Guitar A-String Tuner Circuit

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Introduction:

As the final project in Engineering 84, Electric & Magnetic Circuits & Devices, we decided to build a circuit for a guitar tuner. As two individuals who are entranced by music, and gaining the knowledge from this course, this circuit decision was a no-brainer. The overall circuit is comprised of two subcircuits. The first is an application circuit for the CMA-4544PF-W Electret Condenser Microphone with MAX4465 Microphone Preamplifier (Figure 1). This circuit takes an output AC voltage from the microphone which is then set through a high-pass

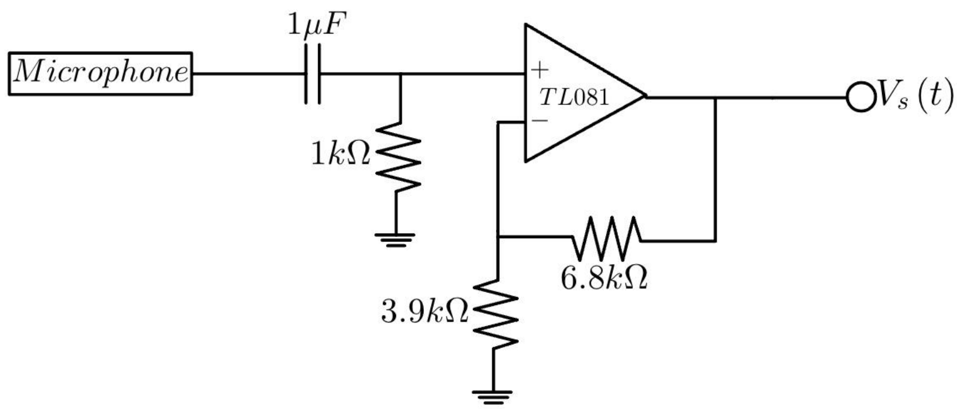

Figure 1: Adafruit Electret Adjustable Pin Microphone Application Circuit Drawing

filter with a corner frequency below that of any guitar string to get rid of any DC bias and is finally amplified and sent into the tuner circuit (Figure 2). This is a more complex circuit with two nearly identical branches. These branches control two LEDs at the end of the circuit in which one or both of the LEDs, depending on the frequency of the input, will turn on. Guitar

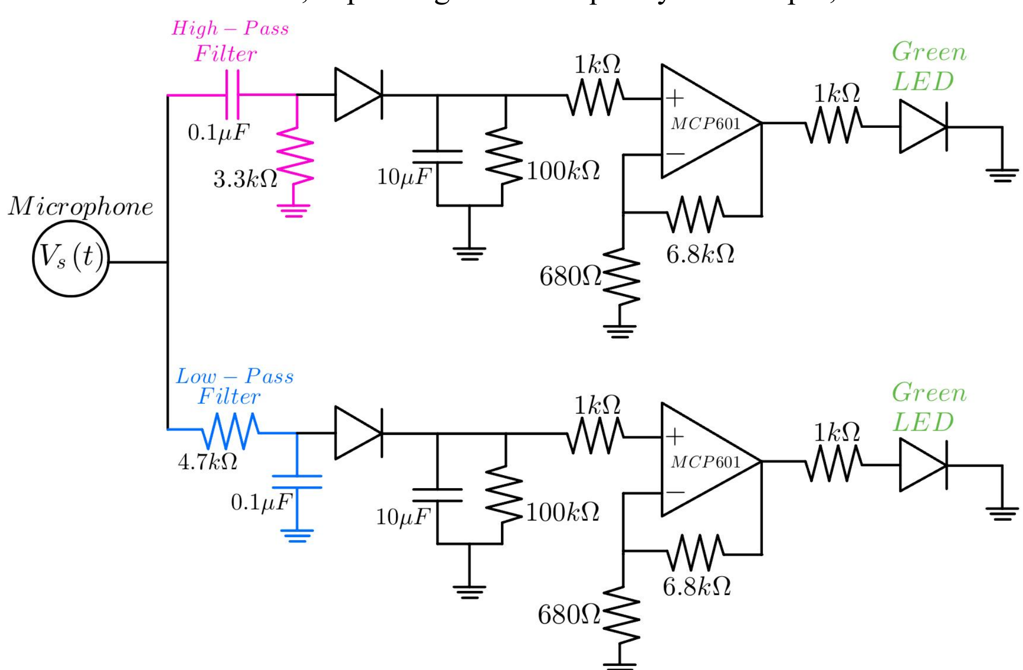

Figure 2: Guitar A-String Tuner Circuit Drawing

strings play at some determined resonant frequency. In our circuit, we decided to target the A-string of a guitar which plays at 440 Hz. The first branch filters out inputs below the desired note frequency, and the second filters out inputs above the desired note frequency. From here, the high- and low-pass branches do the exact same thing. The signals are sent into a half-wave rectifier so that only the positive portion of the signals continue to be amplified by the op-amp. The op-amp is a non-inverting op-amp that gains the signals to be above the forward voltage of a Green LED, 2V. The low-pass LED will light up if the signal is at the desired frequency or lower and the high-pass LED will light up if the signal is at the desired frequency or higher. As a result, you can successfully tune the A-string of the guitar by playing it into the microphone of the circuit. If only the low-pass LED lights up, you know you will need to tune the string higher. If only the high-pass LED lights up, you know you will need to tune the string lower. And if both LEDs light green, then you know that the string is at the desired 440Hz frequency.

Parts:
- MCP601 Op-Amp (x2)
- TL081 Op-Amp (x1)
- CMA-4544PF-W Electret Condenser Microphone with MAX4465 Microphone Preamplifier (x1)
- Green LED (x2)
- 1 kOhm Resistor (x5)
- 100 kOhm Resistor (x2)
- 6.8 kOhm Resistor (x3)
- 3.9 kOhm Resistor (x1)
- 4.7 kOhm Resistor (x1)
- 3.3 kOhm Resistor (x1)
- 680 Ohm Resistor (x2)
- 10 uF Capacitor (x2)
- 1 uF Capacitor (x1)
- 0.1 uF Capacitor (x2)
- Diode (x2)

Circuit Design:
1. Circuit Construction (Microphone Application Circuit)
   When done, circuit hardware should resemble Figure 3 below

   1.1. Locate the Adafruit Electret Condenser Microphone and Preamplifier (Note: may use the microphone of your choice, but the circuit may vary if you use a different one than recommended)
   1.2. Take a 1uF capacitor and 1kΩ resistor and create a passive high-pass filter (corner frequency 159Hz) by connecting the capacitor in series with the microphone's output signal and the resistor in parallel with the capacitor output to ground
   1.3. Pass the capacitor output into a TL081 Op-Amp (or another dual rail op-amp)
   1.4. Construct a non-inverting op-amp (Gain = 1 + 6.8/3.9) by connecting a 3.9kΩ resistor from the negative input of the op-amp to ground and a 6.8kΩ resistor from

the negative input to the output of the op-amp
(Note: depending on the strength and sensitivity of the preamplifier in the microphone, you may need to adjust this op-amp gain to find an ideal value for your circuit. To increase the gain, either exchange the 6.8kΩ resistor for one larger or a 3.9kΩ resistor for one smaller. To decrease the gain, do the opposite)

1.5. Power the microphone with 5V and the positive and negative supply rails of the op-amp with 5V and -5V respectively.

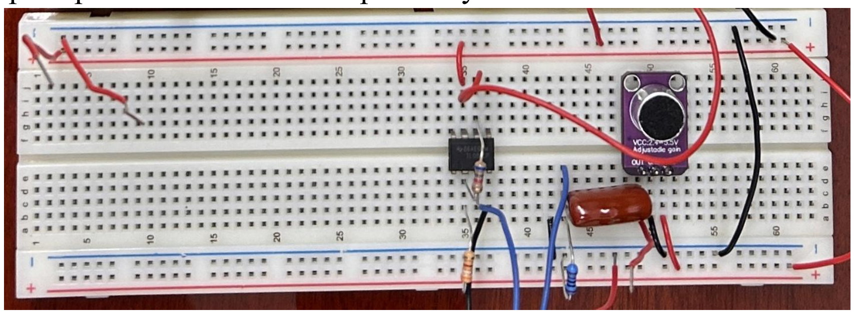

Figure 3: Adafruit Electret Adjustable Pin Microphone Application Circuit Hardware

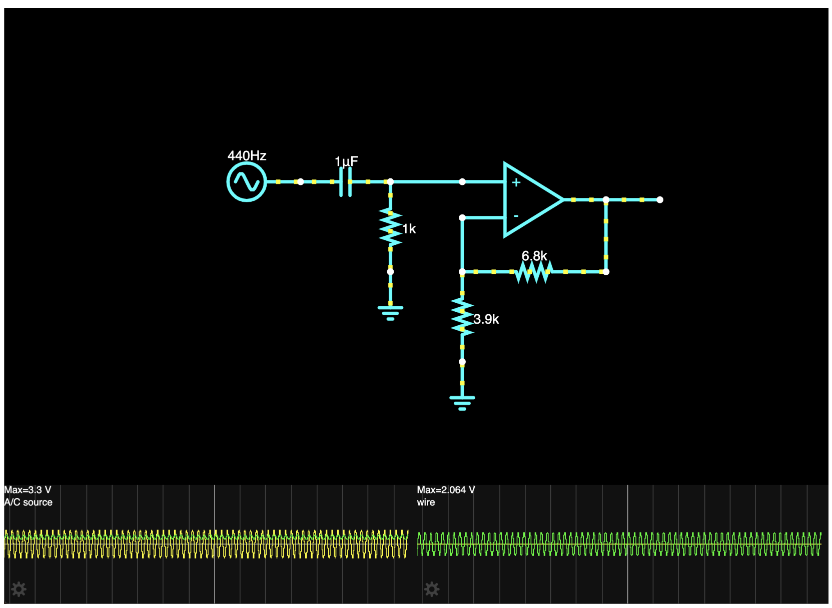

Figure 4: Adafruit Electret Adjustable Pin Microphone Application Circuit Simulation (Microphone output modeled at desired 440Hz and expected 0.8V peak-to-peak). Scopes: input to circuit, output from circuit

2. <u>Circuit Construction (Guitar Tuner Circuit)</u>
When done, circuit hardware should resemble Figure 5 below

2.1. Pass the output from the microphone application circuit into the rails of a new breadboard

2.2. Construct a high-pass filter (corner frequency 482Hz) by connecting a 0.1uF capacitor in series with the microphone output and a 3.3kΩ resistor in parallel with the capacitor output to ground

2.3. On the other side of the breadboard, construct a low-pass filter (corner frequency

339Hz) by connecting a 4.7kΩ resistor in series with the microphone output and a 0.1uF capacitor in parallel with the capacitor output to ground

2.4. Connect a half-wave rectifier to the output of the capacitor from the high-pass filter
   2.4.1. Put a diode ($V_F = 0.7V$) in series with the output
   2.4.2. Connect a 10uF and 100kΩ resistor in parallel to the output from the diode to ground

2.5. Pass the output from the half-wave rectifier into a 1kΩ resistor and then into an MCP601 (single rail) op-amp

2.6. Construct a non-inverting op-amp (Gain = 1 + 6.8/0.68) by connecting a 680kΩ resistor from the negative input of the op-amp to ground and a 6.8kΩ resistor from the negative input to the output of the op-amp

2.7. Connect the positive voltage supply of the op-amp to 5V and the negative voltage supply of the op-amp to ground

2.8. Pass the output from the op-amp into a 1kΩ resistor and finally into a Green LED. Connect the other end of the LED to ground

2.9. Repeat steps 2.4-2.8 with the low-pass filter branch

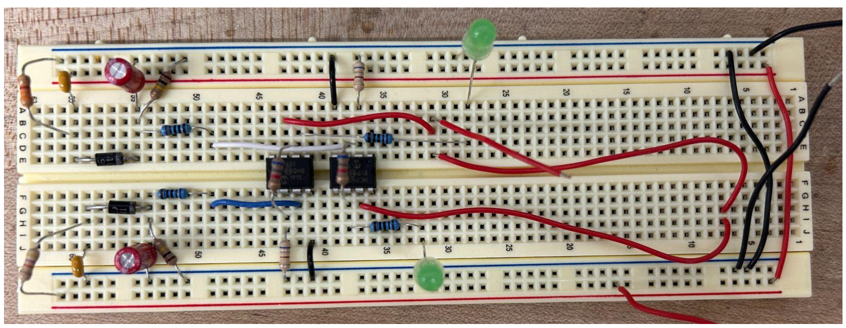

Figure 5: Guitar A-String Tuner Circuit Hardware

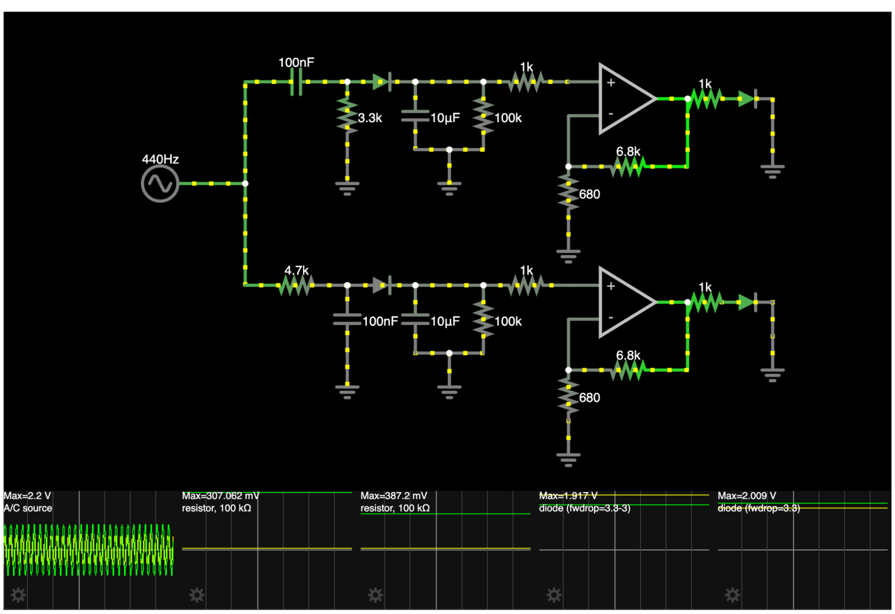

Figure 6: Guitar A-String Tuner Circuit Simulation (Vs modeled at desired 440Hz input and expected 2.2V peak-to-peak) Scopes: Input, Low-pass half-wave rectifier, high-pass half-wave rectifier, low-pass voltage drop

across the Green LED, high-pass voltage drop across the Green LED

3. <u>Testing the Circuit:</u>

3.1. Turn on the oscilloscope and connect scope probes to the microphone output, and the voltage drops across both diodes.
(Note: the circuit will tell you if it is working by the expected LEDs lighting up or not. These scopes are more of a sanity check. Can also connect a probe to the output of the microphone circuit if you wish)

3.2. Play a note of designated low frequency into the microphone and check that only the low-pass LED lights up. Also, check that the voltage drop across the low-pass LED is at the V_D of the diode, 2V, while the voltage drop across the high-pass diode is below that. (Figure 7)

3.3. Play a note of designated high frequency into the microphone and check that only the high-pass LED lights up. Also, check that the voltage drop across the high-pass LED is at the V_D of the diode, 2V, while the voltage drop across the low-pass diode is below that. (Figure 8)

3.4. Play a note of the designated desired frequency into the microphone and check that both LEDs light up. Also, check that the voltage drop across both LEDs is at the V_D of the diode, 2V. (Figure 9)

Figure 7: System Output at Frequency Below A-Note (Input 300 Hz)

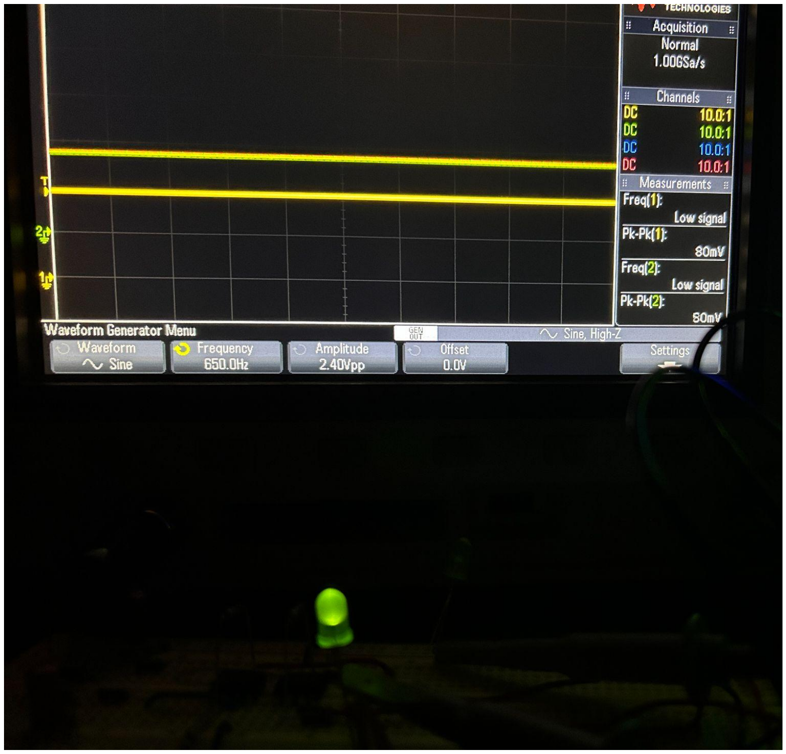

Figure 8: System Output at Frequency Above A-Note (Input 650Hz)

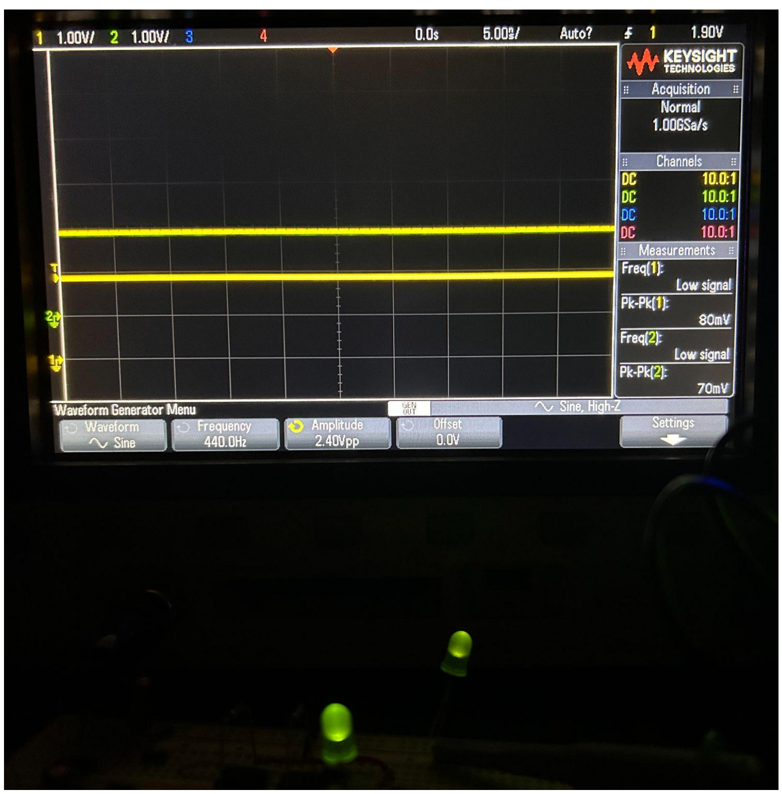

Figure 9: System Output at Desired A-Note (Input 440Hz)

4. Circuit Analysis (Microphone Application Circuit) (Figure 1)

The signal produced by the microphone is consistently around 700-800mV peak-to-peak centered at half of the supply voltage, in our case this centers the signal at 2.5V. The signal needed to drive the tuner circuit is 1.8V – 2.5V centered at 0V. The objective of this circuit is to transform the signal from the microphone's output to the desired input for the tuner circuit. This requires a two-step process, the first is to get rid of the DC bias introduced by the microphone's supply voltage, and the second is to gain the signal. The first step is done by constructing a passive high-pass filter, consisting of a capacitor and resistor. The corner frequency of this filter is given by $1/\tau$, where the time constant τ is given by RC. Using a 1kΩ resistor and 1uF capacitor, this gives a corner frequency of $1/\tau = 1000$ rad/s. We can then convert this to Hz by dividing by 2π giving us a corner frequency of 159Hz. This value was chosen as the lowest frequency guitar string is the "Low E" at about 330Hz. Therefore, any string note played into this high-pass filter should pass through to the rest of the circuit. The second part of the circuit consists of a non-inverting gain amplifier. The range needed for the tuner circuit is very specific as anything below 1.8V will have too much of a voltage drop before the diode in the half-wave rectifier and thus the signal will not be able to pass onto the LEDs, whether or not it is at the desired frequency. Conversely, a signal above 2.5V will result in enough voltage to power the diode on the low-pass branch, effectively holding this LED on even if the frequency is way above the low-pass filter's corner frequency. Therefore, we decided that a gain of approximately 3 would be ideal for this circuit. We calculated the gain of the non-inverting amplifier as $1 + R_f / R_s$. This analysis comes from the voltage representation $V_{out} = V_{in} (1 + R_f / R_s)$. Therefore, we needed to choose a resistor R_f that was approximately double that of R_s to get a gain of 3. Based on the list of standard resistors, we chose $R_f = 6.8k\Omega$ and $R_s = 3.9k\Omega$ which gives a gain of 2.75 and places the signal in the voltage range we are looking for.

5. Circuit Analysis (Guitar Tuner Circuit) (Figure 2)

As mentioned, the Guitar Tuner Circuit takes the output of the microphone application circuit as its input. The objective of this circuit is to determine if a note played into the microphone is too high, too low, or just right, effectively tuning the A-string on a guitar. The upper branch in the circuit design passes the signal through a high-pass filter with a corner frequency set to 482Hz. This is determined by taking $1/\tau$ and dividing by 2π, where $\tau = RC$. We chose a capacitor value that would be consistent for both the high and low-pass filters, therefore, we chose 0.1μF. This gave us a resistor value of 3.3kΩ. Therefore, if the signal from the microphone is below this 482Hz frequency, the signal will not pass on to the rest of the circuit. The lower branch in the circuit design passes the signal through a high-pass filter with a corner frequency set to 339Hz. This is determined by taking $1/\tau$ and dividing by 2π, where $\tau = RC$. We chose a capacitor value that would be consistent for both the high and low-pass filters, therefore, we chose 0.1μF. This gave us a resistor value of 4.7kΩ. Therefore, if the signal from the microphone is above this 339Hz frequency, the signal will not pass on to the rest of the circuit. It is important to note that because these are passive filters, there is some spillover that puts the true boundary of the high- and low-pass filters closer to the desired 440Hz.

Following each filter are two identical branches. The first part of the branches is a half-wave rectifier constructed by a diode and a capacitor and resistor in parallel. The effect of this is the positive peak of the signal passing through the diode, however, the negative portion and any voltage below the forward voltage of the diode will not pass on. While the signal is negative and not passing through the diode, the capacitor and resistor will hold a voltage until the capacitor discharges, given by the time constant, RC. For this portion of the circuit, we wanted the signal to discharge by a negligible amount < 0.001V. To find resistor and capacitor values that satisfied this, we looked at the discharge equation of the rectifier, $e^{-t/\tau} = 1 - \Delta v/V_{out}$. From plugging in our known values ($t = 0.0027s$, $\Delta v = 0.001V$, $V_{out} = 0.4V$) we were able to use the equation to solve for RC. From this, we obtained RC = 1.1, and using normalized values for resistors and capacitors, we chose 100kΩ and 10μF, respectively (RC = 1).

After the half-wave rectifiers, we need to gain the signal of each branch above the forward voltage of a Green LED, 2V. To do this, we use a non-inverting op-amp. Therefore, the LED will turn on given that the signal was passed through by the high pass filter. We chose an MCP601 op-amp for this as it is single-railed and rails out at 5V. Additionally, we wanted to ensure that the 0.4V signal from the half-wave rectifier would be amplified well above the 2V forward voltage of the op-amp to account for any error in the circuit. Therefore, we logistically decided on a gain of 11 where the gain is given by $1 + R_f / R_s$. Therefore, we knew that our R_f value would need to be ten times that of our R_s value. Based on the list of common resistors, we chose these values to be 6.8kΩ and 680Ω, respectively. You would notice that there is also a 1kΩ resistor before the op-amp, however, the output of the op-amp is independent of this resistor and we chose this value as a buffer. Finally, the output of the resistor is fed into another buffer 1kΩ resistor and the green LED. If just the LED from the top branch lights up, then we know that the signal is too high and we need to tune the string down. Similarly, if just the LED from the bottom branch lights up, then we know that the signal is too low and we need to turn the string up. If both LEDs light up, then we will know that the string has reached the desired frequency of 440Hz and will have successfully tuned the string to be the A note.

Reflection:

The original design for the Guitar tuning circuit was extremely close to the final product seen in Figures 2 and 5. The only changes made to this circuit were done in the highpass and lowpass filter components of the resistors. Previously, we found that putting the corner frequency of the filters at 440Hz would result in resistors and capacitors of 3.6kOhms and 0.1uF. However, in testing, we found that it is more beneficial if the high-pass filter's corner frequency is a little above 440Hz and the low-pass filter's corner frequency is a little below 440Hz. The reasoning for this is that we are using passive filters, so our signal does not get cut off right at the corner frequency. By setting our high-pass filter above the desired value and the low-pass filter below the desired value, we see a sharper cutoff at 440Hz. Therefore, we chose the high-pass filter to have a resistor of 3.3kOhms giving a corner frequency of 482Hz and the low-pass filter to have a resistor of 4.7kOhms giving a corner frequency of 339Hz.

There were many changes made to the microphone circuit throughout this project. We originally intended to use the electret microphone that was used in the class E80, CME-1538-100LB. When testing this microphone, we noticed extremely inconsistent output values. The voltage output ranged anywhere from 300mV to 700mV peak-to-peak, much different than the 1V we were seeing during initial testing last week. Luckily, our friend, Tjaard, was in the lab and happened to have an extra CMA-4544PF-W Electret Condenser Microphone with MAX4465 Microphone Preamplifier. When testing the new microphone we noticed a much more consistent output, smoother sinusoid, with a larger voltage peak to peak (700-800 mV).

With this new microphone, we originally created a 2 op-amp circuit. The first op-amp was used to offset the center of the sinusoid, as we noticed that the sinusoid out of the microphone was centered at half of the supply voltage and not zero. We needed to center the sinusoid at 0 volts to ensure that no DC bias would be carried into our guitar tuner circuit. If the bias was left, the low pass LED would be lit by this DC bias continuously. The second op-amp was used to gain the output voltage of the microphone to ensure that the needed voltage range for the guitar tuner (1.8 - 2.5 V) was created. In testing this circuit, we found that the offset was not correctly offsetting the sinusoid to be centered at 0V. At this point, we decided to go back to the drawing board. In conversation with Eli Rejto, we determined that the easiest and most efficient way to center the sinusoid at 0 volts was a high pass filter. We set the corner frequency of this high-pass filter really low to ensure that all signals would pass through it, while also getting rid of the DC bias. We still needed to gain the output voltage of the microphone, so we used the gaining op-amp from the original circuit. The new circuit consisted of a high pass filter with a 1 μF capacitor and a 1kΩ resistor and a gaining op-amp with resistor values of 3.9kΩ and 6.8Ω.

The final circuit design worked incredibly well. However, there were some sources of error within our circuit. The first is that the high- and low-pass filters do not drop off right at the 440Hz mark and therefore will allow frequencies of about 100Hz above or below through. This means that, when tuning the guitar string, we may not be able to get the exact 440Hz desired. However, since the LEDs dim, we should be able to get fairly close to this. We estimate that this causes an error of 5-10% as there is noticeable dimming 50Hz above and below the desired signal. The next source of error lies in the microphone circuit. When playing notes into the microphone, we consistently got 700-800mV, as stated previously, however, this amplitude is dependent on how loud the note is played. Although we played at multiple different volumes and still saw this output range, our input voltage must be above the 0.7V forward voltage of the diode in the half-wave rectifier. To account for this error, we gained the signal by a factor of 3 so that our expected input voltage does not drop below 2V.

Lessons Learned

1. Simulations are a great tool but do not reflect real-world errors that will inevitably be encountered.
2. Accept that when creating a circuit, it probably won't work on the first try.
3. Ask your friends for their opinions and knowledge…and microphones.
4. Take your time to understand why simulations and real-world outputs are not the same.
    a. It will make fixing the circuit much easier.
5. Use the oscilloscope probe on anything you can.
6. Have fun! Build circuits that interest you!
7. Start on circuit building and analysis early.