THE GEORGE WASHINGTON UNIVERSITY

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

Lab Equipment	*Equipment Description*
(1) DC Power Supply	Keysight E36311A Triple Output DC Power Supply
(1) Digital Multimeter (DMM)	Agilent 34460A (DMM)
(1) Breadboard	Prototype Breadboard
(3) Test Leads	Banana to Alligator Lead Set

Table 1 – Equipment List

COMPONENTS

Type	*Value*	*Symbol Name*	*Multisim Part*	*Description*
Resistor	--- Ω	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

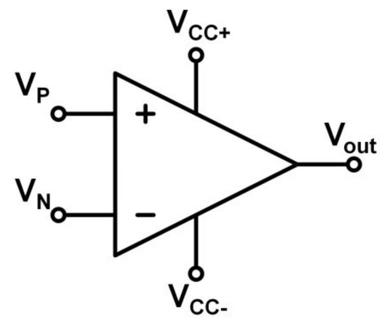


Figure 1 – Op-Amp Symbol

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

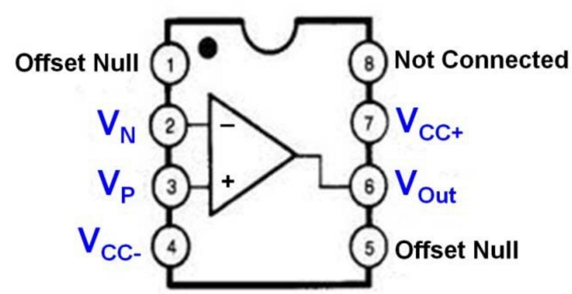


Figure 3 – LM741 Op-Amp Pin Diagram
(*The pins used in this lab are shaded in blue*)

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.

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.

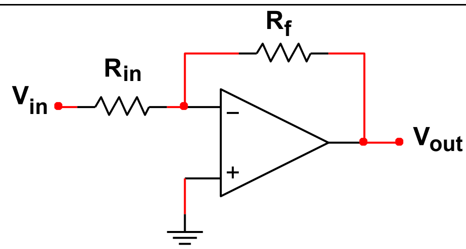
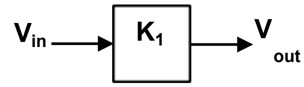
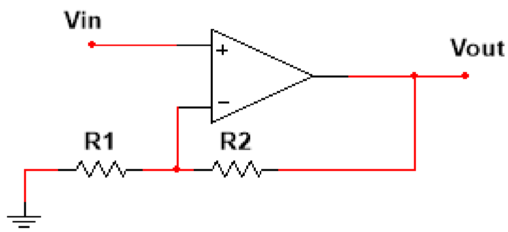
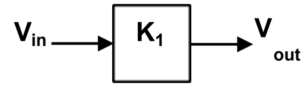
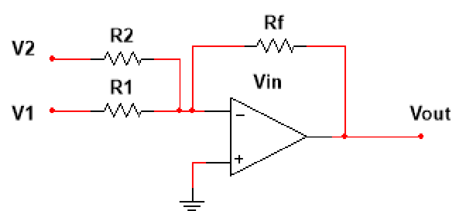
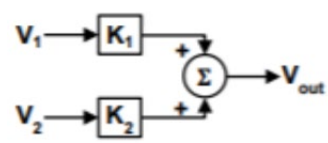
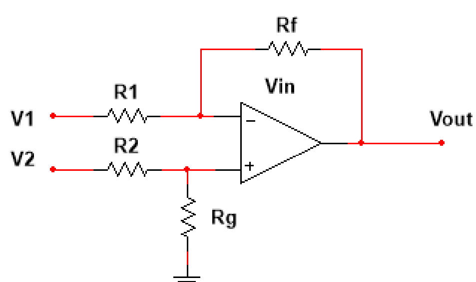
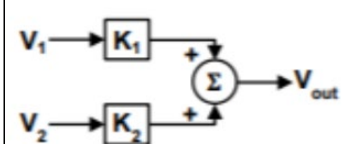
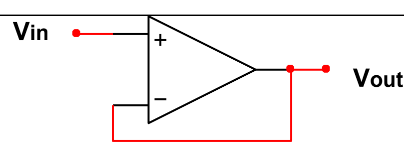
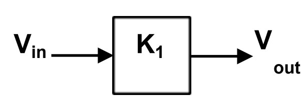
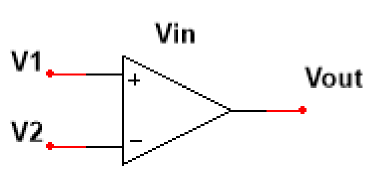
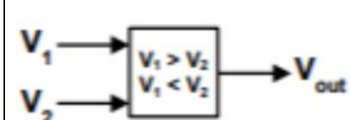
Gains	***Circuit Diagram***	***Block Diagram***
Inverting Amplifier $K1 = -\frac{Rf}{Rin}$		
Non-Inverting Amplifier $K1 = 1 + \frac{R2}{R1}$		
Summing Amplifier $K1 = -\frac{Rf}{R1}$ $K2 = -\frac{Rf}{R2}$		
Difference Amplifier $K1 = -\frac{Rf}{R1}$ $K2 = (\frac{R1 + Rf}{R1})(\frac{Rg}{Rg + R2})$		
Buffer $K1 = 1$		
Comparator If $V_1 > V_2$ then $V_{out} = V_{CC+}$ If $V_1 < V_2$ then $V_{out} = V_{CC-}$		

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***)

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.

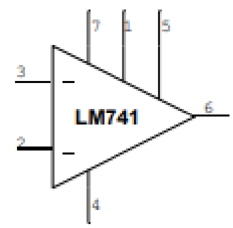
Component Name	***Multisim Part Name***	***Instructions***	***Symbol***
LM741 Operational Amplifier	**Group:** Analog **Family:** OPAMP **Component:** 741	• Click "**Place Analog**" • Click on **OPAMP Family** • Search for **741** • Select and use the **741**	

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 $\mathbf{V_{in}}$ **= 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.

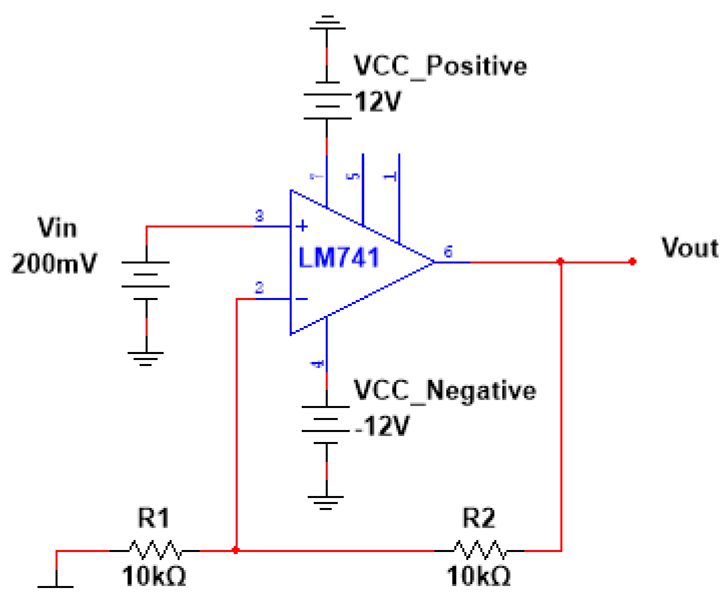


Figure 4 – Non-Inverting Amplifier with V_{in} = 200mV and K = 2

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 Voltage probe button (V) 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, almost every property starts with a Yes. Deselect all properties by clicking the checkbox 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.

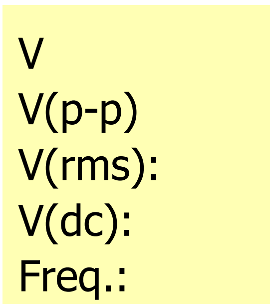


Figure 5 – Voltage Probe Details

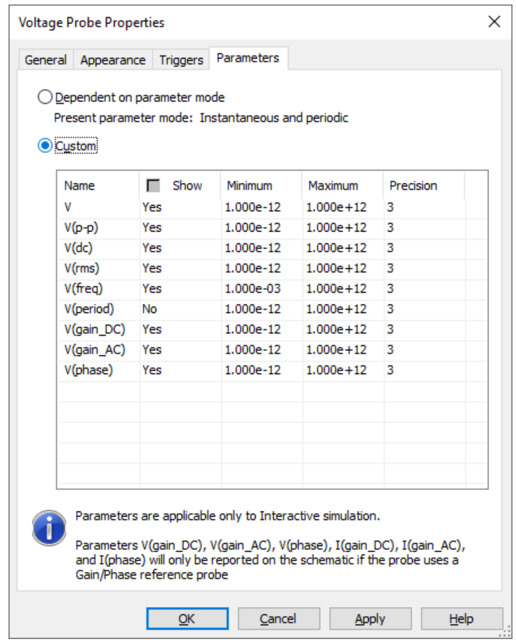


Figure 6 – Probe Properties Window

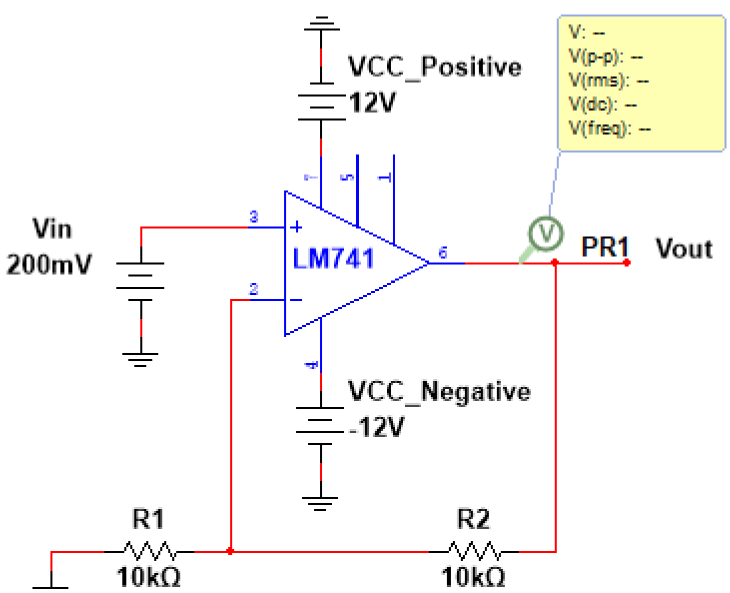


Figure 7 – Probe Showing Simulated V_{out}

PRELAB

Part I – Inverting Amplifier

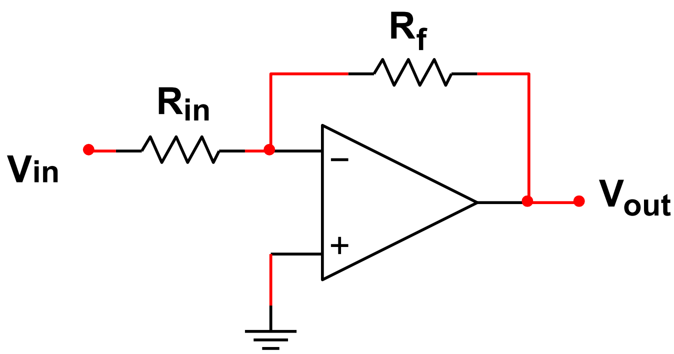


Figure P.1 – Inverting Amplifier

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} = 10kΩ** (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

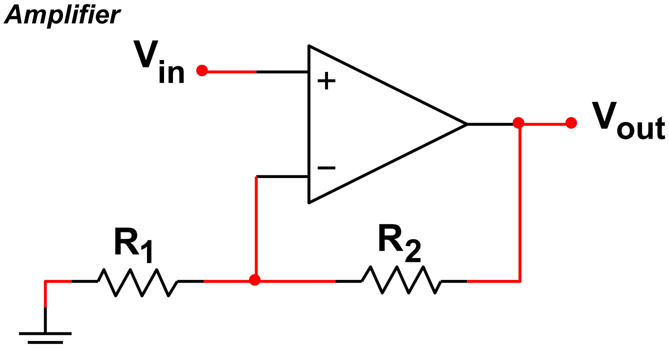


Figure P.2 – Non-Inverting Amplifier

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 = 10kΩ**
2. **Show *all*** general **equations** and **design** steps.
3. **Simulate** your design in Multisim as described in the **Introduction**.

Part III – Summing Amplifier

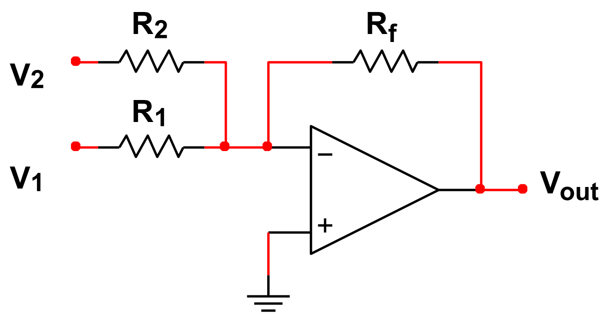


Figure P.3 – Summing Amplifier

1. 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 = 10kΩ**
2. **Show *all*** general **equations** and **design** steps.
3. **Simulate** your design in Multisim as described in the **Introduction**.

Part IV – Difference Amplifier

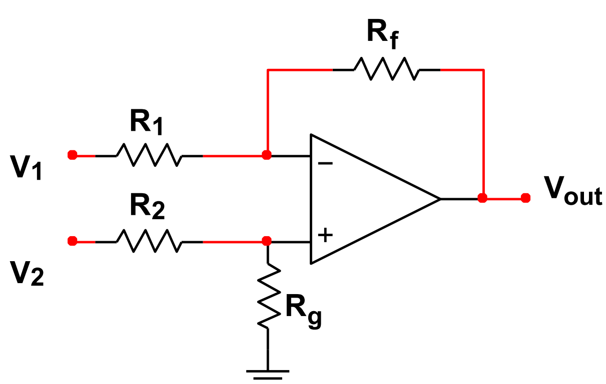


Figure P.4 – Difference Amplifier

1. 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 = 10kΩ**
2. **Show *all*** general **equations** and **design** steps.
3. **Simulate** your design in Multisim as described in the **Introduction**.

Part V – Buffer

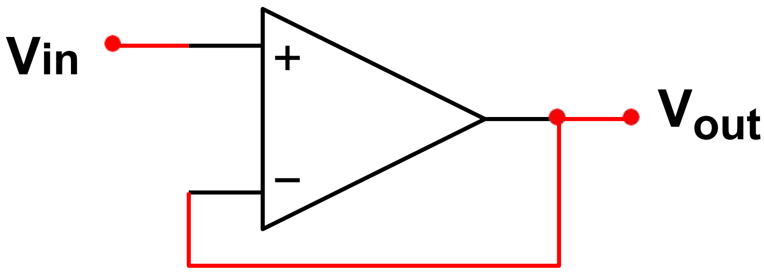


Figure P.5 – Buffer

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

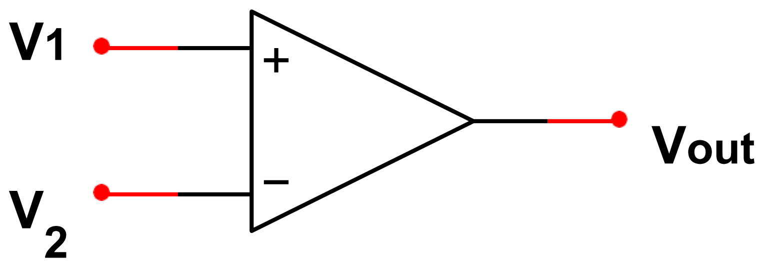


Figure P.6 – Buffer

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

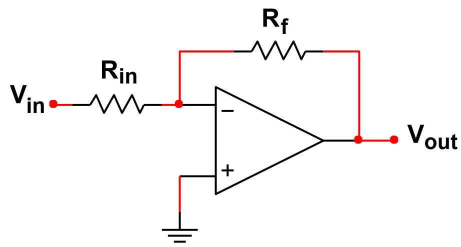


Figure 1.1 – Inverting Amplifier

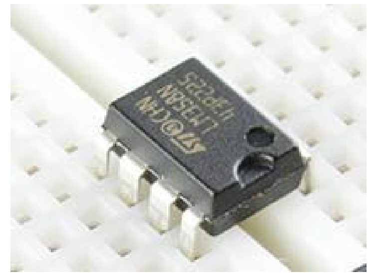


Figure 1.2 – Op-Amp Positioning on Breadboard

1. **Build** the **Inverting Amplifier** according to your prelab design and **Figure 1.1**.
   Note: *The Op-Amp must be positioned as shown in* ***Figure 1.2*** *so that the pins do not short.*
2. **Set** the KEYSIGHT Power Supply +25V terminals to **12V** and the -25V terminals to **-12V**.
   a. **Ensure** the output is **OFF** before attaching the power supply to the LM741.
   b. **Connect** V_{CC+} (pin 7) to the + 12V terminal on the power supply.
   c. **Connect** V_{CC-} (pin 4) to the - 12V terminal on the power supply.
3. **Set** the KEYSIGHT Power Supply 6V terminals to **200mV**.
   a. **Ensure** the output is OFF before attaching the power supply to the LM741.
   b. **Connect** the negative terminal to the common green ground terminal on the KEYSIGHT Power Supply, tying all ground nodes together.
   c. **Connect** the positive terminal to $\mathbf{R_{in}}$, which is then connected to V_N (pin 2).
   d. **Turn on** the power supply once the circuit is fully connected.
4. **Measure** $\mathbf{V_P}$, $\mathbf{V_N}$, and $\mathbf{V_{out}}$ of the Op-Amp using the **DMM**. **Verify** that the voltage gain (K) is **-10**.
   a. **Record** all of your data in **Table 1.1**.
5. **Change** the original 200mV input to 2V. **What** is V_{out}?
   a. **Record** your answer as V_{out2}. **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_f 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 $-R_f/R_{in}$.
   b. Progressively **increase** the gain and measure the output. Is there a limit where the output **does not change** regardless of the gain?
7. **Replace** the DC input voltage with a **400mV**$_{\mathbf{pp}}$ **10kHz sine wave** using the **function generator**.
   a. **Measure** V_{out} using the **oscilloscope**. **Does** the signal invert?
   b. **Save** a screenshot from the oscilloscope showing both $\mathbf{V_{in}}$ and $\mathbf{V_{out}}$.

	Calculated	***Simulated***	***Percent Error***	***Measured***	***Percent Error***
V_P					
V_N					
V_{in}					
V_{out}					
K					
V_{out2}					

Table 1.1 – Inverting Amplifier Data

Part II – Verification of DC Non-Inverting Amplifier

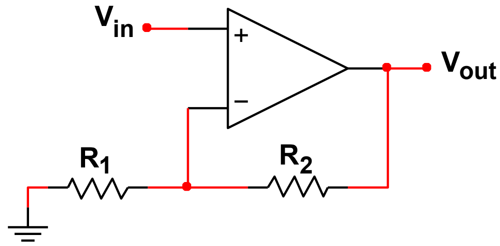


Figure 2.1 – Non-Inverting Amplifier

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**.

	Calculated	*Simulated*	*Percent Error*	*Measured*	*Percent Error*
V_P					
V_N					
V_{in}					
V_{out}					
K					

Table 2.1 – Non-Inverting Amplifier Data

Part III – Verification of Summing Amplifier

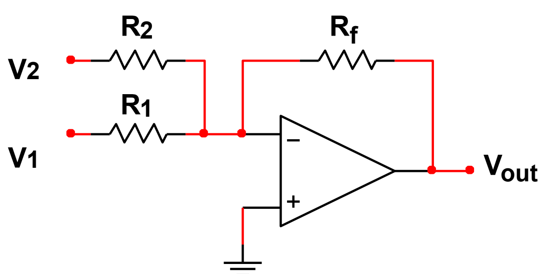


Figure 3.1 – Summing Amplifier

1. **Build** the **Summing Amplifier** according to your prelab design and **Figure 3.1**.
2. **Connect** the power supplies similar to the 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 $V_{out} = -2(V_1 + V_2)$.
   a. **Record** all of your data in **Table 3.1**.

	Calculated	*Simulated*	*Percent Error*	*Measured*	*Percent Error*
V_P					
V_N					
V_{in}					
V_{out}					
K					

Table 3.1 – Summing Amplifier Data

Part IV – Verification of Difference Amplifier

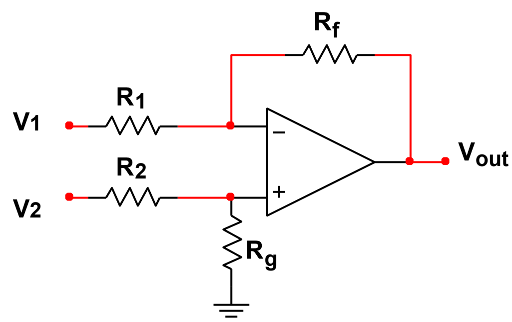


Figure 4.1 – Difference Amplifier

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** $\mathbf{V_P}$, $\mathbf{V_N}$, and $\mathbf{V_{out}}$ 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**.

	Calculated	*Simulated*	*Percent Error*	*Measured*	*Percent Error*
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)

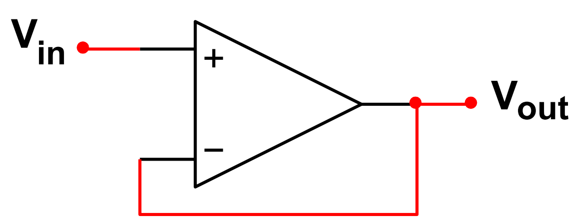


Figure 5.1 – Buffer (Current Amplifier)

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** $\mathbf{V_P}$, $\mathbf{V_N}$, and $\mathbf{V_{out}}$ 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**.

	Calculated	*Simulated*	*Percent Error*	*Measured*	*Percent Error*
V_P					
V_N					
V_{in}					
V_{out}					
K					

Table 5.1 – Buffer (Current Amplifier) Data

Part VI – Verification of the Op-Amp Comparator

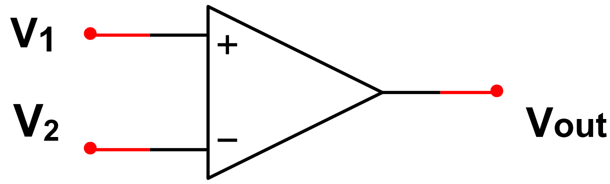


Figure 6.1 – Comparator

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**.

	Calculated	*Simulated*	*Percent Error*	*Measured*	*Percent Error*
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've 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.

[2] "LM741 Operational Amplifier," *Texas Instruments*, http://www.ti.com/lit/ds/symlink/lm741.pdf.

