University of Washington
Department of Electrical Engineering
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Medical Instrumentation Lab 2:
Design of an ECG Amplifier

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Abstract

In this lab we design and build a preamplifier for any 3-lead EKG. The pre-amplifier functions to filter common mode voltage and noise signals from the environment. The circuit is set up to give the user the ability to adjust the gain through a potentiometer. The final circuit is first tested with a simulated heart signal and finally with a simple 3- lead EKG setup (left arm, right arm and leg). To ensure safety in the final test the circuit is powered by a single 9 V battery. The final circuit had a variable gain of 100 to 10,000, a high pass input that removed DC voltage, a low pass stage with cutoff frequency of 40Hz to remove as much noise as possible, and an amplifier stage with a non-inverting fixed gain of 10.

The final circuit was able to cleanly amplify and display the heart rate of a live human subject, with full visibility of the essential P-QRS-T wave.

Introduction

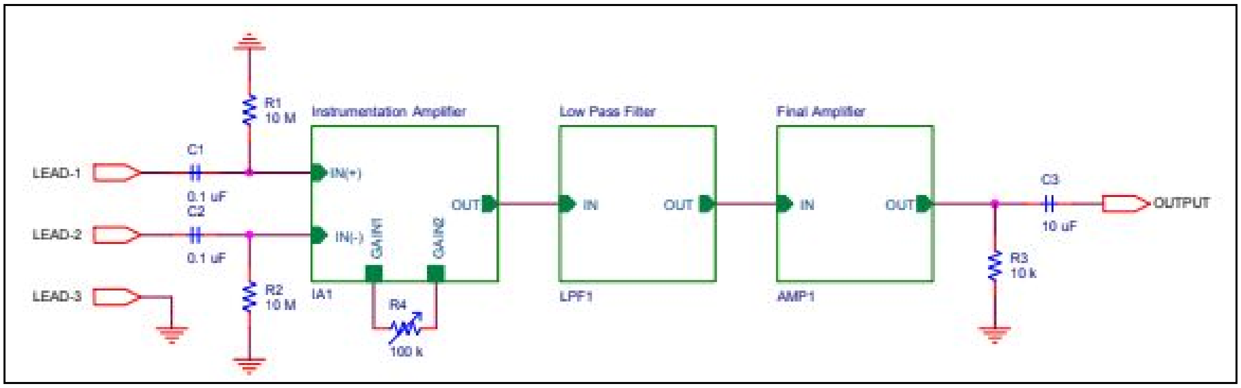
To capture the electrical signals produced by the heart a circuit needed to be designed with multiple stages to capture and process the faint signal given off by the heart. A differential input with decoupling high pass filters leading to an adjustable gain instrumentation amplifier with high CMRR and high input impedance was needed. The high CMRR and high input impedance ensures that the differential signal is not degraded for further stages. The signal then must pass to a low pass filter to remove any noise from the environment (especially 60 and 120Hz). Finally the signal passes to the amplification stage, then another decoupling high pass filter to the output being displayed to the oscilloscope.

Background

Electrocardiograms (EKG) are instruments used to measure the electrical signals of the heart as they propagate to pump blood. Each action of the pump cycle depolarizes at a specific time and in a specific direction. The electric fields generated can be picked up by surface electrodes located around the heart. These signals can then be filtered and amplified to give the common P-QRS-T wave which can be interpreted by doctors to diagnose many problems stemming from the operation of the heart.

This lab focuses on the collecting, filtering and amplifying of the heart’s signal. Each stage is simulated, built and tested with the output being read on an oscilloscope.

Block Design



We want to block DC signals.

Simulation and circuit modules

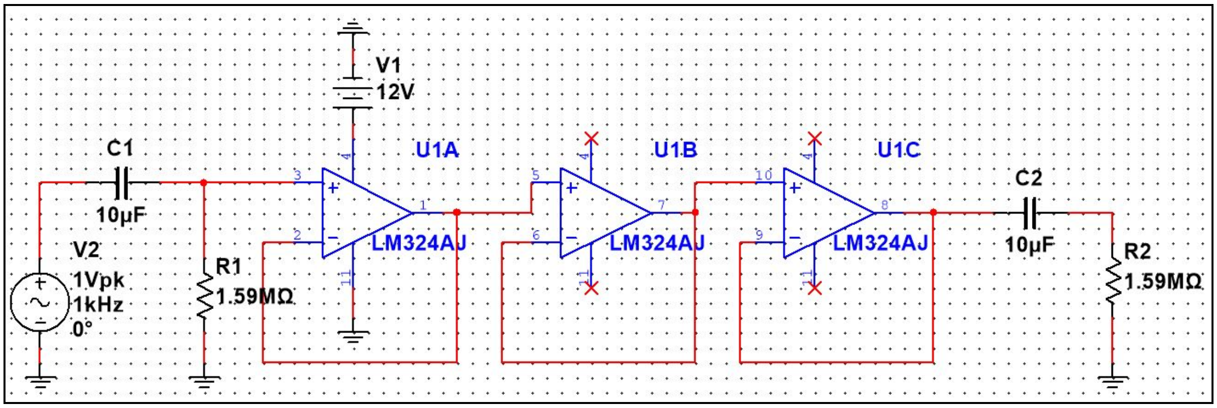
AC Coupled High Pass Filter

Design of the EKG asks for a frequency range of 0.01 to 40 Hz. AC coupling is applied at the input and output of the circuit with a high-pass cut-off frequency 0.01 Hz.

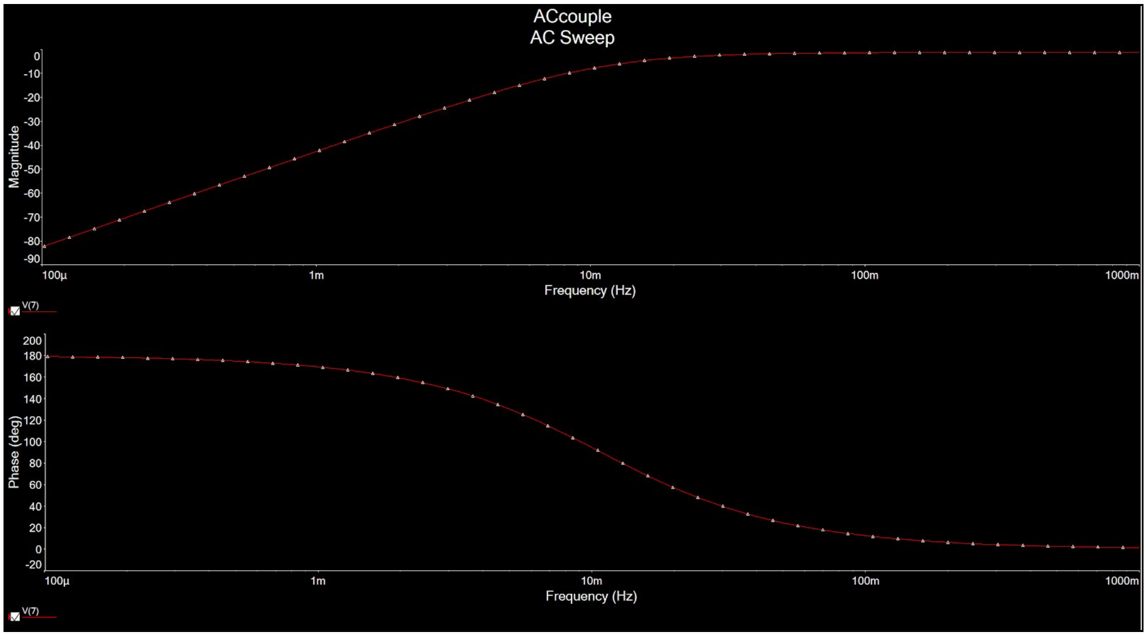
$$f_c = 1/(2\pi RC) \ = \ 0.01$$

Using a 10 uF capacitor we calculate the matching resistor.

$$R \ = 1/(2\pi * 0.01 * 10e - 6) \ = 1.59 \ M\Omega$$



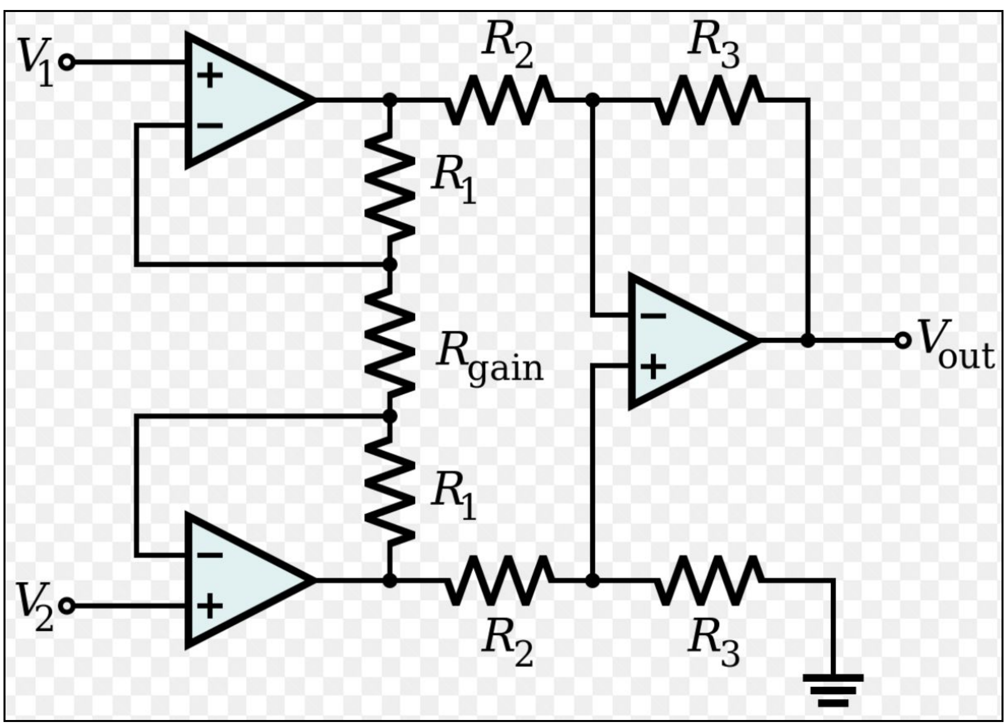
AC coupling with every stage replaced with a buffer



AC sweep of AC coupled circuit with -3dB at f_c

Looking at the AC sweep for the high pass filter, we see the low cut-off frequency for our circuit is ~10 mHz with no high cut-off. The signal attenuates at ~20 db/decade as per a 4 pole filter.

Instrumentation Amplifier



For the instrumentation amplifier, we are given 5 design specifications.

1. Voltage gain of 100 to 10,000 adjustable with a single potentiometer (+40 to +80 dB gain)
2. Common-mode rejection ratio (CMRR) of at least 1000 (+60 dB)
3. Input resistance of greater than 100 MΩ into both the (+) and (-) inputs
4. Low pass frequency response from DC to at least 1000 Hz (-3 dB point)
5. Operates from a single +9.0 V battery power supply

The step we take in our design for the instrumentation amplifier is to design the gain stages shown in the equation below which is essentially broken into two parts.

$$A_v = \frac{V_{\text{out}}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{\text{gain}}}\right)\frac{R_3}{R_2}$$

We can first simplify the design by choosing the gain from R3/R2 as either 1, 10 or 100. Then potentiometers available to us in the laboratories are multi-turn linear trimpots. These trimpots have high precision and resolution which allows us to be more selective in our gain selection.

For our design we choose a gain of 100 for the second stage leaving another 100 gain remaining for the first stage. In this case, we choose R3 as 10 kΩ and R2 as 100 Ω for a gain of 100. This leaves a gain of 1 to 100 left for the remainder of the equation.

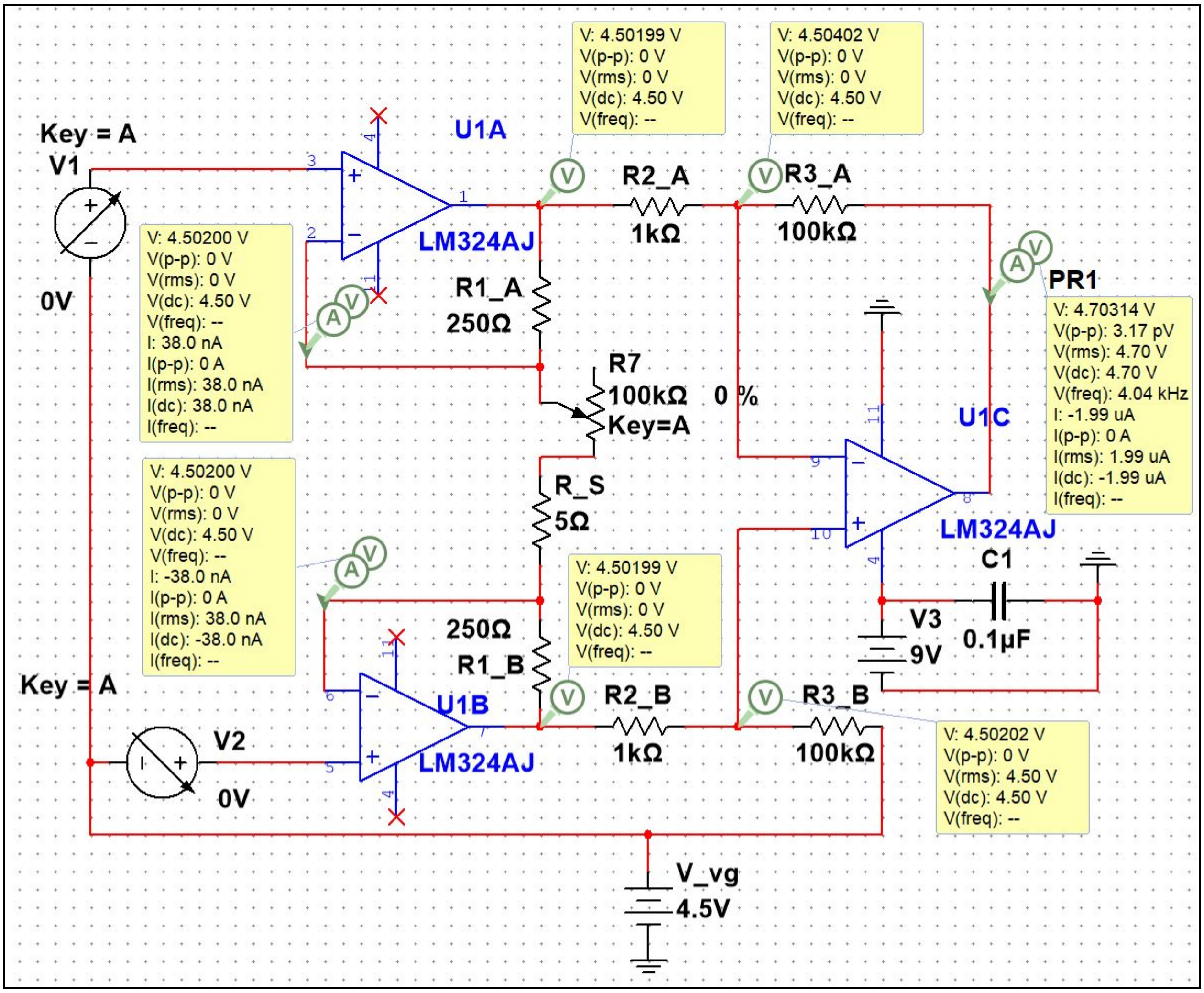
The design asks us to use a potentiometer to adjust the gain of the instrumentation amplifier.

- A larger potentiometer gives the circuit more precision for gain selection at lower gain
- A larger potentiometer moves the lower bound of the gain stage closer to desired
- A smaller potentiometer gives the circuit more gain selection at higher gain

We choose to use a 100 kΩ potentiometer. We include a series resistor for when the potentiometer is ~0 to avoid any impedance issues that would occur from potentially shorting the circuit. This series resistor also determines the maximum gain for this stage, 100.

$$1 + 2R_1/R_{series} = 100$$

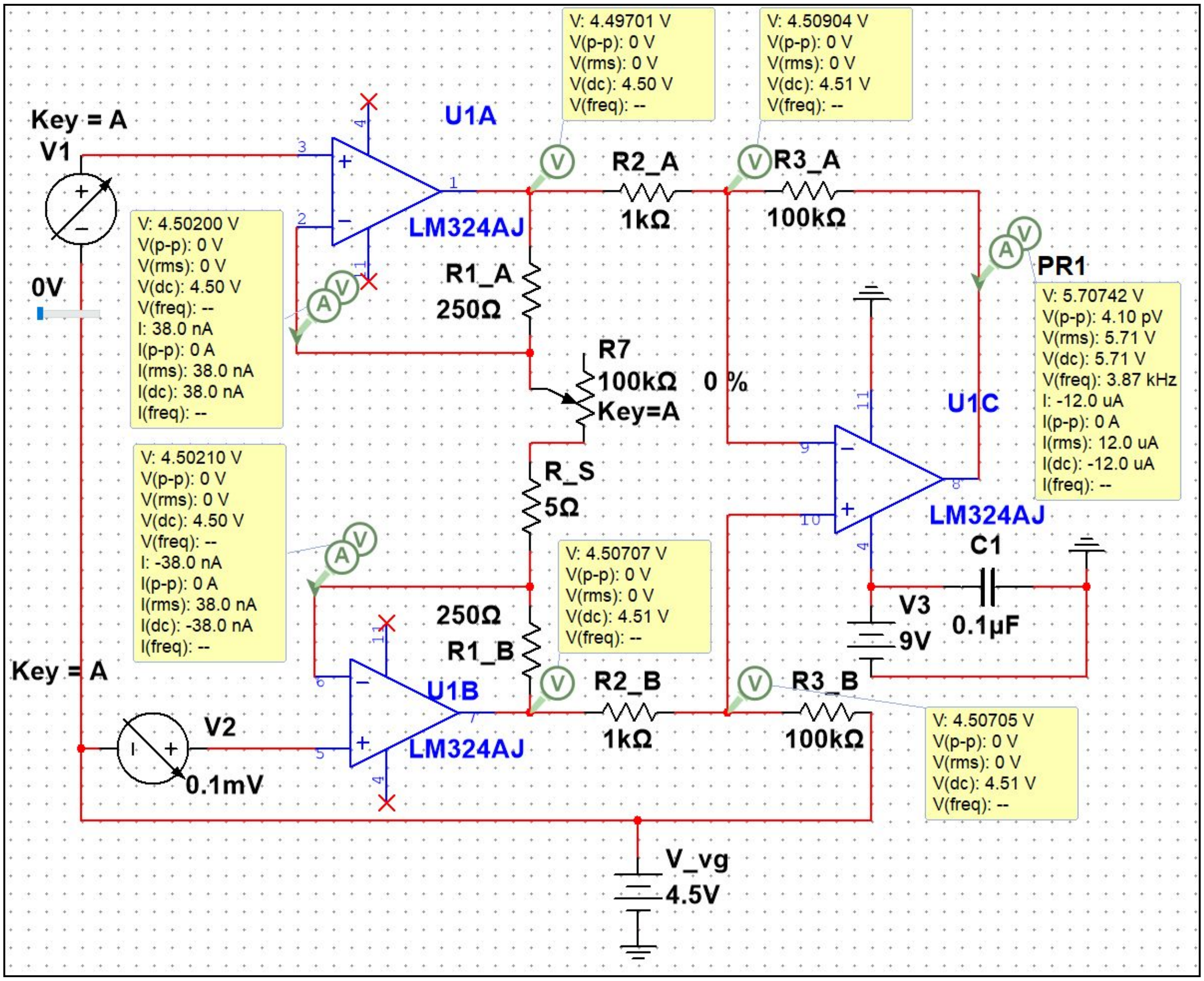
We choose a ratio that isn’t too large to have a gain as close to 100 when the potentiometer is maxed out. We choose R1 = 250 Ω and Rseries = 5 Ω.



In the above MultiSIM simulation setup we set the virtual ground to +4.5 V. The potentiometer is set to 0 Ω for a calculated gain of 10,100.

$$A_V = [1 + 2(250\ \Omega)/5\ \Omega](100\ k\Omega/1\ k\Omega)\ =\ (101)(100)\ =\ 10,100\ V/V$$

Simulating the instrumentation amplifier at common mode inputs using the LM324 quad op-amp, we see that there is a 2 mV offset voltage between the positive and negative inputs of each opamp. This offset voltage doesn’t matter at the first stage of the instrumentation amplifier as the inputs into the difference amplifier are both the same. oIn the difference amplifier, we see another 2 mV offset which is then amplified by 100 for the final output offset of 203.11 mV.



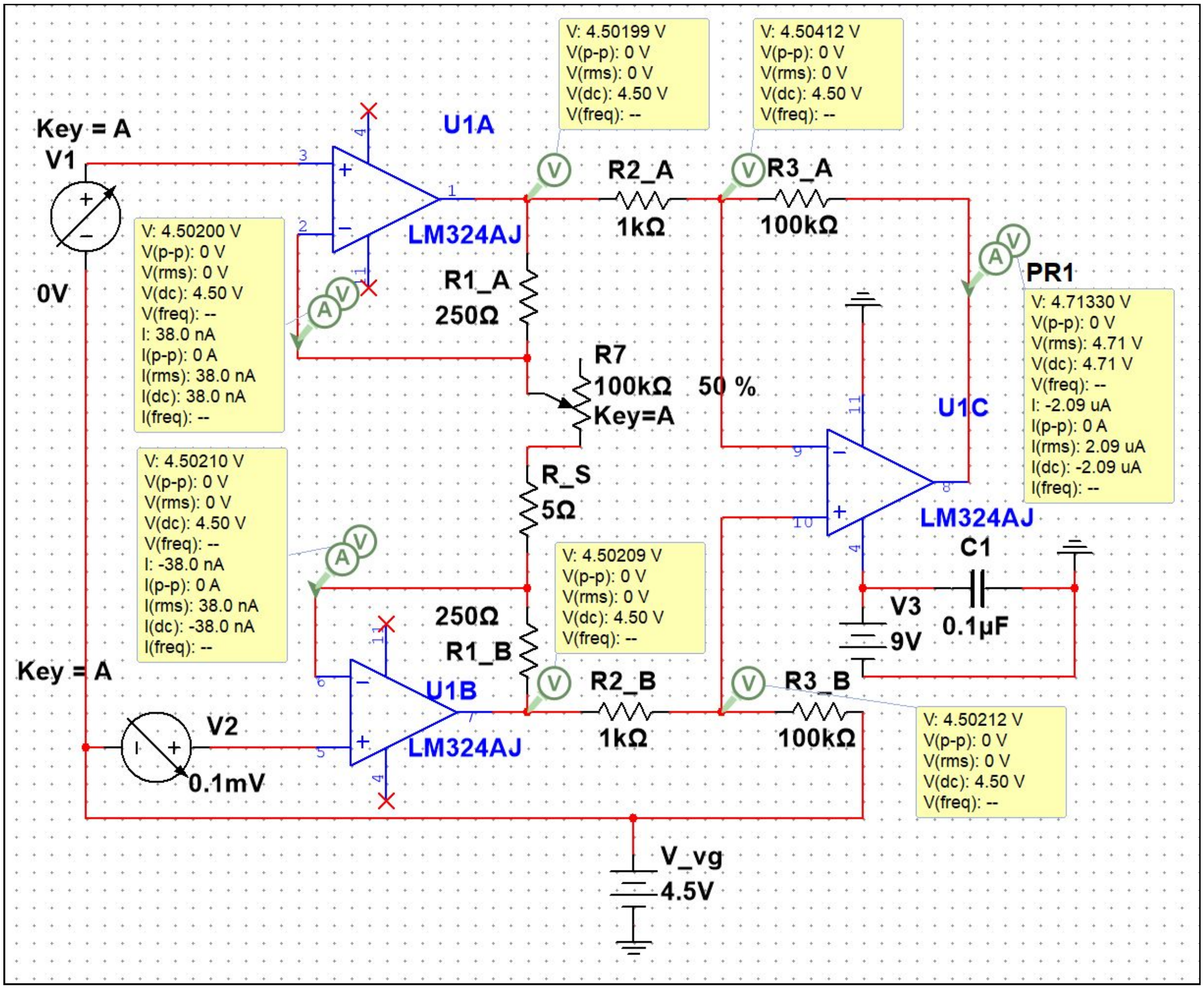
With an input voltage difference of 100 uV or 0.1 mV, we see an output of 5.70742 V which comes to 1.00442 V when accounting for the offset which is close enough to the expected 1 V.

$$5.70742\ V - 4.5\ V - 0.203\ V = 1.00442\ V$$

$$(0.1\ mV)(10,100\ V/V) = 1.001\ V$$

The difference of the outputs at the first stage also matches the designed gain of 100 for ~10 mV.

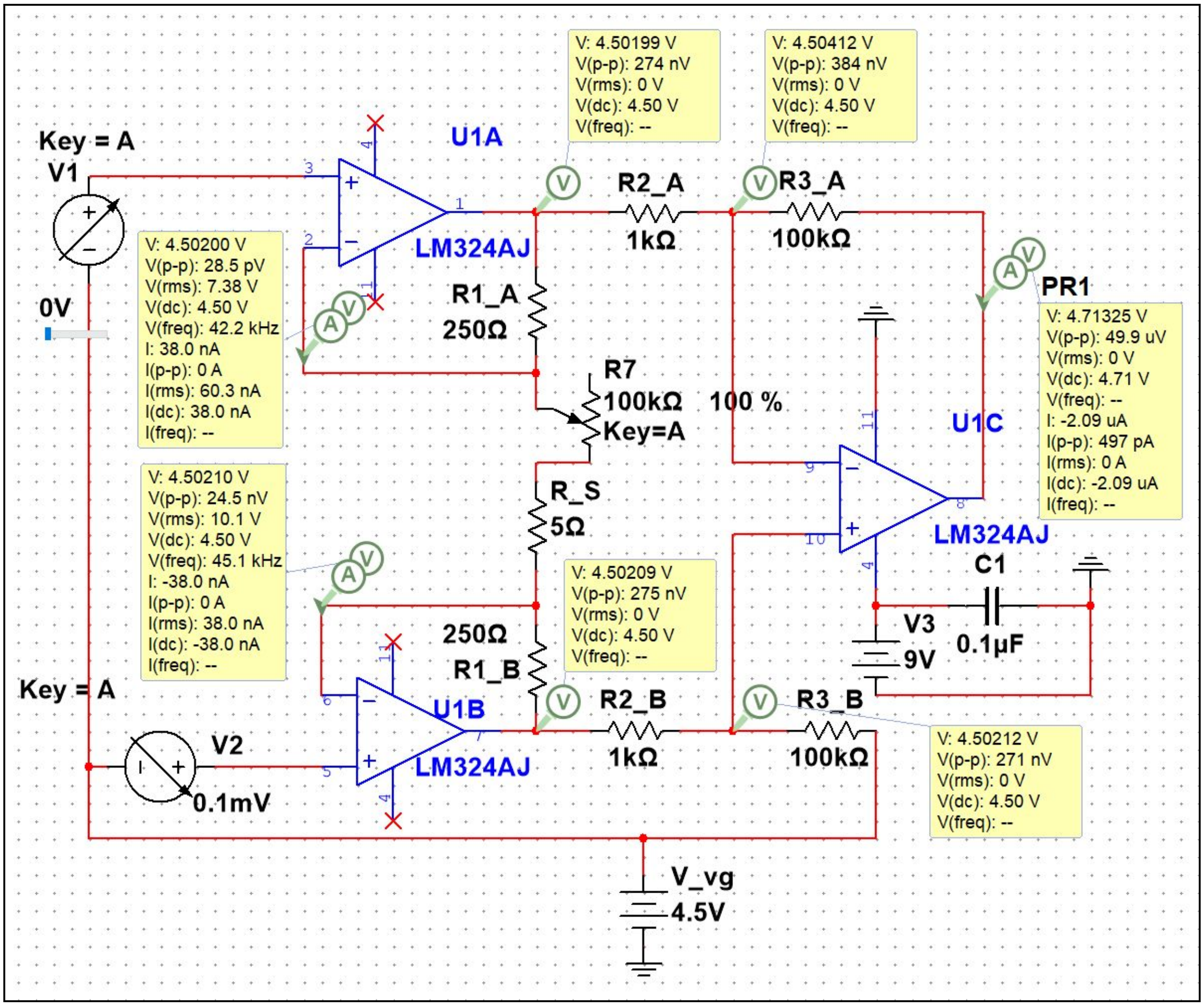
$$4.50707\ V - 4.49701\ V = 10.06\ mV$$



Here we set the potentiometer to 50% or 50 kΩ for an expected gain of ~101. With an input of 0.1 mV we expect to see a gain of 10.1 mV. Looking at our simulation output we see an output voltage of 10.16 mV which matches our calculations.

$$A_V = (1 + 2(250\ \Omega)/(50\ k\Omega\ + 5\ \Omega) * (100\ k\Omega/1\ k\Omega)\ =\ (101)(100)\ =\ 100.99\ V/V$$

$$4.71330\ V\ -\ 4.5\ V\ -\ 0.20314\ V\ \ =\ 10.16\ mV$$



With the potentiometer at maximum impedance, we expect to see a gain of ~100 for 10 mV with a 0.1 mV input.

$$A_V = (1 + 2(250\ \Omega)/(100\ k\Omega\ + 5\ \Omega) * (100\ k\Omega/1\ k\Omega)\ =\ (101)(100)\ =\ 100.50\ V/V$$

$$4.71325\ V\ -\ 4.5\ V\ -\ 0.20314\ V\ \ =\ 10.11\ mV$$

Sallen-Key Low-Pass Filter

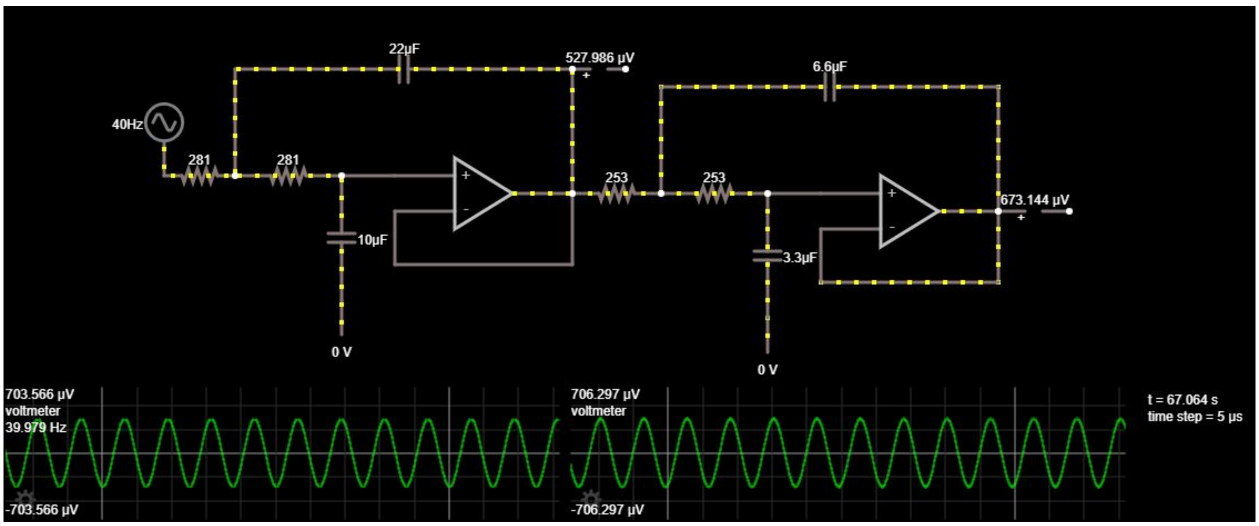
For the low-pass filter we are given 4 design specifications:

1. Voltage gain of 1.0 at DC (0 dB)
2. Low-pass frequency response up to 40 Hz (-3dB frequency)
3. 3 or 4 pole response
4. Operates from a single +9.0 V battery power supply

$$V_{out}/V_{in} = 1/(1 + j\ f/f_o)^2$$

$$f_o = 1/2\pi R_{SK}C_{SK}$$

The filter was designed for known capacitor values (due to their availability) and the resistors were kept small to limit any potential thermal noise. The first and second stage needed to be tweaked to get the -3dB point at 40Hz (instead of -6dB that would come from simply duplicating the first stage).



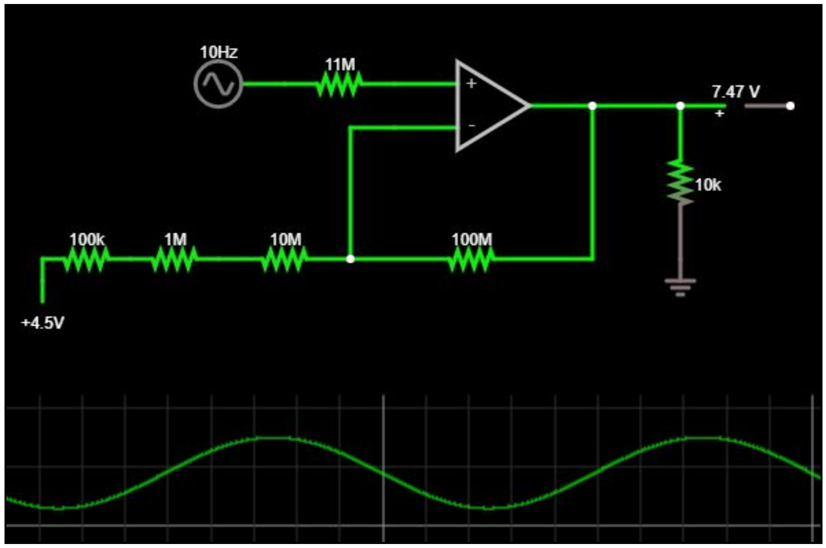
Simulated Sallen Key low pass filter

Final Output Amplifier

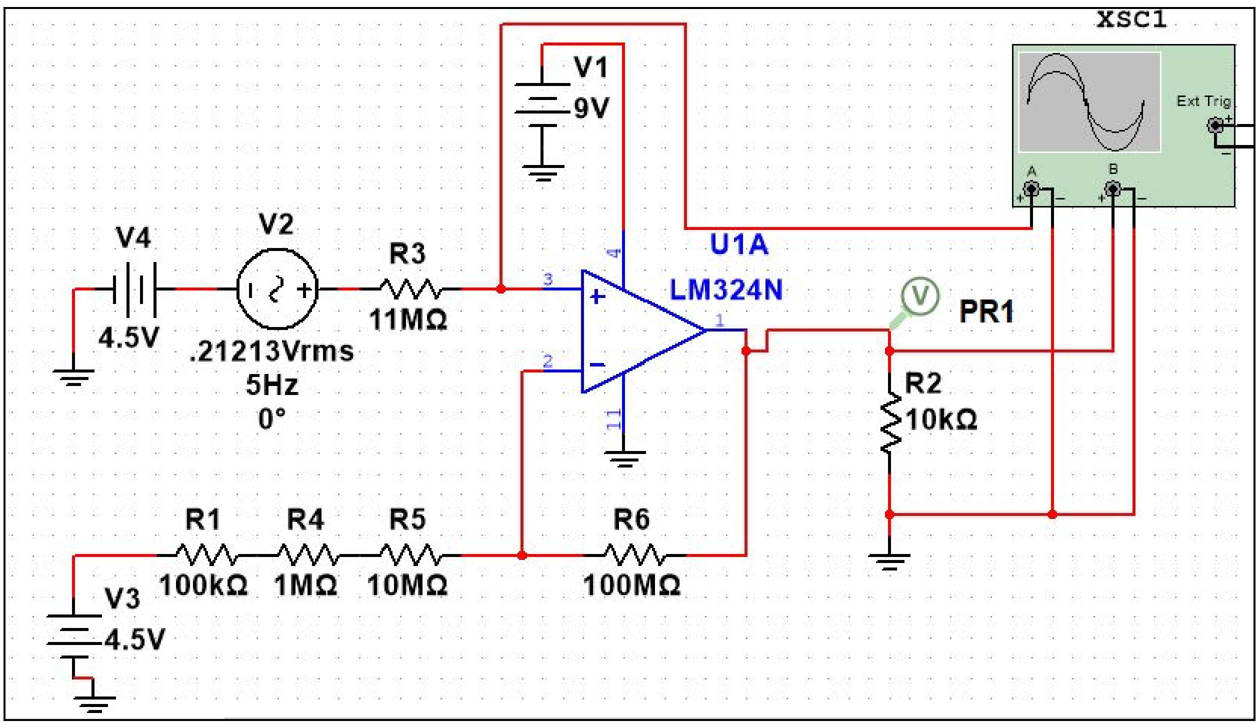
For the final output amplifier we are given 5 design specifications:

1. Fixed mid-band voltage gain of +10 (non-inverting +20 dB gain)
2. Uses only one op-amp
3. Input resistance of at least 10 MΩ
4. Drives a 10 kΩ or larger load resistance with a voltage swing of up to +/- 3 V_peak
5. Operates from a single +9.0 V battery power supply

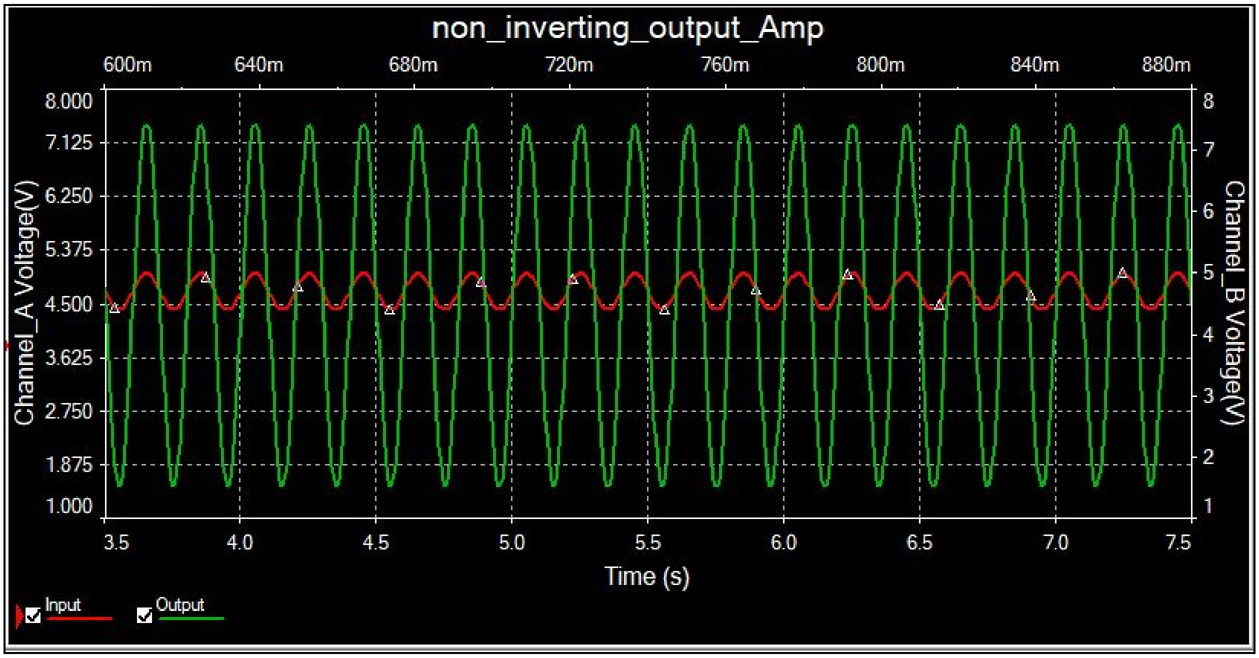
For the final output amplifier the input resistance of at least 10 MΩ was achieved with an input resistance of 11.1MΩ. This value dictated the value of the feedback resistor which in order to get the required gain of 10 needed to be 100MΩ.



Non-inverting amplification stage with a gain of 10 (concept simulation)



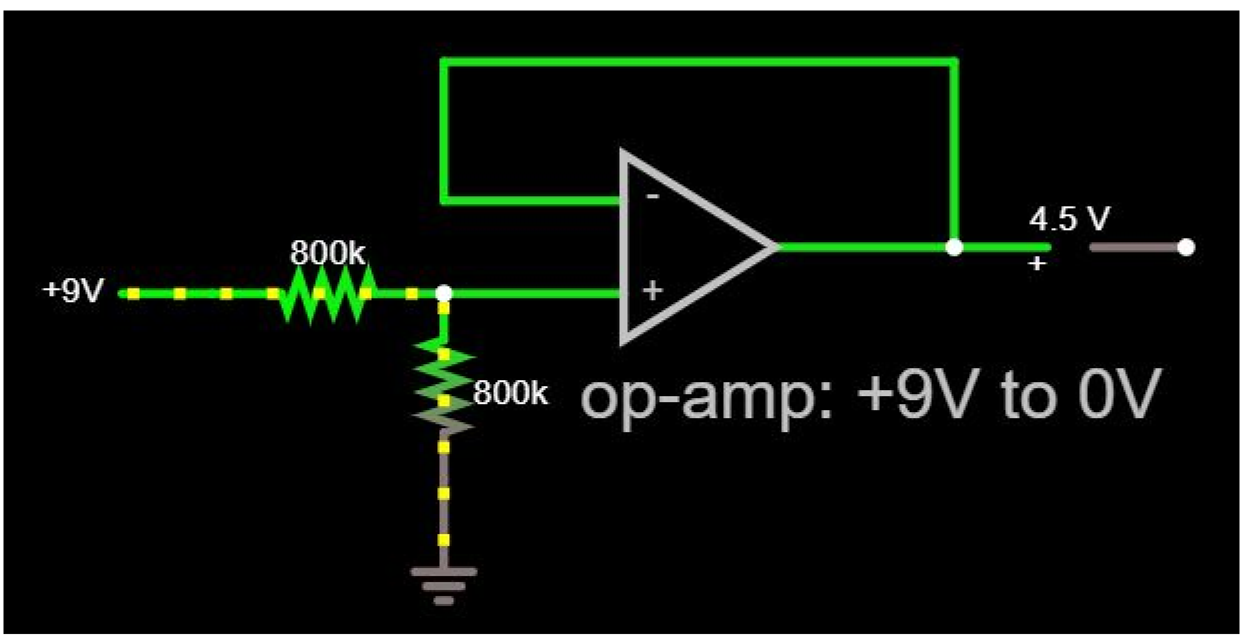
Non-inverting amplification stage with a gain of 10 (Multisim simulation)



Non-inverting prototype simulation output (red: input, green: output) output voltage swing +/- 3Vp

Virtual ground constant voltage source

To maintain the half point voltage (4.5V) of the 9V supply to act as a virtual ground for the circuit a buffer with a voltage divider was designed to keep a constant voltage regardless of the load.

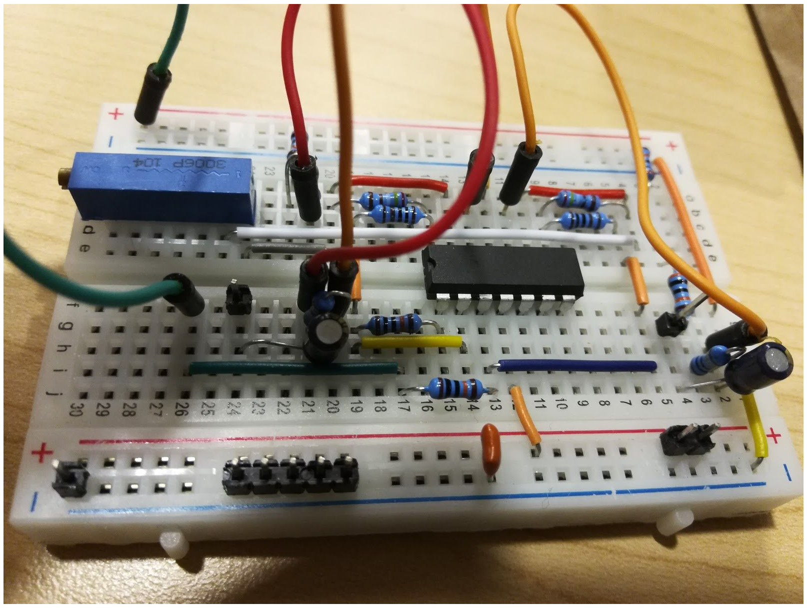


Simulated buffer with a voltage divider

The concept of the constant voltage source is straight forward, instead of using only a voltage divider where each element that it is attached to can change the voltage, the voltage divider is attached to an op-amp with negative feedback that has more of a capability to drive multiple loads. Large resistance values are used to reduce the current used to maintain the voltage on the positive input of the buffer.

Prototype Construction and Results

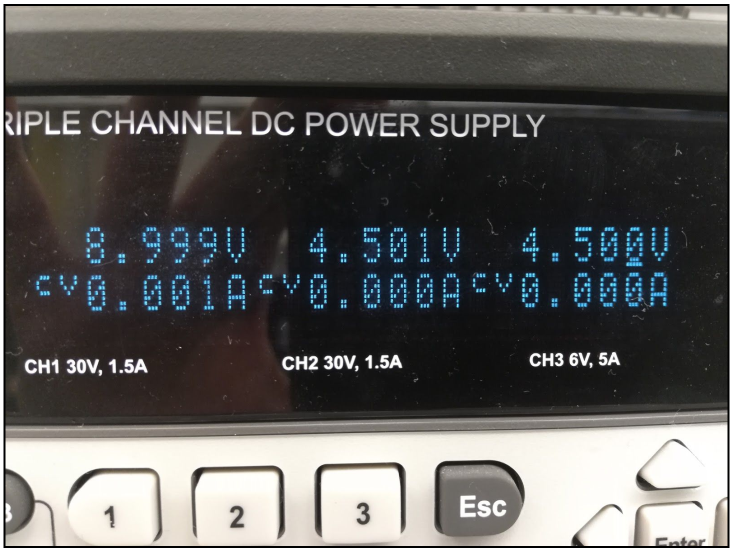
Instrumentation Amplifier



Constructed instrumentation amplifier with AC coupling

For the instrumentation amplifier we can not measure the full gain of the circuit. The highest resolution available from the lab power supplies is 1 mV. A gain of 10,000 by 1 mV means a gain of 10 V, which is outside our range of +9.0 V. The actual range of our op-amp is slightly less at ~7.6 V.

For our actual measurements we measure the circuit after the first stage for a gain range of 1-100.



Input voltages to instrumentation amplifier

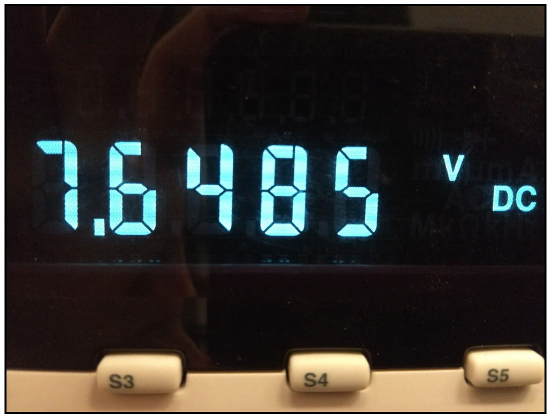
With the above input difference of 1 mV, we expect to see an output difference of 100 mV maximum between the two inputs to the differential amplifier split fairly evenly between the midpoint of 4.5 V.

Input into negative side of differential amplifier

Input into positive side of differential amplifier

Taking the difference between the two outputs we see that it comes to ~100 mV

$$4.5842\ V - 4.4785\ V = 105.7\ mV$$

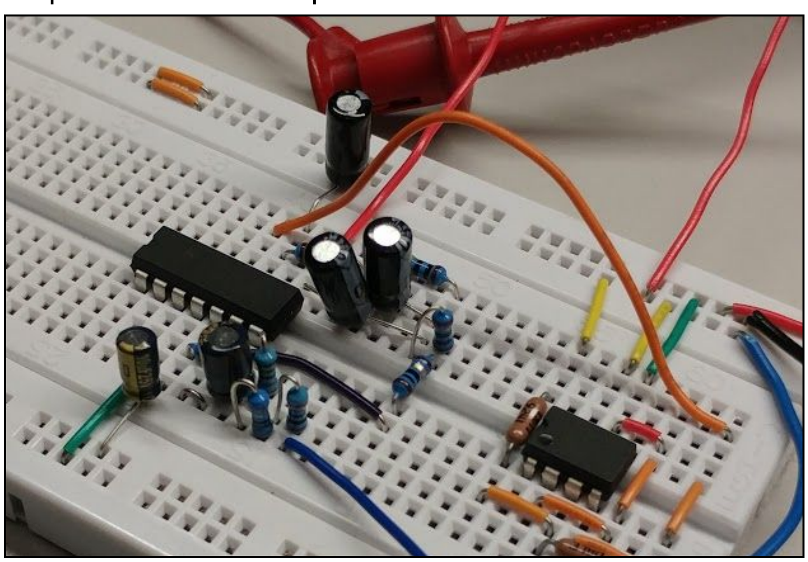


Final output of IA

At the output of the instrumentation amplifier we see that the voltage reaches the rail of the circuit from the +9.0 V power supply.

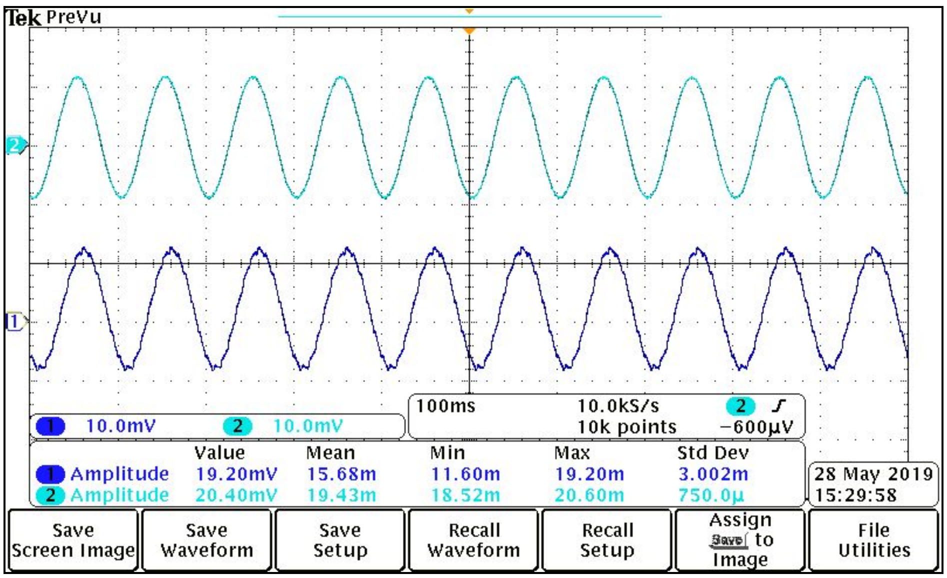
Sallen Key Low Pass Filter

The low pass filter was built around two op-amps of the lm324 op-amp and was made as compact as possible to reduce potential noise. The low pass filter successfully filtered out noise of 40Hz at -3dB and passed all lower frequencies.

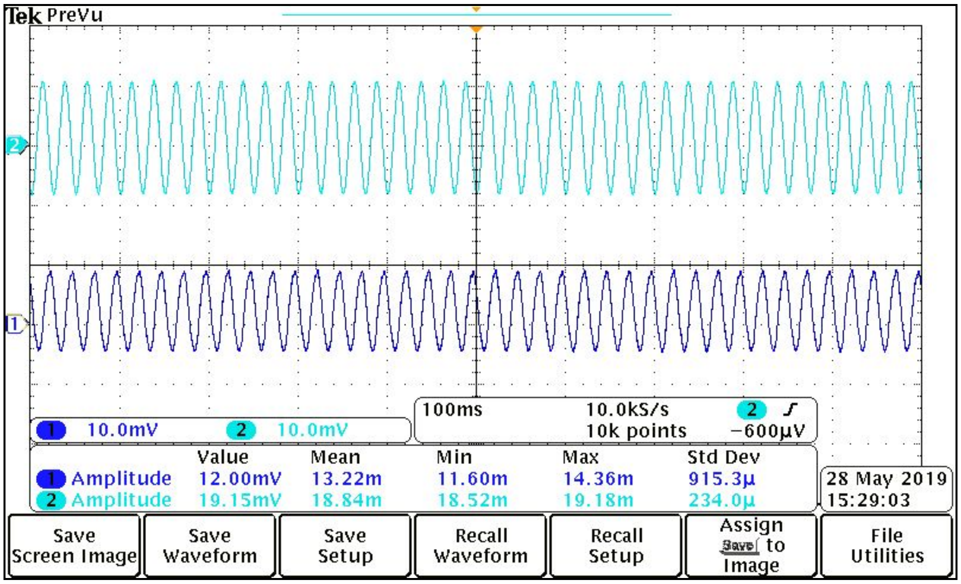


Breadboard layout of the low pass filter (with the constant voltage source to the right

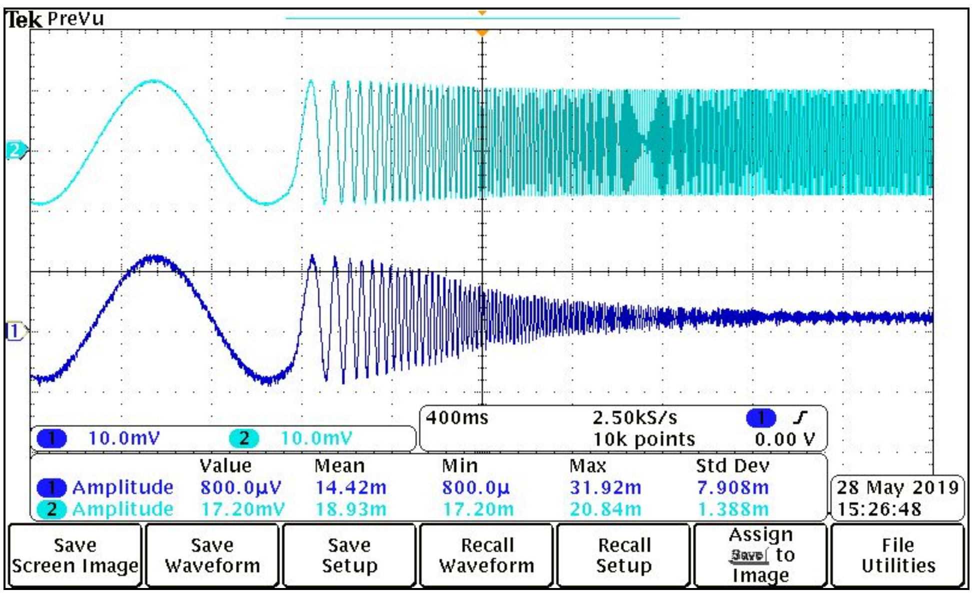
Circuit powered by a single 9V source



Oscilloscope LPF output (20mVpp, 10Hz) (Teal: input, Blue: output)



Oscilloscope LPF output (20mVpp, 40Hz) (Teal: input, Blue: output)

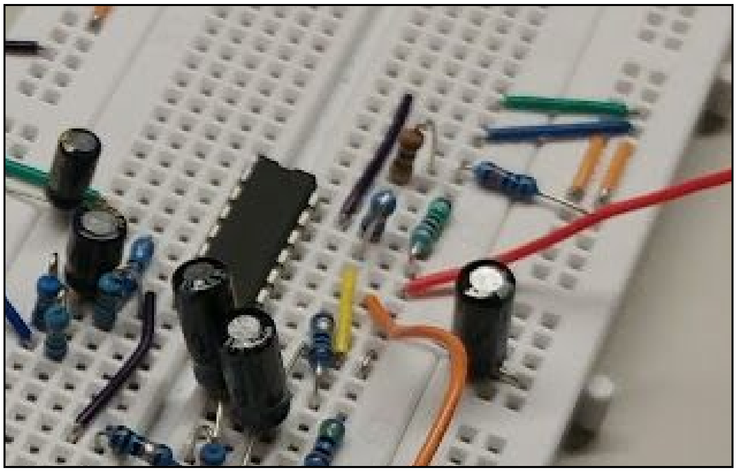


Oscilloscope LPF linear frequency sweep (Teal: input, Blue: output)

The expected operation of the low pass filter was to pass a full signal at frequencies less than the cutoff show in the first oscilloscope image. The filter was then tested at the cutoff of 40Hz which reduced the output to ~-3dB. The final picture is a frequency sweep to show the attenuation that the filter applies to the signal.

Non-inverting amplifier stage

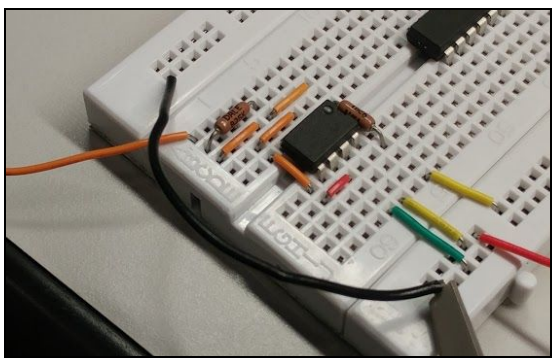
The non-inverting amplifier was built on the same quad op-amp as the Sallen-Key filter. All components were trimmed and positioned to be as compact as possible to reduce the possibility for noise. The measured results aligned with the simulated results and there was a non inverting gain of 10 on the output of the amplifier.



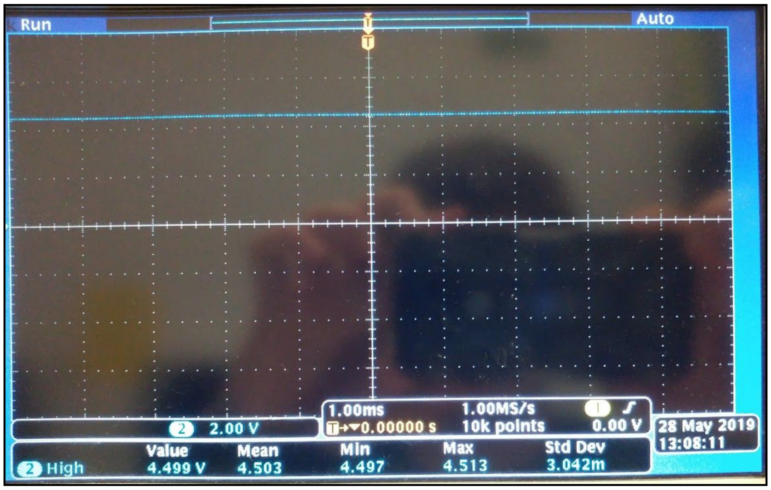
Non-inverting Amplifier (top right of the LM324 quad op-amp)

Constant voltage source

The constant voltage source was built on the end of the breadboard using one 741 op-amp and two 800kΩ resistors. The output was then wired to one of the breadboard rails to act as a ground for the different circuit blocks.

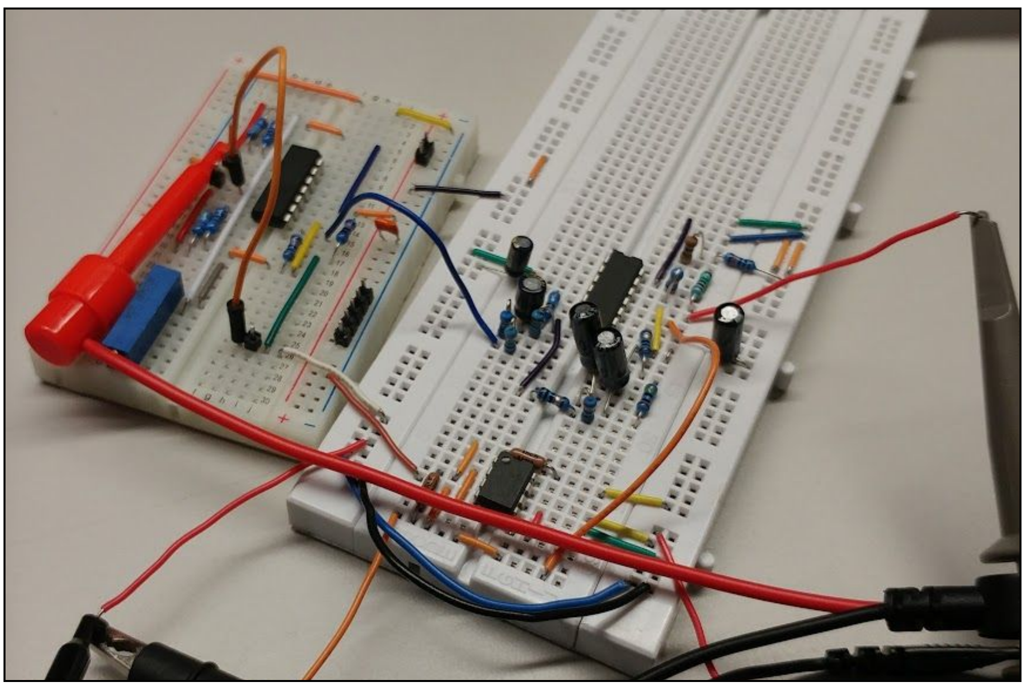


Constant voltage source breadboard layout

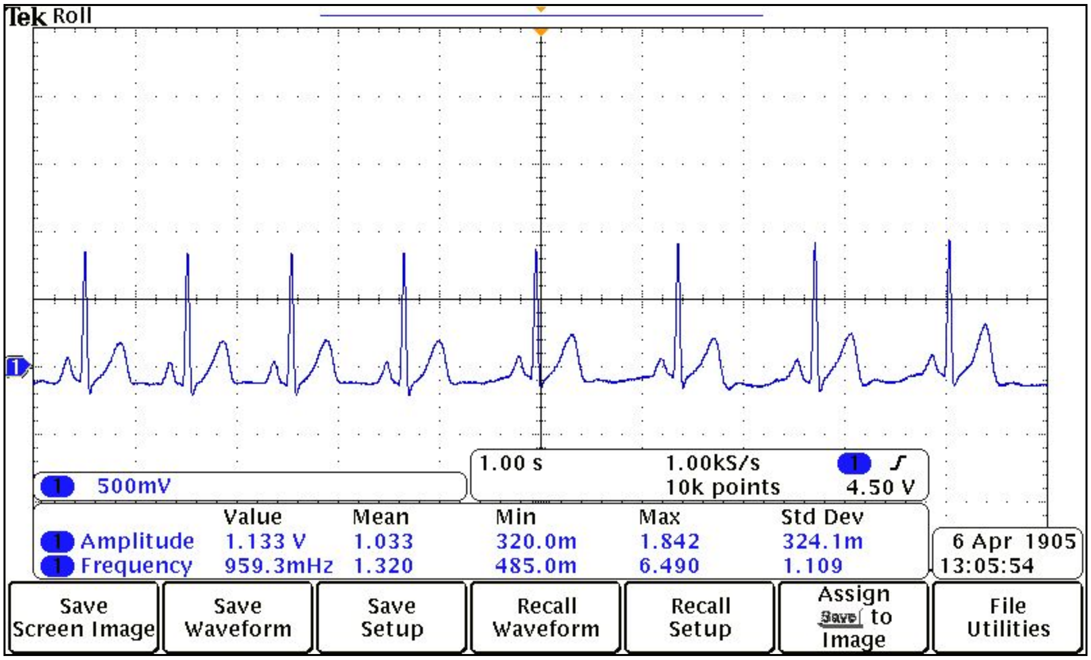


Measurement of the constant voltage source output

Complete Circuit

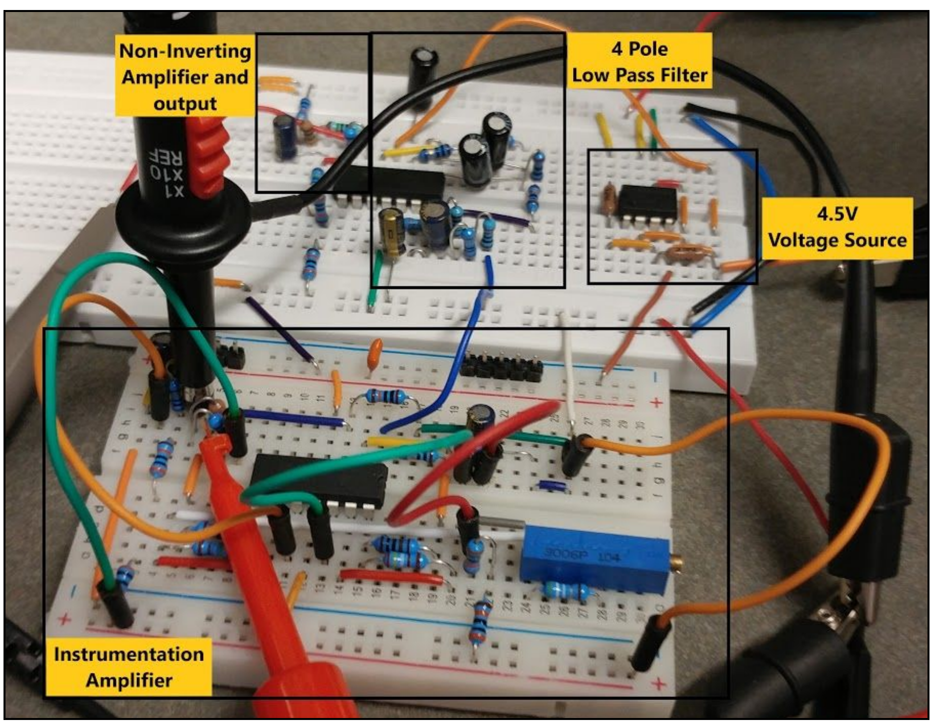


Complete EKG circuit without AC coupling

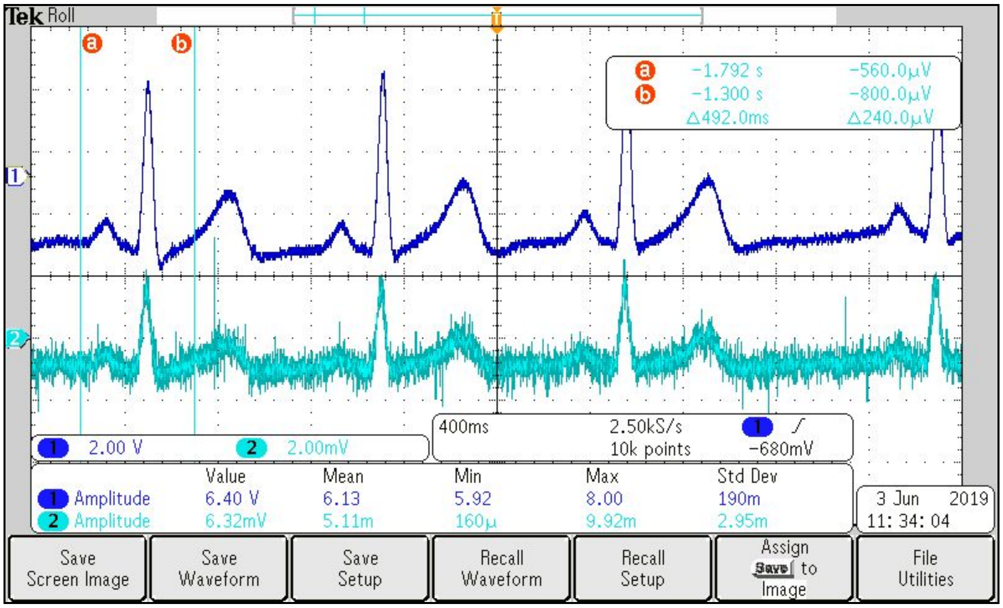


EKG signal test signal without AC coupling

The final measurements for the EKG signal from the function generator without AC coupling or final amplification stage. We also set the gain of the circuit to its minimum so no voltage divider is needed.

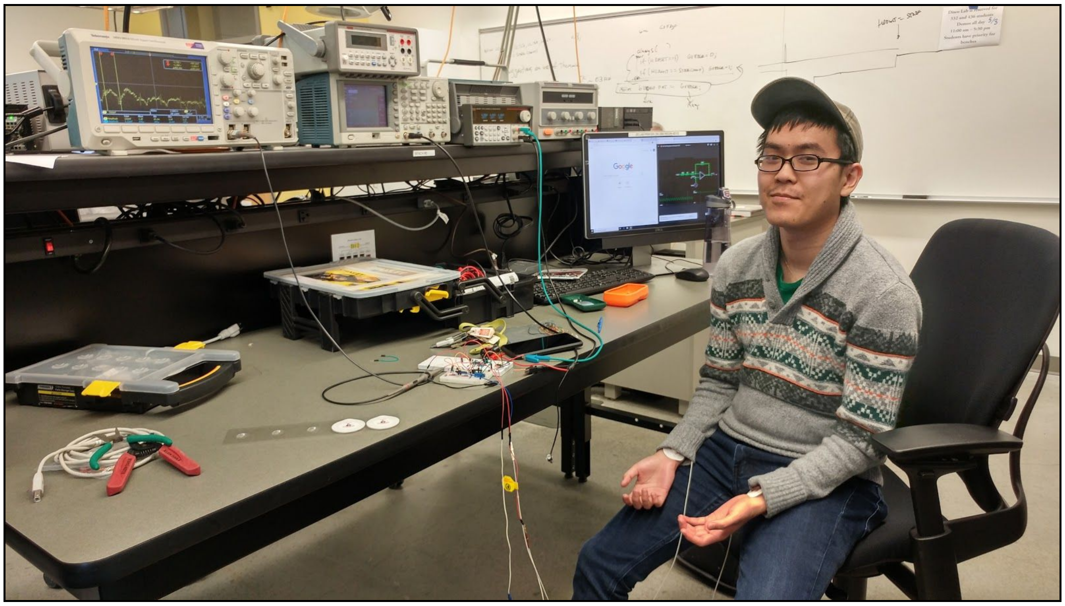


Complete test circuit with voltage divider input

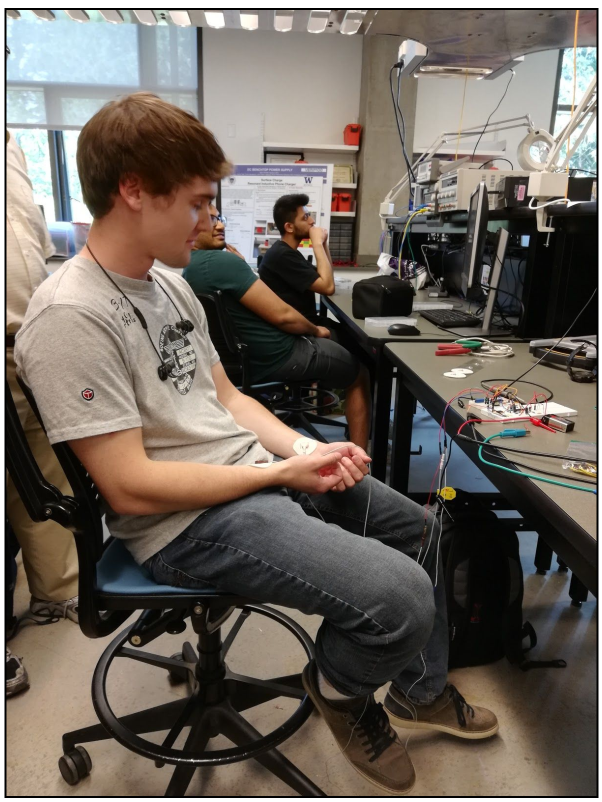


Voltage divider input (Teal), output signal (Blue)

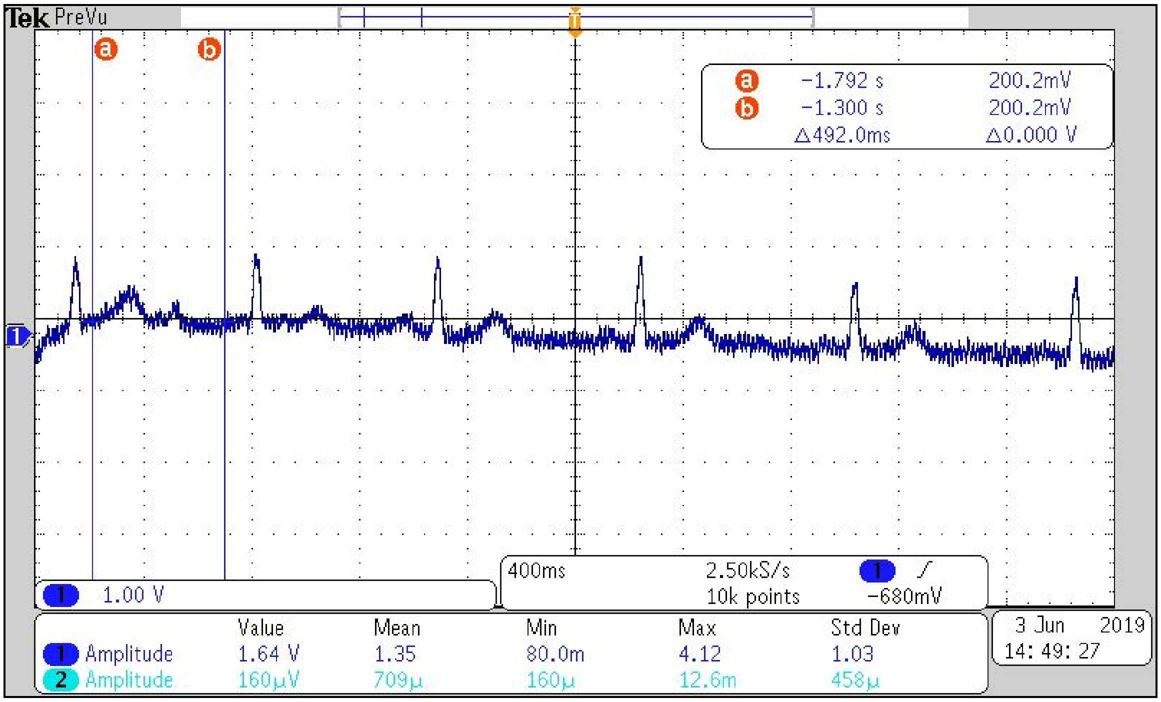
Class nurse Rob applies electrodes to human subject (Minh)



Live human (Minh) test setup (power supply: 9V battery)
Result: non-fatal



Cute boi



Oscilloscope measurements of actual heart rate

The above pictures were measurements taken on a live human subject using a 9V battery power supply. Looking at the frequency of the heart rate, it comes out to ~800ms per beat or 1.25 Hz. This is the average resting heart rate.

Conclusion

The EKG circuit worked according to the specification laid out in the lab description. Both the simulated and real signals were output with the correct gain and with little to no noise. The P-QRS-T signal was very distinct and easy to read on the oscilloscope. The low pass filter stage had more of a gradual rolloff at the cutoff frequency but was dead on -3dB at 40Hz.

References

LM324 Quad op amp - https://www.onsemi.com/pub/Collateral/LM324-D.PDF

LM741 op amp - http://www.ti.com/lit/ds/symlink/lm741.pdf

Sallen key low pass filter calculator - https://www.changpuak.ch/electronics/calc_08.php