Lab 5
Operational Amplifiers

OBJECTIVES
1. Become aware of a dependent source and how it operates.
2. Validate the Ideal Operational Amplifier (Op Amp) Model through experimental measurements for several Op Amp circuits.
3. Demonstrate linearity and the ability of an Op Amp to maintain constant gain over its operating range.

EQUIPMENT
Lab kit, Decade Box, and Power Supply

THEORY
An Operational Amplifier (Op Amp) is typically the first introduction to the workings of a dependent source. Dependent sources are intentionally controlled by what is going on in the circuit to which they are connected. It therefore, must have two connections to its network: an input signal \( v_{in} \) that represents the control that the network will have over the dependent source, and an output \( v_{out} \) that will in some way be modified by the dependent source and then delivered to the connected network. The two common modifications made by a dependent source to its input are an amplitude increase, that is, the output is larger (or smaller) than the input by a factor called the gain, and a change in polarity of the output called inversion.

The operational amplifier output voltage and current must satisfy several conditions:
- \( |v_{out}| \leq v_{sat} = 14V \)
- \( i_{out} \leq i_{sat} \approx 20 – 30mA \)
- \( \left| \frac{dv_{out}(t)}{dt} \right| \leq \text{Slew Rate} = 500,000 \text{ V/s} = 0.5 \text{ V/μs} \)

These restrictions reflect the fact that operational amplifiers cannot produce arbitrarily large voltages or currents. We will use the very popular and common general-purpose IC op-amp, the \( \mu \)A741.

<table>
<thead>
<tr>
<th>Type of Op Amp</th>
<th>Output Voltage ( v_{out} )</th>
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</thead>
<tbody>
<tr>
<td>Voltage Follower</td>
<td>( v_{out} = v_{in} )</td>
</tr>
<tr>
<td>Non-Inverting</td>
<td>( v_{out} = \left( 1 + \frac{R_2}{R_1} \right) v_{in} )</td>
</tr>
<tr>
<td>Inverting</td>
<td>( v_{out} = -\frac{R_2}{R_1} v_{S} )</td>
</tr>
<tr>
<td>Summing Amplifier</td>
<td>( v_{out} = -R \left( \frac{v_1}{R_1} + \frac{v_2}{R_2} \right) )</td>
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</tbody>
</table>

PROCEDURE
A word of caution: the IC terminal connections are very delicate pins. Be careful when inserting the IC into the proto board – don’t crush or bend any of the pins under the IC body. Keep all Op Amp leads as short as possible and try not to commingle input and output leads. Reversing the power supply leads have known to “blow apart” the actual IC unit.
Part 1: Voltage Follower and Current Saturation
In theory, the input voltage \( v_{in} \) should match the output voltage \( v_{out} \). The goal is to determine the amplifier’s ability to maintain a constant output voltage as the load resistance decreases. Construct the circuit

\[ v_{in} = 5 \text{ V} \]

b. Note that the input \( v_{in} \) is directly connected to the output \( v_{out} \) using a short (this is called the negative feedback line). Therefore, \( v_{in} \) should match \( v_{out} \) regardless of the load resistance where \( v_{out} \) is measured. Let’s check this. With the input \( v_{in} \) set at 5V, measure the output voltage \( v_{out} \) and the current \( i_{out} \) for the various load resistances: 20k, 5k, 1k, 500, 100, 50Ω. Record your data in a table and plot \( v_{out} \) vs. \( i_{out} \)

c. Use a percent difference to compare \( v_{in} \) to \( v_{out} \). Does \( v_{in} = v_{out} \)? If not, what is the range in which they do match? What is the saturation current where the Op Amp stops being a voltage follower?

Part 2: Non-Inverting Amplifier and Voltage Saturation
In order for the Op Amp to behave linear, the output voltage must be below the saturation voltage of \( \pm 14 \text{ V} \). Let’s check this linearity with the Non-Inverting Amplifier. Construct the circuit

a. Predict the output voltage \( v_{out} \) for the non-inverting amplifier. Show all your work!

b. Measure \( v_{out} \) and determine the percent difference between the predicted and measured results. How do they compare?

c. To check for linearity, vary the input voltage from 1V to 7V in increments of 0.5V. Record the output voltage \( v_{out} \) for each incremental change in the input voltage \( v_{in} \). Repeat the same for \( -1 \text{ V} \) to \( -5 \text{ V} \) in increments of 0.5V.

d. Plot the output \( v_{out} \) vs. input \( v_{in} \).
   - Is the positive saturation voltage +14V? Is the negative saturation voltage −13V?
   - What range is the Op Amp behavior linear?

Side Note:
It should be mentioned that many op-amps cannot swing their output voltages exactly to \( \pm V_S \) power supply rail voltages. The model 741 is one of those that cannot: when saturated, its output voltage peaks within about one volt of the +V power supply voltage and within about 2 volts of the -V power supply voltage. Therefore, with a split power supply of \( \pm 15 \) volts, a 741 op-amp's output may go as high as +14 volts or as low as -13 volts (approximately), but no further. This is due to its bipolar transistor design. These two voltage limits are known as the **positive saturation voltage** and **negative saturation voltage**, respectively. Other op-amps, such as the model 3130 with field-effect transistors in the final output stage, have the ability to swing their output voltages within millivolts of either power supply rail voltage. Consequently, their positive and negative saturation voltages are practically equal to the supply voltages.

**Part 3: Inverting Amplifier**
Construct the circuit

a. Predict output voltage \( v_{out} \) for the inverting amplifier. For Pspice, use the OPAMP component in the analog library.

b. Measure \( v_{out} \) and determine the percent difference between the predicted and measured results. How do they compare?

**Part 4: Summing Amplifier**
Construct the circuit

a. To set the two input voltages, use two potentiometers in parallel.

b. Predict output voltage \( v_{out} \) for the summing inverting amplifier.

c. Measure \( v_{out} \) and determine the percent difference between the predicted and measured results. How do they compare?