18-100: Intro to Electrical and Computer Engineering

LAB05: Op-Amp Lab

Writeup Due: Thursday, March 14th, 2024 at 10 PM

Check-offs Due: No later than Sunday, March 17th, 2024 at 5:30 PM

Name: ______________________________

Andrew ID: ______________________________

How to submit labs:

Download from this file from *Canvas* and edit it with whatever PDF editor you're most comfortable with. Some recommendations from other students and courses that use Gradescope include:

DocHub	An online PDF annotator that works on desktop and mobile platforms.
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If you have difficulties inserting your image into the PDF, simply append them as an extra page to the END of your lab packet and mark the given box. ***Do NOT insert between pages.***

If you'd prefer not to edit a PDF, you can print the document, write your answers in neatly and scan it as a PDF. *(Note: We do not recommend this as unreadable lab reports will not be graded!).* Once you've completed the lab, upload and submit it to *Gradescope*.

Note that while you may work with other students on completing the lab, this writeup is to be completed alone. Do not exchange or copy measurements, plots, code, calculations, or answers in the lab writeup.

Your lab grade will consist of two components:

1. Answers to all lab questions in your lab handout. The questions consist of measurements taken during the lab activities, calculations on those measurements and questions on the lab material.
2. A demonstration of your working lab circuits and conceptual understanding of the material. These demos are scheduled on an individual basis with your group TA.

Question:	1	2	3	4	5	Total
Points:	12	10	9	11	18	60
Score:						

Lab Outline

This lab aims to teach students op amp configurations, their behaviors and applications.

1. Comparator Light Switch
2. Buffer (Unity-Gain Amplifier)
3. Inverting Amplifier
4. Non-Inverting Amplifier
5. Microphone Amplifier

Small Group Check-off Circuits

- ☐ Comparator light switch
- ☐ Microphone Amplifier

Equipment Required

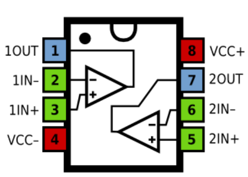
- 1x Breadboard
- 3x 9V Battery with Battery Clip
- 1x Digital Multimeter
- 1x ADALM2000 {`Power Supply`, `Oscilloscope`, `Signal Generator`}
- 1x Wire Strippers
- 1x Diagonal Cutters

Bill of Materials

2x  1kΩ Resistor
3x  10kΩ Resistor
1x  2.2kΩ Resistor
1x Microphone (handed out in small groups)
2x Dual Op Amp IC Chip (TL072, Box 1)
1x Light-dependent resistor (CdS cell, Box 2)
1x Red LED

2x  4.7kΩ Resistor
2x  100kΩ Resistor
1x  100Ω Resistor
1x 20kΩ Potentiometer (`B20K`)
1x 50kΩ Potentiometer (`B50K`)
1x Blue LED

Pinouts



TL072 Op-Amp Pinout

Introduction and Setup

This lab focuses on a versatile subclass of amplifiers known as *operational amplifiers* ('op amps'). Since they are *active devices*, they require external power to run. In this lab, we will use a *dual-sided supply*, providing +9V to $+V_{CC}$ and $-9V$ to $-V_{CC}$. You can do this with two 9V batteries connected in series as shown in Figure 1.

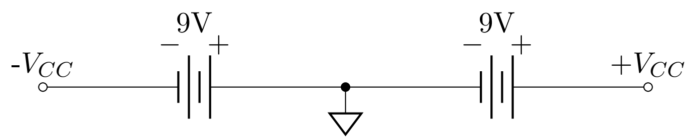


Figure 1: Making a dual-sided supply with two 9V batteries

Note the polarity of the battery terminals (connected positive to negative)

Designate one half of your breadboard to use the ±9V rails. **Please remove the connections connecting all of your supply rails together on this section of the board.** The blue rails will be the reference node (ground), one of the red rails will be +9V, and the other red rail will be −9V. Figure 2 is a breadboard diagram showing how to connect your batteries.

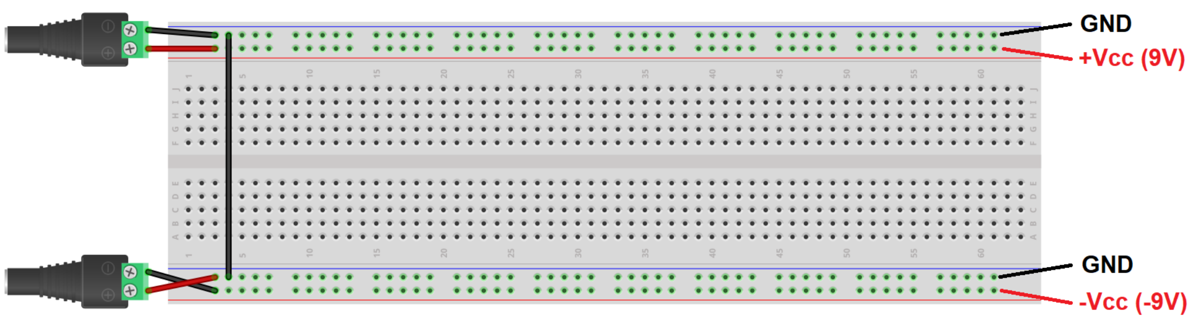


Figure 2: Making a dual-sided supply on a breadboard

Before connecting devices to the supply rails, check voltages with multimeter!

Connect the black probe (COM) to the blue GND rail and you should measure +9V on one red rail and −9V on the other red rail. Make sure that you keep track of which is which. If you reverse the supply voltages going to the op amp chip, it can get very hot. **If the op-amp chip feels warm to the touch, disconnect the batteries immediately.**

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1. Comparator Light Switch

Build the following circuit on your breadboard, which uses the light-dependent resistor (LDR) from Lab 1 to control an LED:

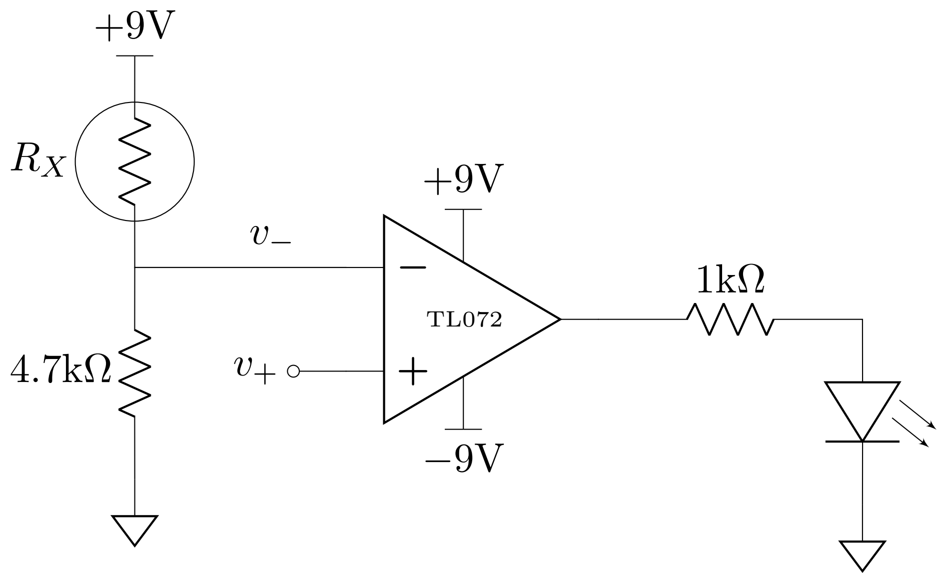

Figure 3: Comparator Circuit with LED indicator at output and light-dependent voltage divider at the inverting input.

This circuit uses the op amp in an open-loop configuration (i.e. no feedback). When the voltage at v_+ exceeds the voltage at v_-, the output will be driven to +9V and the LED will turn on. Otherwise, the LED will be off.

A voltage divider consisting of an LDR R_X and a 4.7 kΩ resistor provides a voltage to the v_- input. You will build a second voltage divider to provide ≈ 4.5V to the v_+ input. The comparator will compare v_- to v_+ and then drive its output to either high (LED on) or low (LED off).

2 pts

1.1 Measure v_- using a digital multimeter, both when the LDR is well-lit and when the LDR is in the dark. What are the dark (V_{dark}) and light (V_{light}) voltages that you measured at v_-?

V_{dark} = ______ V V_{light} = ______ V

10 pts

1.2 Complete your light-switch circuit on your breadboard by adding a voltage divider to provide 4.5V to the v_+ input. The LED should have a different state when the LDR is well-lit versus when the LDR is in the dark. When you are finished, keep this circuit on your breadboard, as you will need it for check-offs.

⚠ **Do NOT take your circuit apart yet! You will need it for lab checkoff!**

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2. Buffer (Unity-Gain Amplifier)

Construct the following circuit in Figure 4. The goal of this circuit is to divide down the initial voltage, 5V, twice. Connect 5V from the breadboard power supply as the power supply for this circuit and measure V_A and V_{out} multimeter. $R_{1,2,3,4} = 10\text{k}\Omega$.

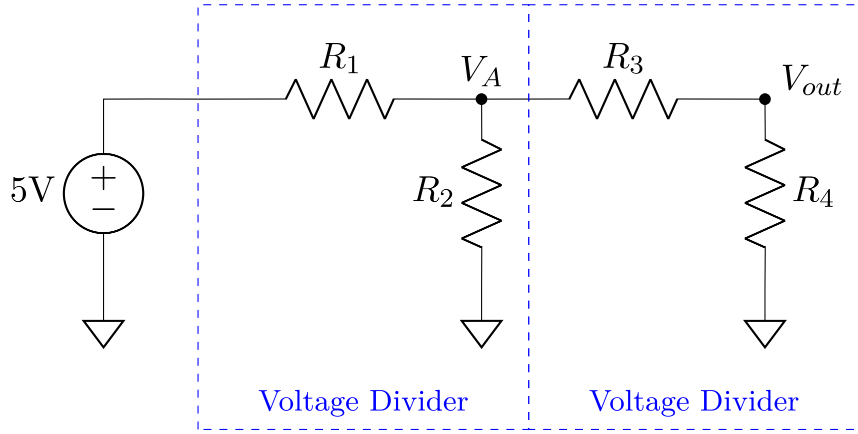

Figure 4: Cascading Voltage Dividers

3 pts

2.1 Measure the voltages V_A and V_{out} with your voltmeter:

$\boldsymbol{V_A}$	$\boldsymbol{V_{out}}$

2 pts

2.2 Is the circuit dividing the voltage in half twice (i.e. is $V_{out} = \frac{V_{in}}{4}$)? Explain why or why not.

Now we introduce a unity-gain buffer between the two voltage dividers in the previous circuit. Build the circuit in Figure 5 and perform the same measurements. Notice in Figure 5 that there is no external supply pictured for the op amp. When you see an op amp from now on, the +9V and −9V supply rails are implied. $R_{1,2,3,4} = 1\text{k}\Omega$.

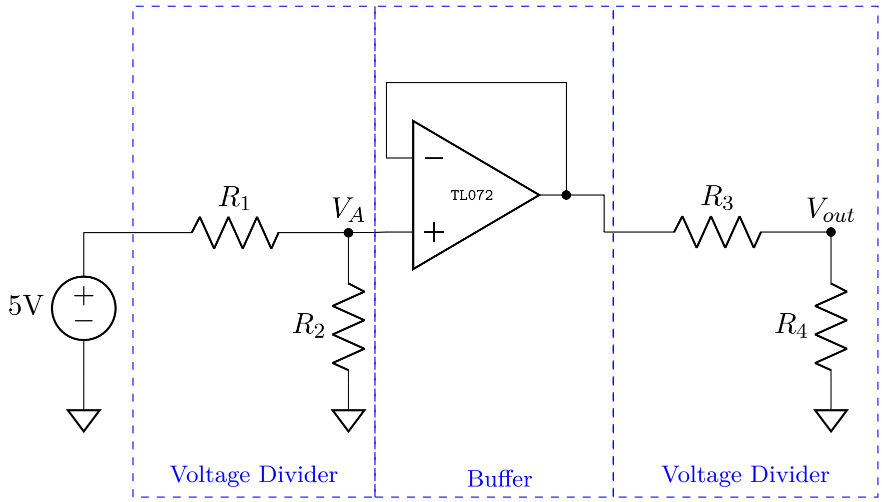

Figure 5: Consecutive voltage dividers separated by op amp buffer

3 pts

2.3 Measure the voltages V_A and V_{out} with your voltmeter:

$\boldsymbol{V_A}$	$\boldsymbol{V_{out}}$

2 pts

2.4 Explain why buffering the voltage dividers causes the correct level of voltage division. Refer to the input and output resistances of the op amp in your answer.

3. Inverting Amplifier

Now we're going to introduce some *amplification* to our op-amp circuits. The Inverting Amplifier (and its cousin the Non-Inverting Amplifier in the next section) use negative feedback and a voltage divider to amplify the signal at its input (V_{in}).

Assemble the following circuit in Figure 6 on your breadboard. Use a 4.7kΩ resistor for R_f and a 1kΩ resistor for R_i.

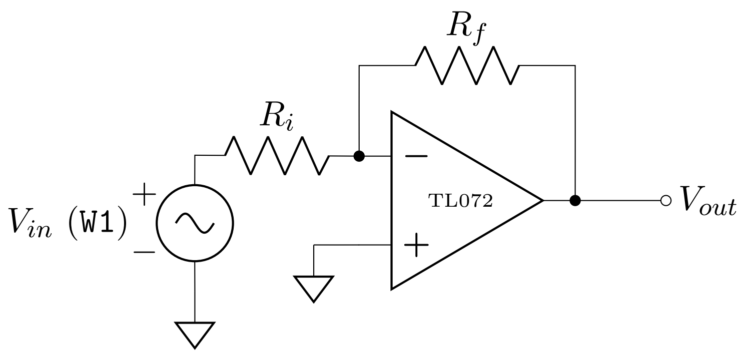

Figure 6: Inverting Amplifier with Fixed Gain

Using the Signal Generator

You may notice the sinusoidal voltage source, op-amps amplify more than just DC! In Scopy, open the `Signal Generator`. Read the following guide on how to configure and use the Signal Generator: `https://wiki.analog.com/university/tools/m2k/scopy/siggen`. Enter the settings menu for 

and select "Waveform." Configure the following settings:

`Signal Generator`	
Sine Wave	
Amplitude: $1V_{pp}$ Frequency: 1kHz	Offset: 0V Phase: 0 deg

In the circuit above, you'll connect the `W1` pin on the ADALM in place of the positive terminal of V_{in} and the ADALM's `GND` pin to the negative terminal of V_{in}.

Using the Oscilloscope

Read the following guide on how to configure and use the Oscilloscope module in Scopy: `https://wiki.analog.com/university/tools/m2k/scopy/oscilloscope`. Configure the following settings for both channels (CH1 and CH2):

`Oscilloscope`		
Horizontal	**Vertical**	**Settings**
Time Base: 1ms Position: 0ms	Volts/Div: 500mV Position: 0V	Probe Attenuation: 1X Software AC Coupling: Off

Connect a probe to CH1 and CH2 on the ADALM2000 Adapter Board. Make sure the switch on the probe is set to 1X and the coupling on the Adapter Board is set to "DC". Then connect CH1 to the input of the inverting amp, and CH2 to the output.

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Once your circuit is set up hit the 

button to start measuring. The oscilloscope is plotting the voltage across the probe as a function of time. Going left to right (the x-axis), each box represents 20ms (the "Time Base" as set above). Top to bottom (the y-axis), each box represents 1V (the "Volts/Div", with 0V being the center line).

3 pts

3.1 Paste a screenshot of your oscilloscope plot for the amplifier circuit. Make sure both CH1 and CH2 are enabled and have the same voltage scale (volts/div). It is up to you to size the window and choose the correct settings. Any window in which both your input and output waveforms are clearly visible, as well as the voltage scale and measurements, will receive full credit.)

`Paste Screenshot Here`

☐ I have appended the screenshot to the back of my lab writeup

3 pts

3.2 Using the oscilloscope, measure the peak-to-peak voltage at both the input and the output. What is the gain of this circuit?

$$\textbf{Gain} = \frac{V_{out} = \boxed{\quad\quad\quad V}}{V_{in} = \boxed{\quad\quad\quad V}} = \boxed{\quad\quad\quad}$$

3 pts

3.3 Calculate the gain for the circuit in Figure 6 given an ideal op-amp. Show that, for the resistance values used, the ideal gain is approximate to the measured gain.

4. Non-Inverting Amplifier

Assemble the following circuit in Figure 7 on your breadboard. Use a 1kHz $1V_{pp}$ sine wave for V_{in}. Supply ±9V to power the rails of the op amp. Use a 20kΩ potentiometer for R_f and a 1kΩ resistor for R_i.

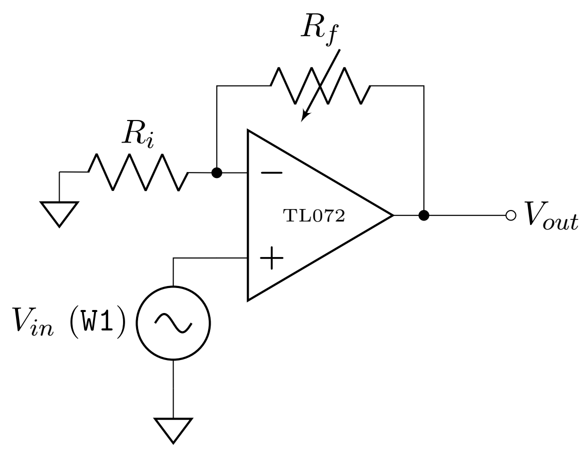

Figure 7: Non-Inverting Amplifier with Variable Gain

Connect CH1 of your oscilloscope to V_{in} and CH2 to V_{out}. Enable measurements for both channels.

3 pts

4.1 Set R_f to 5kΩ. Paste a screenshot of your oscilloscope plot for the amplifier circuit. Make sure both CH1 and CH2 are enabled and have the same voltage scale (volts/div). It is up to you to size the window and choose the correct settings. Any window in which both your input and output waveforms are clearly visible, as well as the voltage scale and measurements, will receive full credit.)

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2 pts

4.2 Measure the peak-to-peak voltage at both the input and the output for your oscilloscope plot from the last part. What is the gain of this circuit?

$$\textbf{Gain} = \frac{V_{out} = \boxed{\quad\quad V}}{V_{in} = \boxed{\quad\quad V}} = \boxed{\quad\quad}$$

2 pts

4.3 Adjust R_f by turning the potentiometer and observe V_{out}. How does increasing R_f affect V_{out}?

2 pts

4.4 Increase the resistance of R_f to 20kΩ, its maximum value. Paste a screenshot of your oscilloscope plot for the amplifier circuit. Make sure both CH1 and CH2 are enabled and have the same voltage scale (volts/div). Also make sure that the entire waveform is visible for both channels.

`Paste Screenshot Here`

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2 pts **4.5** What happens to the output as the input increases? Describe the waveform you see. Why does it look that way?

5. Microphone Amplifier

Now you will build a circuit that will be used again in a few labs: one that amplifies a signal from an **electret microphone** which converts sound waves into an electrical signal. A thin film of charge-embedded dielectric material (the *electret*) is attached to a mechanical diaphragm that vibrates when sound waves hit it. These vibrations result in voltage changes at the gate of a transistor. The electret mic requires a *bias current* that is provided by a voltage source and a resistor outside the capsule. This must be done with the correct polarity.

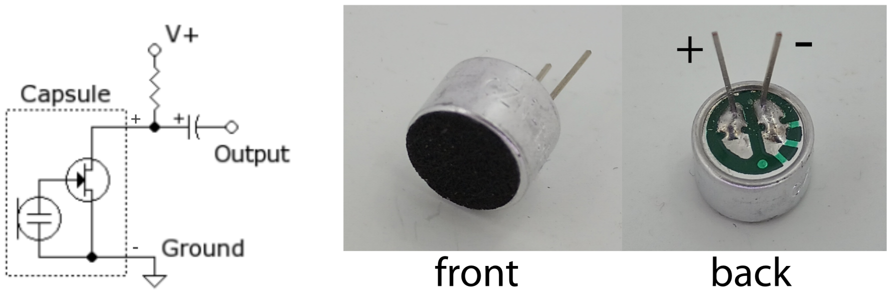

Figure 8: The electret condenser microphone contains a mechanical-wave-sensitive variable capacitor and a transistor (left, image source: Wikipedia). The microphone requires a bias current supplied through a resistor. This bias must be applied with the correct polarity. The negative lead is connected to the microphone's outer case as seen from the back of the mic (right).

Since the microphone will be running off a 5V supply and your op-amps require ±9V supplies, you will need to set up your breadboard as shown in 9. The two op-amp circuits needed for checkoff, the comparator light switch and the microphone amplifier, will be on the section of the breadboard with ±9V rails. The microphone will be on the section of the breadboard with 5V rails. Note that ground wire connects the +5V, +9V, and -9V together.

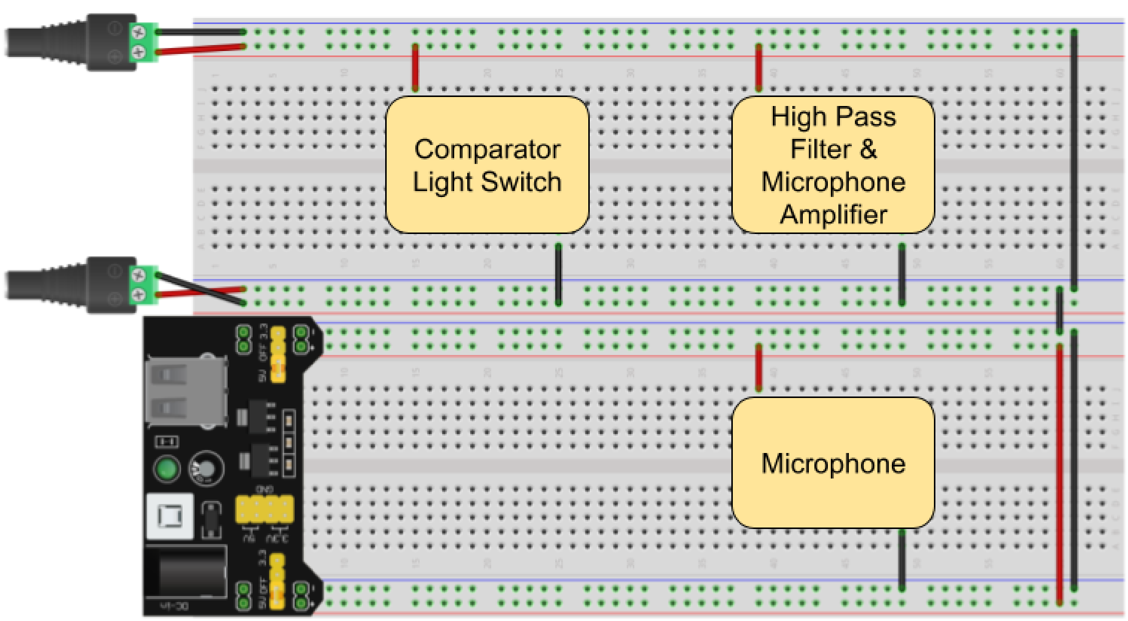

Figure 9: The breadboard setup required for generating +9V, -9V, and +5V on the same breadboard.

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This weak signal generated by the microphone requires pre-amplification before it can be used by the **analog-to-digital converter** you will build in Lab 6. It just so happens that you've already built an amplifier. Modify your non-inverting amplifier circuit to use the electret microphone signal as its input:

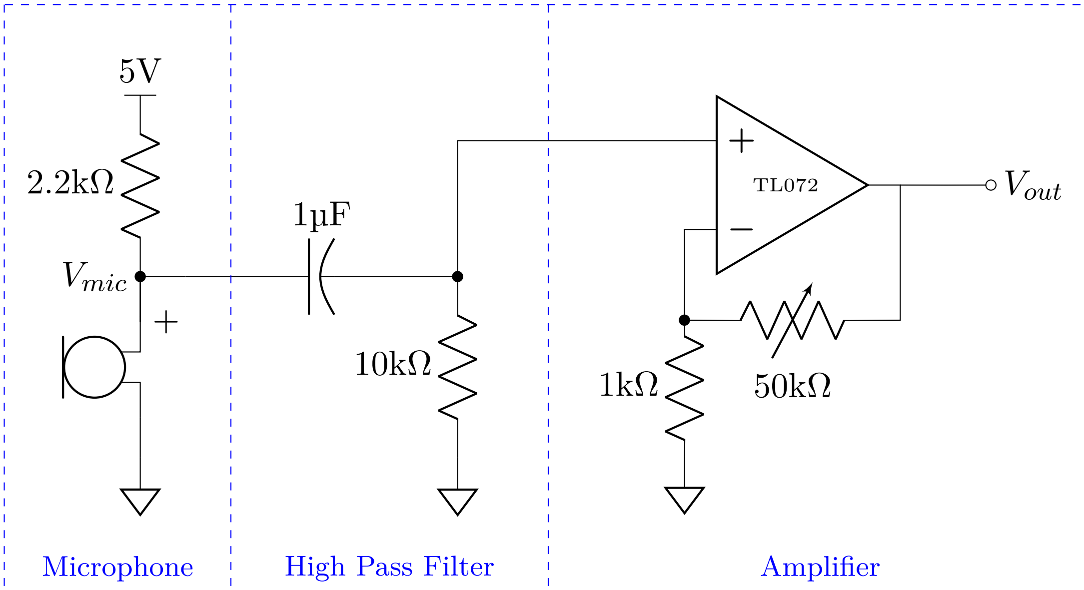

Figure 10: Microphone Amplifier Circuit with Adjustable Gain

2 pts

5.1 What is the minimum and maximum gain of this amplifier when the potentiometer resistance can vary from 0Ω to 50kΩ?

Minimum = ☐ **Maximum** = ☐

In Scopy, configure your settings the the following:

CH1 Settings		**CH2 Settings**	
Time Base	500 μs	**Time Base**	500 μs
Horizontal Position	0 s	**Horizontal Position**	0 s
Vertical Position	0 V	**Vertical Position**	0 V

Trigger mode	auto
Internal (Analog)	on
Source	Channel 1
Condition	Rising Edge
Level	0 V
Hysteresis	50 mV

3 pts

5.2 Connect CH1 of your oscilloscope to V_{out} and CH2 to V_+. Enable measurements for both channels.

Talk into the microphone and adjust R_f until you can visualize sound waves at V_{out}. Paste a screenshot of your oscilloscope plot for the amplifier circuit. Make sure both CH1 and CH2 are enabled and have the same voltage scale (volts/div). It is up to you to size the window and choose the correct settings. Any window in which both your input and output waveforms are clearly visible, as well as the voltage scale and measurements, will receive full credit.

`Paste Screenshot Here`

☐ I have appended the screenshot to the back of my lab writeup

3 pts

5.3 Use your multimeter to measure the DC voltages V_{mic}, V_+, and V_- and complete the table below with your measurements.

$\boldsymbol{V_{mic}}$	$\boldsymbol{V_+}$	$\boldsymbol{V_-}$

10 pts

5.4 Be prepared to check off this microphone op-amp circuit.

⚠ **Do NOT take your circuit apart yet! You will need it for lab checkoff!**