Lab 03: Op Amps, Comparators, and Resistive Sensors

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1 Abstract

This experiment aims to teach the basic properties of operational amplifies (Op Amps). Through the use of the ADALM2000 and several different circuits, the Op Amp's properties are explored. By creating a single comparator circuit and an amplifier circuit, the linear region of the op amp is exploited and put on show. By starting out with no feedback, it is made apparent to how quickly the op amp saturates and how impractical its use in a system like this would be. After applying a feedback loop to the circuit through the use of potentiometers (pots) and a photoresistor, the operational use of the op amp is demonstrated in a physical manner. A small simulation in production ready simulation tools is also included to further stimulate the knowledge on op amps.

2 Introduction

The operational amplifier is a component which can serve many applications, including operating as a differentiator or integrator, as well as other mathematical operations. This provides an analog to the ALU that was taught in CSE2301, in which a digital logic circuit provided a means to shift and manipulate bits stored in registers. The operational amplifier however, is an analog tool that predates the modern sense of an ALU, yet is a powerful tool to understand how certain things such as impedance, amplification gain, and operational characteristics can impact a circuit and its design.

The operational amplifier was introduced in 1947 by John Ragazzini at the National Defense Research Council after World War II. This aligns with the start of the cold war, a time of exponential technological growth, similar to the component itself. This weeks lessons on the operational amplifier abstracted away the inner workings in a "black box" approach to studying the component. This allowed for the abstract analysis of several circuits such as an inverting amplifier, a non-inverting amplifier, a summing circuit, and a subtracting circuit, called the difference amplifier.

In essence, further elaborated upon in the proceeding sections, the component acts as a voltage amplifier with a dedicated power supply with a very high gain. When considered *ideal*, there are certain assumptions that can be made about the component which allows for the extensive analysis of circuits that it is embedded into.

This Op Amp, when combined with other tools such as potentiometers and photoresistors allow for the use of some unique circuits such as the ones built for this experiment.

3 Theory

3.1 The Operational Amplifier

The Operational Amplifier (Op Amp) is an electrical component that allows for an abstracted sense of mathematical operations within a circuit. Functions such as addition, subtraction, multiplication, division, and even calculus such as differentiation and integration are all possible with the correct use of this component.

It is made up of an assortment of resistors, transistors, capacitors, and diodes, however this experiment abstracts most of that away with the aforementioned "black box" approach. That is to say, the inner workings of the component itself are not delved into in particular. The DIP (Dual-In-Line) package used is the $\mu A741$ chip shown in Figure 1.

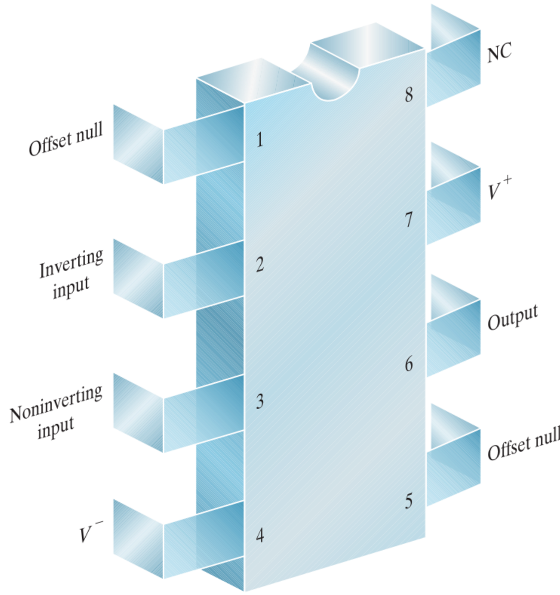

Figure 1: The $\mu A741$

The basic equation for the Op Amp has a lot to do with its specific gain, A. where:

$$V_{out} = A(\upsilon_p - \upsilon_n)$$

For a specific region called the *linearly operational region*

3.2 Linear Operation of Terminal Voltages

The Operational Amplifier quickly saturates in certain cases, which is not a desirable outcome in most applications. Quickly if the input voltage at either of the terminals (υ_p for the positive terminal and υ_n for the negative terminal) reaches beyond the supplied V_{cc}, the output voltage is pegged, or *saturated*. This is similar to maxing out a car stereo where it gets so loud that the output is just *noise*.

It is up to the circuit designer to consider this effect and build the circuit so it can operate in the linear region. When in the linear region,

$$\upsilon_n = \upsilon_p$$

For an ideal op amp with an infinite gain.

This constraint, however can only be taken advantage of in the aforementioned linear operation region. The other constraint, however, has to do with the infinite gain mentioned earlier.

For an ideal op amp, the impedance felt at the positive and negative terminals is infinite, which means that for calculations, one can *always assume*:

$$i_p = i_n = 0$$

This means that the current flowing into the opamp at its terminals is effectively null and can vastly simplify calculations.

3.3 The Potentiometer

A potentiometer is a three-terminal variable resistor that allows for the adjustment of resistance via a mechanical control, typically a rotating knob or a sliding mechanism. The potentiometer used in this experiment is a $10k\Omega$ linear potentiometer rated at 0.25W. This component enables precise control of voltage within a circuit by acting as a voltage divider or a rheostat, depending on the circuit configuration.

In the voltage divider configuration, the potentiometer is connected such that the wiper moves along the resistive element, dividing the input voltage (V_{in}) into two output voltages, one of which varies according to the wiper position:

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

where R_1 and R_2 are the resistances formed by the wiper's position along the resistive track. When used as a variable resistor (rheostat), one terminal is left unconnected, and the resistance between the wiper and one fixed terminal varies from nearly zero to the maximum rated resistance ($10k\Omega$ in this case).

The linear characteristic of the selected potentiometer means that the resistance change is directly proportional to the wiper's displacement. This ensures a predictable and uniform change in resistance, which is useful for applications such as tuning, signal attenuation, and sensor calibration. The power rating of 0.25W ensures it can handle moderate electrical loads without excessive heat dissipation.

When integrating the potentiometer into the circuit, considerations such as contact resistance, mechanical durability, and wiper noise should be taken into account, particularly in precision applications where fluctuations in resistance could impact system performance.

3.4 The Photoresistor

A photoresistor, or light-dependent resistor (LDR), is a variable resistor whose resistance changes as a function of incident light intensity. The Luna Optoelectronics PDV-P8001 photoresistor used in this experiment has a resistance range of $3k\Omega$ to $11k\Omega$ and a diameter of 5.10mm. This component is particularly useful in circuits requiring light sensitivity, such as automatic lighting controls and optical detection systems.

The fundamental working principle of a photoresistor is based on photoconductivity, where increased light intensity reduces the material's resistivity due to photon-induced excitation of charge carriers. The relationship between incident light intensity (E) and resistance (R) can be approximated by:

$$R = R_d \times E^{-\gamma}$$

where R_d is the dark resistance (resistance in complete darkness), and γ is a material-dependent constant that typically ranges between 0.7 and 0.9 for cadmium sulfide (CdS) photoresistors.

When incorporated into a voltage divider circuit, the photoresistor can be used to generate a variable voltage output corresponding to changes in ambient light levels:

$$V_{out} = V_{cc} \times \frac{R_{LDR}}{R_{LDR} + R_{fixed}}$$

where R_{LDR} is the resistance of the photoresistor and R_{fixed} is a reference resistor. This configuration enables the conversion of light intensity variations into a measurable electrical signal, which can then be processed by microcontrollers or analog circuits for automation and feedback control.

Practical considerations for implementing the PDV-P8001 include its spectral response, response time, and temperature sensitivity. The response time of the photoresistor varies with light intensity changes, typically in the range of milliseconds to seconds, making it suitable for slow-to-moderate response applications but less ideal for high-speed optical sensing. Additionally, variations in ambient temperature can affect the resistance characteristics, requiring compensation in precision applications.

By incorporating both the potentiometer and photoresistor in the circuit, a dynamic and adaptable voltage control system can be achieved, useful in applications such as dimming controls, sensor calibration, and interactive electronic designs.

4 Experimental Procedures

4.1 A Quickly Saturated Beginning

The first experiment utilized the circuit shown in Figure 2

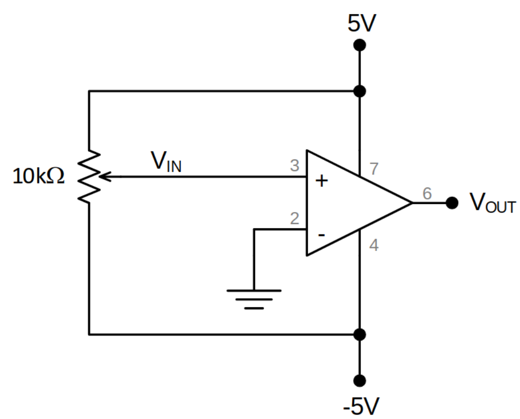

Figure 2: A Feedbackless Op Amp

1. This circuit is called a *Non-Inverting Amplifier Circuit*

   It is a peculiar construction as since there is no feedback loop from V_{out} back to the input at υ_p it quickly saturates as the potentiometer is modified

2. The voltage at the υ_p terminal was recorded via Scopy software through the ADALM2000.

   The output voltage at V_{out} was monitored via multimeter.

3. The output voltage, V_{out}, was measured at small intervals after modifying the potentiometer wiper position

Table 1 contains the data recorded for this first portion. Notice that the circuit quickly saturates with almost no ability to finely be able to tune the voltage to the linear region. This is expected.

4.2 Comparing Two Input Voltages

The second experiment utilized the circuit shown in Figure 3

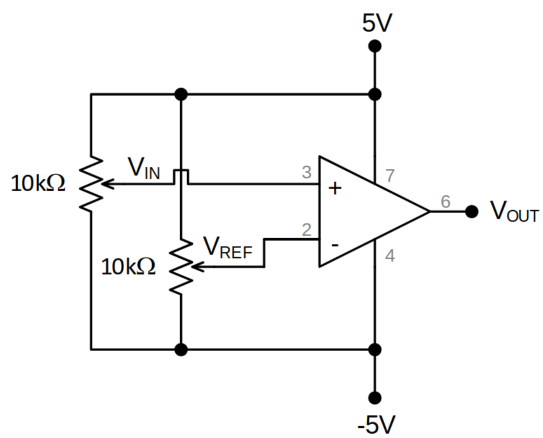

Figure 3: A Basic, Feedbackless Comparator

1. This circuit is called a *Comparator* which compares the two inputs into the operational amplifier.

2. The difference here is that the reference voltage, or V_{ref} allowed for a granularity in the opposite input terminal, υ_n.

   Unfortunately, since the circuit still has no feedback, it very quickly saturated to V_{CC} and V_{EE}

3. The output voltage, V_{out}, was measured at small intervals after modifying the potentiometer wiper position. One set of data was recorded with the reference potentiometer at a minimum wiper position, while another was set at maximum. Educationally, this allowed for a change in the output voltages as the circuit attempted to hold true to its characteristics.

   Table 2 contains the data recorded for this first portion.

4.3 A Mini-Design Challenge

This portion of the experiment provided the freedom to design a circuit which is responsive to the natural world. I chose to employ the photoresistor as a bridge to the negative terminal in order to accomplish the task of having an LED shine brightly as the resistance in the photoresistor increased, that is, got darker.

The desired characteristics were displayed and a circuit design that looks like Figure 4 was incorporated.

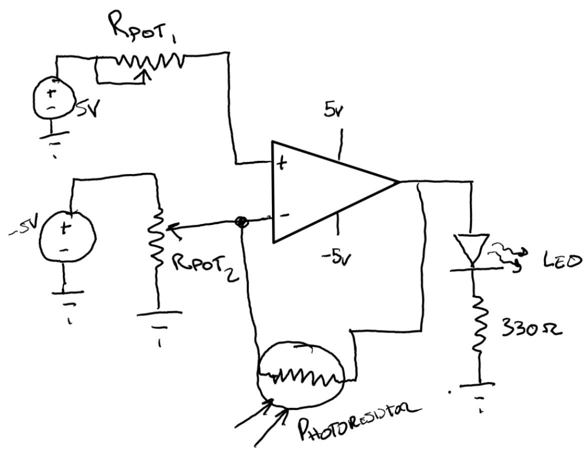

Figure 4: First Design, Photoresistor in Feedback

1. Resistance cannot be measured with the component energized. It will not be accurate due to how an ohmmeter relies on it's supplied current to get an accurate measure of resistivity.

   The Photoresistor's characteristics were measured at full dark, and full light with a cell phone flashlight to simulate full bright conditions.

2. V_{out} was measured at various conditions. This was experimentally problematic as there is no sure fire way in our setup to get a certain percentage of light. Nevertheless various voltages were recorded and notated in Table 3.

4.4 An Inverting Amplifier with Feedback

The fourth experiment utilized the circuit shown in Figure 5

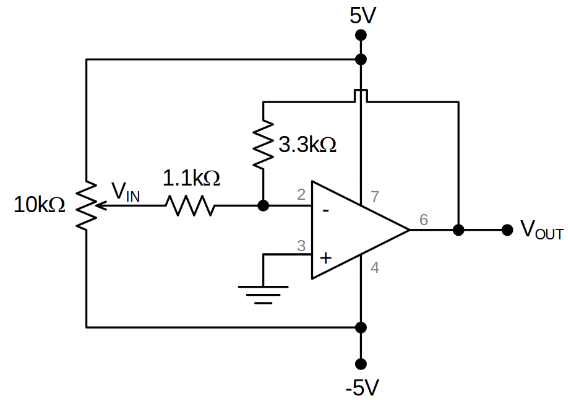

Figure 5: An Inverting Amplifier with Feedback

1. An inverting amplifier was configured to emphasize now how the linear region operates.
2. Positive and negative values of V_{in} provided a different operating characteristic under these conditions.
3. Output results are populated in Figure 11

4.5 Allegro Cadence PSpice Segue

The last part of the experimentation compared the built circuit in the previous part to a simulated circuit utilizing Allegro Cadence PSpice simulation. The circuit built is provided in Figure 6

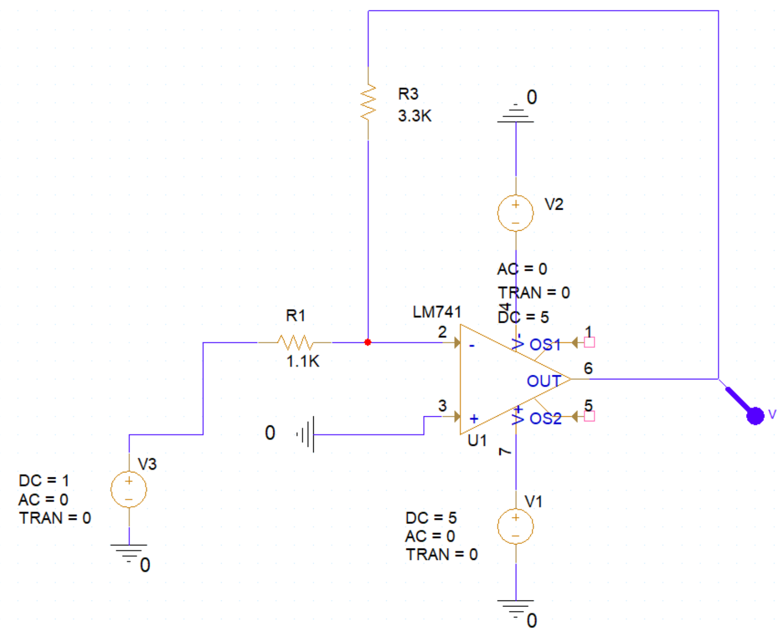

Figure 6: Cadence Simulated Circuit

1. The circuit was built in the simulator utilizing parts that closely resembled the real hardware used previously.
2. Instead of a potentiometer sweep, a DC Voltage sweep was conducted for ease of use and plotting from -5V to 5V.
3. This was able to get down the the microvolts the linear region that was not able to be seen in data closely using the potentiometer sweep.
4. Preliminary data seen from the simulator in Figure 7

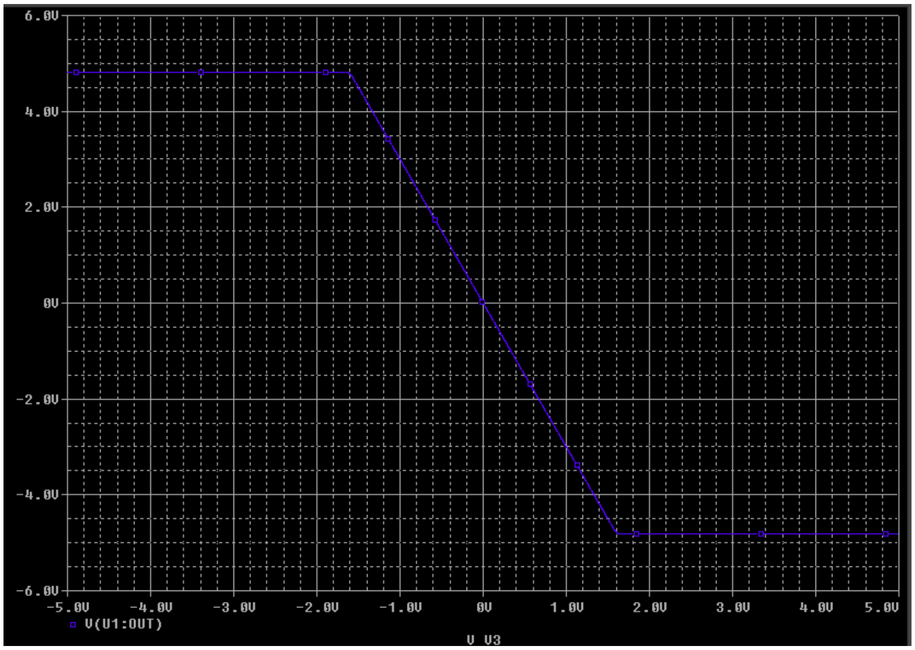

Figure 7: PSpice Sweep

5 Results and Discussion

5.1 A Quickly Saturated Beginning

The first experiment demonstrated how an operational amplifier without feedback rapidly saturates. As seen in Table 1, even small changes in input voltage resulted in immediate saturation to either the positive or negative supply rails. This behavior is expected since, in the absence of feedback, the operational amplifier functions as an open-loop amplifier with an exceedingly high gain. This high gain causes even minute input voltage variations to push the output to its limits.

Figure 8 visually represents this saturation effect. The practical implication of such a circuit is that it cannot be used for controlled amplification but is rather suited for comparator applications. High Saturation and low saturation voltages are plotted in Figure 8.

V_{in} (V)	V_{out} (V)
4.961	4.44
4.226	4.44
3.742	4.44
3.124	4.45
2.756	4.45
2.065	4.45
1.641	4.45
1.027	4.45
0.565	4.45
0.048	4.45
-0.043	-3.00
-0.168	-3.03
-0.314	-3.09
-1.582	-3.04
-2.382	-3.04
-3.408	-3.04
-5.078	-3.04

Table 1: Measured Input and Output Voltages

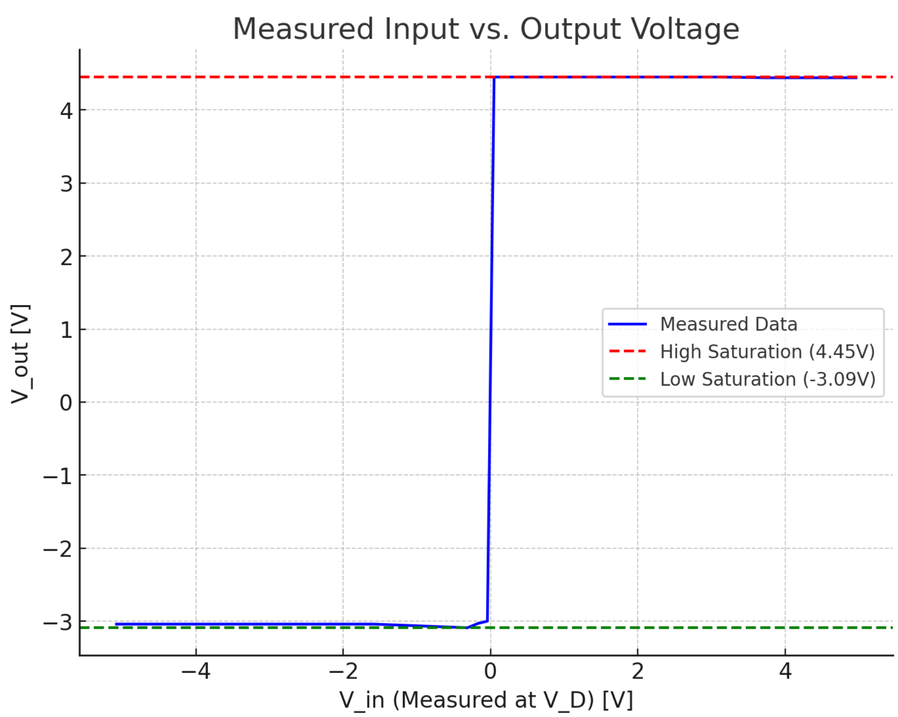

Figure 8: A Quickly Saturated Amplifier

5.2 A Comparator Circuit, Modulating Reference Voltage

Introducing a reference voltage, V_{REF}, provided a method to compare the input voltage against a defined threshold. The experimental data in Table 2 reveal that changing the reference voltage alters the transition point at which the amplifier output flips between the supply rails.

As illustrated in Figure 9, the comparator circuit continues to exhibit the characteristic rapid switching between extremes, confirming that it is well-suited for binary decision-making applications. However, the inability to finely control the output voltage without saturation still poses challenges when precise analog outputs are required. The data points show that the comparator simply outputs the saturation voltage of the greater of the two potentials.

Table 2: Measured Data for Different V_{REF} Settings

V_{in} (V)	V_{out} (V)
V_{REF} More Negative (R_{pot2} at Min)	
5.028	-2.881
3.775	-3.04
2.973	-3.04
-1.330	-3.04
-2.666	-3.04
-3.541	-3.04
-4.193	-3.04
-4.894	-3.04
-5.078	-3.04
V_{REF} More Positive (R_{pot2} at Max)	
4.961	4.45
3.391	4.45
2.382	4.45
1.828	4.45
0.824	4.45
-0.592	4.45
-1.606	4.45
-3.458	4.45
-4.727	4.45
-5.078	4.45

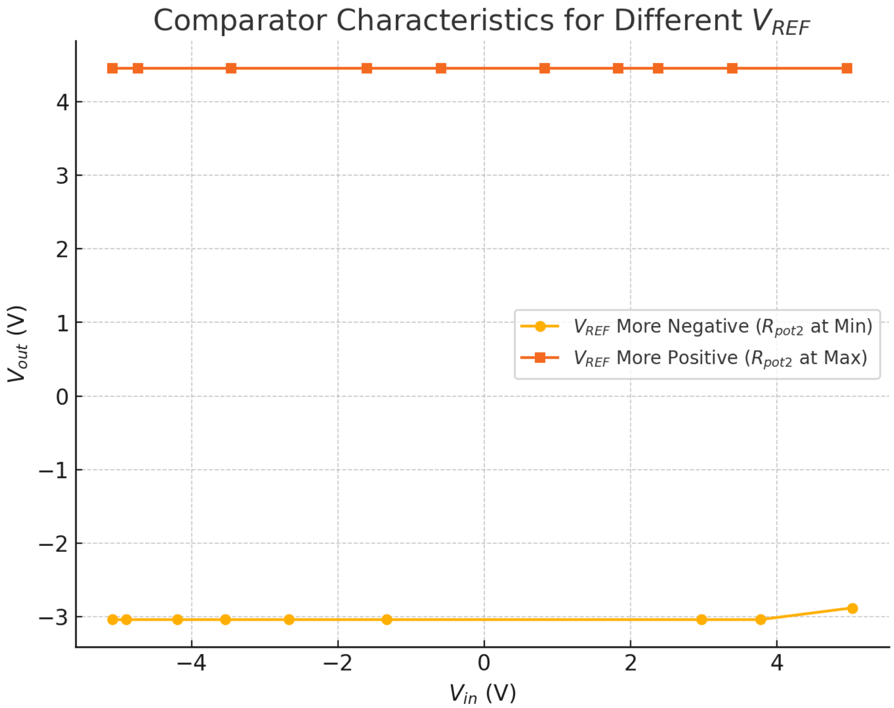

Figure 9: Comparator Circuit Characteristics

It is displayed quite obviously that the feedbackless operational amplifier chooses to saturate based on input conditions alone. Either the output voltage was positive saturation or negative saturation, nothing else, yet the values felt at the output were slightly changed than the first part due to the circuit design.

5.3 An Automatic Night Light Circuit

The experiment involving the photoresistor-based automatic night light circuit successfully showcased the behavior of the component under varying light conditions. The measured resistance values at full light (0.197 kΩ) and full darkness (14.92 kΩ) highlight the significant resistance change as light intensity varies.

Table 3 demonstrates the corresponding output voltages, showing a clear inverse relationship between light intensity and output voltage. As expected, the LED brightness increased in darkness due to the decreasing feedback resistance, leading to a higher output voltage.

The fitted curve in Figure 10 validates the nonlinear nature of the photoresistor response, showing a logarithmic trend rather than a linear progression. This confirms the expected exponential change in resistance as a function of illumination intensity, an essential characteristic for night-light circuit designs.

Light Condition	Voltage (V_{out})
Full Light (0.197 kΩ)	0.334 V
1/3 Dark	1.725 V
2/3 Dark	2.15 V
7/9 Dark	2.63 V
Full Dark (14.92 kΩ)	3.60 V

Table 3: Photoresistor Node Voltages under Different Light Conditions

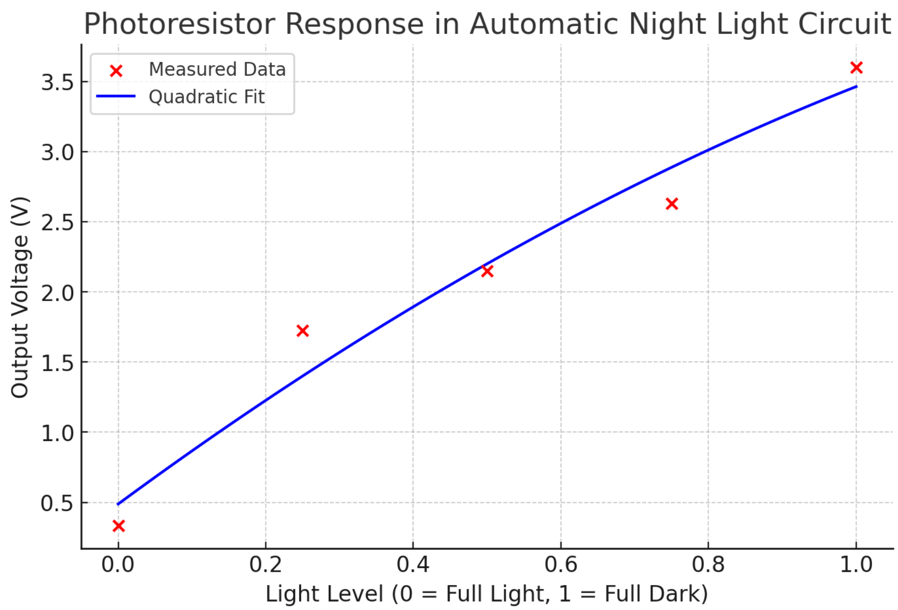

Figure 10: Night Light Circuit Characteristics

The design choice of using the photoresistor as an inverting feedback resistor was made deliberately in order to give better linearity to the behavior of the circuit. This was perhaps different than the task to simply use it as an input resistance, but in effect this circuit is superior and adheres to better practices in the use of operational amplifiers by widening the linear response region while still solving the design problem.

5.4 An Inverting Op-Amp

Unlike the previous circuits, the inverting amplifier configuration in Figure 5 utilized feedback to establish a stable linear region of operation. Table 4 presents measured data that confirm the expected inverting gain relationship between V_{in} and V_{out}.

Unlike previous circuits, this setup allowed for a controlled output range, as seen in Table 4. The amplifier effectively operated within its linear range before hitting saturation limits, demonstrating a stark contrast to the open-loop configurations tested earlier. The use of this circuit is much more apparent now with negative feedback. It amplifies the voltage felt at the negative terminal by a factor which is proportional to the feedback resistor and the input resistance.

During experimentation, there was a "deadzone" in the potentiometer position and the input voltage to the circuit which lasted from $-0.060V \implies +0.060V$. This made obtaining data difficult in this region, but it is expected behavior! As when in the linear region, the operational amplifier applies something called a voltage short condition where the potential felt at the terminals are equal to each other. This allowed for granularity in the output which show a clear linear relationship as the potentiometer was positioned.

This is later confirmed in the Cadence PSpice simulator to be on the scale of nanovolts, which was quite interesting.

V_{in} (V)	V_{out} (V)
2.940	-2.85
1.852	-2.87
1.359	-2.88
0.920	-2.89
0.346	-2.90
-0.006	3.97
-0.605	4.19
-1.154	4.19
-2.014	4.17
-2.723	4.16

Table 4: Measured Data for Inverting Amplifier Circuit

This data shows a linear region in which output voltages were linearly swept through while the voltage felt at the negative inverting terminal was kept shorted to the positive terminal by the voltage short characteristic. As soon as the operational amplifier reached saturation, voltages at the negative terminal were able to be recorded as in the previous examples. These outcomes and behavior was expected.

5.5 The Ideal Simulated Case

The final experiment compared measured results to those obtained from PSpice simulations. This matches up with the behavior seen in the lab, although at slightly different voltages due to tolerances in the experiment. This is expected behavior.

The PSpice-generated curve in Figure 11 illustrates the precise theoretical behavior of the circuit. When zoomed in on, it exhibits expected behavior at a much smaller scale that could be measured in the lab experiment, although it was behaviorally showed in the output voltages. See previous Figure 7.

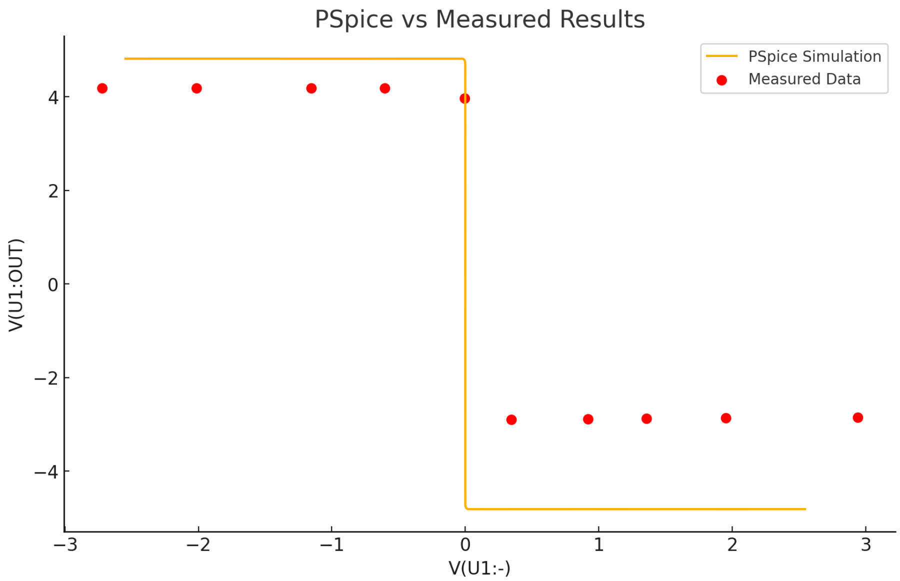

Figure 11: Simulated and Measured Characteristics

Nonetheless, the output voltage during experimentation verified the linear operation of the operational amplifier and showed how it can be used in a potential circuit design.

6 Conclusion

Through this series of experiments, we explored the fundamental operational amplifier configurations and their respective behaviors. The feedbackless amplifier demonstrated the rapid saturation effect, while the comparator circuit highlighted the utility of reference voltage for decision-making applications.

The night light circuit effectively illustrated the nonlinear response of a photoresistor, validating its use in light-sensitive applications. Finally, the inverting amplifier circuit provided a controlled amplification region, proving the necessity of feedback in maintaining operational stability.

Building and modeling the circuit in Cadence Allegro PSpice allowed for further enrichment in utilizing the tool to simulate DC circuits and measure ideal response curves. Comparing this circuit to the one built in the lab offered insight and explanation to the behavior seen in the recording data.

To summarize, this was an excellent opportunity to learn about utilizing the operational amplifier IC and lays good groundwork for experimentation to come.