EECS 16B
March 9 2023

Lab 1

Summary

- Give a summary in your own words of what you did in this lab. Possible details to include: overview of the lab's objective, new components used, issues you encountered, etc. Details NOT to include: how you left your car at home, forgot to enable high-Z mode on your function generator, etc.

So for this very first lab, we got back into the rhythm of using the Digital Multimeter (DMM) and Oscilloscope and reminding ourselves of the usage and purpose of each. Then in the main part of the lab, we were instructed to build an OP-AMP, which its function in short is to amplify any weak electrical signal and to output the voltage from the two output pins. During this lab, it did go smooth for the most part with the exception of some of the resistors not being put in the right place for our circuit board in terms of its alignment hence why our numbers both on the DMM and Oscilloscope were slightly off, in addition to our LED lights not lighting up.

1. Assume that the following equipment corresponds to what is available in the lab.
   - a. Describe a situation where you would use a digital multimeter (DMM) instead of an oscilloscope and vice versa. In short, think of the DMM to get a numerical measurement of things such as current, voltage, and resistance. Oscilloscope is used more so as a VISUAL representation of displaying waveforms and its variation of voltage over a certain period of time.
   - b. Describe a situation where you would use a power supply instead of a function generator and vice versa. Simply put, a power supply is one that converts any given electric current to the desired input value from the user to the correct voltage, current, frequency to a power load. A function generator is a tool that is vital for checking whether or not the functionality of a certain component, and produces waveforms usually in sine/square waves and through discernment of how the waves appear like on the screen, it gives a good indication of whether or not a piece of equipment that is tested by a power supply is working as intended.

2. Given an op-amp amplifier circuit with gain
Av (can be positive or negative) and an input sinusoidal wave with DC offset *b* and maximum amplitude *a*, what are the most restrictive values of *VDD* and *VSS* for the op-amp such that the output is not distorted?

$V_{in} = (a\sin(x) + b)\,A_V$

↑

we can maximize

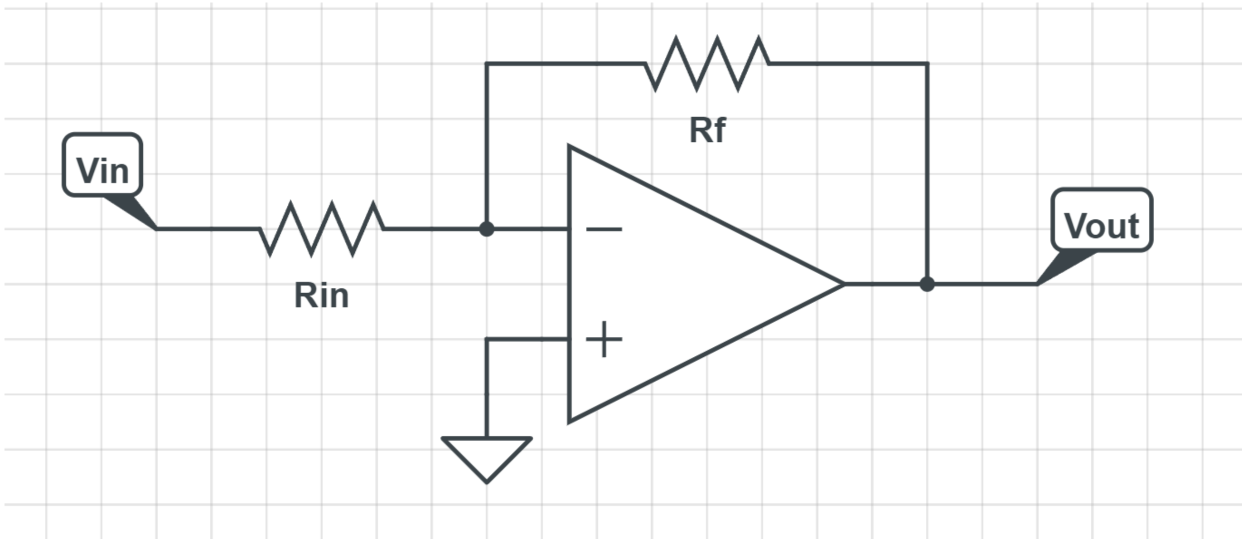
$\sin = 1$

minimize $\Rightarrow$ $\sin = -1$

Max $\longrightarrow$ $(a + b)\,A_V = V_{DD}$

Min $(-a + b)\,A_V = V_{SS}$

3. An inverting amplifier with no reference voltage (non-inverting terminal is connected to GND) is shown in the following figure. Show all of your work.



- a. Assume the op-amp has a finite gain *A*. Derive the amplifier gain *Vout*/*Vin* in terms of *Rin*, *Rf*, and *A*. (Hint: voltage dividers will be useful here.)
- b. Assume the op-amp gain is now infinite. Using this information, simplify the expression for the amplifier gain you derived in part (a). Explain why your simplified expression makes sense.

Images are BELOW

Lab 1 Q3 a & b

a)

$$\frac{-R_{in} + R_f}{A} = \frac{V_{in} R_f + V_{out} R_{in}}{V_{out}}$$

$$\frac{-R_{in} + R_f}{A} = \frac{V_{in} + R_{in}}{V_{out}}$$

$$\frac{-R_{in} + R_f}{A} - R_{in} = \frac{V_{in}}{V_{out}} R_f$$

$$\frac{-\left(R_{in} + R_f + A R_{in}\right)}{A \cdot R_f} = \frac{V_{in}}{V_{out}}$$

$$\Downarrow$$

Reciprocal

$$\boxed{\frac{A R_f}{-\left(R_{in} + R_f + A R_{in}\right)} = \frac{V_{in}}{V_{out}}} \quad *$$

b) $$\lim_{A \to \infty} \frac{AR_f}{-(R_{in} + R_f + AR_{in})} = -\frac{AR_f}{AR_{in}} = \frac{-R_f}{R_{in}}$$

This does make logical sense, infinite gain indicates an ideal op-amp, so the golden rules we previously learned are applicable. $V^+ = V^- = 0$ due to it being in negative feedback *

Lets calculate Vout/Vin to show:

$i_{R_{in}} = V_{in} - 0 \; / \; i_{R_f} = 0 - V_{out} \Rightarrow$

$\Downarrow$

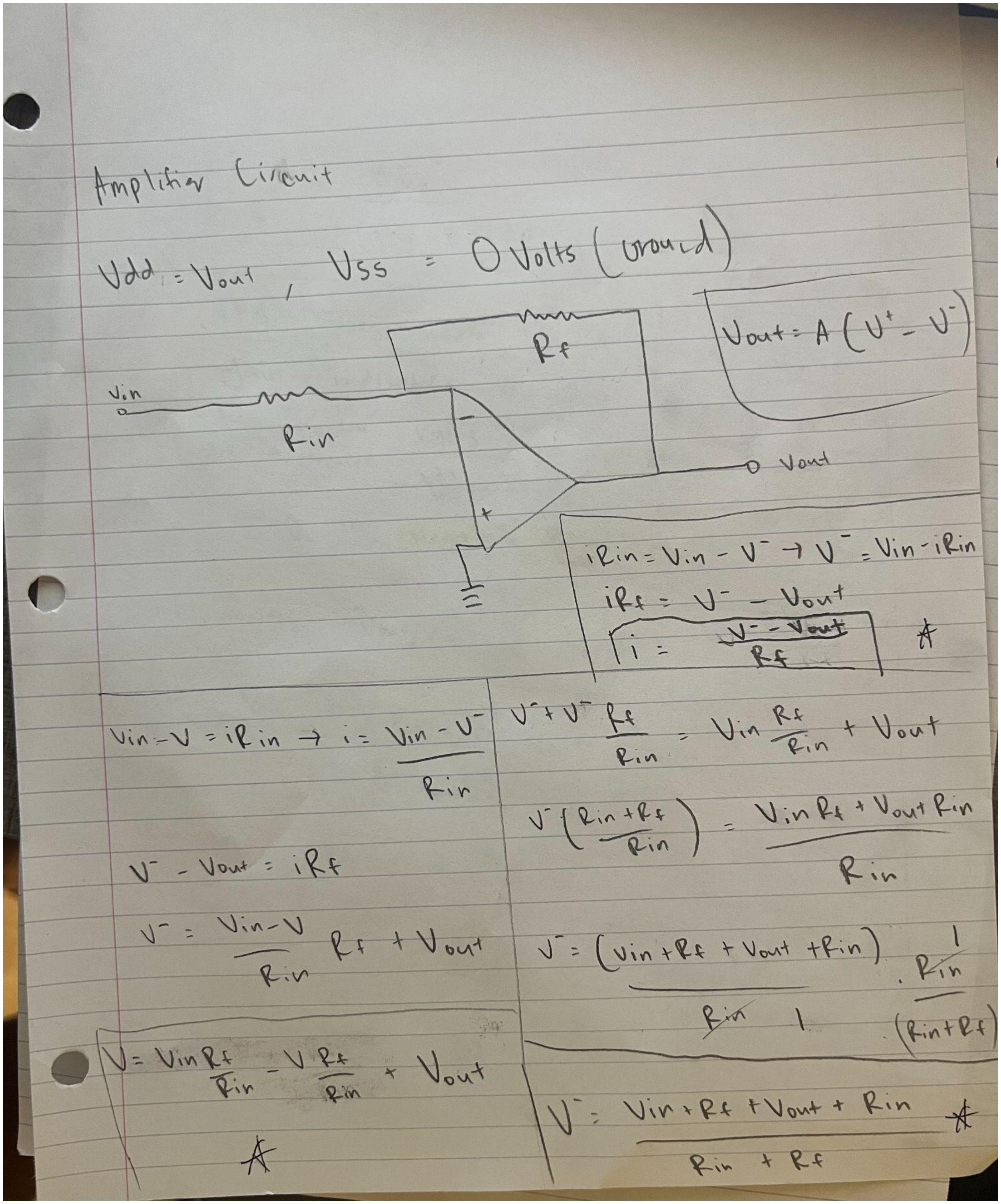
$i_{R_{in}} = V_{in}$, $i_{R_f} = -V_{out}$

$i = \frac{V_{in}}{R_{in}}$ $\quad i = \frac{-V_{out}}{R_f}$

$$\frac{V_{in}}{R_{in}} = -\frac{V_{out}}{R_f}$$

$$\frac{V_{out}}{V_{in}} = \frac{-R_f}{R_{in}}$$ *

Signals are inverting properly in the circuit



4. What are the ideal gain and measured gain of the op-amp circuit in Lab 1? Are there any discrepancies between these two values? Why or why not?

So in a perfect world the ideal gain would be -1, but our gain was around -.96-.97. There are discrepancies between the two values but nothing super significant, and in the real world it is almost always difficult and in most cases impossible to emulate an ideal gain in an op-amp, factors such as input, resistors, etc can cause minor discrepancies for an ideal gain.

Lab 2

Summary

- Give a summary in your own words of what you did in this lab. Possible details to include: overview of the lab's objective, new components used, issues you encountered, etc. Details NOT to include: how you left your car at home, forgot to enable high-Z mode on your function generator, etc.

In Lab 2, we used the Arduino SAR ADC algorithm to convert an analog voltage signal to a digital representation through bits (ones and zeros). Other components in the circuits included a comparator (to compare our digital voltage with the actual) and resistors to control the voltage influence of each individual bit by a power of 2: ½, ¼, ⅛, 1/16. We used an oscilloscope to visualize the voltage output of the multi-resistor setup as the Arduino modulated the output over time and used a power supply unit (PSU) as the analog input. The lab went relatively smoothly, as we only encountered one issue in the middle: the Arduino wasn't updating the output voltage over time. The issue was a very simple fix however: we simply had to connect the output of the op-amp/comparator back into the Arduino at the A1 socket so the Arduino had a VDD (prediction less than) or a VSS (prediction greater than) to work with.

1. What is the SAR ADC algorithm? What are the steps it goes through in order to find the digital representation of its input analog voltage? Besides quantization error, what is a drawback/limitation of the ADC implementation in Lab 2?

SAR (Successive Approximation Register) an algorithm that can be programmed into a computing device, such as an Arduino, that settles on the best digital (using bits) representation of an analog signal through trial and error. It first turns on the most significant bit (MSB) to get closest to the input voltage. If the voltage value of the MSB is greater than the input via an output of VDD from the comparator, then it's recorded as on by the Arduino (1) and the next bit (with half the voltage value) is selected as the MSB. If the comparator output was VSS, then it's recorded as off (0) instead. This is repeated until all of the bits are exhausted and the least significant bit LSB is reached. A drawback is that to get more precise measurements, the Arduino will have to cycle through more bits, increasing processing time and limiting the number of analog signals it can convert.

2. For the following question, answer parts a) and b) in terms of *Vref*(the reference voltage of the ADC). Assume we are using the same resistor values from the lab. Please include all of your work.

- a. What is the maximum voltage achievable by an n-bit ADC? Give your answer in terms of n.

Vmax(n) = Vref(.5 + .5^2 + ... + .5^n)

- b. What is the minimum voltage achievable by an n-bit ADC? Give your answer in terms of n.
  Vmin(n) = Vref(.5 * 0 + .5^2 * 0 + ... + .5^n * 0) = 0
- c. In reality, there are multiple factors, e.g. area, noise, sensitivity of the comparator, that set the limit of the highest resolution (number of bits) we can build. If the smallest Least Significant Bit (LSB, the step size of the DAC voltage in the voltage transfer curve in the lab note) we can have is 2.5 mV, what is the highest resolution (number of bits) we can achieve in the binary SAR ADC with 5V reference voltage? (Note that the step size is constant across codes in the ideal ADC. The answer should be an integer for which the LSB satisfies the constraint.)
  .5^n * 5 = 2.5 * 10^-3 => .5^n = .5 * 10^-3 => n = log(.5)(5 * 10^-4) = 8.644
  floor(n) = 8
  The maximum number of bits possible for the step size is 2.5 mV (due to environmental effects when measurements get too small) is 8 bits.

3. Refer to the datasheet for the TLC7524 8-bit DAC. Please include all of your work.
Settling time marks the time that passes between when the input is applied to a component and when the subsequent component output has stabilized (within some error bound). Classes such as CS 61C and EECS 151 will discuss settling time and related concepts in more detail.
Let's say we want to build a SAR ADC using this resistor-ladder DAC and some microprocessor (i.e. the Arduino). We will assume for this question that there is no delay between the output of one component and the input of the next (e.g. there is no delay between the output of the DAC changing and the inverting input of the comparator changing). We will also assume that the acquisition time for the ADC to read the stable input analog voltage is negligible.
Assume the settling time of the comparator is 200ns.
Assume that it takes 100ns for the microprocessor to look at the comparator output and set the bit off or keep it on. Now, the algorithm repeats for the next bit.

- a. What is the worst-case time required to determine the final value of a single bit in the ADC's register? (Hint: find the settling time of the DAC.)
  200 + 100 = 300 ns
- b. How long would it take in the worst case to see the final correct 8-bit ADC output? What is the maximum frequency at which we could sample the output voltage and still be absolutely certain that the value is correct?
  Worst case: 300 * 8 = 2400 ns = 2.4 ms
  f = 1 / 2.4 = .417 = 417 Hz
- c. At *VDD*=5*V*, provide an upper bound for the total energy dissipation of the DAC for the worst-case time to see the final correct 8-bit ADC output. (Hint: find the specifications related to power.)
  5 mW = 5 mJ / s

P * t = 5 nJ / ms * 2.4 ms = 12 nJ

Lab 3

Summary

- Give a summary in your own words of what you did in this lab. Possible details to include: overview of the lab's objective, new components used, issues you encountered, etc. Details NOT to include: how you left your car at home, forgot to enable high-Z mode on your function generator, etc.

  In this lab we were instructed to build both the circuits for the function of our motors and encoders, to calculate the velocity of our car. Some new components we were able to use to achieve these things in our lab are, diodes, motors, and a terminal switch. Diodes were used as a back-up "current flow capturer" when the BJT was off, motors were used to power on the wheels (with the appropriate circuit), and the terminal switch to control electrical current through a simple 1,2,3 switch. One problem we had was when we were testing and building our encoder as the voltage divider we tried building was faulty because we did not connect to the S-pin and in addition some of our equipment was faulty. A second problem we encountered was that although our motors worked our wheels were turning backwards, but this is easily fixed by a few debugs and fixes in our circuit.

1. What is a PWM signal? What does duty cycle mean for a PWM signal? If we can control a digital signal between 0V and 5V, what will the average voltage of the PWM signal be if the duty cycle is 75%?
A PWM signal better known as a Pulse Width Modulation is something that turns a digital signal into an analog signal (a continuous electrical signal). Duty cycle refers to the ratio of how long it stays on compared to when it is turned off. 5-0 * 0.75 = 3.75 average.
2. The NPN Bipolar Junction Transistor (BJT) serves a very important purpose in our motor controller circuits.
   - a. Describe the function of the BJT. The BJT in short amplifies/filters/remedies power. This is achieved through the 3 terminals in a BJT (emitter, base, and collector), BJT in short is a voltage-controlled switch to turn on and off motors. There is a symbiotic relationship in terms of the base terminal and collector terminal when current is flowed into.
   - b. In your own words, explain the model of the NPN BJT in the ON mode from the lab note. When the BJT is turned on, V_{BE} is shown as a fixed voltage source with valued

ranges between 0.6V-0.8V. When BJT is active, there is a controlled current source (between current sources of C and E) that amplifies the current flowing from terminal B by something called Common-Emitter Current Gain. Current C is conveyed through the equation $I_c = b_F I_B$, and IB in this equation is an amplified current source that goes in the motors to power it.

- c. In your own words, explain the model of the NPN BJT in the OFF mode from the lab note. In short when the NPN BJT is off, there is no current flow, and all open circuits on all three terminals (emitter, base, and collector)

3. The following sub-problems will check for your understanding of the circuits implemented in this lab.

- a. Describe the function of the resistor in the motor circuit that is connected to the Arduino. What will happen to the rotation speed of the motor when the value of the resistor increases? What will happen if it decreases?
  Resistors in this motor circuit controlled the circuit flow and the Audrino in simple terms acted as a protector for the circuit to prevent short-circuiting or damage due to a potential high current. The lower the resistor value, the faster the motor goes due to higher current (common-sense is that the less resistance the greater amount of current there is), and the higher the resistance value the motor goes slower.

- b. What is the function of the diode? Why do we place it in parallel with the motor?
  Diode acts like a safety net for when the BJT is off, it ensures that the motor's current has a place where the current can flow to, and the diode allows it to flow back into the motor (with the correct control of direction) until it stops due to decaying. This is somewhat similar to an Iphone battery.

- c. How are the encoders used to measure velocity? Say we swap your encoder wheels to some with increased cutouts. Would the velocity calculated by the Arduino be faster, slower, or be the same as your actual velocity?

The encoder can measure velocity through a small beacon of light it shoots out between the two legs, which is divided by the inner wheel of the car, also hence why there is a little gap between them. Whenever the car's wheel spins (does revolutions), this beacon of light gets interrupted in a way that is proportional to the velocity of the car. In simpler terms, each time the wheel interrupts the beam of light, it records a mark called a tick. So what the econder does is that it counts the amount of ticks over any time interval and calculates the velocity and distance of the car.

4. Previously, S1XT33N's microcontroller was the TI-Launchpad, which required 5V to be powered. Much of the rest of the car was powered by a 3.3V regulator. After switching to

Arduino, we no longer need two voltage regulators for S1XT33N's smooth sailing. Why could this be the case?

Launchpad's voltage limit is 3.3V, and since mic boards, encoders, op-amps are instructed to be regulated at 3.3V, we use the launchpad for these things. Aurdino on the other hand can use up to 5V, so we can just set the Arduino by powering it with 5V into it, not needing us to set the limit down to 3.3V.

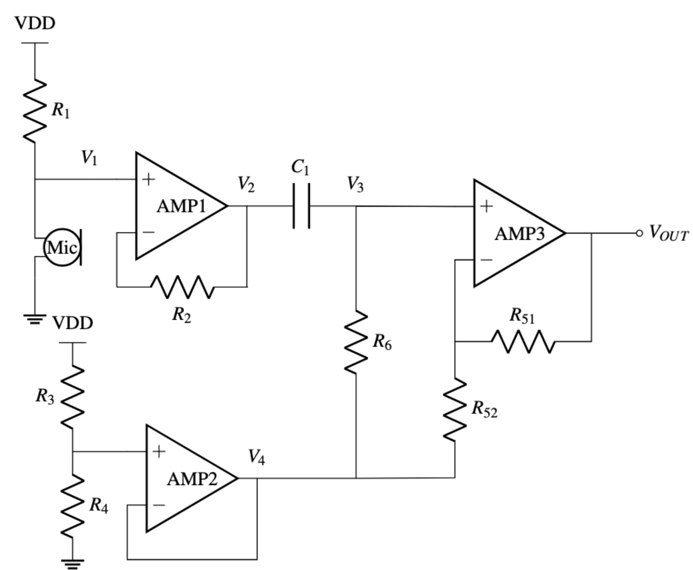
Lab 4

Summary

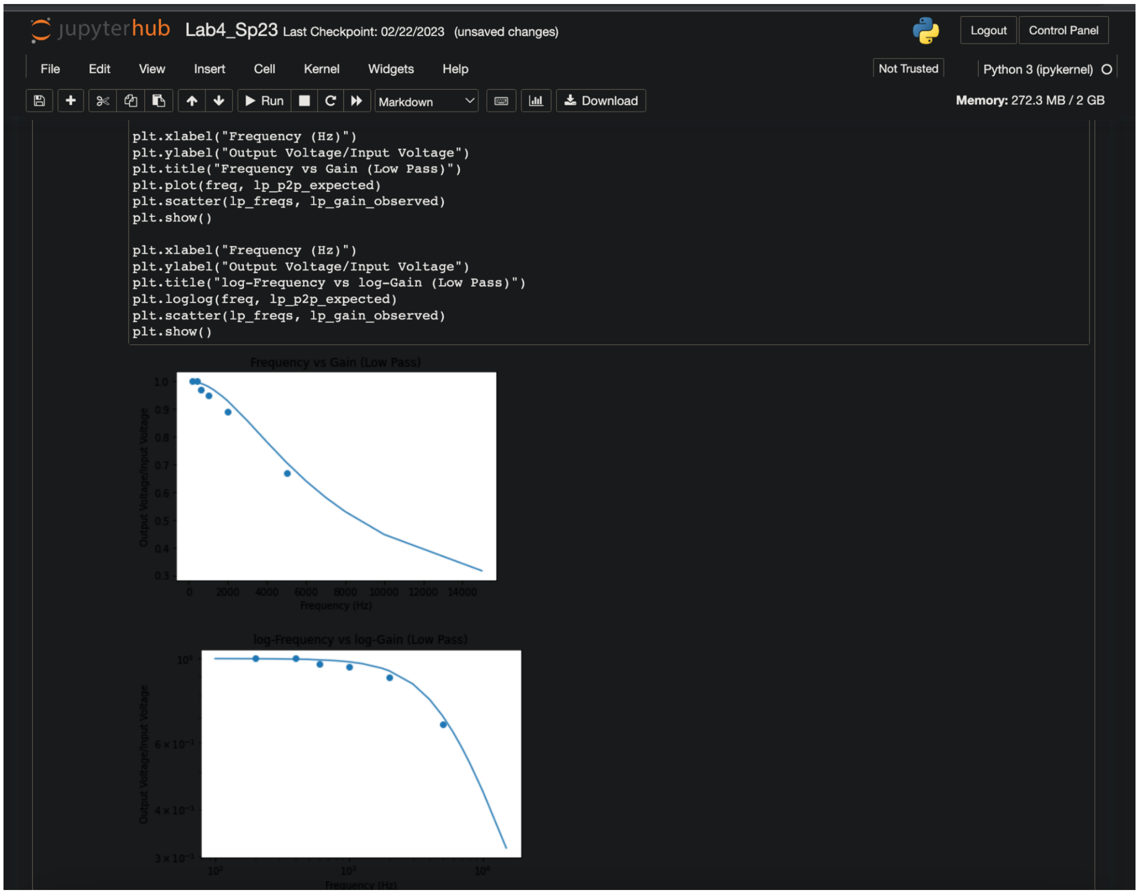
In the past labs, we focused on the power-delivering components of the car such as the voltage regulator and the biasing circuit. But in this lab, we built a voice input system that uses the microphone to convert audio waves into alternating electrical currents that we can process. The four parts of preprocessing were the mic gain (to better detect the input), buffer (to isolate the load parameters), remove mic drift (to nullify any offset), and another amplifier. The next step we encountered an issue because we forgot to set the reference of the non-inverting amplifier to 2.5, but once we realized, we were able to build the low-pass filter with the resistor on the top and capacitor on the bottom. From there we were able to link the low-pass output to the LED with the half-rail as reference (since the signal is centered at 2.5) so that we could observe the brightness of the LED as an indicator of the gain of the input signal.

The following questions will analyze the combined mic board and biasing circuit, which is shown below. The microphone can be modeled as a signal-dependent current source, $I_{MIC} = k\sin(\omega t) + i_{drift}$, where I_{MIC} is the current flowing from VDD to VSS, k is the force[1] to current conversion ratio, ω is the signal's frequency (in rad s^{-1}), and i_{drift} is a constant current offset (in A). Note that R_{51} and R_{52} are resistors of the potentiometer ($R_5 = R_{51} + R_{52}$).

When asked to give an answer in terms of the circuit components, please give your answer only in terms of V_{DD}, R_1, R_3, R_4, R_{51}, R_{52}, k, ω, t, i_{drift}, and/or standard mathematical constants and functions. Throughout this problem, please show all of your work.



1. What is the voltage *V*1 in terms of the circuit components?
I = V / R => Imic * R1 = V1 - VDD => V1 = VDD + Imic * R1 = skin(wt) + Idrift + VDD
2. What is the voltage *V*2 in terms of the circuit components?
V2 = V1 = skin(wt) + Idrift + VDD, since no ground
V2 = kcos(wt - pi/2) + Idrift + VDD
~V2 = ke^(j*-pi/2)
3. What is the voltage *V*4 in terms of the circuit components?
VAMP2+ = VDD * (R4 / (R3 + R4))
V4 = VAMP2+ = VDD * (R4 / (R3 + R4))
4. What is the voltage V3 in terms of V2 and V4? What is the voltage V3 in terms of the circuit components? Assume that C1 and R6 are large enough such that only AC signals pass through C1.
~V3 = ~V2 * (Z6 / (Z6 + ZC1)) = ~V2 * (R6 / (R6 +1/jwC6)) = ~V2 * (jwC6R6 / (jwC6R6 +1))
= ~V2 * wC6R6 / sqrt(wC6R6^2 + 1) * e^(jpi/2) / e^(arctan2(wC6R6, 1))
= k * wC6R6 / sqrt(wC6R6^2 + 1) / e^(arctan2(wC6R6, 1))
V3 = k * wC6R6 / sqrt(wC6R6^2 + 1) * cos(wt - arctan2(wC6R6, 1))
5. What is VOUT in terms of V3 and V4? What is VOUT in terms of the circuit components?
I5 = (V3 - V4) / R52
VOUT = V3 + I5 * R51 = V3 + (V3 - V4) * R51 / R52
= (1 + R51 / R52) * k * wC6R6 / sqrt(wC6R6^2 + 1) * cos(wt - arctan2(wC6R6, 1)) - R51 / R52 * VDD * (R4 / (R3 + R4))
6. Did your mic board performance seem to deviate from your model? Why/why not? Please include a graph of your mic board transfer function with your answer
It doesn't deviate much because our transfer function maps to the low pass filter with 1 / sqrt(1 + (w/wc)^2)



Lab 5

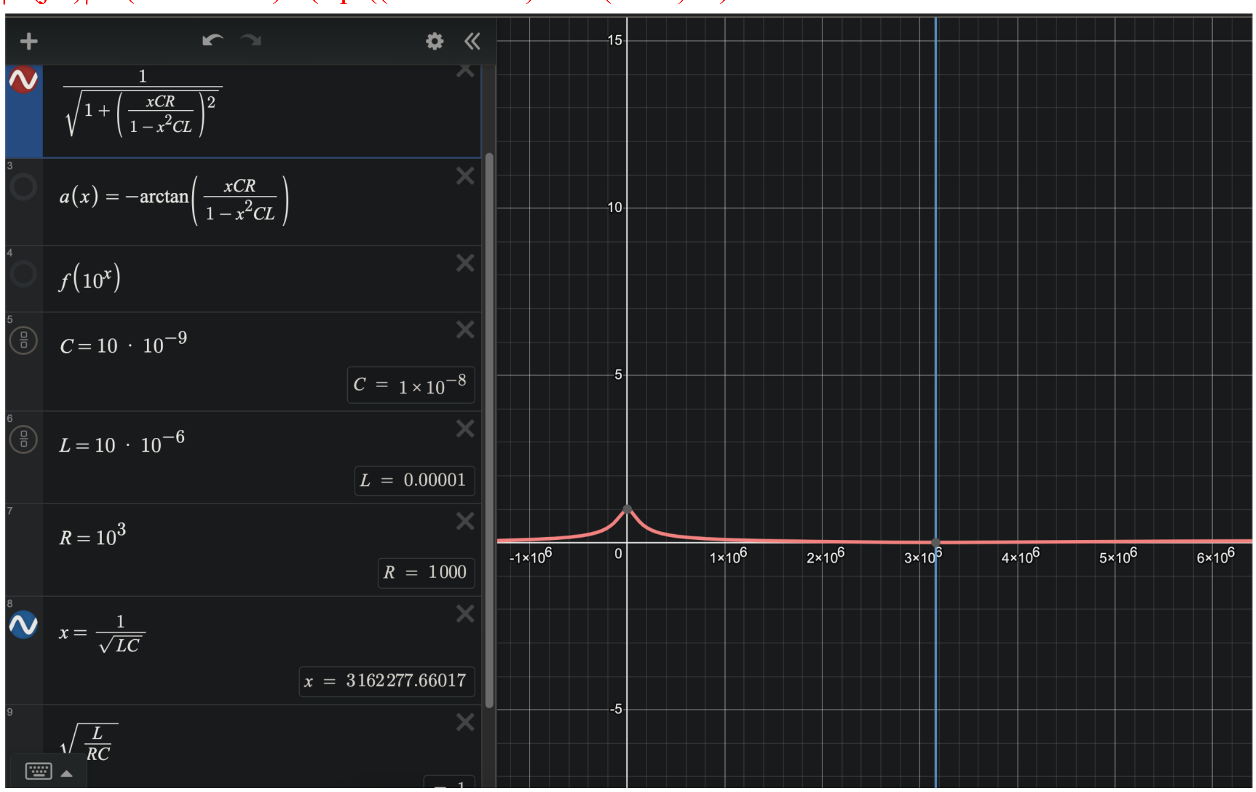
Summary

- Give a summary in your own words of what you did in this lab.

In this lab we had 3 main objectives which is to re-test our mic-board, design, build, and test the high-pass filter and the appropriate circuit. Lastly, build the notch filter and test it as well. We used the function generator to test our high pass filter to check the cutoff frequency was in the correct and expected range. We then connected the filter's input to the mic board's output to check the relationship between the frequency and gain. Essentially we did the same thing with the notch filter with the appropriate procedures for this filter. Two problems we encountered was the very beginning of our lab when we tested the frequency response of the Speaker-Mic Board System, in which when we compile the code in relation to the data our graph was off and to fix this we made fixes to our circuit with the help of TA aid as well. Our second problem came at the very end of the lab with the notch filter as we debugged our circuit for such a long time to find the problem and even our numbers on the function generator were around the correct range, but our problem to our circuit issue was that we forgot a simple reference node, which took us a long time to figure out but fixed our problem with the overall functionality of testing our notch filter.

1. What is the cutoff frequency for a first order RC filter? What is the resonant frequency for an RLC Notch filter?
fc = 1 / (2piRC)
fr = 1 / (2pi * sqrt(LC))
2. Why do we place the output of our color organ filters into a non-inverting amplifier / buffer?
Inserting buffers in between circuit behavior-modifying components (such as filters) prevents subsequent components from drawing current from prior ones, allowing us to cascade circuits.
3. Consider this RLC circuit. We have in series an inductor of 10uH, capacitor of 10nF, and resistor of 1kOhm. We connect the components in series respectively and probe Vout as the voltage over the resistor.

- a. What do you believe the filter's characteristics are? Is it a low-pass, high-pass, notch, or neither? Explain your thinking.
  This is a notch filter because it has a resistor, inductor, and capacitor
- b. Find the transfer function of this system. Leave your answer in terms of R, L, and C, and plot the magnitude response.
  Vout = Vin * (ZL + ZC) / (ZL + ZC + ZR)
  => Vout / Vin = H(jw) = (jwL + 1/(jwC)) / (jwL + 1/(jwC) + R)
  = (1 - w^2CL) / (1 - w^2CL + jwCR)
  |H(jw)| = (1 - w^2CL) / (sqrt((1 - w^2CL)^2 + (wCR)^2)



- c. What is the actual shape given by the magnitude response of this filter? Was it or was it not what you initially predicted it would be? Why could that be the case? (think Q factor).
  It's more like a slope, unlike what I predicted it to be (more of a notch). This is because the Q-factor is so low ($Q = 1$).
- d. When implementing notch filters, do we want a high resistance load or a low resistance load? If we have an ideal notch filter, what are its advantages compared to a band-pass filter with cutoff frequencies that are very close to each other?
  We most likely want to be particular with the frequencies we cut with a notch filter, so we want Q larger and therefore R smaller (low resistance load). A notch filter allows only one filtering system, meaning buffering to counteract inter-process loading isn't required. It also offers more precision for the same amount of calculations: to precisely chain high-pass and low-pass filters, we want cutoff freqs higher and lower than the notch freq so that at the notch freq, the gain is very low, which takes time to determine.

6: Feedback

Extra Credit:

The midterm lab report has been reworked quite a bit this semester, and we would love to hear your feedback. To receive extra credit, please provide 1-2 sentences for each of the following parts:

a) How well do you feel that this assignment evaluated your understanding of labs this semester?

I think it definitely required that we review what we did in all this semester's labs and the circuitry behind it.

b) How much time do you think this assignment took you to complete? (Just a number is fine for this part.)

It took me 5 hours.

c) What changes to the midterm lab report would improve your experience?

I would reduce the difficulty of the lab and provide a 20 minute time period for us to get started on the lab report (notably finish the summary and 1-2 qs)

2. Additionally, please feel free to provide any feedback you have about the 16B lab or anything we can do to better support you.

The labs can be quite confusing at times and the workload with the homework can be overwhelming. More connection between the lab and discussion would be nice.