

Lab Report 5

Syed Murtaza Husain, Lab Partner: Caitlin Coder

June 23, 2026

Chapter 1

Introduction and Theory

1.1 Introduction to Analog Synthesizer

Analog Synthesizers are devices that generate electrical waveforms that become playable music. The early 1960's saw many of these devices built with op-amps and potentiometers, and the many different types of synthesizers used in the decades that followed defined the sounds of most popular music released at the time[1]. While the complexity of synthesizers progressed into intricate and modular circuits with lots of options for waveform alteration, the principles behind creating music through the use of circuit theory and signal processing has remained.

For our final lab project, we will create an Analog Synthesizer [2] reminiscent of the 1960's op-amp and potentiometer synths. This synthesizer consists of four main sub-circuits: An op-amp oscillator, a resistor network, a buffer, and a speaker amplifier. Together, these components will create a complete analog synthesizer that is able to play the key of C through a speaker. This instrument can be re-tuned with different values in the resistor network, and can of course be used for playing music. More generally, this circuit can be used to send one of several frequency and amplitude tuned square waves to an output, making it useful even beyond its musical applications.

1.2 Op-Amp Oscillator Theory

The very first part of the synthesizer is an op-amp relaxation oscillator circuit made with a TL081CP op-amp. In theory, this circuit will create a natural frequency square wave that can then be adjusted to obtain a proper musical frequency. Here is a diagram of the circuit:

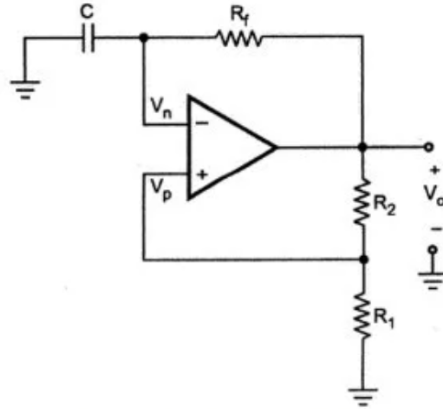


Figure 1.1: Relaxation oscillator diagram [2].

Essentially, this circuit is a Schmitt trigger with a capacitor to ground connected to the inverting input, and another feedback resistor connecting the inverting input to the output as well. As the RC properties of the circuit causes V_n and V_p to oscillate, the output will pull from the positive and negative rail voltages, which is why the output of this circuit will be a square wave. Before we derive the oscillator's natural frequency, we arbitrarily choose values for C , R_1 , and R_2 that will get us in the correct order of magnitude range for our musical frequencies (about $200Hz$ to $500Hz$). These values are $R_1 = R_2 = 220k\Omega$ and $C = 100nF$.

We've explored the properties of a relaxation oscillator in lab and lecture. The frequency of this circuit will be $f = \frac{1}{2R_f C \ln \frac{1+k}{1-k}}$ where k is determined by the voltage divider at the bottom of the circuit: $k = \frac{R_2}{R_1 + R_2}$ [3]. Then the natural frequency of the produced square wave is:

$$f = \frac{1}{2(R_f)100nF \times \ln 3} \approx \frac{4.55}{R_f} \times 10^6 \text{ Hz}$$

With resistors in the 1000Ω to 10000Ω regime, we expect the final frequency to be within the correct range.

1.3 Resistor Network Theory

The purpose of our resistor/pushbutton network is to create combinations of resistances in series that will alter the oscillator frequency to musical notes. For this project, we choose the simple key of C major. A musical key has 8 notes, so we will need 8 pushbutton switches. It's simple to calculate the wavelengths of the square waves generated with different values of R_f , and then find the corresponding frequencies. We used the equation used in the previous section, we can solve for different musical values of f and vary R_f :

$$R_f = \frac{1}{2fC \ln \frac{1+l}{1-l}} \Omega$$

Matching for all the keys in C major, we obtain the following values of total resistance:

Frequency	Note	Total Resistance
261.63Hz	C_4	17395 Ω
293.66Hz	D_4	15498 Ω
329.63Hz	E_4	13806 Ω
349.23Hz	F_4	13032 Ω
392.00Hz	G_4	11610 Ω
440.00Hz	A_4	10343 Ω
493.88Hz	B_4	9215 Ω
523.25Hz	C_5	8697 Ω

Table 1.1: Total resistances for notes.

Then we break these values up into the closest pairings of two resistors. Included in the right-most column of the following data is the difference between the resistances we will get for R_f with our pairing and the calculated resistance. As long as this difference is small (on the order of 100 Ω) the instrument should be usable and the notes will be recognizable. In theory, we can use an arbitrary amount of resistors of different values to tune the frequency. We decide to use at most two resistors in series for every key, to get close to the musical frequency without too much expenditure or effort to make the note match exactly.

Frequency	Note	R_1	R_2	Difference
261.63 Hz	C_4	2.2 k Ω	15 k Ω	195 Ω
293.66 Hz	D_4	15 k Ω	470 Ω	28 Ω
329.63 Hz	E_4	8.2 k Ω	5.6 k Ω	6 Ω
349.23 Hz	F_4	12 k Ω	1 k Ω	32 Ω
392.00 Hz	G_4	4.7 k Ω	6.8 k Ω	110 Ω
440.00 Hz	A_4	10 k Ω	330 Ω	13 Ω
493.88 Hz	B_4	8.2 k Ω	1 k Ω	15 Ω
523.25 Hz	C_5	8.2 k Ω	470 Ω	27 Ω

Table 1.2: Musical frequencies, necessary resistors in series, and differences from calculated values.

A few of the values are larger than we would like, but the notes should all be acceptably close to their actual pitches.

With these resistor values, the diagram for the resistor network is shown below:

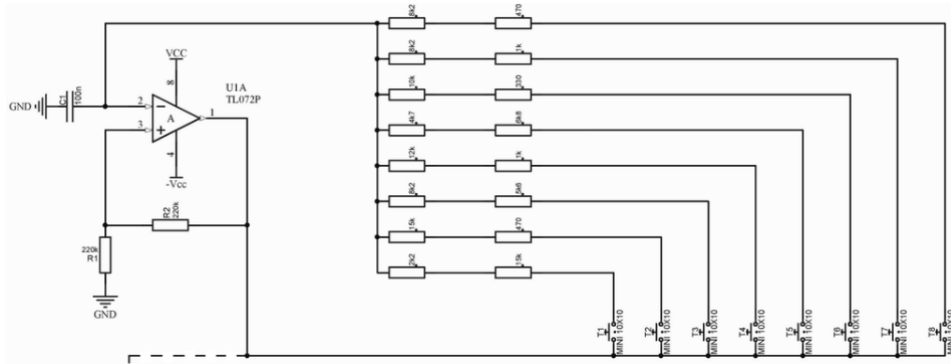


Figure 1.2: Oscillator and keys [2].

1.4 Buffer Theory

An op-amp buffer circuit separates the signal from the oscillator portion of the circuit from the speaker amplifier output. The buffer is made from an op-amp with feedback from its inverting input, but no feedback resistor. This means that the buffer should ideally let through a signal that is essentially the exact same as the input, with no gain. The oscillator signal is fed into the noninverting input, and the output is also connected to a $100\text{ k}\Omega$ log potentiometer. The signal is passed through the buffer for two reasons: to avoid loading effects by impedance matching, and by ensuring there is enough current to drive the class AB amplifier. Here is a diagram of this configuration:

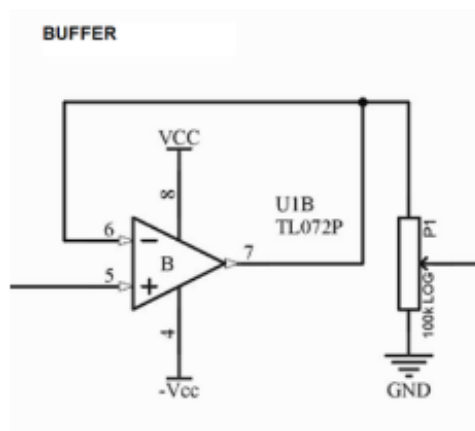


Figure 1.3: Buffer and potentiometer diagram [2].

The potentiometer is meant for volume (square wave amplitude) control over the speaker output. It essentially acts as a voltage divider between the amplifier and ground. In the next section, we will explore how this potentiometer output interacts with the transistor amplifier to control the volume of the synthesizer.

1.5 Speaker Amplifier Theory

The AB speaker amplifier in this circuit is made using two 1N4148 diodes, two $100nF$ capacitors, an NPN and a PNP transistor, and two load $22k\Omega$ resistors. The circuit diagram is shown below:

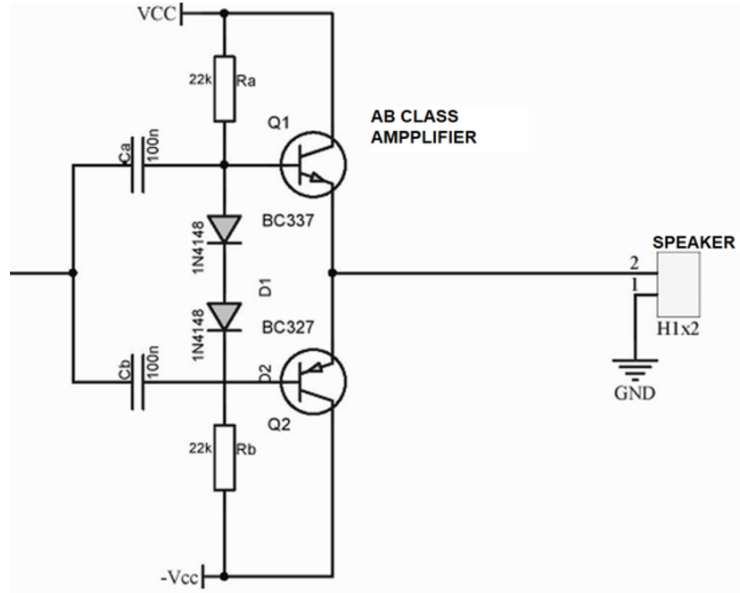


Figure 1.4: Speaker amplifier diagram [2].

The capacitors will block any DC component of the input signal, and the transistors will switch which one is conducting depending on whether the input is positive or negative. Behavior like this characterizes push pull amplifiers. In the center, the two diodes forward bias the voltages at the transistor bases. The supply voltages are $\pm V_{CC} = \pm 15V$, and the corresponding voltages at the base of transistors Q_1 and Q_2 will be just under their saturation points, which is $\approx 0.6V$. This eliminates crossover distortion from occurring in the square wave. Finally, the output between transistors will be sent to a speaker that acts as a resistive load and produces sound.

When more current is let through from the buffer's potentiometer, the amplification of the transistors will increase. Of course, the amplification depends on the transistor's base-collector relation: $\beta = \frac{I_C}{I_B}$. The current leaving the potentiometer is I_B , and increasing it will cause I_C (current taken from the collector) to increase as a response. This allows us to control the current going to the speaker, which essentially controls the volume of the synthesizer as a function of the potentiometer resistance.

1.6 Full Circuit Diagram and Parts List

With all of the major sections of the circuit covered in detail, we can now assemble the diagrams into a full circuit. Here is the diagram of the full circuit:

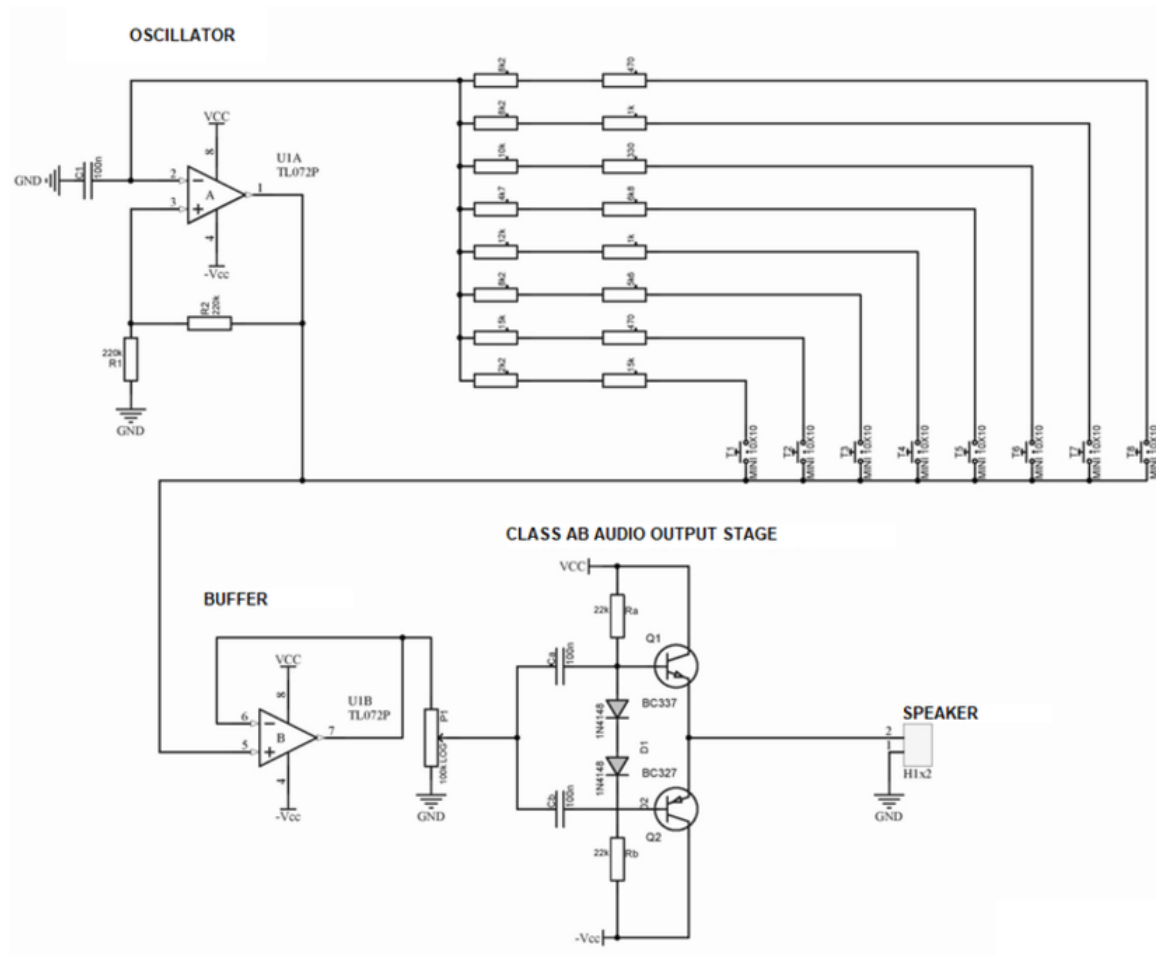


Figure 1.5: Full circuit diagram.

And here is the full list of parts required to build the circuit:

Section	Part	Type	Amount
Oscillator	TL081	Op-Amp	1
Oscillator	100nF	Capacitor	1
Oscillator	220k Ω	Resistor	2
Oscillator	8.2k Ω	Resistor	3
Oscillator	1k Ω	Resistor	2
Oscillator	470 Ω	Resistor	2
Oscillator	2.2k Ω	Resistor	1
Oscillator	15k Ω	Resistor	2
Oscillator	5.6k Ω	Resistor	1
Oscillator	12k Ω	Resistor	1
Oscillator	4.7k Ω	Resistor	1
Oscillator	6.8k Ω	Resistor	1
Oscillator	10k Ω	Resistor	1
Oscillator	330 Ω	Resistor	1
Oscillator	D6C90 F2 LFS	Switch	8
Speaker Amplifier	TL081	Op-Amp	1
Speaker Amplifier	100nF	Capacitor	2
Speaker Amplifier	22k Ω	Resistor	2
Speaker Amplifier	1N14148	Diode	1
Speaker Amplifier	BC337	Transistor	1
Speaker Amplifier	BC327	Transistor	1
Speaker Amplifier	PTV09A-4025U-A104	Potentiometer	1
Speaker Amplifier	P160KN-0QC15C100K	Potentiometer	1
Speaker Amplifier	CVS-1508	Speaker	1
Speaker Amplifier	AST-03208MR-R	Speaker	1
Auxiliary	1N4001	Diode	2
Auxiliary	Any color	LED	2

Table 1.3: All parts necessary for the project.

Chapter 2

Methods and Assembly

2.1 Equipment

Before we begin assembling the circuit in lab, we obtain the relevant equipment. This includes a breadboard, multimeter, oscilloscope, jumper cables, and all of the items outlined in the parts list.

2.2 Testing and Assembly Methodology

As we build this circuit, we plan to test each of the four stages of the synthesizer after their completion to ensure that the results are what we expect. Each main part of the circuit that we will do this for is outlined in the above theory section. Where relevant, we will collect screenshots of oscilloscope output and create tables for interesting data.

In this project, there are three components that we have not used before in lab. These components are standard pushbutton switches (not attached to the breadboard), potentiometers, and 8Ω speakers. When we have to use these in the circuit, we will briefly test each component to understand its operation, and record our findings.

Finally, our project's finished form is meant to create audio output. A link to 3 videos of us showing the finished project will be added in the results section!

2.3 Oscillator Assembly

We begin by creating the op-amp oscillator part of the synthesizer. The TL081CP op-amp is connected to rail voltages $\pm 15V$ from the breadboard power terminals. We expect to see a square wave output from this circuit. For this initial assembly, we replace the resistor/pushbutton network with a single resistor that will be used to test the circuit. We use values of $R_f = 12k\Omega$, $R_1 = R_2 = 220k\Omega$, $C = 100nF$. Our circuit then looks like this:

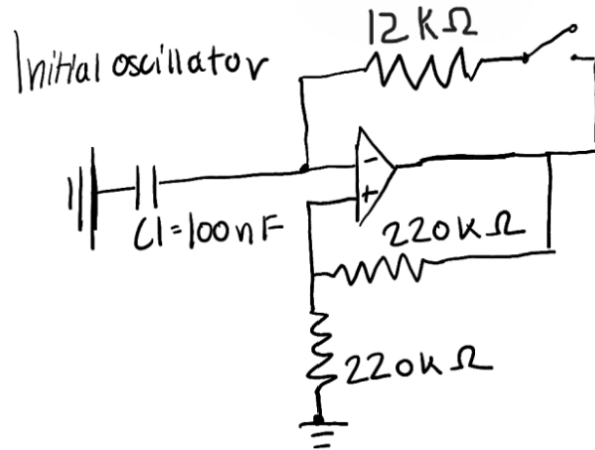


Figure 2.1: Initial oscillator diagram.

We measure the waveform leaving the output pin of the op-amp. Our circuit produces the expected output:

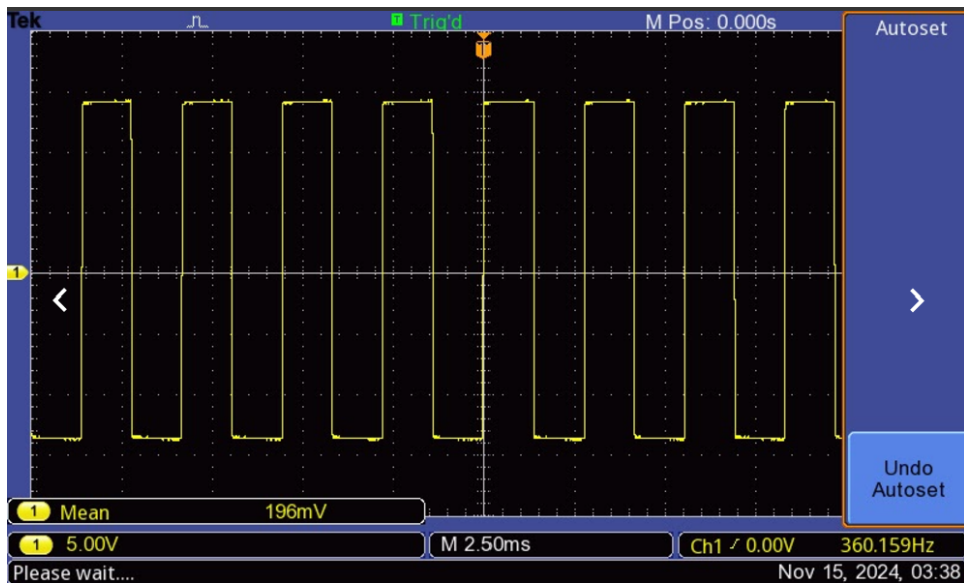


Figure 2.2: Output for oscillator circuit.

We can see that a square wave is generated as the voltage oscillation makes the op-amp pull from its positive and negative rail voltages. Next, we can analyze the frequency of oscillation.

Knowing that $R_f = 12k\Omega$ at the time we measured this frequency, we can compare our equation from theory section 1.2 to this result to make sure the values match. The calculated value is:

$$f = (2 \times 12000\Omega \times 100 \times 10^{-9}nF \times \ln 3)^{-1} = 379 Hz$$

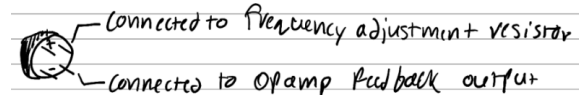
As seen in the screenshot, our experimental value was 360 Hz . The experimental and theoretical values are very close, and the 20 Hz error could be due to any of the resistors or the capacitors having values different than their nominal values.

Next, we replace the $12\text{ k}\Omega$ resistor with a larger one to observe how the frequency responds. After replacing $R_f = 100\text{ k}\Omega$ and then $R_f = 330\text{ k}\Omega$, we note that the frequency of the square wave decreases as expected.

2.4 Resistor Network Assembly

With our initial oscillator assembled, we move on to the resistor/pushbutton network portion of the synthesizer. We use the resistance values calculated in the theory section (Table 1) for the resistor pairs when fully constructing the network.

Initially, we use the combination for the note C_4 , $R_1 = 2.2\text{ k}\Omega$ and $R_2 = 15\text{ k}\Omega$, to test our pushbutton. The pushbutton has two rows of pins that correspond to $+$ and $-$ symbols. We connect to the $+$ row to the resistors and the $-$ row to the feedback output, and find that this achieves the result we want. When the button is pushed down, we see that the square wave is let through. Here is an illustration of the button configuration we found:



Next, we complete the entire network with the 7 additional pairs of resistors and pushbuttons. With each, we confirm the expected behavior and find that the frequency values are slightly different than the exact desired musical frequencies. This is expected because of how the resistance values were calculated (the differences between the resistor values used and resistor values needed is shown in the theory section.) Another source of deviation could be differences in actual resistance to nominal resistance, or slight variation in the initial oscillator frequency. A table of these values is shown below:

Note	Desired Frequency	Obtained Frequency
C_4	262 Hz	250 Hz
D_4	294 Hz	276 Hz
E_4	330 Hz	312 Hz
F_4	349 Hz	333 Hz
G_4	392 Hz	373 Hz
A_4	440 Hz	428 Hz
B_4	494 Hz	467 Hz
C_5	523 Hz	500 Hz

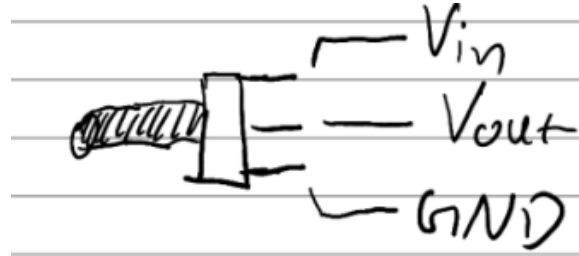
Table 2.1: Desired vs obtained musical frequencies.

With our slightly out of tune resistor network, we move on to the next part of the circuit.

2.5 Buffer Assembly

To create the buffer, we use another TL081CP op-amp and feed the oscillator output into the noninverting input. The inverting input is fed back the op-amp output with no resistor in between.

Because the gain of this circuit at this point is 1, this is a buffer and not an amplifier. Next, we will attach our volume controlling potentiometer. We use a $100k\Omega$ log potentiometer after the buffer. To determine how to connect the potentiometer, we test connections on the three bottom pins and adjust the value til we can make a clear diagram:



The top pin takes V_{in} , and runs it through the chosen resistance to obtain V_{out} . We attach ground to the bottom pin of the potentiometer. Now, we check to see if our output matches what we expect. When the potentiometer is on its lowest resistance setting and any button is pushed, we expect that $V_{in} \approx V_{out}$. Similarly, with the highest resistance setting, we expect $V_{out} \approx 0$. For any other value, we expect that V_{out} is some fraction of V_{in} that will change logarithmically in proportion to how much the potentiometer is twisted (because this is a log pot). We take three screenshots of the buffer and potentiometer output and confirm that our results match theory:

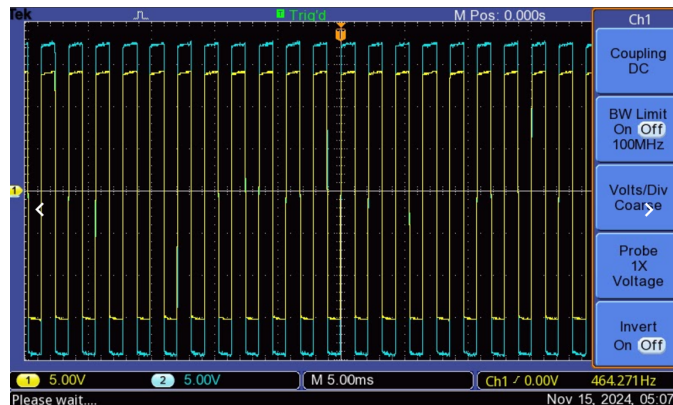


Figure 2.3: Output for lowest resistance potentiometer setting.

Here, the waveform coming out of the potentiometer is essentially unchanged from its input. This is what we expect when we have the potentiometer on low, because there is not much resistance blocking the signal, so the voltage drop will be unnoticeably small.

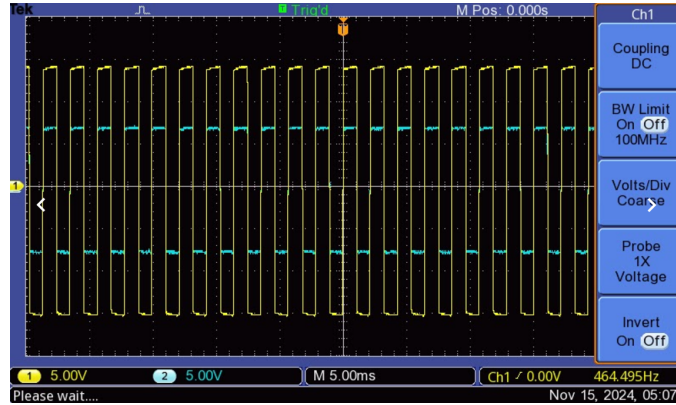


Figure 2.4: Output for middle resistance potentiometer setting.

When we turn the potentiometer enough, we can see the output start to fall off. The output for this waveform is roughly half of the input, but we make a note that we did not turn the knob exactly proportionally to this change. This is because of the logarithmic nature of the potentiometer, which causes the shift in resistance not to be proportional to the amount it is turned.

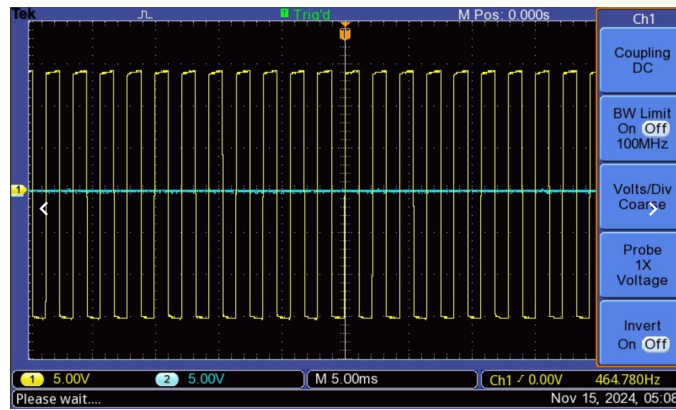


Figure 2.5: Output for highest resistance potentiometer setting.

Finally, we observe that the highest setting of the potentiometer lets almost no current through, and blocks the signal completely.

2.6 Speaker Amplifier Assembly

Now, we move on to the creation of the speaker amplifier, the last main part of the circuit. We assemble the circuit using $C_1 = C_2 = 100 \text{ nF}$, $R_1 = R_2 = 22 \text{ k}\Omega$, and two 1N4001 diodes. Then, we drive the circuit $V_{CC\pm} \approx \pm 12V$ and $V_{in,pp} = 4V$. However, we failed to account for the fact that the speaker we used has a power limit that is much lower than the power we are delivering to it. After a few seconds of this speaker playing, it burns out and stops working. We check the data sheet for this CVS-1508 speaker and find that it has a power limit of $\frac{1}{2}W$ [4]. Given that the speaker

has a resistance $R = 8\Omega$, we can calculate the maximum current that should be going through the speaker:

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{0.5\text{ W}}{8\ \Omega}} \approx 0.25\text{ A}$$

To see what we were delivering to the speaker, we take the following screenshot of the signal to the speaker when a key is pressed down (potentiometer at low resistance):

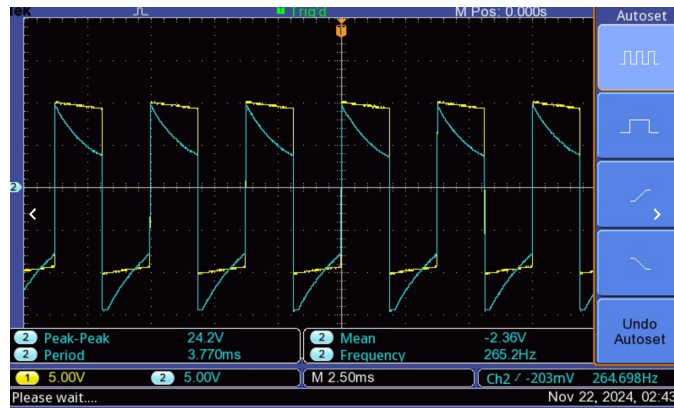


Figure 2.6: Signal to speaker screenshot.

At this point, our amplifier looks like the following:

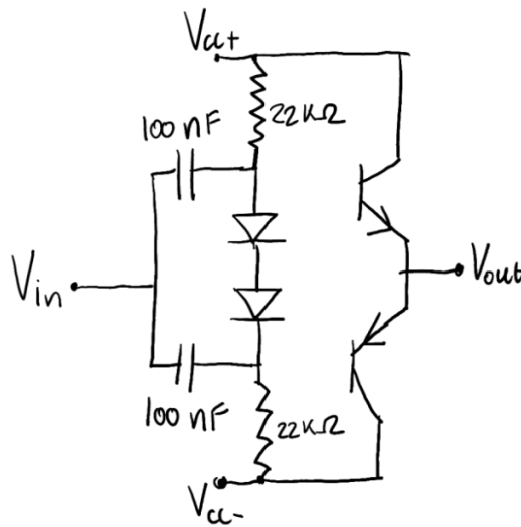


Figure 2.7: Amplifier circuit diagram.

The large voltage ($\approx 24V$ *pp*) explains our failure with the first speaker. This voltage means that $I = \frac{24V}{8\Omega} = 3 A$. Trying again with our second speaker, the AST-03208MR-R, we make sure to check the power limit first and foremost. The data sheet for this speaker tells us that the power limit is $\frac{1}{5}W$ [5]. Using the same formula, we can find the maximum current that can safely be put through the new speaker:

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{0.2 W}{8 \Omega}} \approx 0.16 A$$

We change the circuit to be driven using values of $V_{CC\pm} \approx \pm 15V$, $V_{in,pp} = 4V$. We take a screenshot of the potentiometer output vs the input of the speaker and find this waveform:

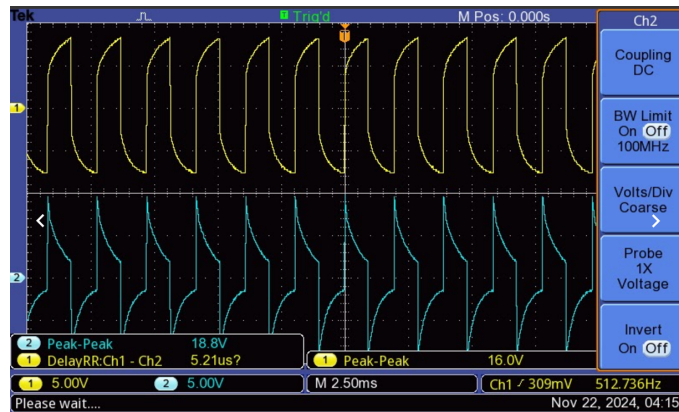


Figure 2.8: Pot output vs speaker input.

The potentiometer output can be explained by the capacitors we use to connect the buffer stage to the speaker amplifier stage. Charging and discharging causes these rounded peaks. Meanwhile, the sharp peaks and slower decays of the speaker input can be explained by the RC filtering process, which causes a more jagged-looking signal as the capacitors charge and discharge. As the diodes drain in and out of saturation, the waveform will become sharper. The transistor switching explains the oscillation, as the positive and negative sources are used to amplify the potentiometer output by β into the speaker.

Now, the voltage across the speaker is $\approx 18.8 V$ *pp*. To account for the lower voltage limit, we decide to add in a $2k\Omega$ resistor between the power input and the speaker to make sure that the power in to the speaker is within the limit. Now, the current through the speaker is $I = \frac{18.8V}{2008\Omega} = 0.009 A$, which is well within the safe limit.

At this point, we want to confirm the operation of our circuit is as expected, and want to do this without the speaker inserted to be cautious. We obtain some characteristic screenshots of the behaviors at different points of the circuit:

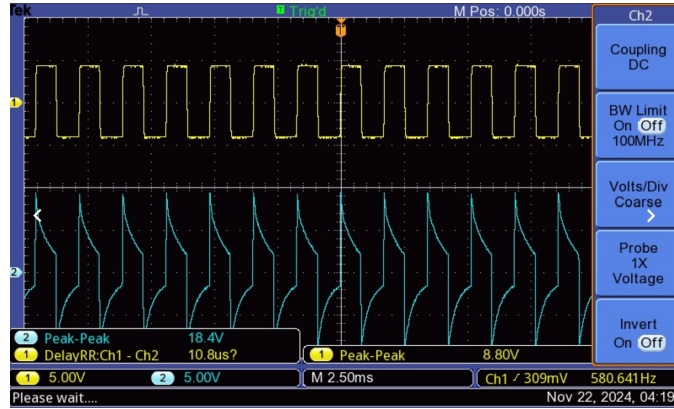


Figure 2.9: Buffer output (pin 3) vs speaker input.

The buffer output is as we expect it to be as well, a perfectly reproduced copy of the oscillator waveform. It is shown in the above screenshot with the previously described speaker input wave.

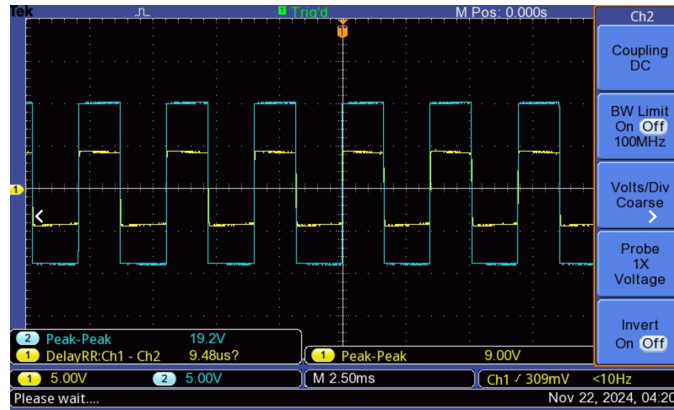


Figure 2.10: Oscillator output (pin 3) vs oscillator output C_4 key.

Finally, we can see the amplification of the key frequency using the op-amp oscillator pulling from its rail voltages. With these characteristic screenshots, we have confirmed that all parts of the project operate as intended. Pressing the keys on the oscillator complete the circuit, and the signal to the buffer where it is held and protected from distorting effects. Then, the signal is altered in amplitude by the potentiometer, and amplified by the transistors. The wave then reaches the speaker, and we can hear the output.

Chapter 3

Results

3.1: Finished Synthesizer

Finally, our synthesizer is finished! Here is a picture of the finished circuit on the breadboard:

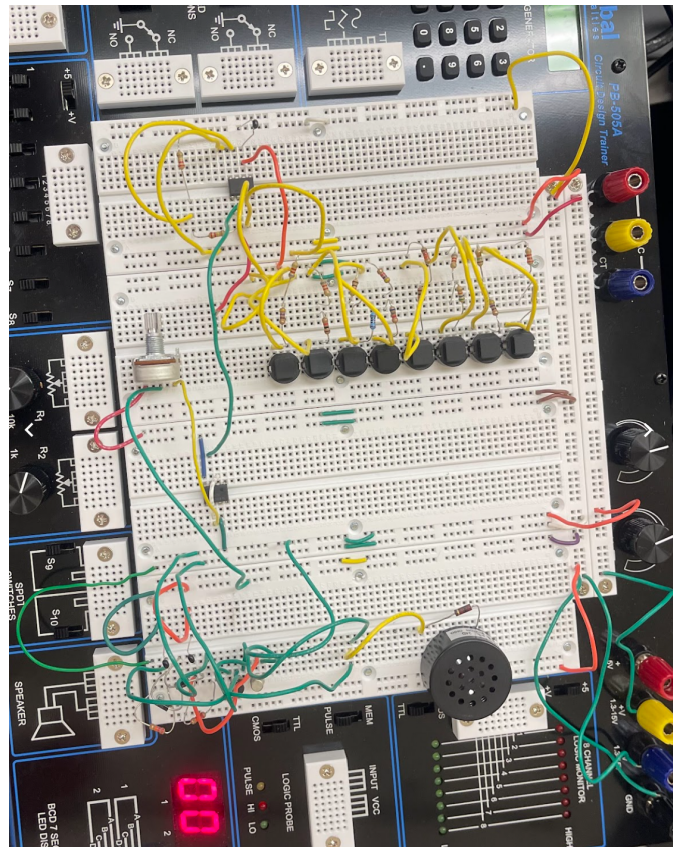


Figure 3.1: Full circuit assembled.

We can hear the output from the speaker, and even play some songs using the keys (as long as the songs are in C!).

3.2: Multiple Notes

An interesting result we come across when playing the synthesizer is that holding down multiple pushbuttons at once will add the resistances of each key in parallel, and lead to a higher frequency. If we use the equivalent resistances of the resistor pairs that constitute each note, then we can calculate the frequency of two pushbuttons being pressed at the same time with the formula for resistors in parallel:

$$f = \frac{1}{2\left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1} C \ln \frac{1+l}{1-l}}$$

Or we can generalize this as:

$$f = \frac{1}{2RC \ln \frac{1+l}{1-l}}$$

With

$$R^{-1} = \sum_n^N \frac{1}{R_n}$$

Where there are N total keys and R_n are resistances in series of each key.

3.3: Playing a Song!

In the shared drive linked below, we include videos of the resistances adding when we play multiple notes at once, the entire scale being played, and a performance of *Ode to Joy* by Beethoven to complete the project. Enjoy!

Link: https://drive.google.com/drive/folders/1tdAj0Z9FINEYluf7_nV8E_hBiDPleiPJ?usp=drive_link

3.4: Conclusion

In conclusion, we have shown how the principles of signal processing and circuit theory can be applied to create a simple instrument that plays the key of C. Using techniques similar to those used in the first analog synthesizers, we have created a fully functioning keyboard. This project has also broadly encompassed many of the topics that we learned in lecture and lab, including op-amp circuits, transistor circuits, diodes, and more.

