EE203 - Electrical Circuits Laboratory

Experiment - 6 Simulation
Operational Amplifiers

Objectives

1. Apply analysis methods for closed loop circuits.
2. Observe closed loop response of operational amplifiers.
3. Understand limitations of operational amplifiers.

Background

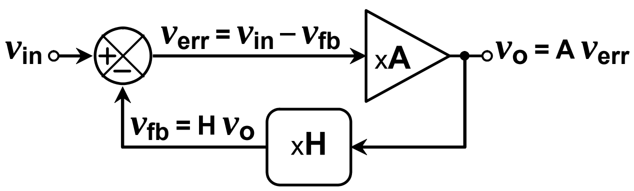
Operational amplifiers (**opamp** in short) enable design of simple circuits for a large variety of purposes because of their idealized characteristics such as infinite input resistance, zero output resistance and infinite voltage gain. Using an amplifier with infinite gain may sound like a confusing idea for a beginner. If an amplifier has a gain of **A = 5**, then its output is easily predictable as $v_o = 5\,v_{in}$, but an amplifier with infinite gain has no practical use as it is. On the other hand, having an infinite gain is just another simplification when an amplifier is used as part of a closed loop feedback circuit. In practice, all opamp circuits have some kind of feedback topology. Understanding operation of closed loop circuits is necessary before attempting to analyze opamp circuits.

Closed Loop Circuits

In a closed loop configuration, an error signal is amplified instead of directly amplifying the input signal as shown below. A closed loop circuit scales the output signal v_o with a feedback gain **H**, and feeds it back to the subtractor that calculates the error. The error signal v_{err} is given by the difference between the input v_{in} and the feedback signal v_{fb}. In the forward path, the output is generated by multiplying v_{err} with a forward gain factor **A**.

To visualize the closed loop behavior, assume that initially the circuit is at a stable state with all signals around the closed loop, v_{in}, v_{fb}, v_{err}, and v_o, are zero. If v_{in} is set to a positive value, then a positive v_{err} is generated, and the output v_o starts to rise. The feedback signal $v_{fb} = H\,v_o$ rises at the same time resulting in a reduced error signal. The closed loop circuit settles at a new stable state depending on v_{in} and the circuit parameters **A** and **H**. The output signal at this new stable state can be calculated as follows.

$$\begin{aligned} v_o &= A\,v_{err} = A(v_{in} - v_{fb}) \\ &= A(v_{in} - H\,v_o) \\ &= A\,v_{in} - AH\,v_o \\ (1 + AH)v_o &= A\,v_{in} \end{aligned}$$



Then the output signal is given by

$$v_o = \frac{A}{1 + AH} v_{in} = G\, v_{in}$$

where, $G = \frac{v_o}{v_{in}} = \frac{A}{1 + AH}$ is the **closed loop gain**.

The following table shows the closed loop gain **G** and error voltage v_{err} for v_{in} **= 1 V** depending on a few values of the forward gain **A** and the feedback scaler factor **H**.

forward gain	G =closed loop gain		error voltage v_{err} (V)	
	for **H=1/10**	for **H=1/11**	for **H=1/10**	for **H=1/11**
A = 100	9.091	9.910	0.0909	0.0991
A = 1,000	9.901	10.880	0.0099	0.0109
A = 10,000	9.990	10.988	0.0010	0.0011
A = 100,000	9.999	10.999	0.0001	0.0001

We can observe the following facts looking at the results given in the table.

1. Closed loop gain **G** is mainly determined by the feedback scaling factor **H** when **A** is sufficiently large. If **H** increases by **10%**, then **G** also changes by **10%** as seen in the table. The same result can be obtained from the closed loop gain expression when **AH >> 1**:

$$G = \frac{A}{1 + AH} \simeq \frac{A}{AH} = \frac{1}{H} \quad \text{when } \mathbf{AH >> 1}$$

2. The forward gain **A** does not have a significant effect on the closed loop gain. If **AH >> 1**, then the closed loop gain **G** is nearly equal to **1/H**. **G** changes by only **1%** when **A** is increased by a factor of **100**, from **1,000** to **100,000** in the table given above. As a consequence, the forward amplifier is not required to have a linear behavior in order to obtain linear closed loop response. On the other hand, nonlinearity or any irregularity in the feedback scaling factor **H** directly affects the closed loop response.

3. Error signal v_{err} approaches to zero as the forward gain **A** increases. In other words, if the forward amplifier has nearly infinite gain, then voltage at its inputs must be nearly zero when it has a measurable output voltage.

$$v_{err} = \frac{v_o}{A} = \frac{v_{in}}{1 + AH} \simeq 0 \quad \text{when } \mathbf{AH >> 1}.$$

Smaller v_{err} also means that v_O follows the expected output v_{in}/H more closely.

The three blocks in the closed loop circuit diagram are replaced by actual electronic components in opamp applications:

1. An operational amplifier provides a large forward gain **A**, typically greater than **100,000**.
2. The feedback scaling factor **H** is obtained easily by using simple resistive divider networks.
3. Subtraction of feedback signal v_{fb} from the input v_{in} is achieved at the differential inputs of the opamp when **G > 0** (closed loop gain is positive). The error signal can be obtained on the resistive divider network when **G < 0**.

Operational Amplifiers

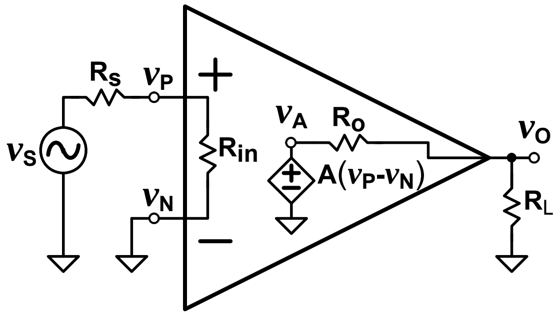
Operational amplifier is a <u>differential amplifier that generates an output proportional to the voltage difference between its positive and negative input terminals</u>. In practice, all amplifiers have a finite input resistance, $\mathbf{R_{in}}$, a non-zero output resistance, $\mathbf{R_O}$, and a finite gain, **A**, as shown in the model given below. Similarly, the input signal source v_S has a non-zero output resistance, $\mathbf{R_S}$. Calculation of amplifier response is possible after considering all loading effects at the input and output.

Amplifier output voltage v_O is divided between $\mathbf{R_O}$ and $\mathbf{R_L}$:

$$v_O = \frac{R_L}{R_O+R_L} A(v_P - v_N)$$

and the input source voltage v_S is divided between $\mathbf{R_S}$ and $\mathbf{R_{in}}$:

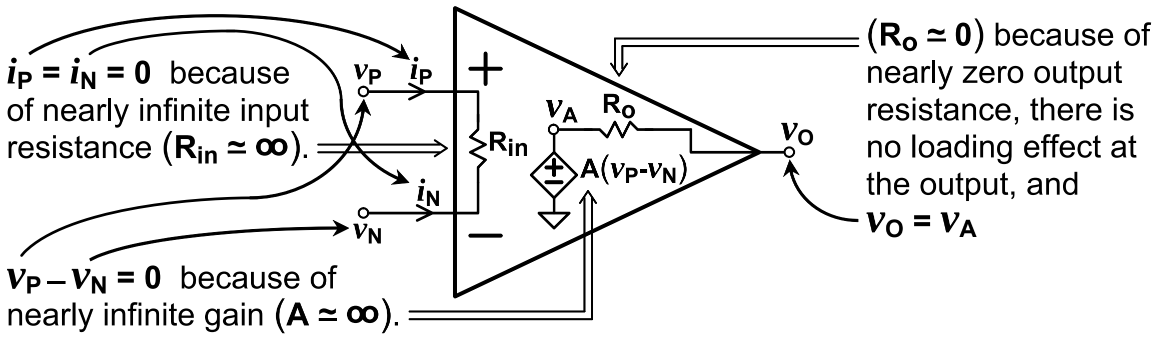
$$v_P - v_N = \frac{R_{in}}{R_S+R_{in}} v_S$$



The output voltage can be related to the input source voltage by taking into account both of the loading effects.

$$v_O = \frac{R_L}{R_o+R_L} A \frac{R_{in}}{R_s+R_{in}} v_S$$

Operational amplifiers have idealized characteristics that simplify circuit analysis and design in ordinary applications. These characteristics are summarized in the following figure.

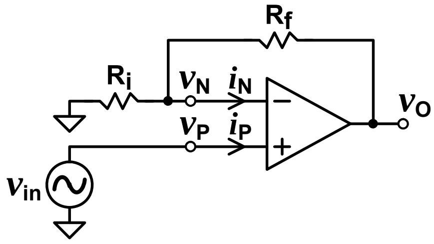


- $i_P = i_N = 0$ **:** It is not necessary to consider the loading effect at the opamp inputs when $\mathbf{R_{in}}$ is much bigger than the resistors used in the circuit. Currents through the opamp inputs can be ignored when we apply Kirchhoff's current law at these circuit nodes.
- $v_P - v_N = 0$ **:** Remember that $v_O = A(v_P - v_N)$ means $v_P - v_N = v_O/A$. If $v_O = 1$ **V** and **A = 100,000**, then $v_P - v_N = 0.01$ **mV**, which is much smaller than other voltages in ordinary applications. Closed loop circuit analysis is simplified by assuming $v_P = v_N$ at the opamp inputs.
- $v_O = v_A$ **:** Loading effect at the opamp output can be ignored when $\mathbf{R_O}$ is much smaller than the resistors used in the circuit.

The main idea in design of closed loop opamp circuits is to build a feedback mechanism that makes the differential input voltage zero when the output voltage produces the desired response. Similarly, when it comes to the analysis, the main function of a closed loop opamp circuit can be found by identifying the output response that makes the differential input voltage zero. Differential inputs of operational amplifiers provide positive and negative gain factors that allow design of several closed loop circuit topologies. The basic feedback mechanisms for closed loop voltage amplifiers are described in the following sections.

Non-Inverting Amplifier

The input voltage is directly applied to the positive or non-inverting input of the opamp in this configuration. The feedback signal is obtained with a resistive divider connected to the negative or inverting input of the opamp. The opamp output settles at a point where the feedback signal at v_N is equal to the input signal at v_P.



$$v_N = v_P = v_{in} \quad (\text{because } v_P - v_N \simeq 0)$$

$$v_N = \frac{R_i}{R_i + R_f} v_O \quad (\text{because } i_N \simeq 0)$$

Combine these two equations to obtain v_O as a function of v_{in}:

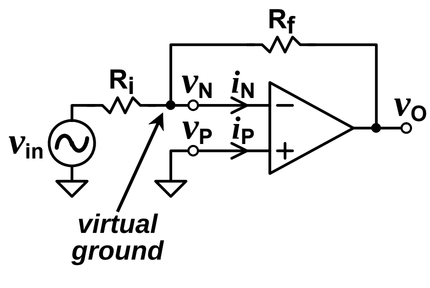
$$v_o = \frac{R_i + R_f}{R_i} v_{in} = \left(1 + \frac{R_f}{R_i}\right) v_{in}$$

Then the closed loop gain is

$$G = \frac{v_o}{v_{in}} = 1 + \frac{R_f}{R_i} .$$

Inverting Amplifier

In this configuration, the input voltage is applied to the negative input of the opamp through a resistor R_i and the positive input is connected to **0 V** reference ground. The output v_O has the opposite polarity of the input v_{in} resulting in a negative closed loop gain. Therefore, subtraction of the feedback signal from the input signal is achived on the resistive feedback network. The opamp output settles at a point where the feedback signal at v_N is equal to v_P **= 0 V.**

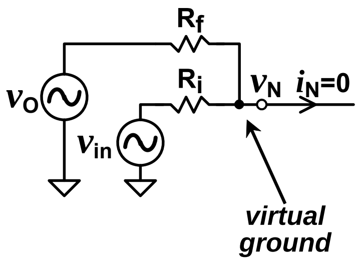


$$v_P = 0 = v_N = \frac{R_f}{R_i + R_f} v_{in} + \frac{R_i}{R_i + R_f} v_O$$

$$\frac{R_i}{R_i + R_f} v_O = -\frac{R_f}{R_i + R_f} v_{in}$$

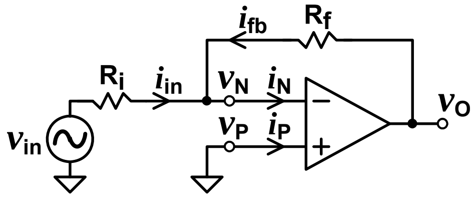
$$v_O = -\frac{R_f}{R_i} v_{in}, \text{ and } G = \frac{v_O}{v_{in}} = -\frac{R_f}{R_i}$$

The voltage at v_N is calculated as a superposition of the two voltage sources, v_O and v_{in}, as shown on the right. Calculating an amplifier output by assuming **0 V** input may seem like a contradiction. In fact, v_N is not exactly zero since it is given by $v_N = -v_O/A$. It is just assumed that v_N is negligible compared to v_O and v_{in} in these calculations.



The v_N node is considered as a ***virtual ground*** in this particular configuration. This node is not directly connected to the actual ground, but it is forced to be at the ground level through the feedback network, since the non-inverting opamp input v_P is connected to ground.

Another way to find the closed loop gain is to apply the Kirchhoff's current law at the v_N node:

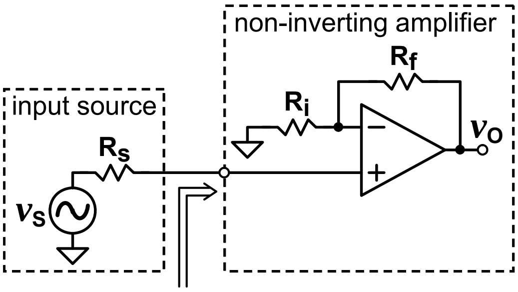


$$i_{in} = -i_{fb} \qquad \text{(because } i_N \simeq 0\text{)}$$

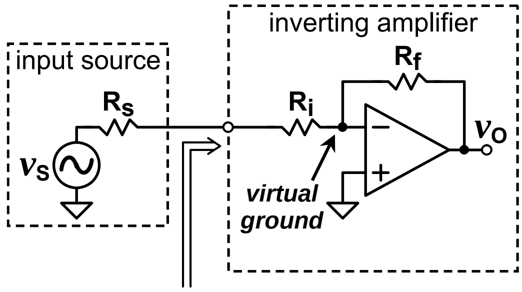
$$\frac{v_{in}}{R_i} = -\frac{v_O}{R_f} \qquad \text{(because } v_N \simeq v_P = 0\text{)}$$

$$v_O = -\frac{R_f}{R_i} v_{in}$$

An important difference between the non-inverting and inverting configurations is the load resistance seen by the input signal source at the input of the closed loop amplifier as shown below. Output resistance R_S of the signal source does not affect the closed loop gain of the non-inverting amplifier, as long as R_S is much smaller than R_{in} of the operational amplifier. In case of an inverting amplifier, R_S of the signal source is added in series with R_i in the gain calculation.



R_{in} seen by v_S is given by R_{in} of the operational amplifier. Closed loop gain is not affected by R_S.

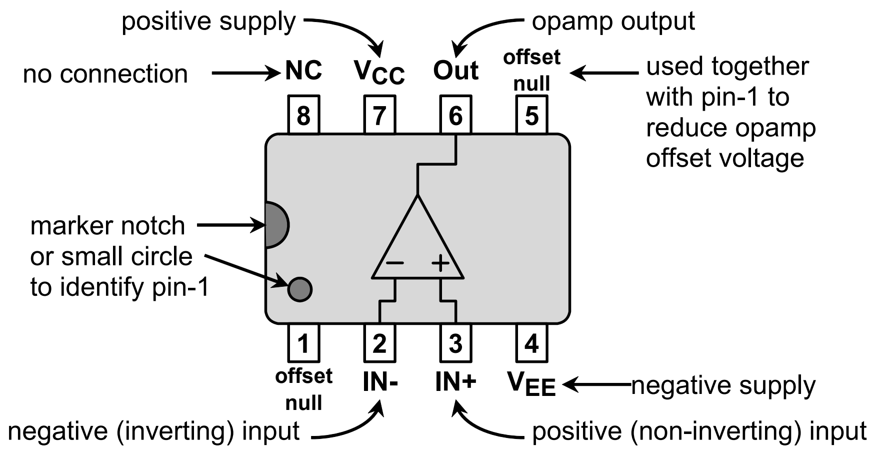


R_{in} seen by v_S is equal to R_i. Closed loop gain changes depending on R_S.

$$G = \frac{v_O}{v_S} = -\frac{R_f}{R_S + R_i}$$

LM741 Operational Amplifier

LM741 opamp is an integrated circuit (**IC**) available in an 8-pin package. Pin functions are listed in the datasheet provided by the manufacturer and they are summarized in the following figure. Pins are numbered starting at a notch or circular marker on the IC package and incremented in counter-clockwise direction around the IC package.



An operational amplifier controls the current flow from DC supplies to its output pin in order to generate the amplified output signal, and it requires supply connections like any other active integrated circuit. You should note that, the opamp IC has no ground connection pin, although the dependent output source in the previously given opamp model is referenced to ground. The output voltage is always determined relative to the opamp inputs according to the feedback circuit. Therefore, the **0 V** reference level of the input sources at the opamp inputs also determine the reference level at the opamp output.

The assumptions based on the idealized opamp characteristics in the circuit analysis can be verified by using the following specifications given in the datasheet.

- $i_P = i_N = 0$ **:** Check if the **opamp input resistance R_{in}** specified in the datasheet is much bigger than the input and feedback resistors in the feedback circuit. Also check that the specified **input bias current I_{BIAS}** is much smaller than the input source and feedback currents.
- $v_P - v_N = 0$ **:** Verify that the input voltage of the closed loop circuit is much bigger than the specified **input offset voltage V_{IO}**.
- $v_O = v_A$ **:** Verify that the specified **output resistance R_O** is much smaller than the feedback resistor in parallel with any load resistor driven by the opamp output.

These specifications may be given for different conditions depending on supply voltages or ambient temperature range in some datasheets. Some of the specifications can be in graphical form as a function of frequency, temperature or another parameter.

Preliminary Work

1. Refer to the LM741 datasheet and write the specified values for the following parameters.

Supply voltage range:

Maximum power dissipation:

Input voltage range:

Output voltage range:

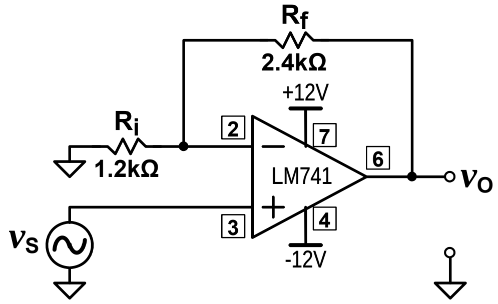
Input offset voltage:

Input bias current:

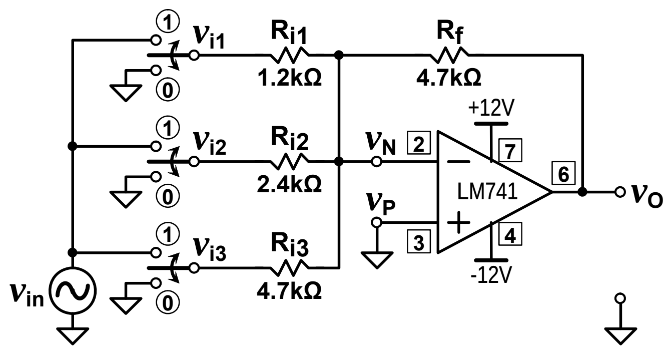
Input resistance:

Output resistance:

2. Calculate the closed loop gain **G =** v_O / v_S of the following circuit.



3. Calculate the closed loop gain of the following summing amplifier for each of the three inputs, v_{i1}, v_{i2}, and v_{i3}. Write an expression for v_O as a function of all inputs, and calculate the v_O amplitude for all switch positions listed in the table given for **step–2** of the procedure.



4. An opamp circuit is required to generate the output, v_O **= 3V + 3V** ***sin*****(ωt)**, when the input signal is v_{in} **= 2V** ***sin*****(ωt)**. In other words, the input is amplified by **1.5x** gain and a **3 V** offset is added at the output.

a) Draw the mathematical transfer function, where horizontal axis shows the input for **–3V <** v_{in} **< +3V**, and vertical axis shows the corresponding output v_O.

b) Design this amplifier by using a single opamp, **+12 V** and **–12 V** supplies and resistors. All resistors must be **>1 kΩ** to prevent over-heating of the components. You should find solutions to the following questions.

Do you need an inverting or non-inverting amplifier?

How can you add the required offset by using **+12 V** or **–12 V** supply?

What should be the closed loop gain of the amplifier?

Procedure

The model of **LT1001** operational amplifier will be used instead of **LM741** to obtain the simulation results on LTspice. Although **LT1001** has much better characteristics compared to **LM741**, both of the devices satisfy the basic requirements of an operational amplifier and the results obtained in the following steps will not be significantly different.

You should follow the instructions given below while working in laboratory and keep them in mind all the time even though there is no risk of damaging a component in simulation.

Important Note:

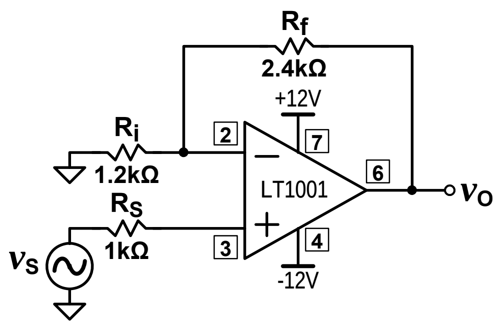
LM741 operational amplifier can be damaged easily if any of the specifications given in the **Absolute Maximum Ratings** section of the datasheet is exceeded. You must carefully follow the instructions given below in all parts of the experiment to minimize the risk of damaging the operational amplifier.

- ✓ Adjust DC supply and signal generator outputs without connecting them to the breadboard.
- ✓ Turned off DC supply and signal generator outputs before connecting them to your circuit.
- ✓ Check all circuit connections before turning on any of the sources. DC supply connections are the most critical.
- ✓ First turn on DC supplies, and then turn on signal generator.

Always turn off all sources before making changes in the circuit:

- ✓ First turn off signal generator, and then turn off DC supplies.
- ✓ Make the necessary changes in the circuit.
- ✓ First turn on DC supplies, and then turn on signal generator.

1. Build the circuit given below. Place separate DC voltage sources to obtain **+12 V** and **–12 V** supplies required for the opamp. It is practical to connect these sources to net labels for each supply and use the same net labels for the opamp supply connections. Set the v_S signal source to obtain **1 kHz** sine wave with **1 V**p-p amplitude.



1.1 Adjust v_S signal source to obtain the amplitudes in the following table and measure the corresponding v_O amplitudes on the oscilloscope.

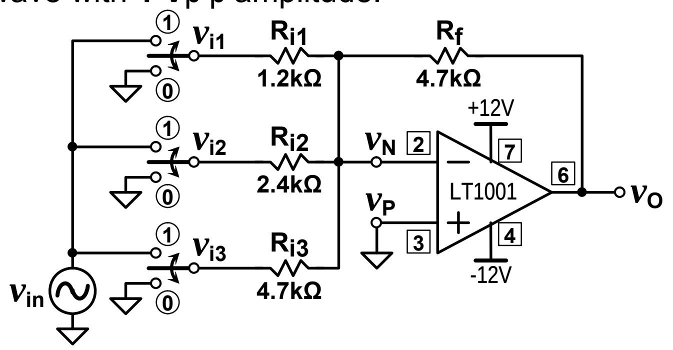
v_S amplitude (Vp-p)	v_O amplitude (Vp-p)	voltage gain $\lvert v_O\rvert/\lvert v_S\rvert$
1.0		
2.0		
3.0		
4.0		

1.2 Calculate the voltage gain for each v_S setting and record the result in the last column. Compare the results with the gain calculated in the preliminary work.

1.3 Gradually increase the v_S amplitude until you see clipping distortion in the v_O waveform. Record the v_S and v_O amplitudes at the onset of distortion.

$|v_S|$ = _________ $|v_O|$ = _________

2. Build the following summing amplifier circuit and adjust the v_{in} signal source to obtain **1 kHz** sine wave with **1 V**p-p amplitude.



2.1 This circuit is a simple ***digital-to-analog converter*** that generates an output proportional to the binary number given by the **0** or **1** switch positions. Measure and record the output voltage v_O for the sequence of input voltage combinations shown in the following table. Connect the input resistors, $\mathbf{R_{i1}}$, $\mathbf{R_{i2}}$, and $\mathbf{R_{i3}}$ either to ground or to the signal source output to obtain the input amplitudes listed in the table.

switch positions	input amplitudes (Vp-p)			measured v_O amplitude (Vp-p)	calculated v_O amplitude (Vp-p)
	v_{i1}	v_{i2}	v_{i3}		
0 0 0	0	0	0		
0 0 1	0	0	1		
0 1 0	0	1	0		
0 1 1	0	1	1		
1 0 0	1	0	0		
1 0 1	1	0	1		
1 1 0	1	1	0		
1 1 1	1	1	1		

2.2 Compare the measured values with the output amplitudes calculated in the preliminary work.

3. Build the circuit you designed for question **4** of the preliminary work.

3.1 Measure the output voltage for the input voltage settings given in the following table to verify how well your design is working. You need to figure out a way to create **+2 V** and **–2 V DC** for your inputs.

DC voltage (**V**) at v_{in}	measured v_O (**V**)	expected v_O (**V**)
-2.0		
-1.0		
0.0		
+1.0		
+2.0		

3.2 Use the signal generator to obtain a **1 kHz 4 V**p-p (**–2 V** to **+2 V**) sine wave input signal and observe the output of your circuit. Comment on the results.

Questions

Q1.a) What would happen to v_O, if **R_S = 1 kΩ** is replaced by a **100 Ω** resistor or a **10 kΩ** resistor in the circuit built for step **1**? Why?
a) What is the usage of **R_S = 1 kΩ** in step-**1** of this experiment?

Q2. You observed a clipping distortion at the output in step **1.3**. Which specification in the **LM741** datasheet can help you predict the voltage level at the onset of clipping distortion? How?

Q3. What are the advantages of using operational amplifiers in circuit design?