UMass ECE 210 – Fall 2023

Lab 5: Operational Amplifiers

DATA required for Lab report:

PLOT – Output of 'Buffer Amplifier' (with input)
PLOT – Output of Inverting Amplifier
PLOT – Output of Summing Inverting Amplifier (with ALL three inputs)

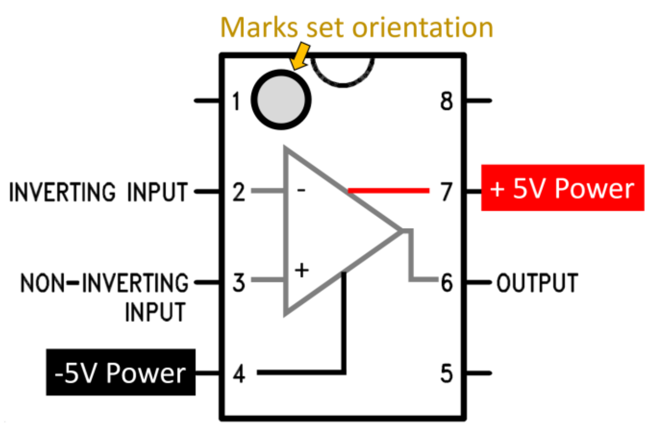
Operational amplifiers (aka 'op-amps') are the Swiss army knives of analog electronics, as they can be reconfigured to a nearly innumerable set of applications with different configurations of components with feedback to their inputs. In this lab you will look at the three op-amp configurations:

1. Buffer amplifier (Follower)
2. Inverting amplifier
3. Summing inverting amplifier

You will measure their response to a sinusoidal input and compare each response to your theoretical design and simulation.

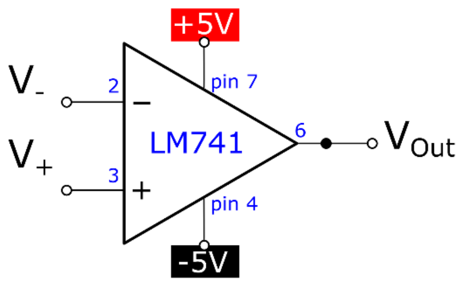
Reference – Op-Amp circuit collection (pg. 3,5): https://www.ti.com/lit/pdf/snla140

LM741 op-amp datasheet: *https://www.ti.com/lit/gpn/lm741*



Open Loop Gain – VERY quick check of very large gain:

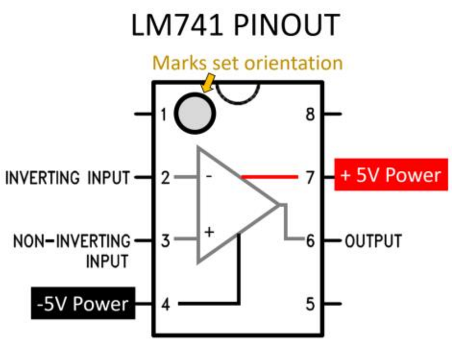
Op-Amps have an exceedingly large open loop gain.
We can **quickly** observe this in open-loop mode just to check it is very large (A > 100).

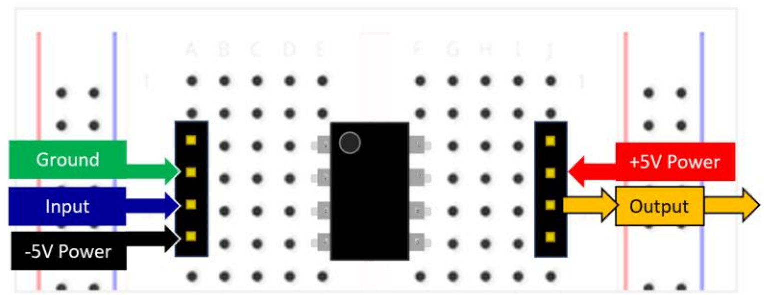


$$V_{out} = A \cdot (V_+ - V_-)$$

If pin 2 is grounded
(setting $V_- = 0$)

Then: $V_{out} = A \cdot V_+$





Power:
Banana clips
→ Micro grabbers
→ header pins

Signal:
BNC
→ Micro grabbers
→ header pins

Header pins

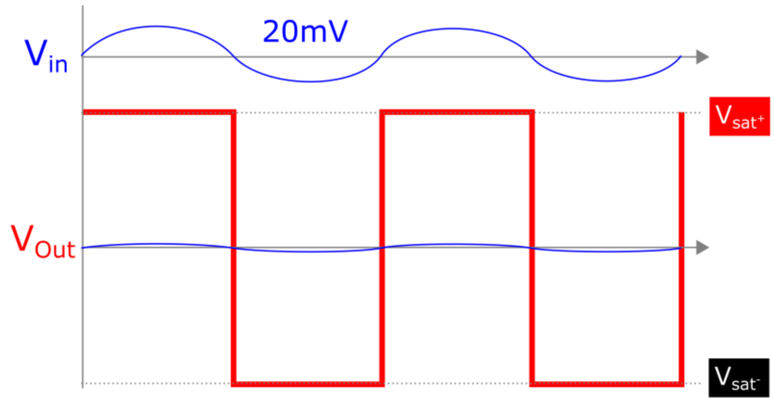
1. Insert the LM471 op-amp into the breadboard
2. Supply $+5V$ to pin 7 and $-5V$ to pin 4 (using the $\pm 20V$ outputs of the power supply)
    a. Verify that the COM and GND are connected with a wire

3. Connect pin 3 (non-inverting input V_+) to the signal generator (red micro grabber)
4. Ground pin 2 (with the **black** micro grabber from the BNC from the signal generator)
   This grounds the inverting input V_- to zero volts.

5. Monitor the input from the signal generator on Ch1 of the oscilloscope
   (split with a BNC T and BNC cable so it is also input to the circuit)

6. Connect pin 6 (V_{output}) to Ch2 of the oscilloscope using another red micro grabber BNC

7. Send in a very small voltage (~20mV) at a frequency of 1kHz
    a. *Make sure the OFFSET is ZERO!*



What type of wave do you see on the output?
What sets the maximum voltages at the output?

8. Quickly estimate the gain A = $\frac{V_{out}}{V_{in}}$ (should be over 100)
9. Increase the power supply voltage to $\pm 15V$ and observe what happens.
(Keep the power supply at 15V)
10. Increase the signal generator amplitude to 1Vpp.

Next, we'll move on to CLOSED LOOP Feedback, the intended use of the Op-Amp.

Closed Loop Feedback - Buffer Amplifier (Follower):

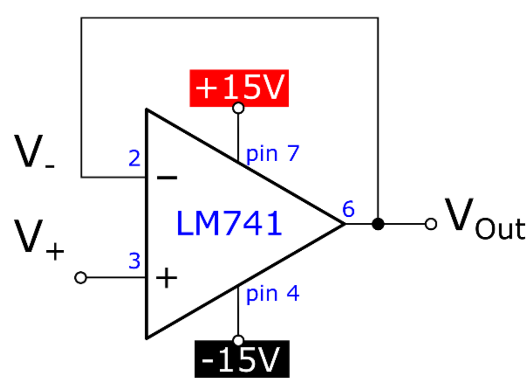
Now we'll add a wire from the output (V_{Out}, pin 6) to the inverting input (V_- , pin 2), which creates a 'closed loop' feedback by setting the inverting input equal to the output.
This defines the closed loop gain $G = 1 = \frac{V_+}{V_{Out}}$ very precisely if $A \gg 1$ (as shown below).
It is called a 'Follower' because the output V_{Out} follows the non-inverting input V_+.

*Followers act as a buffer within a circuit, because they have a very large input impedance (resistance) which draws very little current, but at the same time it can **supply** a large amount of current with a low output impedance (resistance). So, it acts as a buffer between circuits, isolating their designs.*

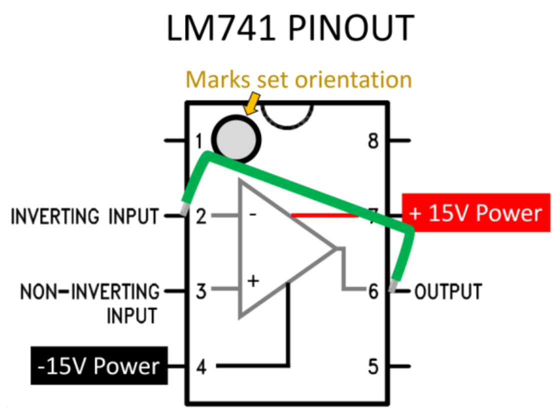
$$V_{Out} = A \cdot (V_+ - V_-)$$
$$\textit{wire sets} \rightarrow \boldsymbol{V_- = V_{Out}}$$

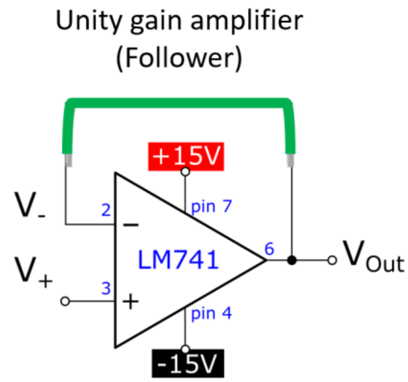
$$V_{Out} = A \cdot V_+ \; - A \cdot \boldsymbol{V_{Out}}$$
$$A \cdot V_{Out} + V_{Out} = A \cdot V_+$$
$$\cancel{(1+A)} \cdot V_{Out} = \cancel{A} \cdot V_+$$

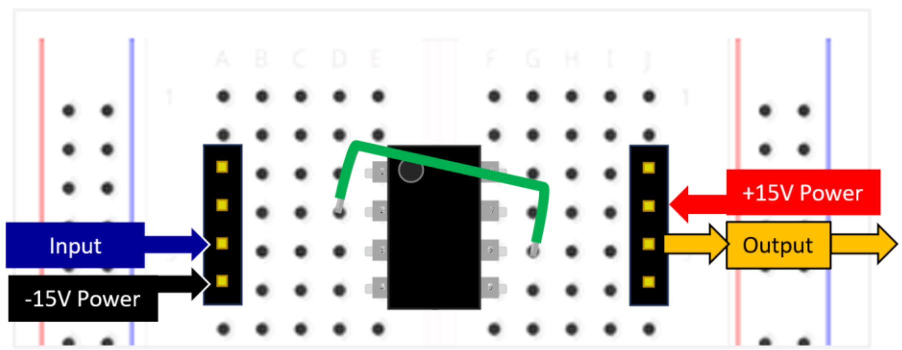
$$\boldsymbol{V_{Out} = V_+}$$



Building a Buffer Amplifier (‘Follower’):

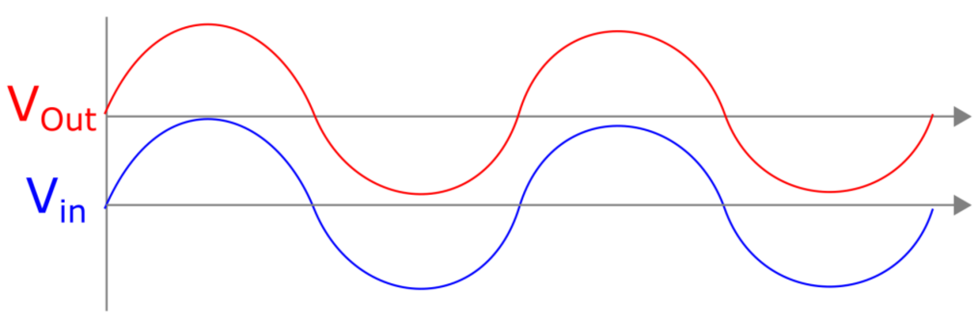






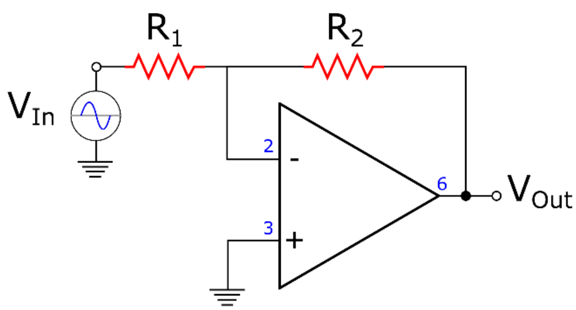
1. Remove the ground connection on Pin 2
2. Get a small wire
3. Use the wire to connect pin 2 (inverting input , V_{-}) to pin 6 (output, V_{Out})

4. Measure and RECORD the output. (It should be identical to your input)
   It can be helpful to slightly offset the signals on the oscilloscope so you can see both. Use the Vertical adjustment knobs to position them and set the V/div vertically.



1. Inverting Amplifier

Next, we will create an inverting amplifier by swapping the wire with a resistor (R2) and moving the input signal, so it is forced to travel through a resistor (R1) and is NOT directly connected to pin 2. Now the op-amp must drive current through the feedback resistor (R_2) to cancel the current from the input through R_1. The gain is **negative**, so it is called an inverting amplifier.

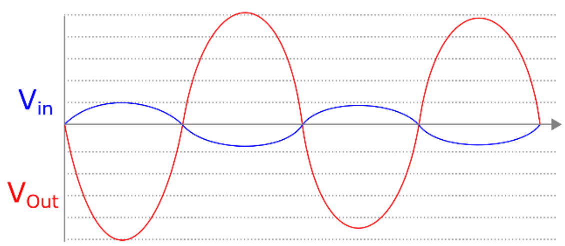


$$i_{R1} + i_{R2} = 0$$

$$\frac{V_{in} - V_-}{R_1} + \frac{V_{Out} - V_-}{R_2} = 0$$

$$\boldsymbol{V_{out} = A\,(V_+ - V_-)}$$
$$V_{out} = -A \cdot V_-$$
$$V_- = \frac{-V_{out}}{A}$$

if A is large, then $V_- \approx 0 = V_+$



$$\frac{V_{in} + \cancel{\frac{V_{out}}{A}}}{R_1} + \frac{V_{Out} + \cancel{\frac{V_{out}}{A}}}{R_2} = 0$$

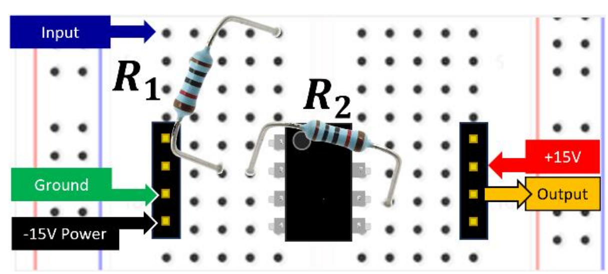
$$\boldsymbol{V_{out} = -\frac{R_2}{R_1} \cdot V_{input}}$$

What resistors : R1 and R2 are needed to create an inverting amplifier with Gain ≈ -5?
(See page 3: https://www.ti.com/lit/pdf/snla140 , Pick resistances $\geq 1k\ \Omega$)

To create an inverting amplifier:

1. Get two resistors from the front of the lab for a gain of about -5
   (e.g. 2k and 10k or 5k and 25k etc.)
2. Measure and record their values.

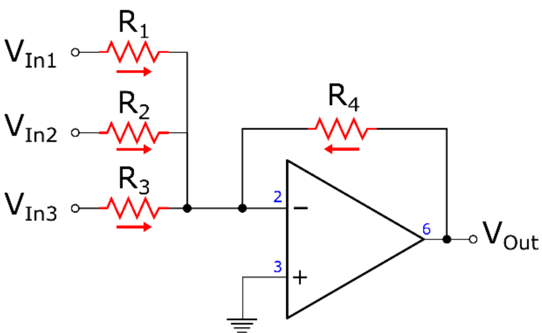
3. Remove the signal generator from pin 2
4. **Connect R1 to pin 2 and an entirely NEW row of the breadboard**
5. Insert the input from the signal generator into this new row of the breadboard



6. Remove the wire connecting pin 2 and pin 6
7. Replace that wire with R2 so that R2 connects pin 2 and pin 6
8. Record Ch1 and Ch2 (input and output)
9. Measure the voltage gain.
   NOTE: Vpp is not capable of showing the gain is negative on its own!
   How else can we measure the gain?
   Compare the measured gain to your calculated theoretical gain.

2. Summing Inverting Amplifier

Next, we will create a summing inverting amplifier by adding additional resistors and inputs. Voltage applied at each input resistor will create current into the node connected to the inverting input. The op-amp will drive current through R4 such that the voltage at the inverting input matches the non-inverting input voltage (which is grounded). Therefore, this effectively 'sums' the currents from the inputs. Further, if R1,R2, and R3 are equal, the circuit sums the input voltages with a gain set by the ratio of the feedback resistance over that input resistance.



$$i_{R1} + i_{R2} + i_{R3} + i_{R4} = 0$$

$$\frac{V_{in1} - V_-}{R_1} + \frac{V_{in2} - V_-}{R_2} + \frac{V_{in3} - V_-}{R_3} + \frac{V_{Out} - V_-}{R_4} = 0$$

$$V_- = V_+ = 0$$

$$V_{out} = -R_4\left(\frac{V_{in1}}{R_1} + \frac{V_{in2}}{R_2} + \frac{V_{in3}}{R_3}\right)$$

Now we have multiple inputs so we will need multiple voltage sources:

1. Add a small DC offset (~1V) using the last output of your power supply (labeled +6V)
2. Use an additional resistor to add your signal generator signal twice to your circuit
   -OR-
3. Use an auxiliary AC output from your oscilloscope (two on the back right side).

(Make sure to ground them all properly)

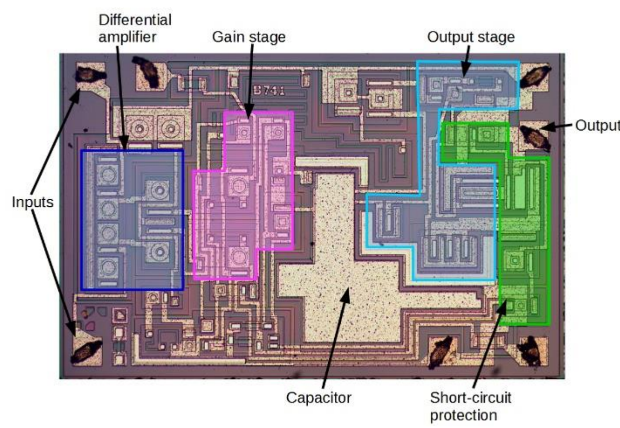
REFERENCE: https://www.ti.com/lit/pdf/snla140 (page 5)

Measure the voltage gain. Again, Vpp will not capture the gain with the offset. You must measure the voltage out and voltage in instantaneously.
Compare your measured gain to your calculated theoretical gain. They should match exactly. Record your data and note the % errors.

Further Reading:

Ken Shirriff's blog
Understanding silicon circuits:
inside the ubiquitous 741 op amp

https://www.righto.com/2015/10/inside-ubiquitous-741-op-amp-circuits.html



Lab Report 5 – Rubric

2,000-word limit 1 report/group

		Points	**Grade**
	Introduce and define all concepts (include references)	5	
	Motivation for experiment (note practical applications)	5	
1	Experimental Diagram (drawing + PICTURE with labels)	5	
	PLOT – Output of **'Buffer Amplifier'** (with input)	5	
	Analysis (show your work for calculations, compare to measurements)	5	
2	Experimental Diagram (drawing + PICTURE with labels)	5	
	PLOT – Output of **Inverting Amplifier** (with input)	5	
	Analysis (show your work for calculations, compare to measurements)	5	
3	Experimental Diagram (drawing + PICTURE with labels)	5	
	PLOT – Output of **Summing Inverting Amplifier**	5	
	Analysis (show your work for calculations, compare to measurements)	5	
	Conclusion – with quantitative comparison of measurements and calculations and discussion of sources of error and uncertainty	5	
		60	