PHYB10 Experiment Guide

Lab 4: Operational Amplifiers

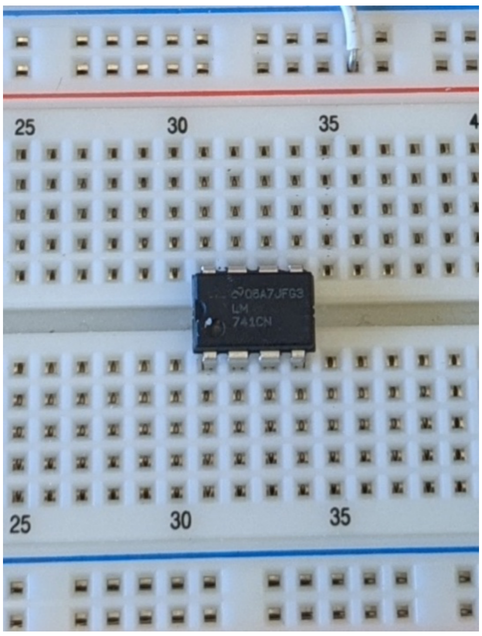
In this lab you will be studying an Integrated Circuit (IC). ICs are small packages that contain complete circuits consisting mainly of transistors. ICs can be built to have many different functions, including analogue to digital converters (ADC), timers and clocks, logic gates, and many more. You may already be familiar with important ICs in computers: Central Processing Unit (CPU), Graphics Processing Unit (GPU), Memory, etc. The Arduino used in this course is an IC as well.

This lab will look at the operational amplifier (op amp). This highly versatile and useful component is used in many circuits.

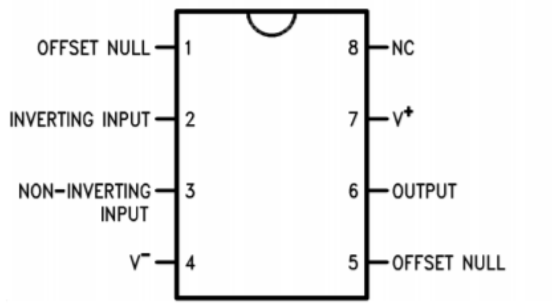
Setting up your Op Amp

Let's set up the op amp on your breadboard and examine some of the details of working with ICs.

ICs come in many different packages. The op amp you will be studying today is the LM741 from Texas Instruments. It comes in an 8 pin Dual-in-Line Package (8DIP). Your breadboard is designed to work with IC that use DIP packages. Carefully place the op amp over the middle channel of your breadboard. Recall that there are no electrical connections across this channel. This allows you to make connections to all the pins on the DIP package without connecting any of them.

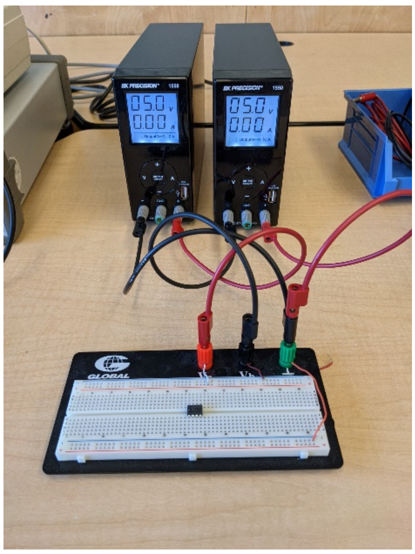


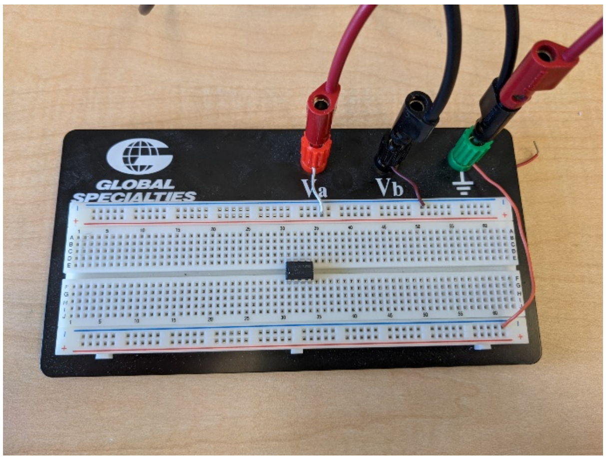
Next let's take a quick look at what these pins do. The pin out of ICs can always be found on their data sheets. The pin out below was found on the LM741 data sheet that you can find in the course documents.



You will learn the function of all these pins throughout the lab. To start, let's focus on pins 4 and 7, the V^- and V^+. These are the power pins. We will be providing +5 V to the V^+ pin and –5 V to the V^- pin. Set up the +5 V supply in the same manner as previous labs. Put the + terminal of the power supply to red binding post, and then connect the binding post to the "+" rail of the breadboard. Connect the binding post to the "+" rail on the same side as the V^+ pin on the op amp. Similarly, connect the –terminal of the power supply to the GND binding post and then to the "–" rail on the far side of the breadboard.

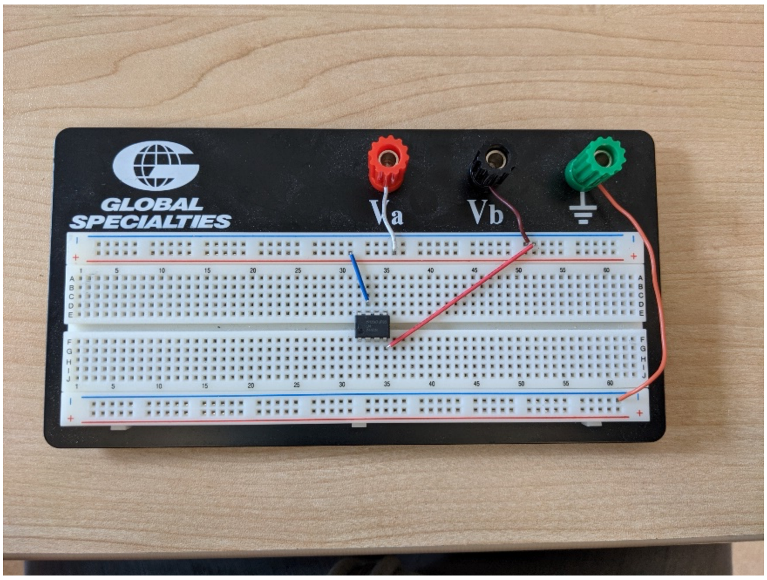
Next, connect a second power supply to your breadboard to supply –5 V. Pay very close attention to the polarity of the power supply. Connect the – terminal of this power supply to the negative binding post and the + terminal to GND. Then, connect the negative binding post to the "–" rail on near side of the breadboard.





Before connecting the op amp, check this configuration using a multimeter. Turn on both power supplies and set them to 5 V with a current limit of 40 mA. Set the multimeter to 20 V DC voltmeter and connect the COM port to GND on your breadboard. The red binding post should read +5 V and the black binding post –5 V.

Also check that the breadboard rails are at the specified voltages. Once this has been confirmed, turn off the output and attach V^- (pin 4) to the –5 V rail and V^+ (pin 7) to the +5 V rail.

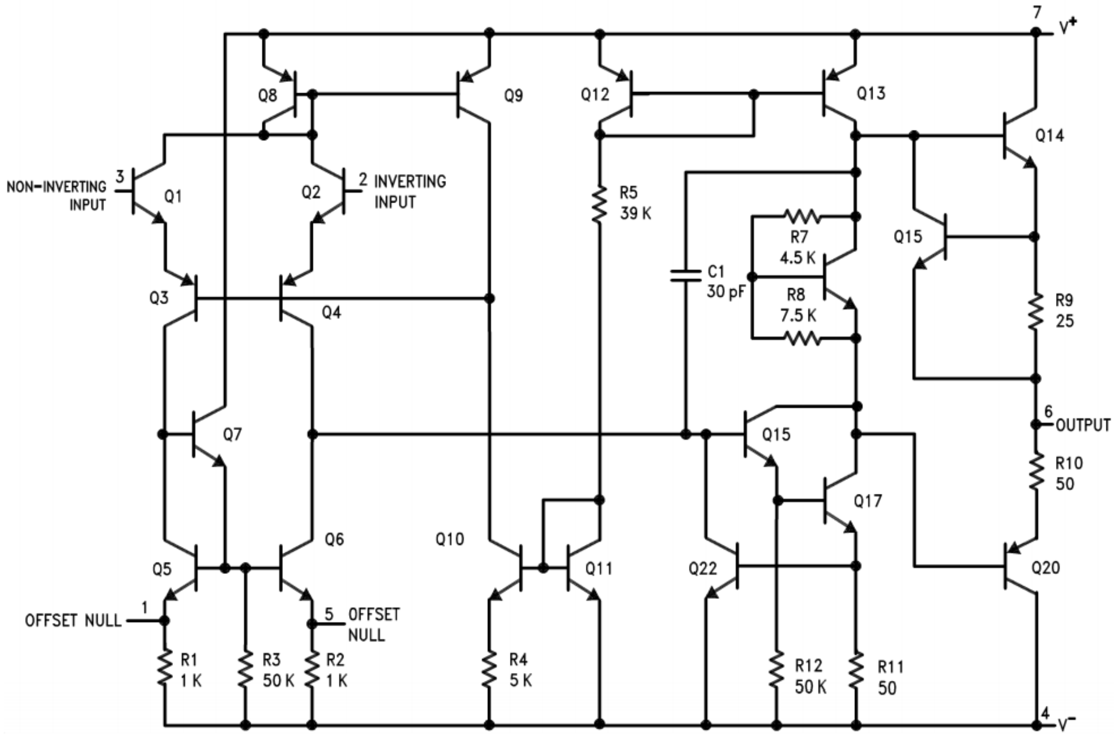


Your op amp is now ready to study!

Ideal Op Amp Theory

An op amp is exactly what its name suggests: a multistage amplifier like the one studied in the last section of Lab 3. However, instead of using two transistors, LM741 has 20. Two stages exponentially increased the gain of the transistor amplifier in Lab 3.

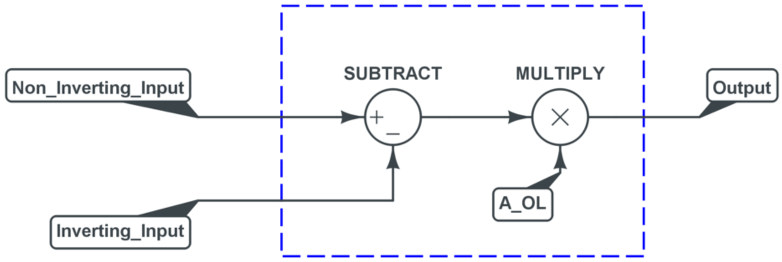
Image how much gain a 20-stage amplifier will provide. For determining the behaviour of the circuit, we can assume the gain is infinite!



The figure above shows the basic circuit that is inside the LM741. As you can see, it is complicated. You have learned the basic idea of how it works: It is a multistage amplifier and all the resistors and capacitors make sure the transistors are properly biased and are in their active behaviour region.

A significant advantage of op amps is that you do not need to worry about all the details in the circuit. If you provide the op amp with power and a signal, it does everything else for you. You will not even have to use the “offset” setting on the function generators. Give an op amp an AC signal and it will amplify it.

However, the amplifier you studied in Lab 3 only had one input; op amps have two inputs. This increases the practical use of the op amp. You will see the practical purpose of having two inputs throughout this lab. The ideal mathematical model of the op amp is given in the block diagram below:



IDEAL OP-AMP

The output of the op amp is giving by the following equation:

$$V_{out} = A_{OL}(V_{non} - V_{in})$$

Where A_{OL} is the open loop gain, which we are assuming is infinite. V_{non} is the voltage at the non-inverting input and V_{in} is the voltage at the inverting input. At first glance it may seem like this device is not that useful. Unless the input voltages cancel to zero, the output will always be infinite. However, we have not yet considered “feedback”.

Feedback is when the output of the device is connected back to an input. Feedback is what unlocks the real potential of the op amp. We will be looking at several op amp configurations with feedback throughout this lab. We will first look at a configuration without any feedback to learn about the limitation of real op amps from this ideal theory.

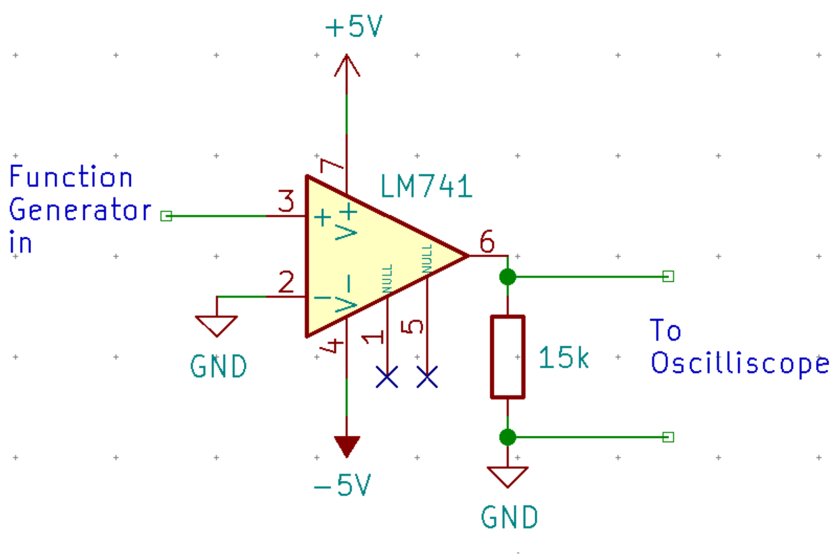
Exercise 1: Operational Amplifier Open Loop Gain

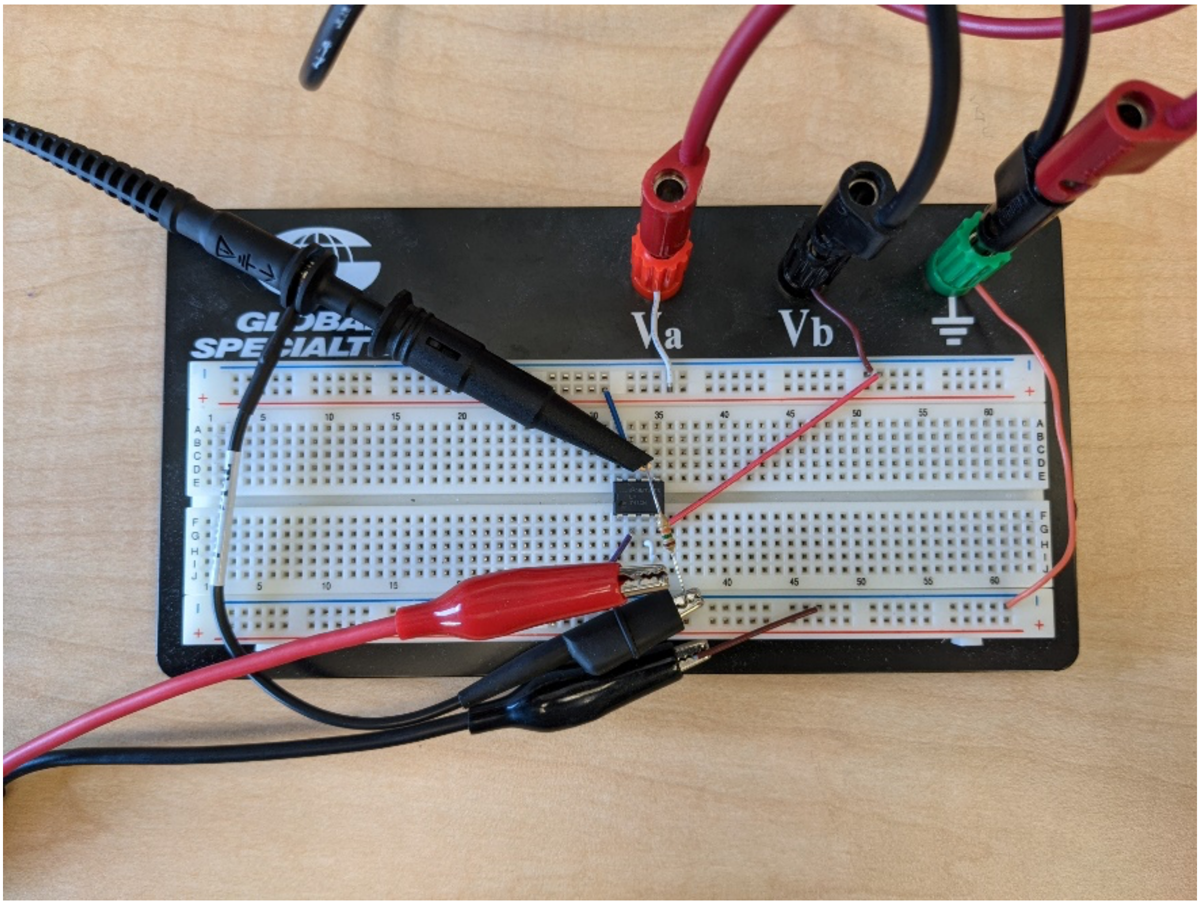
In this first exercise, we will look at the open loop gain of the amplifier to see if our assumption that gain is infinite is justifiable. You can probably already guess that a real op amp will not output an infinitely large signal. Clearly, that is impossible. We will be looking to see what the limitations of our real op amp are.

Step 1: Build the circuit below.

There are a few new conventions for circuit diagrams with ICs. The schematic symbol for an op amp is a triangle. The symbol gives prominence to the most important pins on the IC: the two inputs and output. The non-inverting input is marked with a "+" and the inverting input with a "–". The output is the point of the triangle. There are still five other pins on the chip. All the pins on the chip are numbered on the diagram.

- Pins 1 and 5 are labelled "offset null". These are to correct a small error in the reference point of 0V within the op amp circuit (typically within 5mV). This is an advanced use of the op amp and will not be considered in this course.
- Pin 8 is labelled non-connect in the data sheet. It is not connected to anything in the IC. Do not connect it to anything on your breadboard. It is not included in the diagram.
- You have already connected pins 4 and 7 when initially setting up your op amp circuit. This are the power pins V^+ and V^-, respectively.
- All you need to worry about is pins 2, 3, and 6.





Step 2: Connect the oscilloscope across the resistor to measure the output of the op amp in channel 2. Turn on the power supplies and oscilloscope. Set the function generator to a 1 kHz sine wave 2 V pk-pk and measure it in channel 1 of the oscilloscope.

Take a screen shot of the output of the op amp using the oscilloscope.

(Note: make sure the multipliers on Channel 1 and 2 are set appropriately.)

Question 1: [2 points]

Describe the output of the op amp. Is it a sine wave? Is it distorted? [1 point]

Use the cursor function of the oscilloscope to determine the maximum output voltages (positive and negative), of the op amp. Increase the voltages of the power supplies to 8 V. What happens to the output voltages? [1 point]

Return the power supplies to 5 V when you have completed this question.

Question 2: [2 points]

Calculate the Gain of the op amp from the pk-pk amplitude measurements of the input and output. [1 point]

Decrease the amplitude of the input sine wave to 1 V pk-pk. Reduce it further to 500 mV Does the gain change? [1 point]

Question 3: [3 points]

Comment on the true limits to the op amp's functionality. Is the gain limited by the function of the op amp or the by the voltage supplied to it? [1 point]

Is our assumption that the gain is infinite justified? [2 points]

Question 4: [2 points]

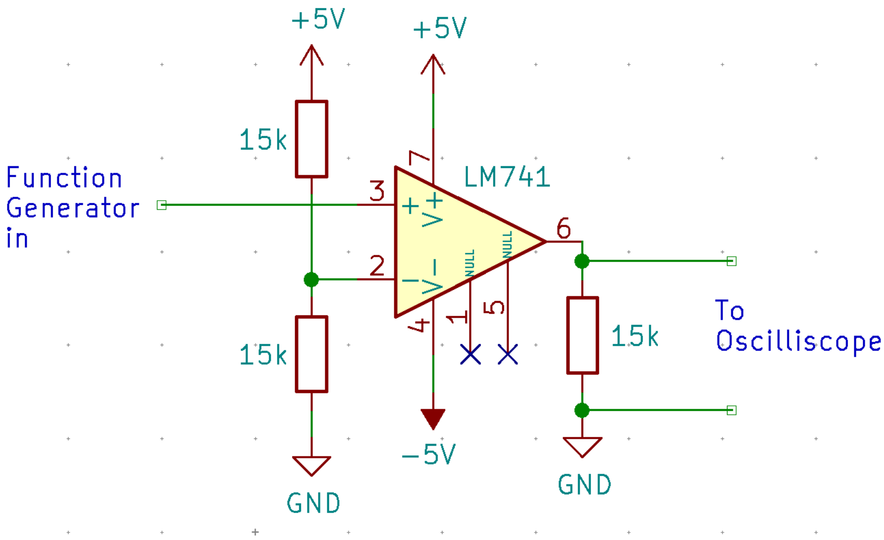
You may have noticed that the maximum voltages of the output signal were less than the power supply settings. Based on what you know about transistors, bias voltages and internal resistance, explain why the output voltage is lower than the supply.

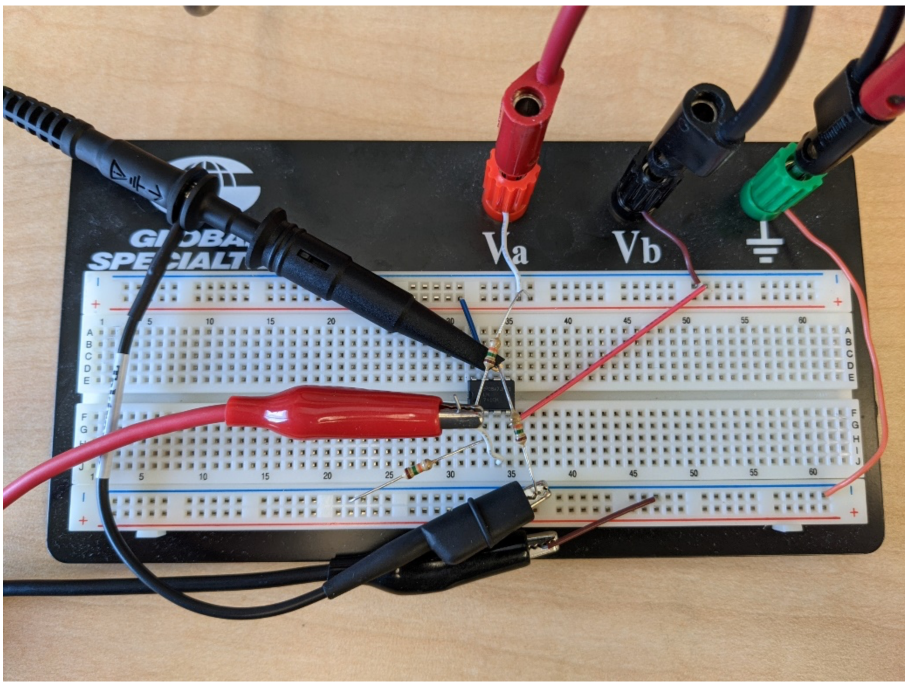
Note for the rest of the lab we will be working well within the limits of the power supplies, therefore we are not concerned with this loss.

Exercise 2: Op Amp as Comparator

We will know look at how the open loop gain can be used for a very important practical device: the comparator.

Step 1: Build the following circuit. It is very similar as the circuit above, but instead we have added a voltage divider to the inverting input. Note that there is no connection from the non-inverting input to the voltage divider. While the line in the schematic cross, a connection only occurs where there is a dot.

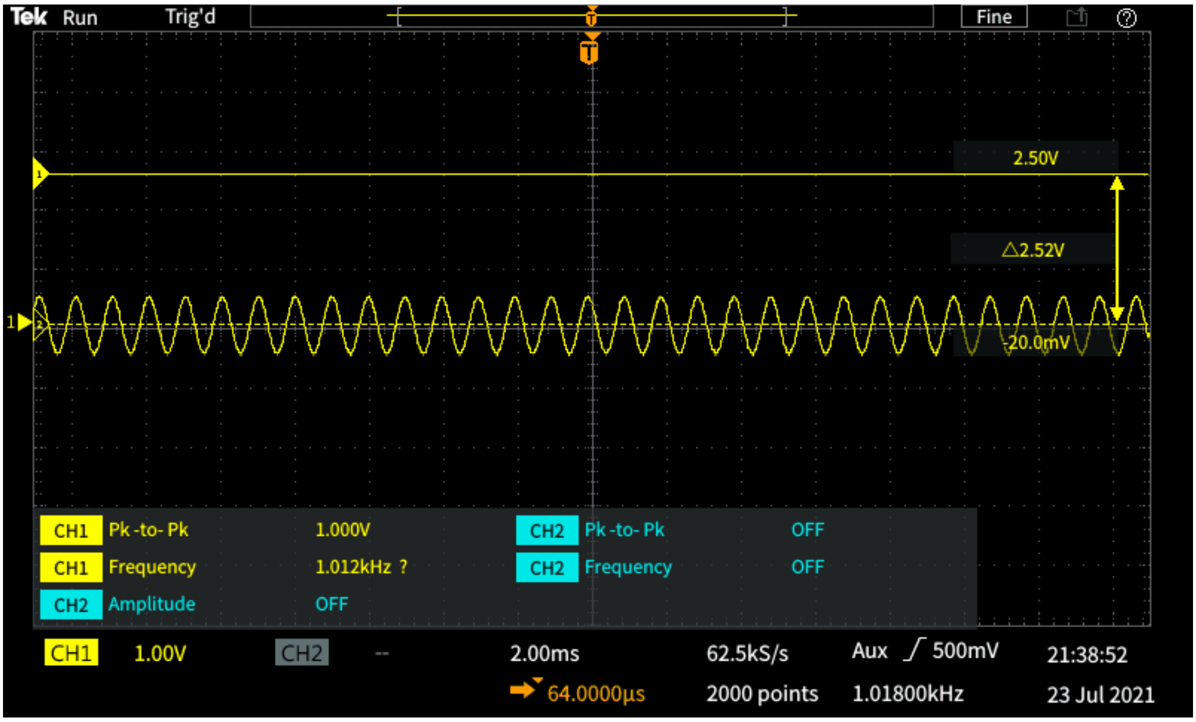




Step 2: Set the function generator to output a 1 kHz sine wave with 1 V pk-pk. Set the oscilloscope cursors on the input (channel 1) to 0 V and 2.5 V.

(Do not worry if you see no signal in channel 2 at first.)

Note: to get greater precision in the adjustment of the cursor lines, you can toggle between course and fine mode by pressing and briefly holding the main selection button.

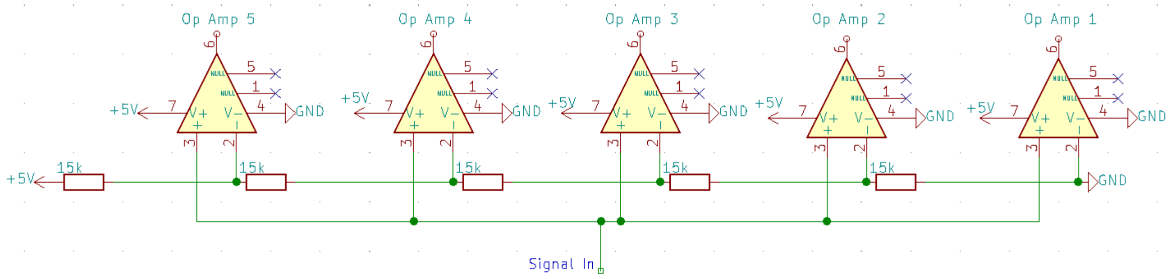


Question 5: [4 points]

Slowly increase the amplitude of the input sine wave. What happens to the output as the wave crosses 2.5 V? Include an image from the oscilloscope. [2 point]

Why is this op amp called a comparator? [2 point]

Comparators are a vital component as they are necessary for analog-to-digital conversion (ADC). A simple ADC design is a series of comparators in parallel.



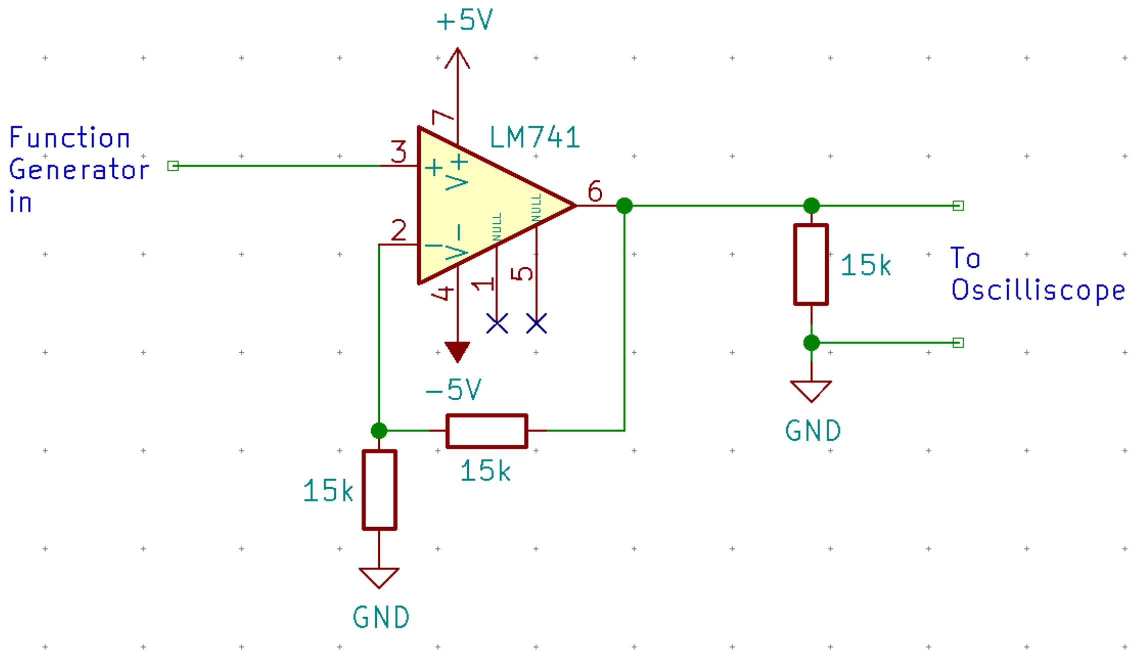
In the circuit above: op amp 1 will output 5 V for any signal above 0 V, op amp 2 will output 5 V for any signal above 1 V, and similarly with op amp 3 above 2 V, op amp 4 above 3 V, and op amp 5 above 4 V. This is a binary code with 5 V equal to “1” and 0 V equal to “0”. The logic table for the above ADC would be:

Input Signal Level	Op Amp 1	Op Amp 2	Op Amp 3	Op Amp 4	Op Amp 5
0V – 1V	1	0	0	0	0
1V – 2V	1	1	0	0	0
2V – 3V	1	1	1	0	0
3V – 4V	1	1	1	1	0
4V – 5V	1	1	1	1	1

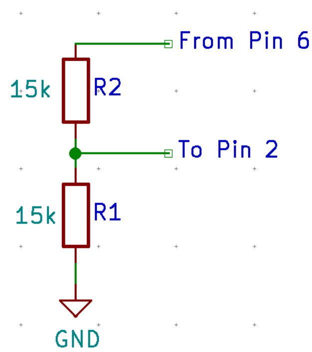
ADC design gets much more complicated and is beyond the scope of this course. But every ADC design has op amp used as comparators. This discussion was included to give you a peak into how the ADC on your Arduino works.

Exercise 3: Voltage Divider Feedback – Non-Inverting Amplifier

Consider the following op amp configuration:



Let focus in on just the feedback loop from pin 6 back to pin 2.



This is a voltage divider. The output voltage from the op amp is divided back into the inverting input. We can then use the voltage divider equation to set the input to the inverting pin V_{in}:

$$V_{in} = V_{out}\frac{R_1}{R_1 + R_2}$$

In the specific case above both R_1 and R_2 are 15 kΩ. However, we can solve for the general case with any resistors. Plugging into our ideal op amp equation we have:

$$V_{out} = A_{OL}\left(V_{non} - V_{out}\frac{R_1}{R_1 + R_2}\right)$$

Rearranging and isolating V_{out} we get:

$$V_{out}\left(\frac{1}{A_{OL}} + \frac{R_1}{R_1 + R_2}\right) = V_{non}$$

Since the open loop gain is infinite, its inverse is 0, leaving us with:

$$V_{out}\left(\frac{R_1}{R_1 + R_2}\right) = V_{non}$$

Now just rearranging to get V_{out} in terms of the input to V_{non}:

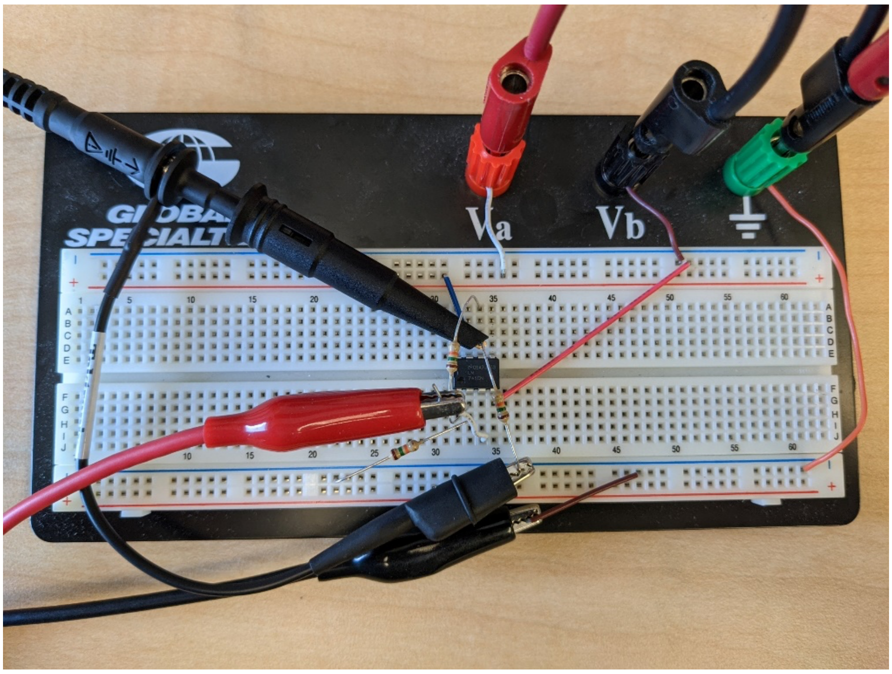
$$V_{non}\left(1 + \frac{R_2}{R_1}\right) = V_{out}$$

The term in brackets is the gain of our amplifier which will call the non-inverting gain A_{non}:

$$A_{non} = \left(1 + \frac{R_2}{R_1}\right)$$

In the specific case we will be studying, with $R_1 = R_2$, we should expect the output of the op amp to be 2x the input. Let’s build it and find out!

Step one: Build the non-inverting amplifier circuit above.



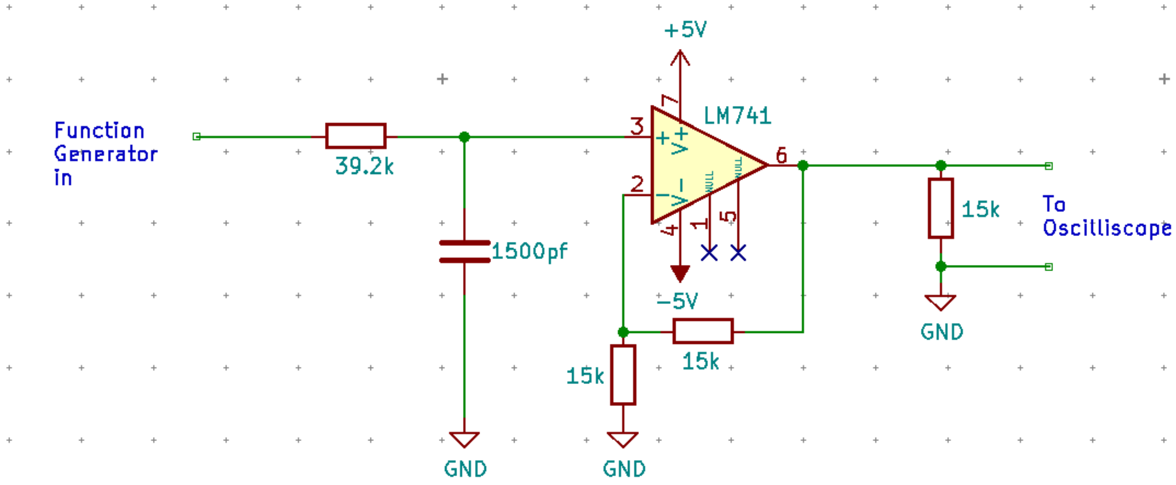
Step two: Set the function generator to a 1 kHz 1 V pk-pk sine wave. Use the measurement tools to measure the gain of the non-inverting amplifier. Take measurements of the gain at frequencies of 10 kHz, 100 kHz, and 1 MHz.

Question 6: [3 points]

Does the gain of the actual circuit match its gain from theory? [1 point]
How does the gain change at higher frequencies? [1 point]
We refer to the range of frequencies of a device that have a constant gain as the “Bandwidth”. What is the bandwidth of this op amp? [1 point]

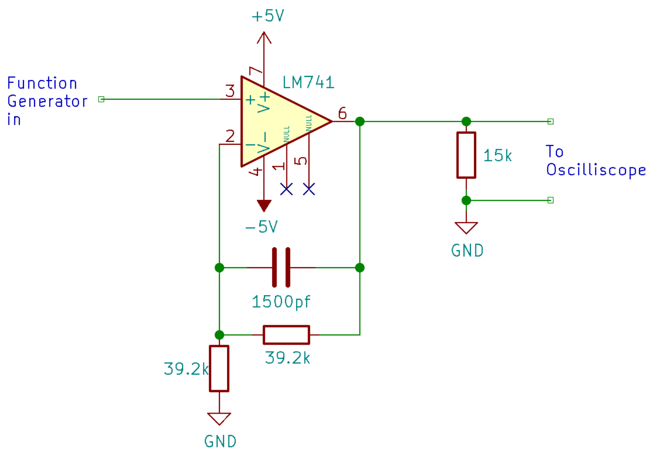
Exercise 4: Capacitor Feedback – Active Low Pass Filter

Consider a circuit combining a low pass filter like lab 2 and a set gain amplifier from the last exercise.



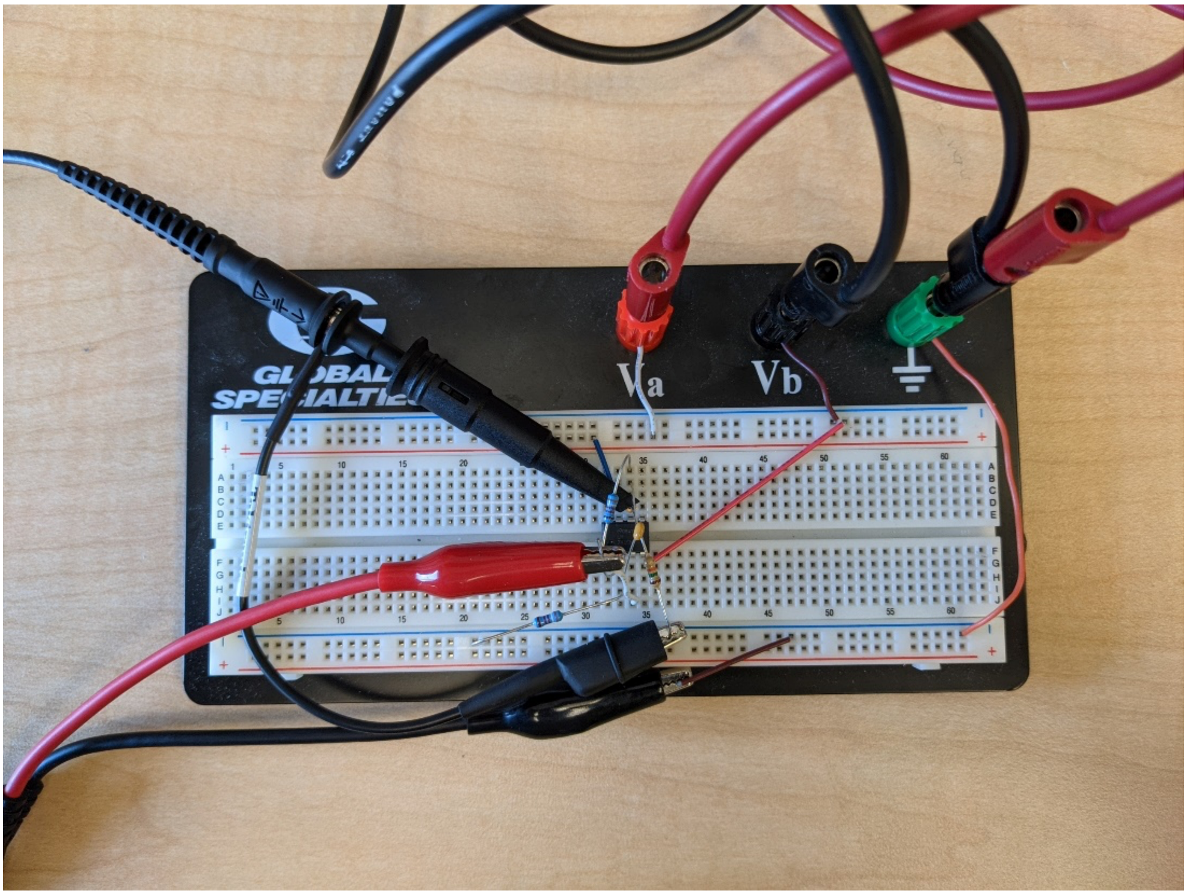
A signal inputted from the function generator would first be attenuated by the filter. The resulting waveform would then be amplified with a gain 2 by the op amp. Combining these effects, frequencies in the "low pass" range of the filter would be amplified by 2, while higher frequencies would be amplified with less gain, eventually being attenuated at very high frequencies.

Now consider a very similar circuit with the capacitor in the feedback loop of the op amp:



The object of this exercise is to convince you that both circuits function in a very similar way. In real designs the 2nd circuit here is preferred as it does not impact the input impedance of Op Amp.

Step 1: Build the 2nd circuit above. It has a capacitor in the feedback loop.



Step 2: Set the function generator to 200 Hz 1V pk-pk sine wave. Just like in Lab 2 record the amplitude and phase change of the output wave form using the oscilloscope. Take 10 measurements roughly doubling the frequency for each point. Make a plot of Amplitude vs. Frequency and Phase Change vs. Frequency.

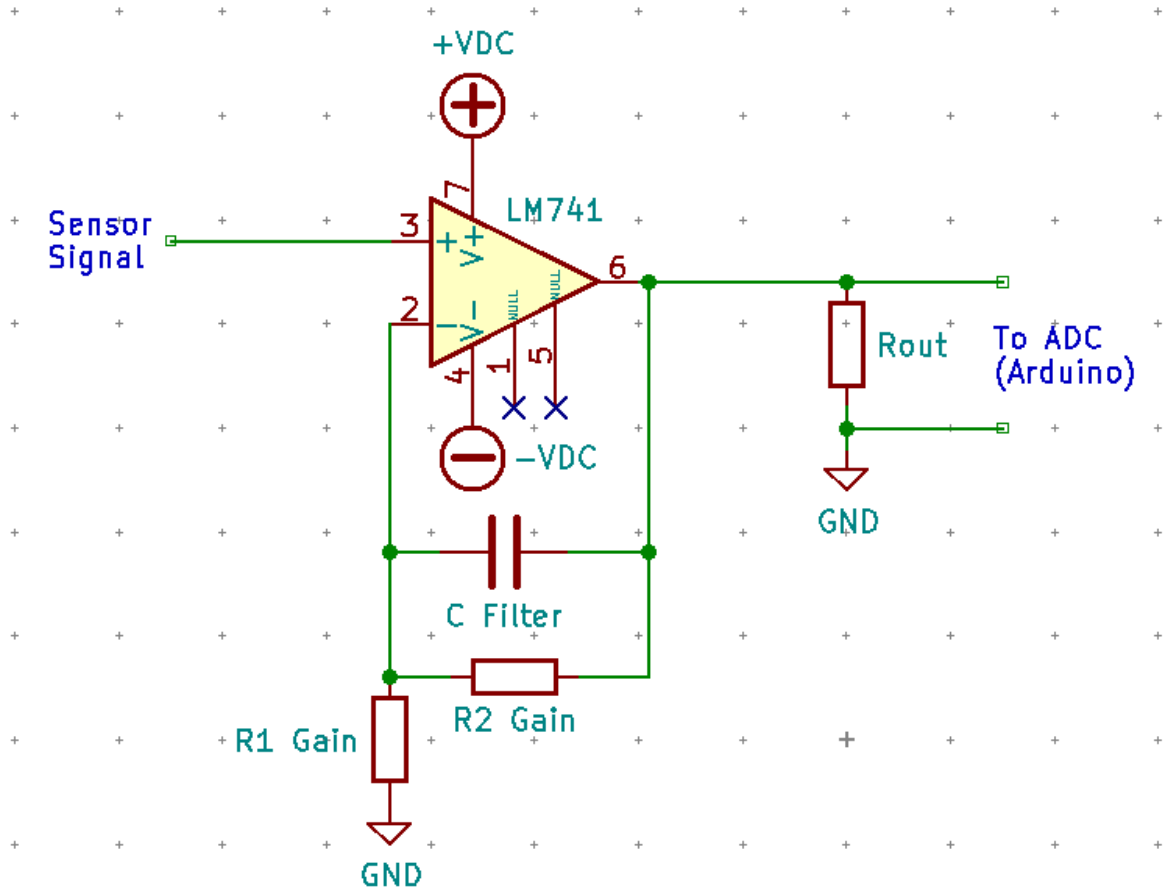
Question 7: [2 points]

Compare the plots from this circuit to the low pass filter from Lab 2. How are they different?

Question 8: [2 points]
So far you have studied these components using a waveform that consists of a single sine wave. Explain how having a filter that does not change the phase of different frequencies aid in studying signals composed of multiple superimposed frequencies.

Conclusion: Putting it all together

Consider a generalized form of the circuit from the last exercise.



This circuit combines concepts from all 4 labs. It combines all the required electrical components to take a signal from any sensor and process the signal for an ADC to turn it into a digital number for later mathematical analysis.

- From Lab 1: The op amp acts as an impedance buffer between the sensor and ADC. R_{out} can be chosen to minimize error for the input to the ADC.
- From Lab 2: The capacitor in the op amp's feedback acts as a filter. The capacitance can be chosen to select the bandwidth of the Low pass filter. This will reduce or eliminate high frequency noise and sampling error from the ADC.
- From Lab 3: The op amp is a better version of the BJT amplifier. R_1 and R_2 can be used the set the gain very precisely. This allows the signal from the sensor to use as much headroom or fidelity of the ADC as possible improving the precision of the sensor.
- From Lab 4: The op amp is the most important component of the whole thing. Not only is the op amp used in the signal processing before the ADC, the ADC itself is made of a op amp comparators as well!

This course looked at some of the simpler configurations of these electronic circuits, but every piece of equipment you use take measurements with will contain more complicated circuits with same basic functionality: impendence matching, filtering, and amplification.