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# THE GEORGE WASHINGTON UNIVERSITY

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WASHINGTON, DC

SCHOOL OF ENGINEERING AND APPLIED SCIENCE  
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING  
ECE 2110: CIRCUIT THEORY LABORATORY

Experiment #8:  
*Operational Amplifiers and Applications*

## **EQUIPMENT**

<i>Lab Equipment</i>	<i>Equipment Description</i>
(1) DC Power Supply	Supplied by the AD2 and KLY-2402000 Power Supply
(1) Digital Multimeter (DMM)	Harbor Freight Model 63759 Handheld Digital Multimeter
(1) Breadboard	Prototype Breadboard
(3) Test Leads	Banana to Alligator Lead Set

Table 1 – Equipment List

## **COMPONENTS**

<i>Type</i>	<i>Value</i>	<i>Symbol Name</i>	<i>Multisim Part</i>	<i>Description</i>
Resistor	--- $\Omega$	R	Basic/Resistor	---
Op-Amp	LM741	LM741	Basic/Analog/OpAmp/741	---

Table 2 – Component List

## **OBJECTIVES**

- Verify Ideal Model Op-Amp Characteristics
- Design, build, and test a DC Inverting Amplifier
- Design, build, and test a DC Non-Inverting Amplifier
- Design, build, and test a DC Summing Amplifier
- Design, build, and test a DC Difference Amplifier
- Design, build, and test a Buffer (Current Amplifier)
- Design, build, and test a Comparator

## INTRODUCTION

**Operational Amplifiers** or “**Op-Amps**” are important building blocks for a wide range of electronic circuits. They are among the most widely used electronic devices today with usage in a vast array of consumer, industrial, and scientific devices. The term ‘operational’ is used because they can perform all the basic arithmetic operations (addition – summing, subtraction – difference, multiplication, and division). In this lab, we will examine the characteristics of an ideal Op-Amp, build fundamental DC Operational Amplifier Feedback Circuits and see the effects of the Op-Amps on the output of those circuits.

### General Operational Amplifier Physical Details

The circuit symbol for an Op-Amp is shown on the right in **Figure 1** where:

- $V_P$ : Non-Inverting Input
- $V_N$ : Inverting Input
- $V_{out}$ : Output Voltage
- $V_{CC+}$ : Positive Power Supply
- $V_{CC-}$ : Negative Power Supply

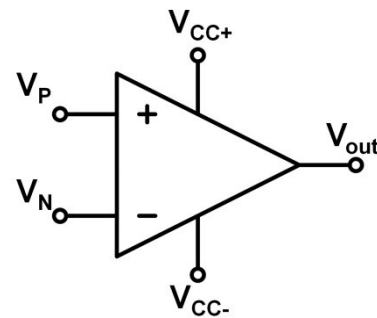


Figure 1 – Op-Amp Symbol

### LM741 Operational Amplifier

For this lab, you will use the **LM741 Op-Amp**, which is included in your ECE 2110 toolkit. LM741 series are general purpose Op-Amps intended for a wide range of applications and provide superior performance in general feedback circuits. A picture of the LM741 and its internal connection diagram are shown in **Figure 2** and **Figure 3**, respectively.



Figure 2 – Picture of the LM741 Op-Amp

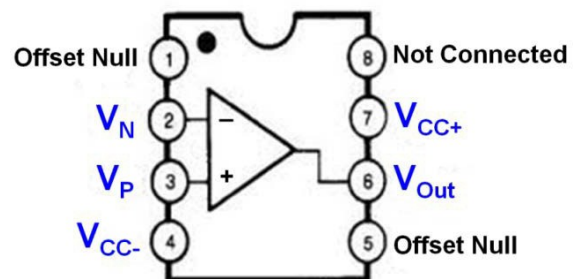


Figure 3 – LM741 Op-Amp Pin Diagram  
(The pins used in this lab are shaded in blue)

If you examine your LM741 Op-Amp, you will find a notch/dot in one of the corners. The notch/dot is located right next to **Pin 1**, thus it is used as a marking to identify the orientation of the Op-Amp. There are a total of eight pins within the LM741.

It is also important to note that if you look at the datasheet for the LM741, it has a recommended range of +10-15 V for  $V_{CC+}$  and -10-15 V for  $V_{CC-}$ . Normally, in the lab, we would use +12V and -12V for each  $V_{CC}$  respectively. **If you only have the AD2**, it can only supply +5V and -5V, these are the values you will have to use. Anytime you see +12V or -12V, you can just use +5V and -5V respectively. The LM741 does still work under these conditions, as the datasheet does not list an actual minimum value, only a recommended one. It is always important to check the datasheets for any component you use, and is especially important when designing new circuits.

### Operational Amplifier Multisim Tips

Op-Amp Circuits can be simulated using Multisim. Once you have created a new design and have access to the schematic page, you can click on the “Place Analog” icon located near the upper left corner of the window. Once the component window pops up, select the OPAMP family, then type in and search for “741.” Although there are several types of LM741 available in the Multisim Part Database, we will use the simple 741 model. This is the actual part included in your ECE 2110 parts kit. **Table 2** shows Multisim Part Information for the LM741 Op-Amp.

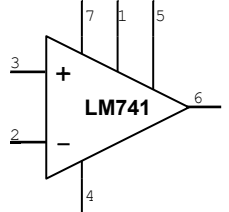
Component Name	Multisim Part Name	Instructions	Symbol
LM741 Operational Amplifier	<b>Group:</b> Analog <b>Family:</b> OPAMP <b>Component:</b> 741	<ul style="list-style-type: none"> <li>• Click “Place Analog”</li> <li>• Click on <b>OPAMP Family</b></li> <li>• Search for <b>741</b></li> <li>• Select and use the <b>741</b></li> </ul>	

Table 2 – Multisim Part Information

The pin definition of the LM741 in Multisim is identical to the pin definition given in **Figure 3**. Op-Amp Circuits can be constructed by connecting components to the different pins. **Figure 4** shows the final Multisim schematic for a Non-Inverting Amplifier with  $V_{in} = 200mV$  and  $K = 2$ . Keep in mind that for  $V_{CC-}$ , the negative terminal of the power supply goes into pin 4. For  $V_{CC+}$ , the positive terminal of the power supply goes into pin 7.

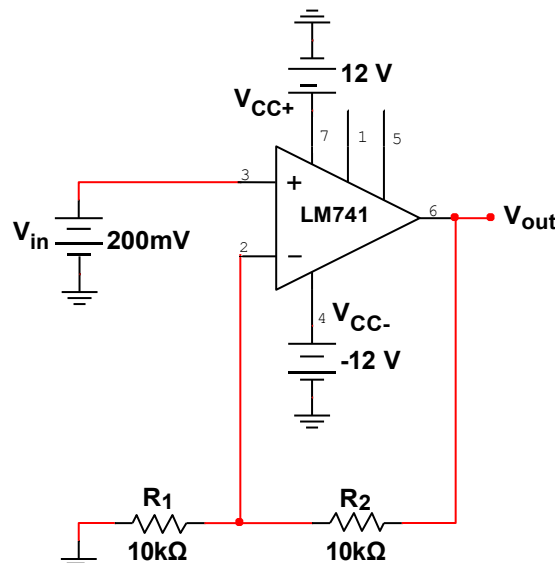
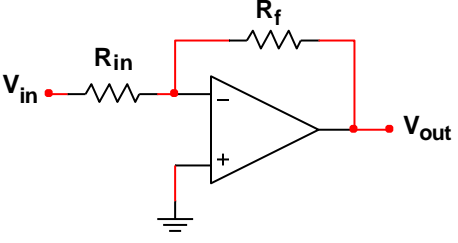
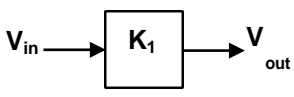
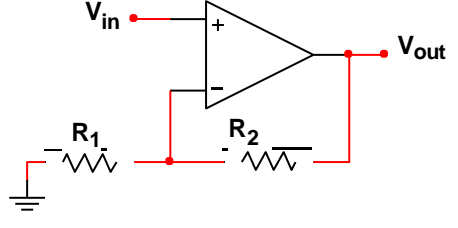
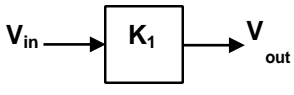
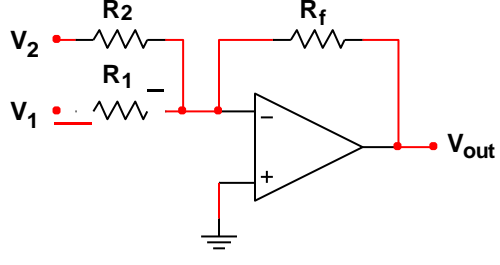
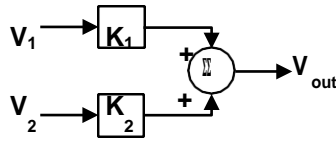
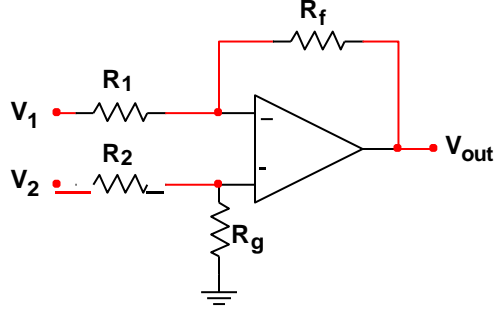
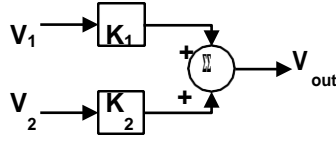
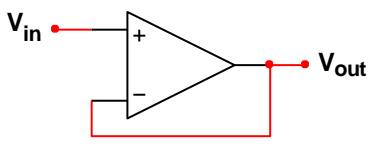
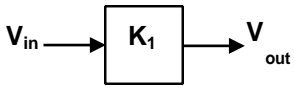
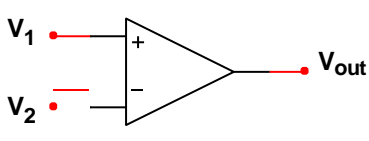
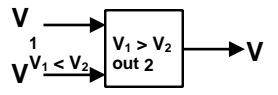


Figure 4 – Non-Inverting Amplifier with  $V_{in} = 200mV$  and  $K = 2$


**Basic Operational Amplifier Circuits**

**Table 1** shows several fundamental feedback Op-Amp circuits including the DC Inverting Amplifier, DC Non-Inverting Amplifier, Summing Amplifier, Difference Amplifier, Buffer, and Comparator.

Gains	Circuit Diagram	Block Diagram
<b>Inverting Amplifier</b>		
<b>Non-Inverting Amplifier</b>		
<b>Summing Amplifier</b>		
<b>Difference Amplifier</b>		
<b>Buffer</b>		
<p><b>Comparator</b></p> <p>If <math>V_1 &gt; V_2</math> then <math>V_{out} = V_{CC+}</math>          If <math>V_1 &lt; V_2</math> then <math>V_{out} = V_{CC-}</math></p>		

**Table 1 – Summary of Basic Op-Amp Circuits**  
*(Op-Amp figures are simplified to save space but it is understood that  $V_{CC+}$  and  $V_{CC-}$  are still there)*

**Multisim DC Simulation**

The output voltage of an Op-Amp Circuit using only DC input voltages can be simulated quickly and easily. Once your circuit is complete, click the green arrow to run the simulation. Once the simulation is running, click on the “Measurement Probe” button  and place a probe at  $V_{out}$ , or any other location on the circuit where you would like to make a measurement. Initially, the probe will show much more information than is currently necessary. Double-click the probe information to bring up the window shown in **Figure 6**. Notice that under the Show column, every property starts with a Yes. Deselect all properties by clicking the red check mark at the top of the Show column, then proceed to select the desired properties. In this case, we will only need the top voltage property **V**. We can also change the **Precision** to show **six** significant figures.

V(rms):  
 V(dc):  
 I:  
 I(p-p):  
 I(rms):  
 I(dc):  
 Freq.:

Figure 5 – Standard Probe Details

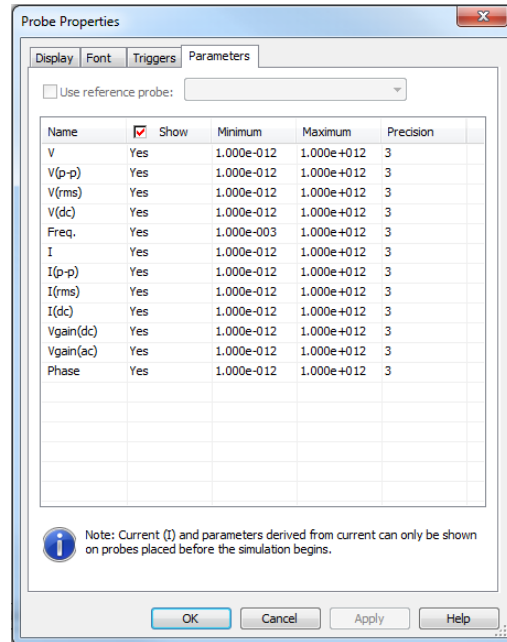


Figure 6 – Probe Properties Window

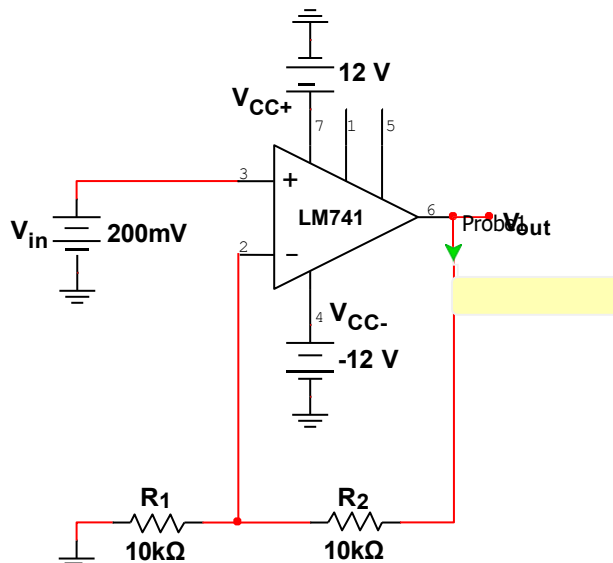


Figure 7 – Probe Showing Simulated  $V_{out}$

**PRELAB**

**Part I – Inverting Amplifier**

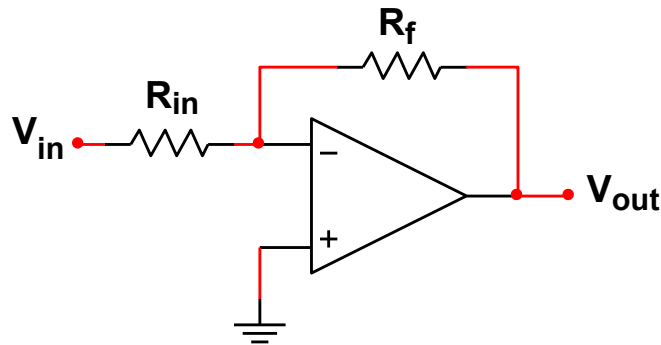


Figure P.1 – Inverting Amplifier

1. Using **Table 1** and **Figure P.1**, design an **DC Inverting Amplifier** that has the following specifications:
  - $V_{CC+} = +12V$
  - $V_{CC-} = -12V$
  - $V_{in} = 200mV$
  - **Closed Loop Voltage Gain (K) = -10**
  - **Assume  $R_{in} = 10k\Omega$**  (see the textbook to better understand this choice)
2. **Show all** general **equations** and **design** steps.
3. **Simulate** your design in Multisim as described in the **Introduction**.

**Part II – Non-Inverting Amplifier**

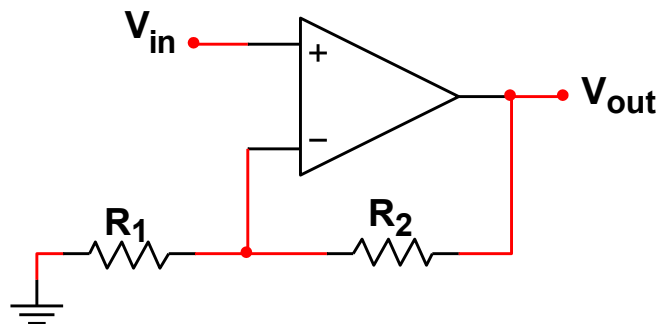


Figure P.2 – Non-Inverting Amplifier

1. Using **Table 1** and **Figure P.2**, design a **DC Non-Inverting Amplifier** that has the following specifications:
  - $V_{CC+} = +12V$
  - $V_{CC-} = -12V$
  - $V_{in} = 200mV$
  - **Closed Loop Voltage Gain (K) = 10**
  - **Assume  $R_1 = 10k\Omega$**
2. **Show all** general **equations** and **design** steps.
3. **Simulate** your design in Multisim as described in the **Introduction**.

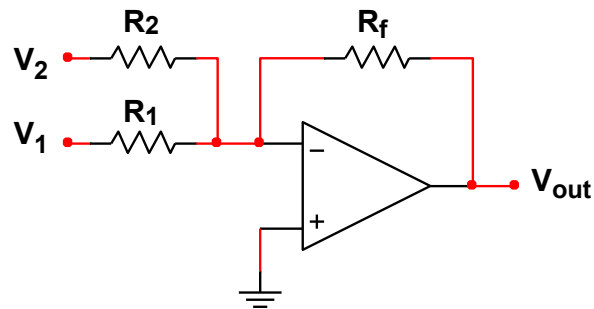
**Part III – Summing Amplifier**


Figure P.3 – Summing Amplifier

- Using **Table 1** and **Figure P.3**, design a DC Summing Amplifier that has the following specifications:
  - $V_{CC+} = +12V$
  - $V_{CC-} = -12V$
  - $V_1 = 500mV$
  - $V_2 = 500mV$
  - Closed Loop Voltage Gain ( $K$ ) =  $K_1 = K_2 = -2$
  - Assume  $R_f = 10k\Omega$
- Show *all* general equations and design steps.
- Simulate your design in Multisim as described in the Introduction.

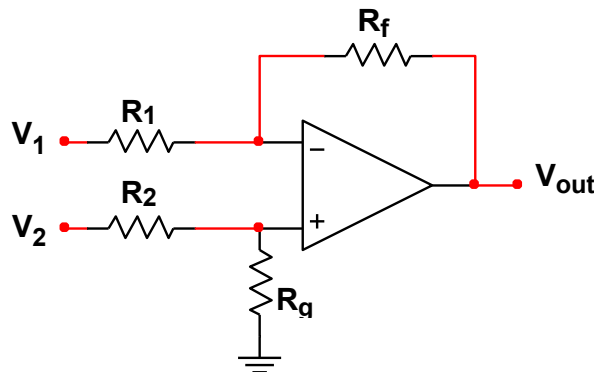
**Part IV – Difference Amplifier**


Figure P.4 – Difference Amplifier

- Using **Table 1** and **Figure P.4**, design a DC Difference Amplifier that has the following specifications:
  - $V_{CC+} = +12V$
  - $V_{CC-} = -12V$
  - $V_1 = 400mV$
  - $V_2 = 900mV$
  - Closed Loop Voltage Gain ( $K$ ) =  $K_1 = K_2 = 2$
  - Assume  $R_1 = R_2 = 10k\Omega$
- Show *all* general equations and design steps.
- Simulate your design in Multisim as described in the Introduction.

**Part V – Buffer**

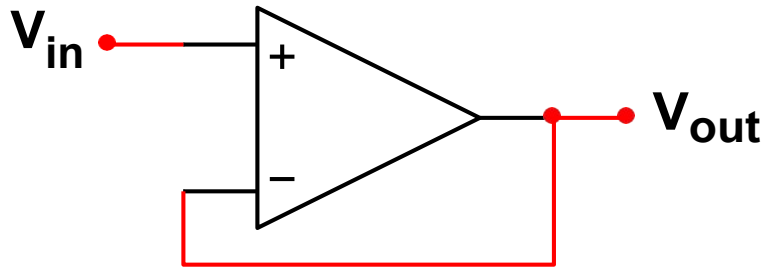


Figure P.5 – Buffer

1. Using **Table 1** and **Figure P.5**, design a **Buffer** that has the following specifications:
  - $V_{CC+} = +12V$
  - $V_{CC-} = -12V$
  - $V_{in} = 500mV$
  - **Closed Loop Voltage Gain (K) = 1**
2. **Show all** general **equations** and **design** steps.
3. **Simulate** your design in Multisim as described in the **Introduction**.

**Part VI – Comparator**

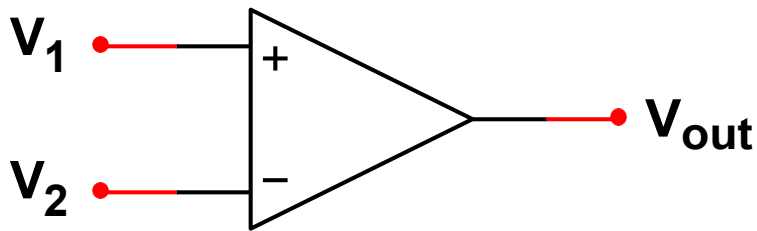


Figure P.6 – Buffer

1. Using **Table 1** and **Figure P.6**, design a **Comparator** that has the following specifications:
  - $V_{CC+} = +12V$
  - $V_{CC-} = -12V$
  - $V_1 = 1V$
  - $V_2 = 500mV$
  - **If  $V_1 > V_2$ , then  $V_{out} = 12V$**
  - **If  $V_1 < V_2$ , then  $V_{out} = -12V$**
2. **Show all** general **equations** and **design** steps.
3. **Simulate** your design in Multisim as described in the **Introduction**.



**LAB**

**Part I – Verification of Inverting Amplifier**

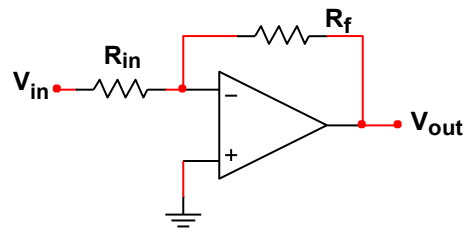


Figure 1.1 – Inverting Amplifier

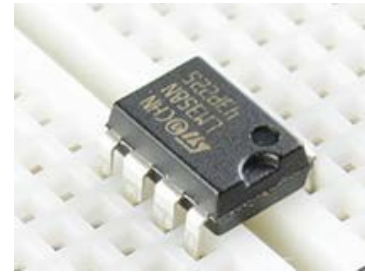
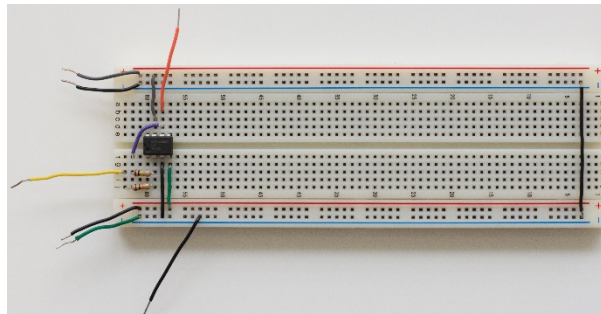


Figure 1.2 – Op-Amp Positioning on Breadboard



1. **Build the Inverting Amplifier** according to your prelab design and **Figure 1.1**.  
**Note:** For this lab, we can utilize the breadboard optimally by plugging the Op-Amp into the breadboard so that it straddles the gap between the left and right sections of the socket strip. The Op-Amp must be positioned as shown in **Figure 1.2** so that the pins do not short.
2. **Set** the AC DC Adapter to +12V for Vcc+ and -12V for Vcc-.
3. **Set** Wavegen channel 1 to output **200mV DC**.
  - a. Open the WaveGen tab.
  - b. Set the "Type:" to DC.
  - c. Set the offset to 200mV.
  - d. **Ensure** the output is OFF before attaching the power supply to the LM741. Remember, when the Wavegen tab uses DC, the "Enable" check box controls whether it is on or not.
  - e. **Connect** the Wavegen (Pin W1) to **Rin**, which is then connected to **V<sub>N</sub>** (pin 2).
  - f. **Turn on** the Supplies tab first, and then click the "enable" box in the Wavegen tab.
4. **Measure** **V<sub>P</sub>**, **V<sub>N</sub>**, and **V<sub>out</sub>** of the Op-Amp using the **DMM**. **Verify** that the voltage gain (K) is **-10**.
  - a. **Record** all of your data in **Table 1.1**.
5. **Change** the original 200mV input to 2V. **What** is V<sub>out</sub>?
  - a. **Record** your answer as V<sub>out2</sub>. **Discuss** any limitations you find in the analysis section of your lab report.
6. **Change** the input back to 200mV and **substitute** the feedback resistor R<sub>f</sub> on the inverting amplifier with a resistor of large value.
  - a. **Measure** the output and confirm that the gain corresponds to the nominal gain given by -R<sub>f</sub>/R<sub>in</sub>.
  - b. Progressively **increase** the gain and measure the output. Is there a limit where the output **does not change** regardless of the gain?
7. **Change** WaveGen channel 1 to **400mV<sub>pp</sub> 10kHz sine wave** waveform. This will require you to change the "type:" back to Sine and the "Offset" back to 0.
  - a. **Measure** V<sub>out</sub> using the **oscilloscope**. Make sure the "1-" pin is connected to ground or you will experience some noise in your reading. **Does** the signal invert?
  - b. **Save** a screenshot from the oscilloscope showing both **V<sub>in</sub>** and **V<sub>out</sub>**.

	<b>Calculated</b>	<b>Simulated</b>	<b>Percent Error</b>	<b>Measured</b>	<b>Percent Error</b>
<b>V<sub>P</sub></b>					
<b>V<sub>N</sub></b>					
<b>V<sub>in</sub></b>					
<b>V<sub>out</sub></b>					
<b>K</b>					
<b>V<sub>out2</sub></b>					

Table 1.1 – Inverting Amplifier Data

**Part II – Verification of DC Non-Inverting Amplifier**

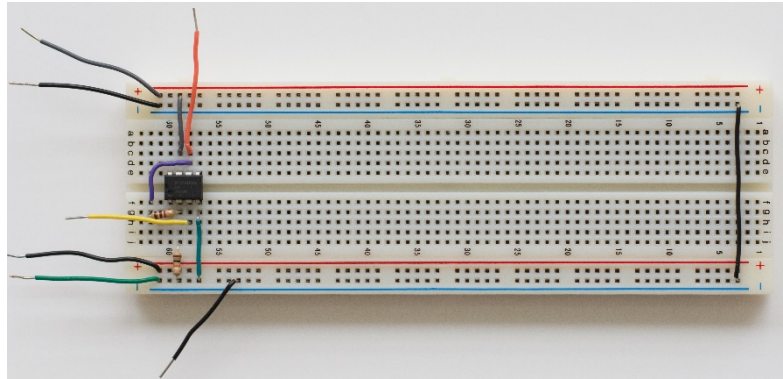
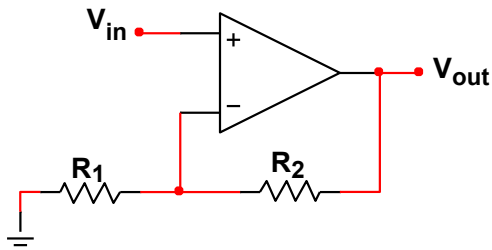


Figure 2.1 – Non-Inverting Amplifier

1. **Build the Non-Inverting Amplifier** according to your prelab design and **Figure 2.1**.
2. **Connect** the power supplies similar to the connection done in **Part I**.
3. **Measure**  $V_P$ ,  $V_N$ , and  $V_{out}$  of the Op-Amp using the **DMM**. **Verify** that the voltage gain ( $K$ ) is **10**.
  - a. **Record** all of your data in **Table 2.1**.

	<i>Calculated</i>	<i>Simulated</i>	<i>Percent Error</i>	<i>Measured</i>	<i>Percent Error</i>
$V_P$					
$V_N$					
$V_{in}$					
$V_{out}$					
$K$					

Table 2.1 – Non-Inverting Amplifier Data

**Part III – Verification of Summing Amplifier**

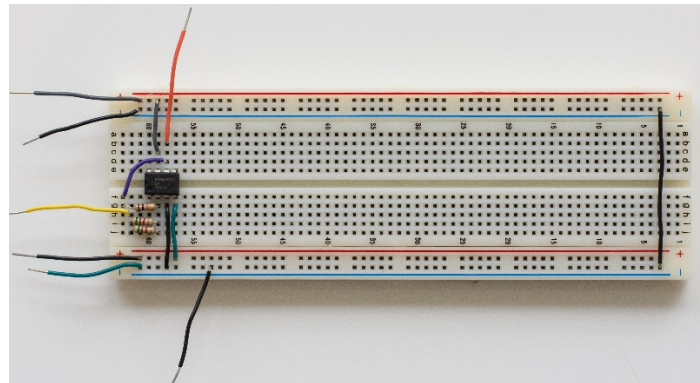
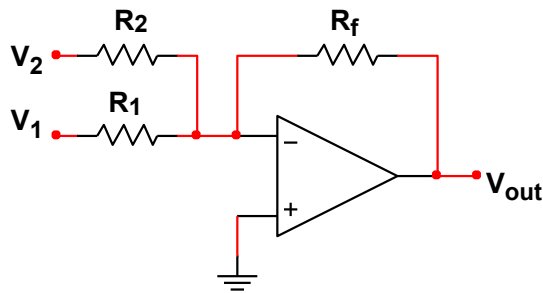


Figure 3.1 – Summing Amplifier

1. **Build the Summing Amplifier** according to your prelab design and **Figure 3.1**.
2. **Connect** the power supplies similar to the connections done in **Part I**.
3. **Measure**  $V_P$ ,  $V_N$ , and  $V_{out}$  of the Op-Amp using the **DMM**. **Verify** that the voltage gain ( $K$ ) is **-2** and  $V_{out} = -2(V_1 + V_2)$ .
  - a. **Record** all of your data in **Table 3.1**.

	<i>Calculated</i>	<i>Simulated</i>	<i>Percent Error</i>	<i>Measured</i>	<i>Percent Error</i>
$V_P$					
$V_N$					
$V_{in}$					
$V_{out}$					
$K$					

Table 3.1 – Summing Amplifier Data

**Part IV – Verification of Difference Amplifier**

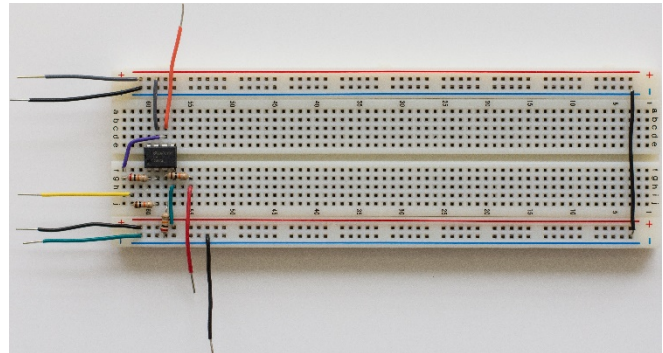
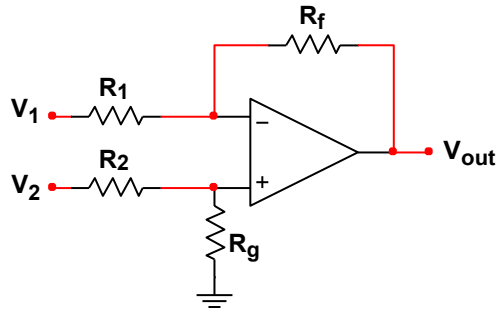


Figure 4.1 – Difference Amplifier

1. **Build the Summing Amplifier** according to your prelab design and **Figure 4.1**.
2. **Connect** the power supplies similar to the connection done in **Part I**.
3. **Measure**  $V_P$ ,  $V_N$ , and  $V_{out}$  of the Op-Amp using the **DMM**. **Verify** that the voltage gain ( $K$ ) is 2 and  $V_{out} = 2(V_2 - V_1)$ .
  - a. **Record** all of your data in **Table 4.1**.

	<i>Calculated</i>	<i>Simulated</i>	<i>Percent Error</i>	<i>Measured</i>	<i>Percent Error</i>
$V_P$					
$V_N$					
$V_1$					
$V_2$					
$V_{out}$					
$K$					

Table 4.1 – Difference Amplifier Data

**Part V – Verification of the Op-Amp Buffer (Current Amplifier)**

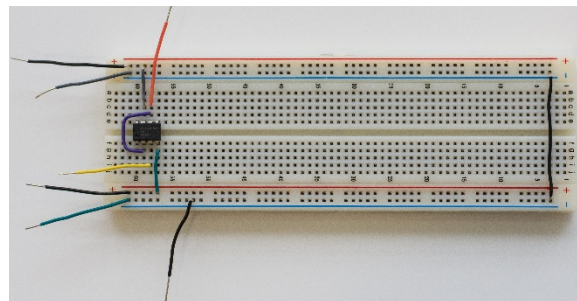
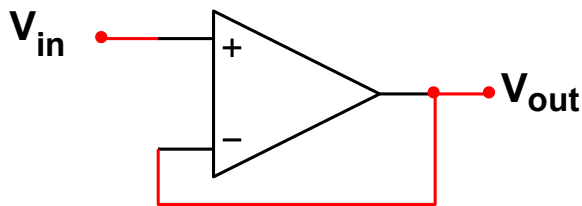


Figure 5.1 – Buffer (Current Amplifier)

1. **Build the Buffer (Current Amplifier)** according to your prelab design and **Figure 5.1**.
2. **Connect** the power supplies similar to the connection done in **Part I**.
3. **Measure**  $V_P$ ,  $V_N$ , and  $V_{out}$  of the Op-Amp using the **DMM**. **Verify** that the voltage gain ( $K$ ) is 1.
  - a. **Record** all of your data in **Table 5.1**.

	<i>Calculated</i>	<i>Simulated</i>	<i>Percent Error</i>	<i>Measured</i>	<i>Percent Error</i>
$V_P$					
$V_N$					
$V_{in}$					
$V_{out}$					
$K$					

Table 5.1 – Buffer (Current Amplifier) Data

**Part VI – Verification of the Op-Amp Comparator**

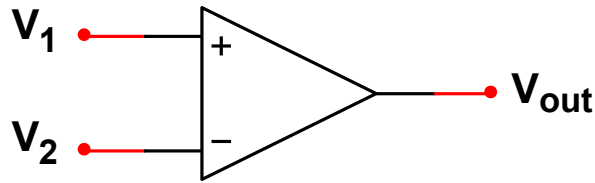
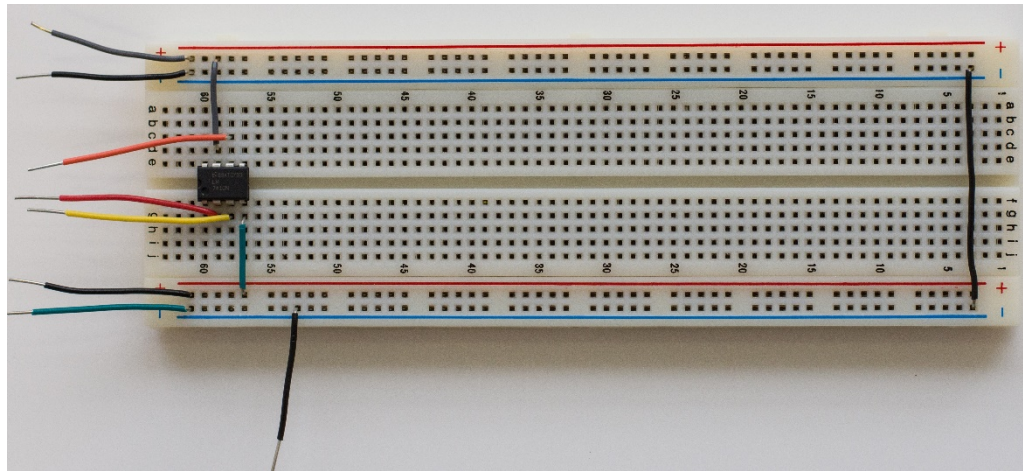


Figure 6.1 – Comparator



1. **Build the Comparator** according to your prelab design and **Figure 6.1**.
2. **Connect** the power supplies similar to the connection done in **Part I**.
3. **Measure**  $V_P$ ,  $V_N$ , and  $V_{out}$  of the Op-Amp using the **DMM**. **Verify** that the comparator follows the behavior specified in the prelab.
  - a. **Record** all of your data in **Table 6.1**.

	<i>Calculated</i>	<i>Simulated</i>	<i>Percent Error</i>	<i>Measured</i>	<i>Percent Error</i>
$V_{CC+}$					
$V_{CC-}$					
$V_1$					
$V_2$					
$V_{out}$					
$K$					

Table 6.1 – Comparator Data

## **POST-LAB ANALYSIS**

Compare and contrast the calculated and simulated results from your prelab to the DC measurements made from the experiments.

1. Explain the reasons for any differences between prelab design and measurements.
2. Explain how each mathematical operation can be performed using the circuits you have built in lab.
3. Give one example where a comparator circuit can be used in a practical application.
4. Give one example where a current amplifier circuit can be used in a practical application.
5. Also, explain why the output reaches a limit and saturates regardless of the gain.

## **REFERENCES**

- [1] "Operational Amplifier," *Wikipedia: The Free Encyclopedia*,  
[http://en.wikipedia.org/wiki/Operational\\_amplifier](http://en.wikipedia.org/wiki/Operational_amplifier).
- [2] "LM741 Operational Amplifier," *Texas Instruments*,  
<http://www.ti.com/lit/ds/symlink/lm741.pdf>.