using a voltage divider of 100 kΩ resistors to turn on a certain amount of LEDs based on the amount of voltage that is inputted.



Comparators and Rows of LEDs

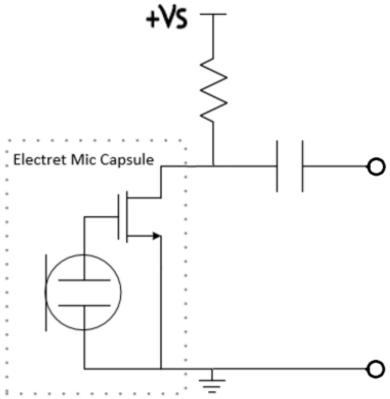
In order to check that the comparator was working properly, we probed each pin of the LM311 comparator to check the voltages. The positive input pins all showed a voltage that was equal to the amplified voltage from the peak detector, and the negative input pins decreased in voltage proportionally to their location in the voltage divider. By connecting the LEDs, we were able to see that the comparator drew current when the input+ was greater than the input-. Since the input- reference voltage increases the higher the LEDs are, the top LEDs will only turn on when the input voltage is large. Therefore, the LEDs properly display the magnitude of the sound.

Demonstration of One Comparator
(blue line represents the amplified peak detector, green line represents the reference voltage; the LED is on when the blue line is higher than the green line)

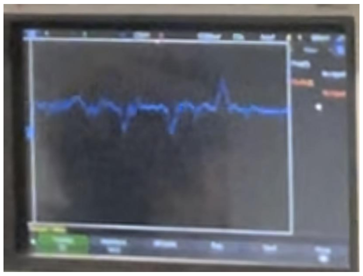
We also changed the amplitude of the AC signal we were inputting using the oscilloscope to check if the number of LEDs that turned on varied depending on the input. When testing the LEDs with a signal with varying amplitude, we were able to see that the number of LEDs that turned on went up and down, representing the changing amplitude. So, our comparator was properly comparing the voltages and turning on the correct corresponding number of LEDs.

Microphone:

Until this point, we had been using the waveform generator on the oscilloscope to test the functionality of all of our circuit components. However, for our final project, we needed a way to capture an audio signal to display using our LED matrix. Therefore, we used an electret microphone biased with a 2.2 kΩ resistor, based on the datasheet. Additionally, we needed to use a capacitor because the microphone was powered by a DC signal, but we only wanted the AC signal of the audio input. So, we used a coupling capacitor to eliminate the DC signal, meaning that our output would only be the AC signal which represented the input sound.



Microphone Circuit Schematic

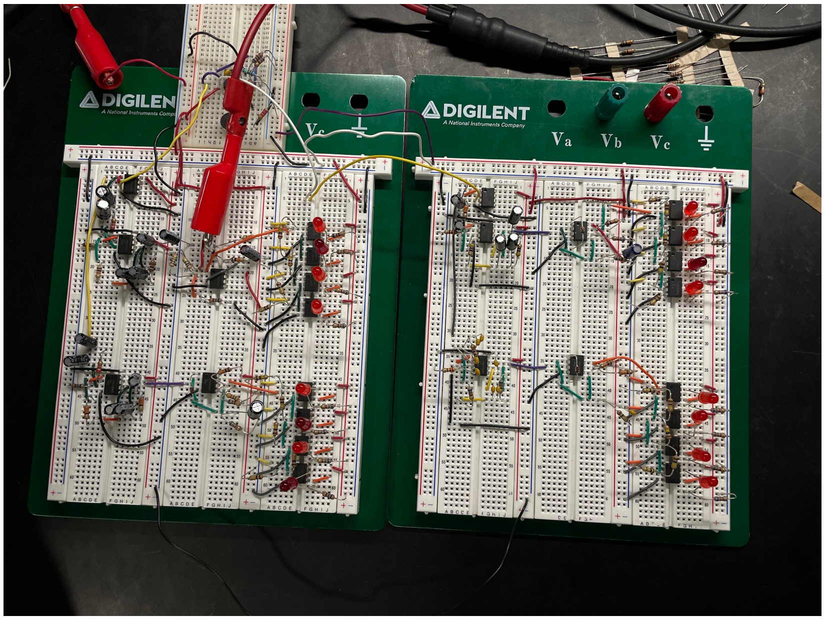


Amplified Microphone Output

We also used another non-inverting amplifier to amplify the signal from the microphone, since without amplification, the output was only a few millivolts. After we determined that our microphone was fully functioning and picking up sound as expected, we connected it to the filters, and we had a fully functioning circuit with four rows of LEDs.

Fully Functioning Circuit:

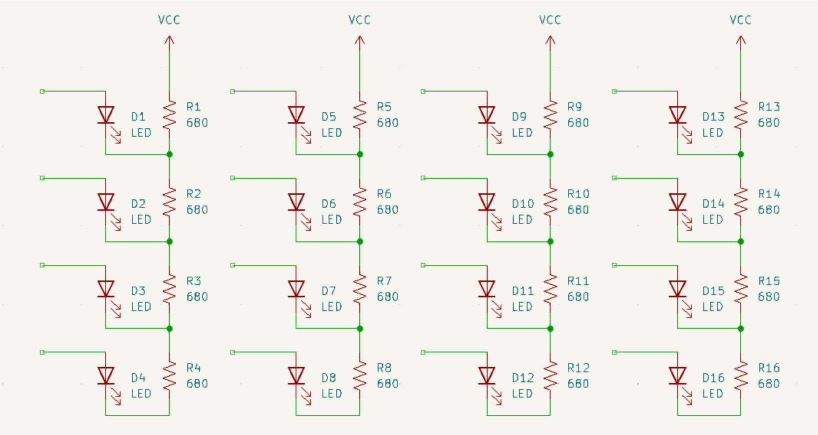
After the microphone was connected, we had a fully functioning circuit which displayed the frequency spectrum of an audio input. We were able to conclude that our final circuit functioned properly since all of the subcircuits worked as expected when probed with the oscilloscope. We did not run into any issues when combining the subcircuits, so adding the functioning microphone was our last step to reaching a working end product. The final circuit consists of one microphone, four filters, four peak detectors, and sixteen comparators and sixteen LEDs.



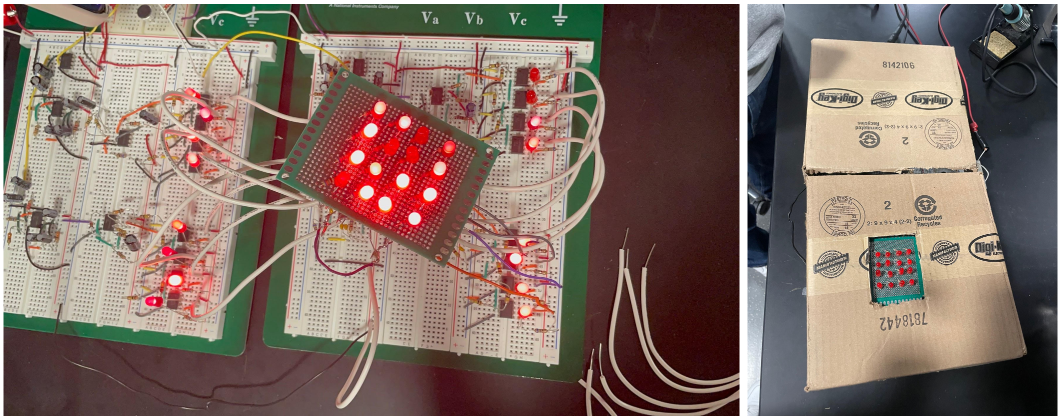
Final Circuit without Perfboard

Perfboard:

After we finished the final circuit, we decided to solder the LEDs and resistors that were connected to the comparators onto a perfboard to make the final product neater. We then soldered wires to the cathode of the LEDs so we could connect them to the outputs of the comparators on the breadboard. This functioning LED matrix was our final milestone.



LED Matrix Perfboard Layout



Final Soldered Perfboard

Challenges and Successes:

Challenges:

Filters:

Our struggles for the filter included choosing resistor and capacitor values, and we had to place some capacitors in parallel to obtain the correct capacitance for our filter design. Additionally, due to inexperience with circuitry, we made mistakes when recreating the circuit schematic on the breadboard. The incorrect wiring delayed our process and required us to debug our filter multiple times. Specifically, incorrect wiring which we didn't notice on one of our filters led to a

DC offset, but we were able to correct that by adding an RC high-pass filter to the output of that filter. Also, in order to get a cleaner signal, we had to add a buffer before our filters. However the signal was still incorrect, and we realized some time into testing that we were plugging the input AC waveform from the oscilloscope into the inverting input of the op-amp instead of the non-inverting input. After these mistakes, we paid more attention to detail and made sure to check that our circuits on the breadboard actually matched the schematics.

Peak Detector:

Our original circuit design for the peak detector using a diode, capacitor, and resistor worked well for our filter which filtered the lowest frequencies. However, when we tried to use the same circuit for our other filters, we realized that it no longer functioned properly. We tried to use a half-wave rectifier, but the signal was not large enough to charge the capacitor. We also attempted a full-wave rectifier, but after some more trial and error, we realized that adding an op amp to our prior peak detector design allowed it to function properly for the higher frequencies. Additionally, we ran into the problem of a peak voltage which was too small, so we had to amplify the signal before we could use the output of the peak detector for our next subcircuits.

Comparator and LEDs:

Initially, we used an LM339 IC instead of four LM311 ICs, and we were able to create a proper functioning column of LEDs with that IC. However, we ran out of the LM339s, so we switched to using the LM311s, which still worked similarly. In the end, we ended up replacing the single LM339 chip with four LM311s anyway. The main problem we encountered with both chips though, was that the comparator worked in the opposite way than we initially predicted. For the LM399, the row of LEDs were lighting up from top to bottom based on the voltage instead of bottom to top. So, to fix this problem, we had to change the wiring of the wires and the resistors. For example, instead of connecting input 1+ to input 2+ with a wire, we connected it with a resistor, and used a wire to connect input 1- and input 2-. Similarly for the LM311 comparators, we needed to create the voltage divider across the positive inputs instead of the negative ones. Switching the positive and negative inputs was what allowed us to properly illuminate the LEDs from bottom to top.

Microphone:

The main issue we ran into with our microphone circuit was that the output of the microphone was too small, so we needed to amplify it by a large amount. This problem was easily solved by adding an amplifier with a large gain.

Perfboard:

A problem that we encountered while testing the comparator and LEDs was that some of the LEDs we were using were broken, so we had to test that all of the

LEDs we had chosen functioned properly before we soldered them onto the perfboard. We also struggled a little with the layout of the perfboard, since we had to place both the resistors and LEDs onto the board. We were able to overcome this issue by placing the anode of the LED and a lead of the resistor in the same hole so we could solder the two components together. Additionally, we needed to connect all of the resistors to power, but the leads of the resistors were too short to place through the holes again, so we had to connect them all less securely on the back.

Successes:

In the end, we were able to create filters with frequency response graphs which matched the ones that we simulated. Also, we were able to alter the resistor values for the amplifiers to obtain the gain we needed for each particular circuit, along with choosing unique capacitor and resistor values for the four different peak detectors by testing with the oscilloscope and different audio inputs. In addition, towards the end of the semester, we were unsure if we would be able to finish soldering the LED matrix, but we managed to complete that part of our project. Ultimately, we completed a minimum viable product that met the goal of our project.

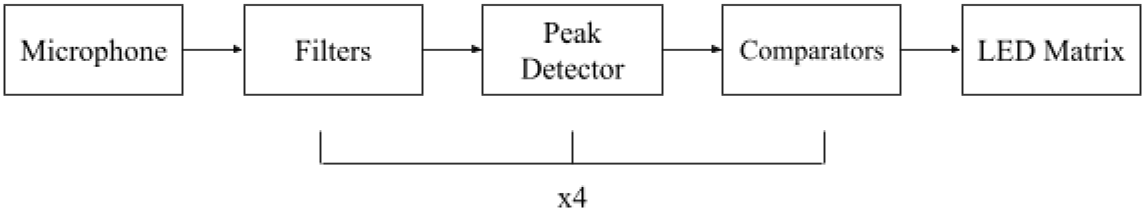
Contributions

Caroline: designed and simulated filters by choosing resistor and capacitor values; built the filters, peak detectors, and comparator circuit; soldered the LED matrix; created circuit schematics

Ashmit: designed the comparator circuit; built the filters, peak detectors, and comparator circuit; soldered the LED matrix; cleaned up the wiring of the breadboard

Conclusion

Overall, we were able to successfully complete an LED display which displayed the audio spectrum on a frequency vs magnitude graph. Our project followed the basic block diagram shown below, but there are multiple ways that the project could be improved in the future.



In our initial proposal, we sought to create a final product which was a 4x8 LED matrix, instead of a 4x4. We were unable to do so due to time constraints, but it would provide us with a way to improve our filter designing abilities and more accurately display the audio frequency spectrum. We could also try to improve our filters because currently, they successfully filter the bandwidth that we want, but also there are some additional peaks in our frequency response graphs, specifically at higher frequencies, which would interfere with our measurement of the magnitude of the frequencies. Additionally, we could consider using the 4x8 to display our current 4x4 matrix, but move that signal over to the right half of the matrix, and use the left half to display the new signal. So, the LED matrix would cycle through every few seconds. We would be able to control this cycle by switching our quasi peak detectors to actual peak detectors, which use MOSFETs. The MOSFETs would allow the capacitor to keep the peak value until the MOSFET is turned on. So, by controlling when the MOSFET is on or off using a square wave oscillator with a duty cycle that is less than 50%, we would be able to sync the peak detection of all of our filters, instead of letting the capacitors discharge at different rates through resistors. Another option to alter our project would be using the MSGEQ7 IC, which would filter the signals into seven frequency ranges without having to build any filters, so that more effort could be concentrated on the LED display. We could also consider 3D printing a case or try to diffuse the light from the LEDs, which we could choose to be different colors instead of all red.

In general, our project is an amusing way to enhance the experience of listening to a song or any other audio, and it is vibrant and eye-catching.