OPERATIONAL AMPLIFIERS (OP-AMPS) I

LAB 4 INTRO: INTRODUCTION TO ONE OF TWO OF THE MOST USED OP-AMP CIRCUITS: NON-INVERTING AMPLIFIERS

GOALS

In this lab, you will characterize the gain and frequency dependence of op-amp circuits, one of the most useful components in electronics (unless you like using vacuum tubes). You will also measure input and output impedances of these circuits. The op-amp is the most important building block of analog electronics.

Proficiency with new equipment:

- o Op-amps: Non-inverting amps with finite gain and unity gain (voltage follower)

Proficiency with new analysis and plotting techniques:

- o Bode plots

Modeling the physical system:

- o Frequency dependence of op-amp circuits
- o Input and output impedances of op-amp circuits

DEFINITIONS

Closed-loop gain, G – gain of the *op-amp circuit* at all frequencies with feedback applied
Low frequency gain, G_0 – gain of the *op-amp circuit* at DC (f = 0 Hz)
Open-loop gain, A – gain of the *op-amp itself* at all frequencies with no feedback applied
DC gain, A_0 – gain of the *op-amp itself* at DC (f = 0 Hz) with no feedback applied
f_0 – 3 dB frequency for an *op-amp itself* with no feedback
f_B – 3 dB frequency for an *op-amp circuit* with feedback applied
f_T – unity gain frequency, frequency where the open loop gain A is equal to one

GENERAL PURPOSE OF OP-AMPS

One of the main purposes of an amplifier is to increase the voltage level of a signal while preserving as accurately as possible the original waveform. In the physical sciences, transducers are used to convert basic physical quantities into electric signals, as shown in Figure 1. An amplifier is usually needed to raise the small transducer voltage (μV to mV) to a useful level (mV to V).
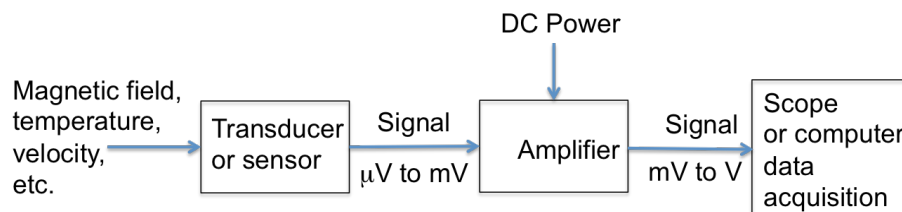

Figure 1: Typical Laboratory Measurement System

Measuring and recording equipment typically requires input signals of 10 mV to 10 V. To meet such needs, a typical laboratory amplifier might have the following characteristics:

1.   Predictable and stable gain. The magnitude of the gain is equal to the ratio of the output signal amplitude to the input signal amplitude.
2.   Linear amplitude response, so that the output signal is directly proportional to the input signal.
3.   According to the application, the frequency dependence of the gain might be a constant independent of frequency up to the highest frequency component in the input signal (wideband amplifier), or a sharply tuned resonance response if a particular frequency must be picked out.
4.   High input impedance and low output impedance are usually desirable. These characteristics minimize changes of gain when the amplifier is connected to the input transducer and to other instruments at the output.
5.   Low noise is usually important. Every amplifier adds some random noise to the signals it processes, and this noise often limits the sensitivity of an experiment.

Commercial laboratory amplifiers are readily available, but a general-purpose amplifier is expensive (>$1000), and most of its features might be unneeded in a given application. Often, it is preferable to design your own circuit using a cheap (<$1) op-amp chip.

Op-amps have many other circuit applications. They can be used to make filters, limiters, rectifiers, oscillators, integrators, and other devices (see FC 12.9 – 12.15). We will build some of these circuits in the next lab, Lab 5.

OP-AMP BASICS

The two basic op-amp circuit configurations are shown in Figs. 2(a) and 2(b). Both circuits use **negative feedback**, which means that a portion of the output signal is sent back to the negative input of the op-amp. The op-amp itself has very high gain, but relatively poor gain stability and linearity. When negative feedback is used, the circuit gain is greatly reduced, but it becomes very stable. At the same time, linearity is improved and the output impedance decreases.
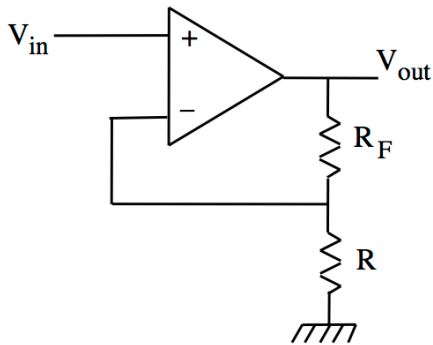

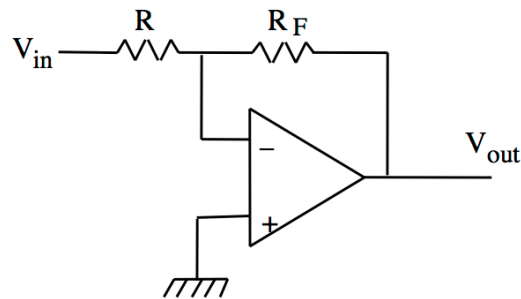Figure 2(a) Non-inverting Amplifier   Figure 2(b): Inverting Amplifier

Both configurations are widely used because they have different advantages. Besides the fact that the second circuit inverts the signal, the main differences are that the first circuit has much higher input impedance, while the second has lower distortion because both inputs remain very close to ground. In this lab, we will be focusing on the first-type, non-inverting.

The gain or transfer function, A, of the **op-amp alone** is given by

$$A \equiv \frac{V_{out}}{V_{in}^+ - V_{in}^-}$$

where the denominator is the difference between the voltages applied to the + and - inputs. We use the symbol G for the gain of the complete amplifier with feedback: $G = V_{out}/V_{in}$. This gain depends on the resistor divider ratio

$$B = \frac{R}{R + R_f}$$

If we assume an ideal situation where A = ∞, that the op-amp input impedance is infinite, and that the output impedance is zero, then the behavior of these circuits can be understood using the simple "Golden Rules":

I. **The voltage difference between the inputs is zero. ("voltage rule")**
II. **No current flows into (or out of) each input. ("current rule")**

The "Golden Rule" analysis is very important and is always the first step is designing op-amp circuits, so be sure you understand it before you read the material below, where we consider the effect of finite values of A, mainly so that the frequency dependence of the closed loop gain G can be understood.

Non-inverting amplifier

The basic formula for the low frequency gain of non-inverting amplifiers is derived in FC, Section 12.5. Using just the Golden rules, which assumes A>>1, the gain is given by

$$G_0 = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R}$$

Formulas for the input and output impedance of the entire circuit are derived in H&H Section 4.26. The results are

$$R_i' = R_i(1 + AB)$$

$$R_o' = R_o/(1 + AB)$$

where R_i and R_o are the input and output impedances of the *op-amp alone*, while the primed symbols refer to the whole amplifier with feedback. These impedances will be improved from the values for the bare op-amp if A·B is large.

The above formulas are still correct when A and/or B depend on frequency. B will be frequency independent if we have a resistive feedback network (in other cases that use complex impedance it may not be), but A always varies with frequency. For most op-amps, including the LF356, the open loop gain varies with frequency like an RC low-pass filter:

$$A = \frac{A_0}{1 + j\dfrac{f}{f_0}}$$ (2)

The 3dB frequency, f_0, is usually very low, around 10 Hz. Data sheets do not usually give f_0 directly;

instead they give the dc gain, A_0, and the unity gain frequency f_T, which is the frequency where the magnitude of the open loop gain A is equal to one. The relation between A_0, f_0, and f_T is

$$f_T = A_0 f_0$$

The frequency dependence of the closed loop gain G is then given by

$$G = \frac{G_0}{1 + j\dfrac{f}{f_B}}$$

The frequency response of the amplifier with feedback is therefore also the same as for an RC low-pass filter.

We can now derive an example of a very important general rule connecting the gain and bandwidth of feedback amplifiers. Multiplying the low frequency gain G_0 by the 3 dB bandwidth f_B gives

$$A_0 f_0 = G_0 f_B = f_T$$

In words, this very important formula says that the gain-bandwidth product $G_0 f_B$ equals the unity gain frequency f_T. Thus if an op-amp has a unity gain frequency f_T of 1 MHz, it can be used to make a non-inverting amplifier with a gain of one and a bandwidth of 1 MHz, or with a gain of 10 and a bandwidth of 100 kHz, *etc*. We will consider what this means for the transfer function as a function of frequency on a Bode plot.

1.   FC Sections 12.2 – 12.15. The basic rules of op-amp behavior and the most important op-amp circuits. [Note while FC discussed basic characteristics of op amps in 12.2 it does not have the "Golden Rule" analysis that we will discuss in class.] Do not worry right now about the transistor guts of op-amps. We will learn about transistors in Experiments 7-8.
2.   Horowitz and Hill, Chapter 4.

LAB PREP ACTIVITIES

Answer the following questions using Mathematica for the plots. You can use either Mathematica for the rest the questions as well or do them by hand in your lab book. **Bring an electronic copy of your notebook to lab, preferably on your own laptop. You will use it to plot your data during the lab session.**

Question 1	**Properties of an Op-amp**
	 The first step in using a new component is to look up its basic characteristics. Find the following specs using the data sheet for the op-amp you will use in the lab for the rest of the semester. Data for the LF356 op-amp (same as LF156) are given at the National Semiconductor Web Site. (There is a also a link from the 3330 web page under *Useful Docs*).
	
	     a. Unity gain frequency, f_T (same as GBW in tables)
	     b. DC voltage gain, A_0 (same as A_{VOL} in tables) (Note: listed as V/mV, milli = 10^{-3})
	     c. Maximum output voltage (same as V_O in tables)
	     d. Maximum output current
	     e. Input resistance, R_i

Question 2	**Non-inverting amplifier**
	     a. Calculate the values of low frequency gain G_0 and the bandwidth f_B for the non-inverting amplifier in Fig. 2(a) for the following two circuits you will build in lab.
	
	        1) R_F = 10 kΩ, R=100Ω
	        2) R_F=0, R=∞ (this is a voltage follower)
	
	     b. Predict the output voltage, V_{out}, for the non-inverting amp with R_F = 10 kΩ ⬤ R=100Ω when
	        1) V_{in} = 1 mV DC
	        2) V_{in} = 1 V DC, Explain your reasoning.
	
	 HINT: see answer for Question 1 part c.
	
	     c. Plot Bode plots for the open loop gain and the two closed loop gains from part (a) on the same graph using Mathematica.
	     d. Estimate the input impedance of the complete amplifier circuit (R_i') with R_F = 10 kΩ and R = 100 Ω for 1 kHz sine waves.
	     e. Estimate the output impedance of the complete amplifier circuit (Ro') with R_F=10 kOhm and R=100 Ohm for 1 kHz sine waves. The nominal output impedance of the LF356 alone is 40 Ohms. To obtain the circuit output impedance at 1 kHz, one can use this value and determine Ro' using the formula given above. Alternatively, one can read off the value from the top left plot on page 7 of the datasheet. This shows the output impedance for an inverting amplifier (which has the same output impedance as a non-inverting amplifier) as a function of frequency for gains of A_V = 1, 10, 100.

Question 3	**Lab activities**
	a. Read through all of the lab steps and identify the step (or sub-step) that you think will be the most challenging.
	b. List at least one question you have about the lab activity.

SETTING UP A BASIC OP-AMP CIRCUT

All op-amp circuits start out by making the basic power connections. Op-amps are active components, which means they need external power to function unlike passive components such as resistors.
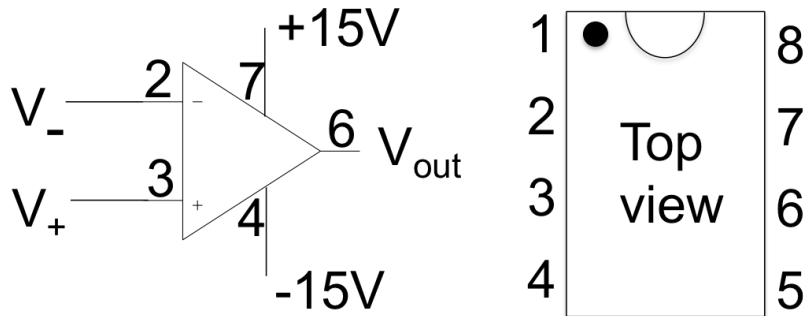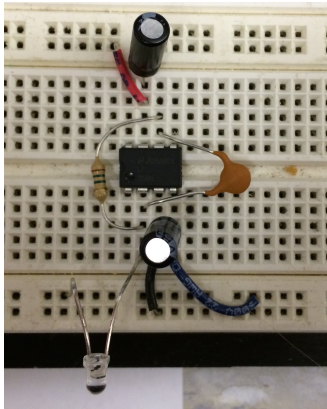

Figure 3. LF356 pin-out and schematic.

Figure 4. Good placement of op-amp and bypass capacitors on proto-board. Note short wires are used for all connections.

Step 1	**Op-amp Tips**
	a. This experiment will use both +15V and -15V to power the LF356 op-amp. Turn off the power while wiring your op-amp. Everyone makes mistakes in wiring-up circuits. Thus, it's a good idea to check your circuit before applying power. Fig. 3 shows a pin-out for the LF356 chip. Familiarize yourself with the layout.
	The following procedure will help you wire up a circuit accurately:
	1. Draw a complete schematic in your lab book, including all ground and power connections, and all IC pin numbers. Try to layout your prototype so the parts are arranged in the same way as on the schematic, as far as possible.
	2. Measure all resistor and capacitor values before putting them in the circuit. Be care with unit prefixes. It is easy to mistake a 1 nF capacitor for a 1 µF one. (You don't need to know the precise values of the bypass capacitors, so there is no need to measure them.)

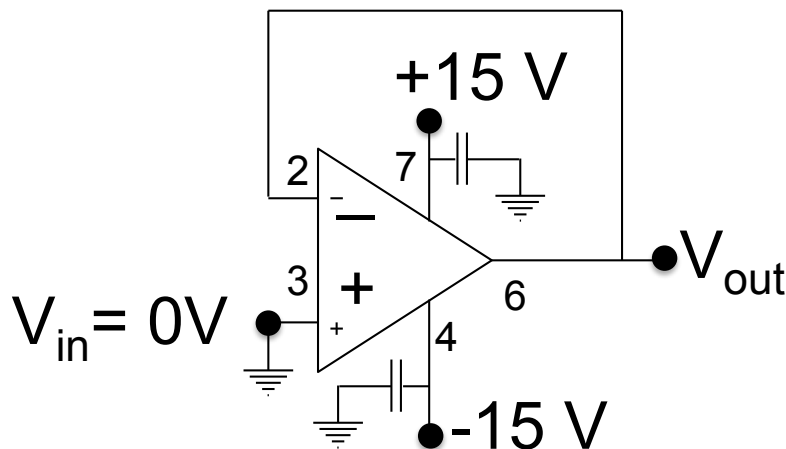|	

	3. Adhere to a color code for wires. For example:
	
	        0 V (ground) Black
	        +15 V Red
	        -15 V Blue
	
	b. The op-amp chip sits across a groove in the prototyping board (see Fig 4). Before inserting a chip, gently straighten the pins. After insertion, check visually that no pin is broken or bent under the chip. To remove the chip, use a small screwdriver in the groove to pry it out.
	c. You will have less trouble with spontaneous oscillations if the circuit layout is neat and compact, in particular the feedback path should be as short as possible to reduced unwanted capacitive coupling and lead inductance. (see Fig 4). Hint: do not wire over the chip but around it.
	d. To help prevent spontaneous oscillations due to unintended coupling via the power supplies, use bypass capacitors to filter the supply lines. A bypass capacitor between each power supply lead and ground will provide a miniature current "reservoir" that can quickly supply current when needed. This capacitor is normally in the range 1 µF – 10 µF. The exact value is usually unimportant. Compact capacitors in this range are usually electrolytic, tantalum, or aluminum and are *polarized*, meaning that one terminal must always be positive relative to the other. The capacitors are labeled which side is which, but each manufacture uses different markings. If you put a polarized capacitor in backwards, it will burn out. Bypass capacitors should be placed as close as possible to the op-amp pins. (see Fig 4).

Step 2	**Testing the op-amp**
	    a. You can save yourself some frustration by testing your op-amp chips to make sure they are not burned out. Connect the op-amp as a *voltage follower* with the (positive) input grounded (see Fig. 5). What is the predicted voltage on pins 2, 3, 4, 6 and 7 using the Golden Rule model? Measure and record the measured voltages on these pins. If your predictions do not match your measurements check your connections to the chip to find the problem. Make sure your predictions match your measurements before going on.
	    b. If you find you have a bad chip, throw it in the trash to save another person from having to deal with it. (In case you are wondering, the LF356 costs $0.50)

Figure 5. Schematic of a voltage follower with the input grounded.

VOLTAGE FOLLOWER

A voltage follower is the simplest version of a non-inverting amplifier. The voltage follower has no voltage gain ($G_0=1$), but it lets you convert a signal with high impedance (i.e. very little current) to a much lower impedance output for driving loads. The voltage follower is also often called a unity gain buffer.
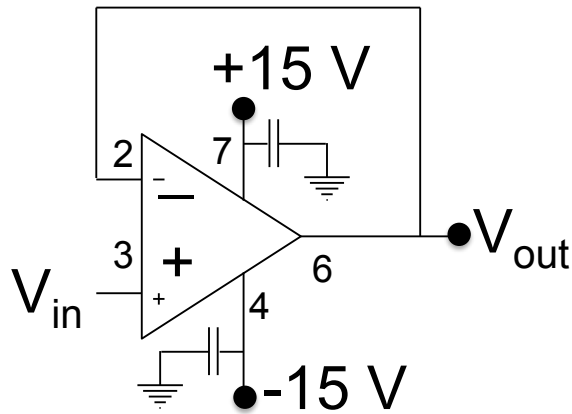

Figure 6. Voltage Follower

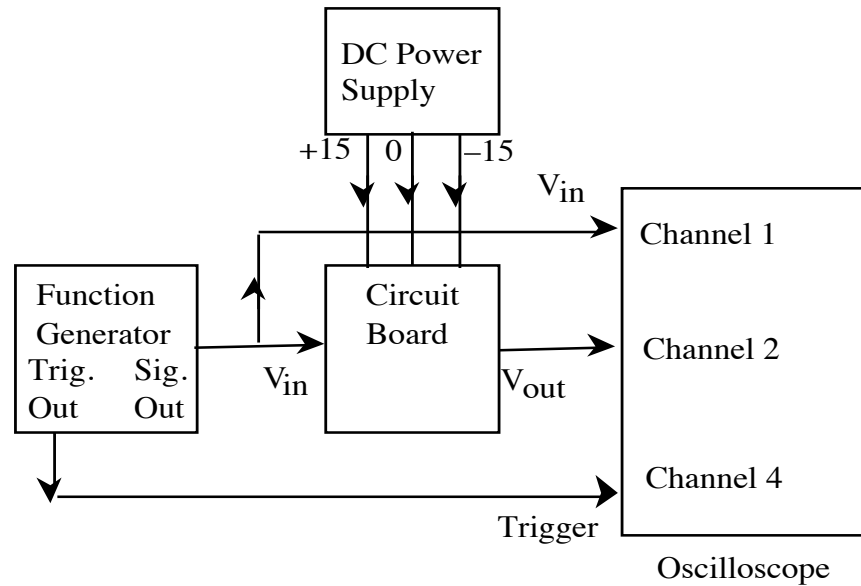| Step 3	**Low frequency gain and frequency dependence of the gain.** a. The voltage follower circuit is nearly the same as the test circuit, except that now a signal enters the positive input (Fig. 6). The basic test and measurement setup is shown in Fig. 7. b. Use the function generator to measure the low frequency gain. What frequency should you use to test the low frequency gain (i.e., what frequency should the signal be below)? Consider the gain-bandwidth product for a unity gain amplifier. What is gain-bandwidth product for this circuit? How did you find the value? What is the predicted gain for the frequency you chose? Measure the low frequency gain G_0 by measuring V_{in} and V_{out} using the scope. Do your measurements agree with your predictions? c. Now vary the frequency and look for deviation from the performance of an ideal follower model. The measurement at high frequency will depend on many details of your setup and you are unlikely to find a simple RC filter type falloff. Using the 10X scope-probe, measure the gain at every decade in frequency from 10 MHz down to 10 Hz, with (as usual) a few extra points anywhere things are starting to change. Do you find any deviation from unity gain? *HINT: Be sure that the output amplitude is below the level affected by the slew rate For help, see H&H p. 192.* Plot the low and high frequency data and predicted behavior on your Bode plot from your lab prep. Do you find a simple fall-off as suggested by the theory for the ideal follower ($f_T=f_B$)? If so, find the 3dB frequency. How does your measured 3dB frequency compare to what is expected from the op-amp datasheet? d. If you observed ideal behavior, you're lucky! At frequencies above a few MHz, the simple model of the frequency response of the op-amp is not accurate. Once you are in this frequency range, many physical details of your circuit and breadboard can have large effects in the circuit (see notes in Step 1(d) above) . You could model these effects, but a better procedure to follow is to modify the physical setup. Building reliable circuits at these frequencies typically requires careful attention to grounding and minimization of capacitive and inductive coupling between circuit elements and to ground. Printed circuit boards are much better for high-frequency applications. At lower frequencies, our model of the circuit will work much better.

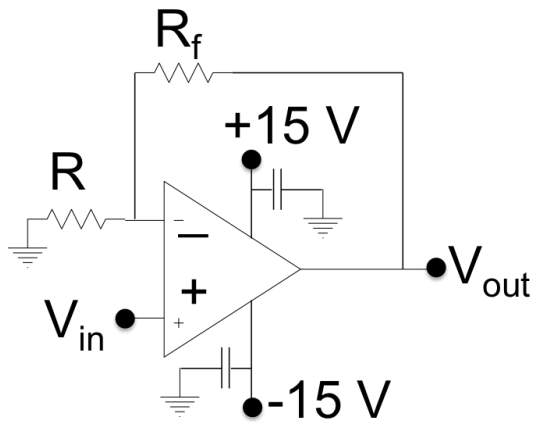Figure 7. Test and measurement setup for op-amp circuits.

NON-INVERTING AMPLIFIER

Figure 8. Non-inverting Amplifier

Step 4	**Frequency Dependent Gain** a. Change the negative feedback loop in your circuit to the one shown in Fig. 8., with $R_F = 10 \text{ k}\Omega$ and $R = 100 \text{ }\Omega$. Measure R and R_F with the DMM before inserting them into the circuit board. Predict G_0 and f_B from these measured values and the op-amp's value of f_T from the data sheet. (You should be able to review your lab-prep work here too!) b. Use the function generator to measure the low frequency gain. What frequency should you use to test the low frequency gain (i.e., what frequency should the signal be below)? Consider the gain-bandwidth product for a unity gain amplifier. What is gain-bandwidth product for this circuit? How did you find the value? What is the predicted gain for the frequency you chose? Measure the low frequency gain G_0 by measuring V_{in} and V_{out} using the scope. Do your measurements agree with your predictions?

	c. Measure the voltage saturation values for your circuit. Vary the input amplitude until you observe saturation in the output. What are the output saturation levels, +Vsat and -Vsat? Record how you determined Vsat. Can the op-amp produce voltages from the positive rail (+15V) to the negative rail (-15V)? The model of the op-amp you have been working with does not include saturation effects. To make sure you are working within the range where your model is valid, always make sure the output amplitude is below *half* the saturated value. e. Predict the 3 dB frequency for your circuit. Include your calculations in your lab book. Now, determine the 3 dB frequency experimentally. Describe the procedure you followed to determine the f_B. Does your measurement agree with your prediction? Explicitly record what criteria you used to determine whether or not the model and measurements agree. d. Using the gain-bandwidth relation $G_0 f_B = f_T$ and your measurements of G_0 and f_B, determine the f_T for your op-amp. Does your measured value of f_T agree with the one from the datasheet? e. Measure the frequency dependence of your circuit. Measure the gain at every decade in frequency from 10 MHz down to 10 Hz, with extra points near your cutoff frequency. Should you use a 10X probe or coax cable to make your measurements? Explain your reasoning. Plot your measurements and predicted gain curve on the same plot. Where, if at all, is the simple model of the op-amp circuit not valid? Suggest possible model refinements and/or physical system refinements to get better agreement between the model predictions and measurements.
Step 5	**Input / Output Impedances and Current Limit of the Circuit** a. Predict the input impedance of your non-inverting amplifier circuit, R_i'. *(HINT: You found the input impedance of the op-amp alone in your prelab.)* Explain how you determined this number. If you were to increase the input impedance by placing a 1 MΩ resistor in series with the input, predict how much the output voltage will change. *HINT: consider the voltage drop across the 1 MΩ resistor to get the voltage at Pin 3.* Measure V_{out} with and without the 1 MΩ resistor in place. Do your measurements agree with your model predictions? **b.** Predict the output impedance of your circuit, Ro', at a frequency of 1 kHz. *(HINT: See prelab 2e.)* Predict the output voltage based on your input voltage when your circuit is used to drive a load of 200 Ω and a load of 8 Ω (Model as a voltage divider with the output impedance and your load resistor.) Measure the output voltages in all three configurations (no load, 200 Ω load, 8 Ω load). Do the measured values agree with your model prediction? If not, can you make modifications to your model to understand the discrepancy? *HINT: Consider the maximum current output of the op-amp.*