Toronto Metropolitan University
Department of Electrical, Computer, & Biomedical Engineering
Faculty of Engineering & Architectural Science

ELE 302
Laboratory #1

Operational Amplifier Circuit Configurations

1.0 INTRODUCTION:

Note: This lab will be completed in two 3-hr lab sessions. Please submit Prelab assignments and results from Step 1 to Step 6 of the lab procedures to your TAs at the end of the first 3-hr lab session. Please submit results from Step 7 to Step 11 of the lab procedures and answers to post-lab questions to your TAs at the end of the second 3-hr lab session.

This experiment examines the behavior of a general-purpose operational amplifier, µA741, as a circuit-building component. In addition, it investigates the mechanism of negative-feedback applied around the Operational Amplifier (Op-Amp). The characteristics of the two basic Op-Amp circuit configurations (inverting & non-inverting) are also investigated. **Figure 1.0a** shows the physical appearance of the µA741 Op-Amp. The Op-Amp is contained in an 8-pin integrated circuit package. The package contains 3 unused pins (pin 1, 5, and 8), two power pins (pin 4 and 7), 2 input pins (pin 2 and 3) and 1 output pin (pin 6).
The equivalent circuit model of the Op-Amp contained in the 8-pin package is shown in **Figure 1.0b**. As shown, there is a 2 MΩ input resistance between pin 2 and pin 3. The output of the Op-Amp (pin 6) is driven by a voltage-controlled voltage source. The controlling voltage for the source, $v_d(t)$, is the difference between the voltage applied to pin 3 and the voltage applied to pin 2. Note that the power pins (pin 4 and 7) provide the energy required by the voltage-controlled voltage source and are not directly shown in the model. Finally, **Figure 1.0c** shows the symbolic representation of the same Op-Amp circuit with the pin numbers from the physical packages labelled on their corresponding signals.

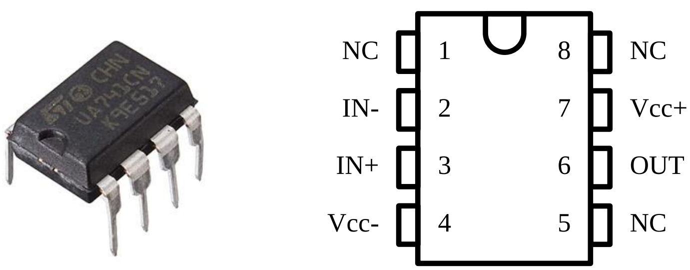


Figure 1.0a: Op-Amp Package View

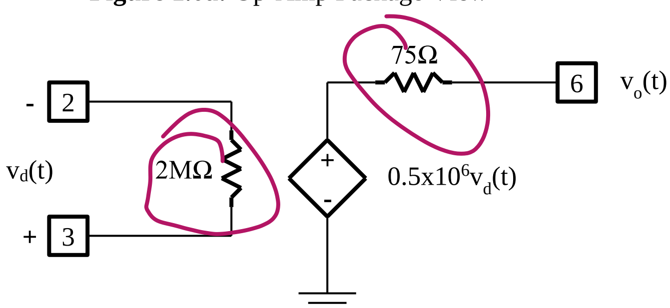


Figure 1.0b: Op-Amp Equivalent Circuit View

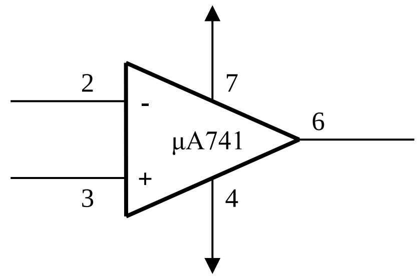


Figure 1.0c: Op-Amp Symbolic View

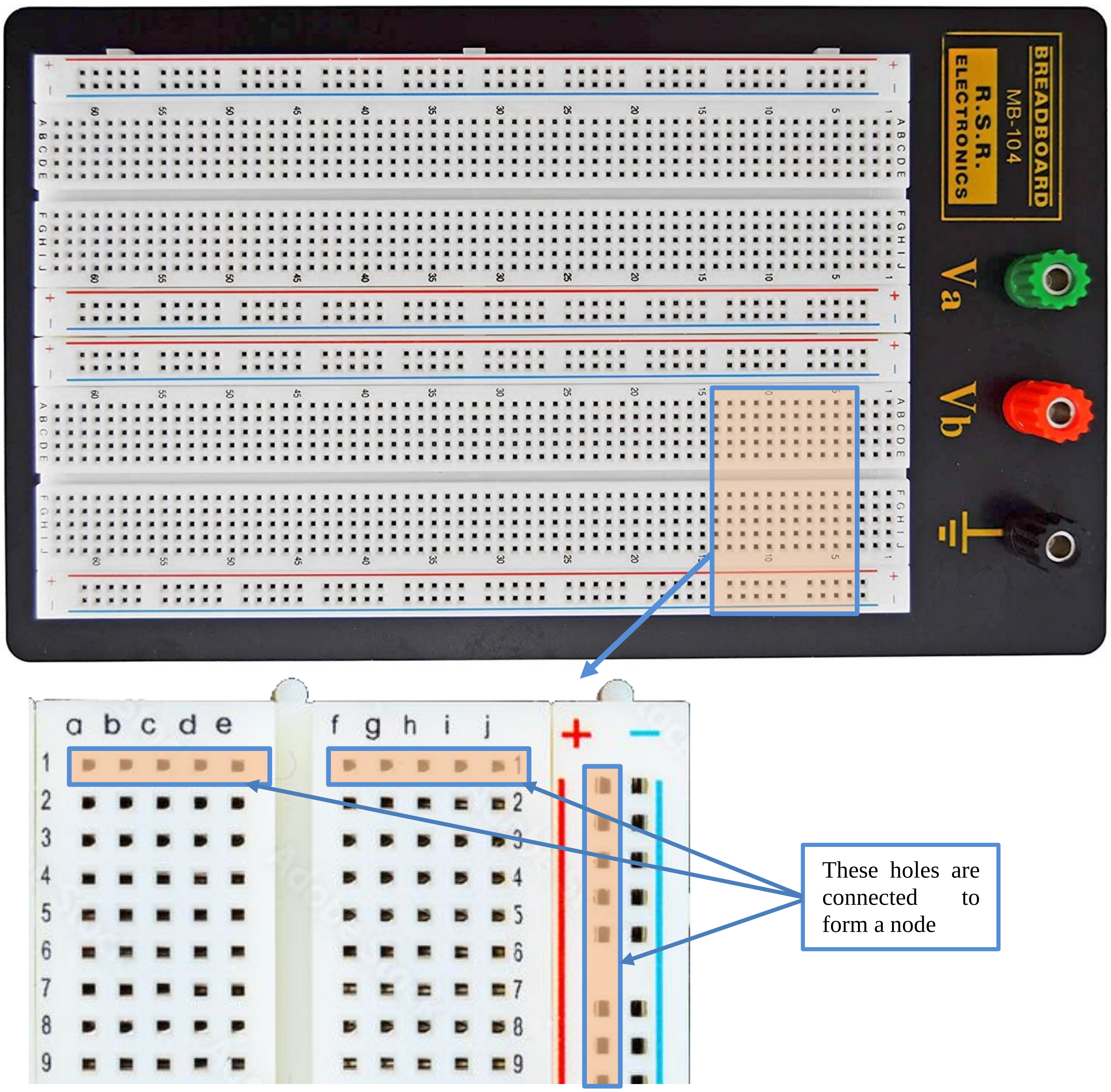


Figure 1.0d: Breadboard

In this experiment, you will use the μA741 Op-Amp from your lab kit along with the following circuit components and instruments to investigate the behavior of Op-Amp circuits. The remainder of this section provides a brief review of the main circuit components and instruments that will be used in this lab. Please also refer to you ELE202 lab manual for more detailed descriptions.

1.1 Breadboard

A breadboard is a convenient device for prototyping electrical and electronic circuits in a form that can be easily tested and changed. **Figure 1.0d** illustrates a typical breadboard, and its layout consists of a rectangular matrix of insertion points (or holes) which can be used to plug resistors, capacitors, inductors, Integrated Chips (ICs), wires, connectors, etc. Each group of five holes of the breadboard are connected inside the board by a metal strip to form a single five-hole node. Different components at a given node are connected by pushing in a corresponding end of each component into holes connected to the same node. The horizontal lines of nodes (shown as blue and red lines) are common nodes that are all connected., i.e., all the holes (nodes) across the red (or blue) line are connected from one end to the other, and these are typically used for power supply connections or for those nodes to which many components are connected. A jumper wire can also be used to combine two nodes into one. The three binding posts (**RED**, **BLACK** and **GREEN**) are typically used for DC or AC power supply connections, from which jumper wires are used to connect to the respective horizontal common nodes. _Refer to the Breadboarding instructions, FAQs and video tutorials on the course website (D2L) for proper use of the breadboard to implement and test circuits_

1.2 Standard Resistor Color-Code

COLOR		VALUE of RESISTANCE		
Black			0	$10^0 = 1$
Brown		1	1	$10^1 = 10$
Red		2	2	$10^2 = 100$
Orange		3	3	$10^3 = 1{,}000$
Yellow		4	4	$10^4 = 10{,}000$
Green		5	5	$10^5 = 100{,}000$
Blue		6	6	$10^6 = 1{,}000{,}000$
Violet		7	7	$10^7 = 10{,}000{,}000$
Grey		8	8	$10^8 = 100{,}000{,}000$
White		9	9	$10^9 = 1{,}000{,}000{,}000$
		1st band	***2nd band***	***3rd band***

COLOR		TOLERANCE
Red		2 %
Gold		5 %
Silver		10 %
None		20 %
		4th band

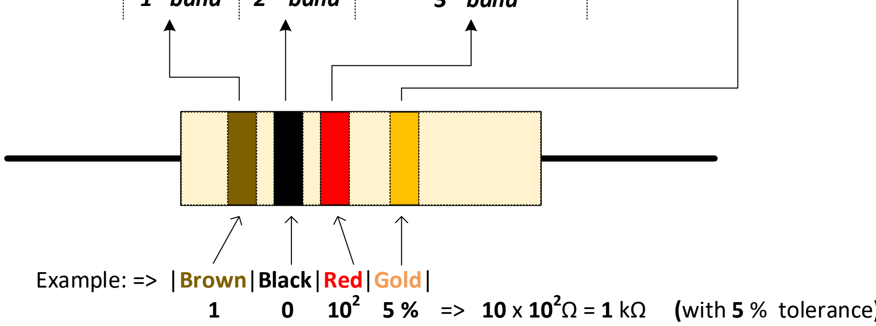


Figure 1.0e: Standard Resistor Color-Code Chart

The resistance of a resistor determines how much current it will carry when a given voltage is applied across it. A resistor is a passive electrical component to create specific resistance in the flow of electric current, commonly found in almost all electrical networks and circuits. The unit of measure is Ohms (Ω), which is the resistance of a conductor such that a constant current of *one* Ampere in it produces a voltage across it of *one* Volt between its ends. Hence, the current (**I**) *through* a resistor (**R**) is proportional to the voltage (**V**) *across* the resistor, and this is represented by Ohm's Law: **I** = **V**/**R**. This expression can be used as V = IR to calculate the voltage across the resistor, or as R = V/I to find the resistance value.
Manufacturers specify a resistor's *nominal* resistance value and its *tolerance* using color-codes on the resistor. The *tolerance* means that the **actual value** of the resistor is guaranteed to be within this amount of its *nominal* value. For example, a resistor with its nominal value labelled as 1kΩ +/- 5% means that the manufacturer guarantees the actual resistance will be between 950Ω and 1050Ω. The standard resistor Color-Codes Chart is illustrated in **Figure 1.0e**.

1.3 DC Power Supply (PS)

Active electronic circuits require a power supply providing electrical energy as the driving electromotive force (EMF) to operate the circuit. The power supply can be a battery, a DC supply operating from the AC power line, or some other source such as a solar source, fuel cell, generator or thermoelectric element. A DC Power Supply (PS) is an instrument or device that supplies DC voltage and current to a circuit, and used for the lab experiments in this course. The one used for this lab is **Keysight Model EDU36311A** as shown in **Figure 1.0f**. *Refer to the Power Supply user manual, related FAQs and video tutorials on the course website (D2L) for proper setup and operations.* This Power Supply accommodates ***triple*** DC power supply sources, and each has a "*floating*" ground ("-" terminal), meaning it is not internally connected to each other or any other instruments. Hence, each power supply source can be used as an ***independent*** DC input source.

Figure 1.0f: Keysight Power Supply

1.4 The Function Generator

Function generator is an instrument that is capable of producing a variety of voltage signals that vary with time. Common functions include the ***sine-wave*** (sinusoid), the ***square-wave*** (alternates between two voltages) and the ***triangular-wave*** (linearly ramps between two voltages) over a wide range of frequencies. The frequency generator used in the lab is **Keysight Model EDU33211A** shown in **Figure 1.0g**. *Prior to this lab exercise, students are required to familiarize with the basic setup and operations of the Function Generator by reviewing its User Manual, related FAQs and video tutorials on the course website (D2L).*
The AC signal waveform that is output from the function generator can be used as the input signal to different circuits in a variety of applications. This AC signal can be easily and intuitively configured using some basic functions on the instrument:

- Waveform type: selections of Sine, Square or Triangular (Ramp) are most common.
- Frequency: controls the frequency value which can be set in units of Hz (one cycle per second), KHz or MHz.
- Amplitude: controls the waveform amplitude, as Peak-Voltage (**V_P**) or Peak-to-Peak Voltage (**V_{P-P}**).
- DC Offset: adds a DC offset voltage (with respect to the “ground” reference) to the generated AC signal.
- Frequency Sweep: controls the ability to automatically vary (sweep) the frequency of the generated AC signal between a minimum and maximum value.

Figure 1.0g: Keysight Function Generator

1.5 The Oscilloscope

Oscilloscope is often regarded by engineers as the most useful of the various electronic instruments to measure and display a variety of AC signals as plots of ***input voltage*** versus ***time***. Oscilloscopes vary widely depending on the manufacturer and model but the basic operation remains the same. Most oscilloscopes will have two input channels, normally labelled either as 1-2 or A-B, allowing two input voltage signals for ***simultaneous*** comparison and analysis. A digital storage oscilloscope, **Keysight Model DSOX1202G** shown in **Figure 1.0e** is used in the lab. *Prior to this lab exercise, students are required to familiarize with the basic setup and operations of the Oscilloscope by reviewing its User Manual, related FAQs and video tutorials on the course website (D2L).*
Unlike their analog counterparts, digital oscilloscopes work by digitizing the input signal at a very high rate. Because the signal waveform is acquired as series of digital data points over time, a digital oscilloscope can internally process the signal and auto-measure its amplitude, frequency, period, rise time and fall time. In addition, a digital oscilloscope may have a number of built-in mathematical functions and can perform Fast Fourier Transforms (FFT) in addition to capturing and storing the display for direct printing or retrieval using a USB storage device. Notwithstanding, all oscilloscopes share certain ***basic features***, the typical controls for which should be found on the oscilloscope instrument:

- Input Voltage Channels: there are two (2) input channels, CH1 (Yellow) and CH2 (Green). The same colored and numbered function key turns channel ON or OFF when that specific channel is selected to be controlled. Input voltage signal on a channel can be coupled as: direct – “**DC**” **coupling**” (default setting) or through an internal blocking capacitor – “**AC**” **coupling**” which removes any DC information present in the time-varying input signal.

- Vertical Sensitivity (volts/div): the amplification applied for each input channel to control the amount of its signal to be displayed per division, vertically along the y-axis.
- Horizontal Time Base (time/div): controls the time it takes to sweep the screen to capture the amount of waveform cycle(s) of the signal to display along the x-axis. The higher the number the more compact the signal will look by capturing more of the waveform cycles across the screen.
- Trigger Source: selects the source to trigger the sweep, either an "INT - Internal source" (CH1 or CH2) or the "EXT - external source". The trigger function is an important setup variable as it synchronizes the horizontal sweep to produce a stable waveform on the display. The most common choice is the use of INT source, with the waveform signal on CH1 used as the primary trigger reference. The mode for the trigger point can be set to AUTO or in the "normal" mode on positive slope trigger with the level set to 0 volts, ensuring it will trigger the scope at the start of every cycle.
- Position Knob: allows for relative positioning of each CH1 and CH2 input waveforms over the vertical plane of the display.

In addition to the above basic controls, the Keysight Oscilloscope allows measurement of different values of the signal waveform such as peak or peak-to-peak voltages, rms voltage, phase, period, frequency, etc., from convenient use of ***cursors***. Like in the MultiSIM simulator, there are ***two vertical*** and ***two horizontal*** cursor lines that can be moved and positioned on the displayed waveform to make ***differential*** measurements. For example, if the vertical cursors lines are used, the oscilloscope will display the ***time difference*** between them. On the other hand, if the horizontal cursor lines are used, the oscilloscope will display the ***voltage difference*** between them.

Figure 1.0e: Keysight Oscilloscope

2.0 OBJECTIVES:

- To be familiar with the µA741 Op-Amp terminal connections, and to recognize the need for utilizing two dc-power supplies.
- To measure the voltage-transfer characteristics of the Op-Amp.
- To demonstrate the effects of applying negative feedback (around the Op-Amp) on the overall voltage-transfer characteristics of circuits.
- To demonstrate the basic properties of the inverting and non-inverting Op-Amp circuit configurations.

3.0 REQUIRED LAB EQUIPMENT & PARTS:

- DC Power Supply (PS), Function Generator (FG) and Oscilloscope.
- ELE202 Lab Kit and ELE302 Lab Kit: various components, breadboard, wires and jumpers.

4.0 PRE-LAB ASSIGNMENT (3 marks with 1 mark for each step):

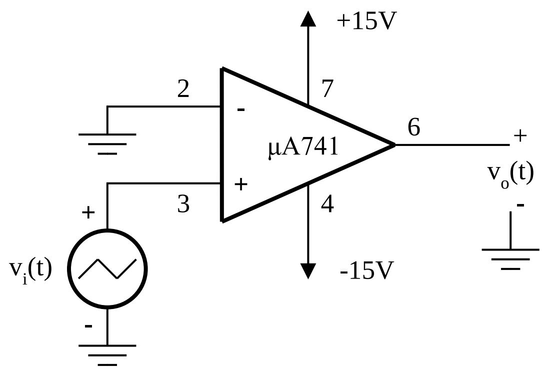
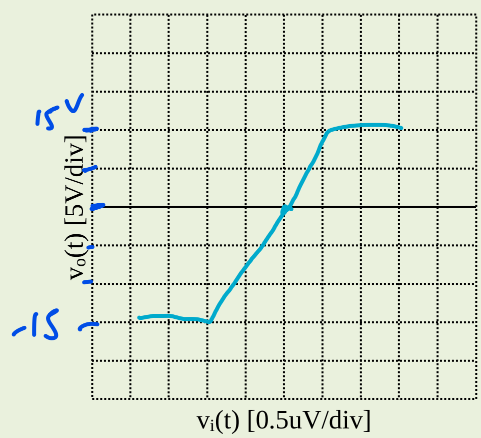


Figure 2.0: Op-Amp without Feedback

(a) Step 1: The circuit in **Figure 2.0** shows the pin identification for the µA741 Op-Amp and the connections of the two dc-power supplies that are required for its operation. In particular, pin (2) is connected to the common ground (COM), while a triangular wave, voltage $v_i(t)$, is applied to pin (3), use the **Graph 1.0a** to show how the resulting voltage-transfer characteristics, [$v_o(t)$ vs $v_i(t)$], would look like, given that the output saturation voltages of the Op-Amp are ±15V and the equivalent-circuit model of the Op-Amp is shown in **Figure 1.0b**.

Pre-Lab workspace



Graph 1.0a

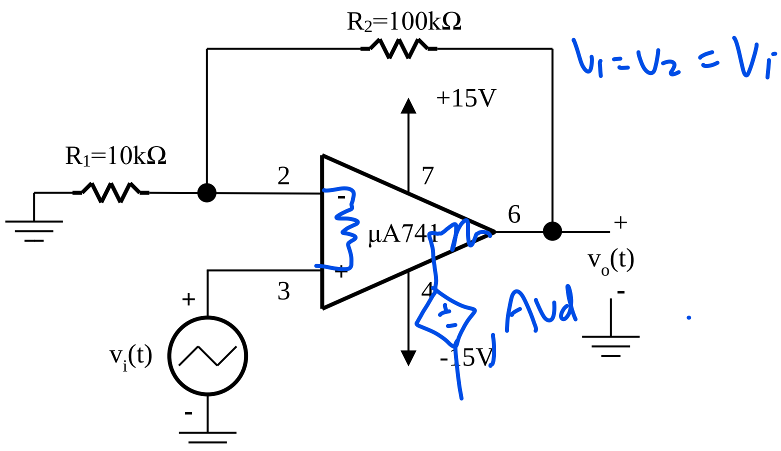


Figure 3.0: Non-Inverting Configuration

(b) Step 2: Assume that the circuit shown in **Figure 3.0** is working properly:

i) Use the equivalent-circuit model of the ideal Op-Amp to find the voltage gain, $A_v = v_o(t) / v_i(t)$, of the amplifier circuit.

Pre-Lab workspace (show your analysis here)

Non-inverting

$$V_o = v_i\left(1+\frac{R_f}{R_i}\right)$$

$$A_v = \frac{V_o(t)}{V_i(t)}$$

$$= \frac{\cancel{V_i}\left(1+\frac{R_f}{R_i}\right)}{\cancel{V_i}}$$

$$= 1 + \frac{100k}{10k}$$

$$A_v = 11$$

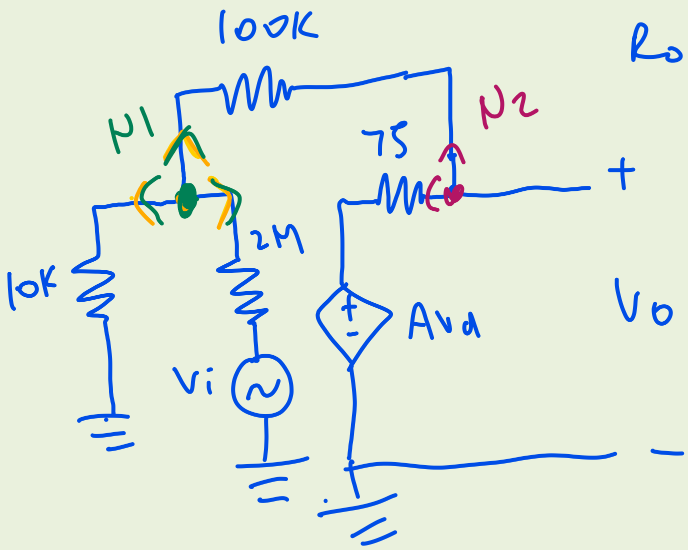
ii) Use the equivalent-circuit model of the μA741 shown in **Figure 1.0b** instead to find A_v.

Pre-Lab workspace (show your analysis here)

	ideal	calc
R_i	∞	2 M
R_o	0	75

$A_v = \frac{V_o}{V_i}$

$A = 0.5\times10^6$



$\frac{V_o - V_1}{\cancel{100K}} + \frac{V_o - AV_d}{\cancel{75\Omega}} = 0$

$V_o - V_1 + 1333.33V_o - 1333.33AV_d$

$0 = 1334V_o - V_1 - 1333.33A(V_i - V_1)$

$0 = 1334V_o - 1333AV_i - V_1 + 1333AV_1$

$0 = \frac{V_1 - 0}{10K} + \frac{V_1 - V_o}{100K} + \frac{V_1 - V_i}{2M}$

$= V_1\left(\frac{1}{\cancel{10K}} + \frac{1}{\cancel{100K}} + \frac{V_1}{\cancel{2M}}\right) + \frac{V_o}{\cancel{100K}} - \frac{V_i}{\cancel{2M}}$

$0 = V_1(200 + 20 + 1) + 20V_o - V_i$

$V_i = 221V_1 + 20V_o$

$0 = 1334V_o - 1333(0.5\times10^6)(221V_1 + 20V_o) - V_1 + 1333(0.5\times10^6)V_1$

$= 1334V_o - 6.67\times10^8(221V_1 + 20V_o) - V_1 + 6.67\times10^8V_1$

$= 1334V_o - 1.473\times10^{11}V_1 + 1.333\times10^{10}V_o - V_1 + 6.67\times10^8V_1$

$= V_o(1334 + 1.333\times10^{10}) + V_1(-1.473\times10^{11} + 6.67\times10^8)$

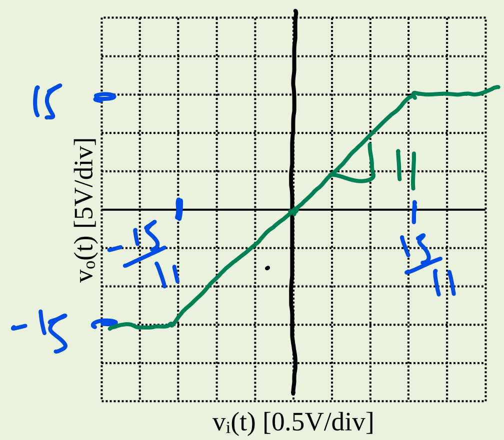
$1.46633\times10^{11}V_1 = 1.333\times10^{10}V_o$

$\frac{1}{0.09} = \frac{V_o}{V_1}$

$A = 11$

iii) Use **Graph 1.0b** to plot the voltage transfer characteristics, given that the output saturation voltages of the Op-Amp are ±15V.

Pre-Lab workspace



Graph 1.0b

$V_o = 11 V_i$

Max when:

$15 = 11 V_i$

$\frac{15}{11} = V_i$

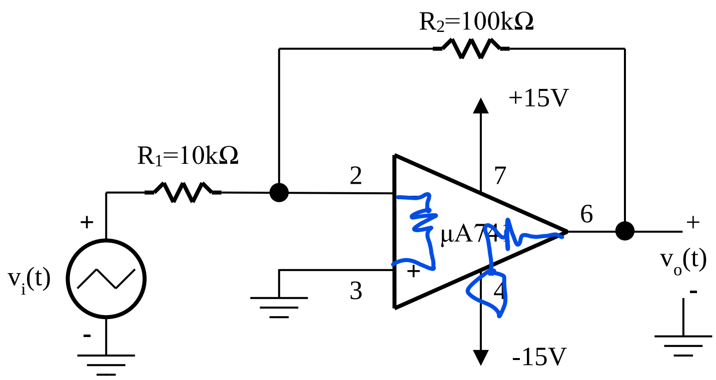


Figure 4.0: Inverting Configuration

(c) Step 3: Assume that the circuit in **Figure 4.0** is working properly.

i) Use the equivalent-circuit model of the ideal Op-Amp instead to determine the values for A_V.

Pre-Lab workspace (show your analysis here)

Inverting:

$$V_o = -\frac{R_f}{R_i} V_i$$

$$A = \frac{V_o(t)}{V_i(t)} = -\frac{R_f}{R_i} = -\frac{100}{10}$$

$$A = -10$$

ii) What is the value of the voltage at node (2)?

Pre-Lab workspace (show your analysis here)

Inverting neg feed back, $V_1 = V_2 = 0$.

5.0 IN-LAB IMPEMENTATION & MEASUREMENTS (5 marks in total):

(a) Step 1: Connect the circuit as shown in **Figure 2.0**. Connect pin (2) of the Op-Amp to common ground. Use a function generator to provide the input voltage, $v_i(t)$, by connecting the function generator output to pin (3) of the Op-Amp. Connect Channel (2) of the oscilloscope to display the output voltage $v_o(t)$, which is between pin (6) and the common ground. Connect Channel (1) of the oscilloscope to display the input voltage $v_i(t)$ provided by the function generator.

Press "AutoScale" to capture Channel (1) and Channel (2) signals on the oscilloscope display.

Adjust this initial display by setting the oscilloscope "Vertical Controls" as follows:

- Channel (1): Coupling => DC, V/div => 2V.
- Channel (2): Coupling => DC, V/div => 5V.

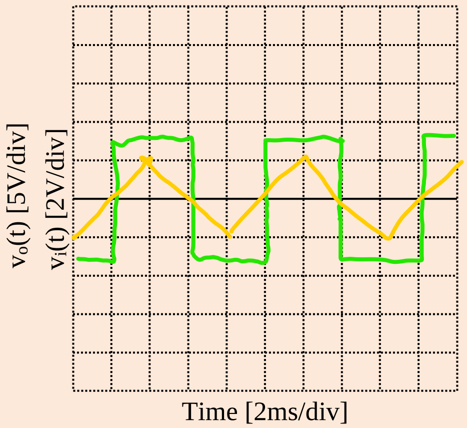
Setting the oscilloscope "Trigger" and "Horizontal Controls" as follows:

- Time base: Trigger Source -> Channel (1), Trigger Type => Edge, Time/div => 2ms.

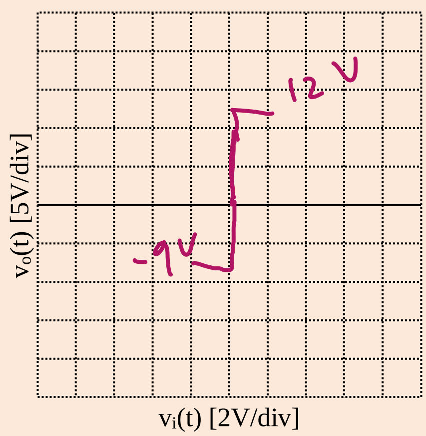
(b) Step 2: Set the controls of the function generator to provide triangular input signal $v_i(t)$ of 8V (peak-to-peak) at a frequency of 50Hz. Use **Graph 2.0** to plot $v_i(t)$ & $v_o(t)$ as functions of time.
Function Generator: Press Waveform → More → **Triangle**, Amplitude → **4 V_{PP}**, Frequency → **50 Hz**

(c) Step 3: Change the oscilloscope setting to the XY-display mode. The oscilloscope are now displaying: [$v_o(t)$ vs $v_i(t)$], which is called the voltage-transfer characteristics of the Op-Amp Circuit. Use **Graph 3.0** to plot this voltage-transfer [$v_o(t)$ vs $v_i(t)$] characteristics of the Op-Amp circuit.

(d) Step 4: Change the values of the positive dc-supply voltage to 12V and the negative dc-supply voltage to 9V. Use **Graph 3.0** to plot the resulting voltage-transfer characteristics, [$v_o(t)$ vs $v_i(t)$].



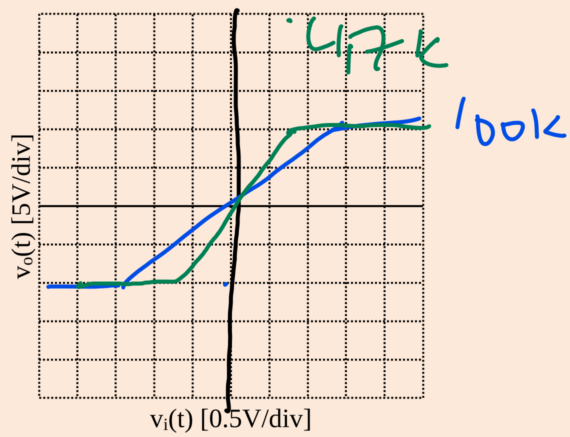
Graph 2.0 (0.5 marks)



Graph 3.0 (0.5 marks)

(e) Step 5: Change the values of both the positive & negative dc-supply voltages to +15V and -15V, respective, and modify your circuit as shown in **Figure 3.0**. Negative feedback is now said to be applied around the Op-Amp, with feedback factor $\beta = R_1/(R_1 + R_2)$, and the circuit is said to operate as a non-inverting amplifier. Plot the resulting voltage-transfer characteristics on **Graph 4.0**. Record feedback factor β in **Table 1.0**. Use your graph to record the Dynamic Range and Voltage Gain also in **Table 1.0**. (The **Dynamic Range** is the linear region of the voltage-transfer characteristics**.)**

(f) Step 6: This concludes the first 3-hr lab session. Please demonstrate Step 1 to Step 5 to your TA and submit your answers to the prelab assignments and the results collected from Step 1 to Step 5 to your TA at the end of the lab session. (1 mark)



Graph 4.0 (0.5 marks)

Table 1.0 (0.5 marks)

Circuit Conditions	Feedback Factor β	Valid Input Range (Dynamic Range) for $v_i(t)$ ΔX	Voltage Gain $[v_o(t)/v_i(t)]$ A
Negative feedback [R_1=10kΩ & R_2=100kΩ]	0.091	2.50	11.1
Negative feedback [R_1= 10kΩ & R_2=47kΩ]	0.175	4.80	5.6
Negative feedback [R_1=inf & R_2=0]	∞	8.20	0.9

(g) Step 7: Replace R_2 with a 47kΩ resistor on the **Figure 3.0** circuit. Use **Graph 4.0** to plot the resulting XY-mode voltage transfer curve. Use your plot to fill-in **Table 1.0**.

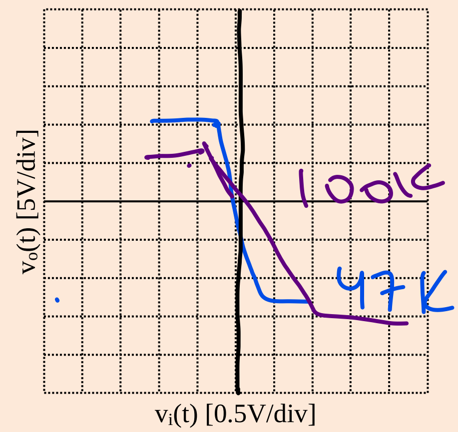
(h) Step 8: By replacing the resistor R_1 with an open-circuit and the resistor R_2 with a short-circuit, your circuit is now said to operate as a voltage follower. Use **Graph 4.0** to plot the resulting voltage-transfer curve, and fill-in the blanks in **Table 1.0**.

(i) Step 9: Modify your circuit as shown in **Figure 4.0**. The circuit is now said to operate as an inverting amplifier. Use **Graph 5.0** to plot the resulting voltage-transfer characteristics and fill-in the blanks in **Table 2.0**.

(j) Step 10: Replace R_2 with a 47kΩ resistor. Use **Graph 5.0** to plot the resulting voltage transfer curve. Use your plot to fill-in the blanks in **Table 2.0**.

(k) Step 11: Demonstrate Step 7 to Step 10 to your TA. (1 mark)

$$\beta = \frac{R_1}{R_1+R_2}$$



Graph 5.0 (0.5 marks)

Table 2.0 (0.5 marks)

Circuit Conditions	Feedback Factor β	Valid Input Range (Dynamic Range) for $v_i(t)$	Voltage Gain [$v_o(t)/v_i(t)$]
Negative feedback [R_1=10kΩ & R_2=100kΩ]	0.091	2.70	-10
Negative feedback [R_1= 10kΩ & R_2=47kΩ]	0.173	5.88	-4.75

6.0 POST-LAB QUESTIONS (2 marks in total, 0.5 marks for each question):

(1) By examining your plots on **Graph 3.0**, answer the following:

a) What are the effects of the dc-supply voltages on the voltage-transfer characteristics?

b) Would the solo Op-amp qualify as a practical amplifier circuit? Comment on your answer.

a) DC V supply controls the peak max/min values of the op amp, as the voltage never passes the max/min supple voltage.

b) I believe that as long as sufficient power is supplied, a solo op amp can be practical

(2) By considering your plots on **Graphs 3.0, 4.0 & 5.0**, answer the following:

a) What does the application of negative feedback (around the Op-amp) have on the amplifier-circuit behavior?

b) Does the application of negative feedback have any effect on the output saturation voltages? Comment on your answer.

a) The negative feedback appears to increase the saturation limit, as seen in the graph, a small amount of V causes the op Amp to saturate immediately. In the

b) Yes, in some capacity. As stated above it changes the rate sat voltage is reached, but it doesn't change the value of the sat voltage.

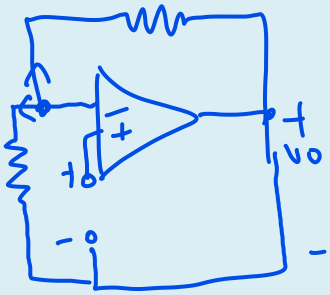
(3) Thevenin Equivalent Input Resistance:

a) Calculate the Thevenin equivalent resistance seen by $v_i(t)$ for the non-inverting configuration shown in **Figure 3.0**.

b) Calculate the Thevenin equivalent resistance seen by $v_i(t)$ for the inverting configuration shown in **Figure 4.0**.

c) Which configuration has higher Thevenin equivalent resistance as seen by $v_i(t)$?

a)



$R_{th} = \frac{V_{th}}{i_{sc}}$ $\quad V_{th} = R_i\, i_2 + V_i$

$= \frac{V_{th}}{V_i} \cdot R_i \quad \frac{V_o - V_i}{R_1 + R_2}$

$V_{th} = \frac{1}{11} V_o - \frac{1}{11} V_{in} + V_{in}$

$= \frac{1}{11} V_o + \frac{10}{11} V_{in}$

$= \frac{1}{11}(28) + \frac{10}{11}(2.475)$

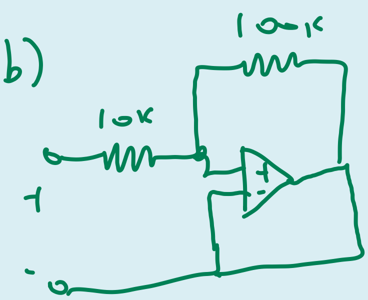
$V_{th} = 4.795\ V$

$R_{th} = \frac{V_{th}}{V_i} \cdot R_i$

$= \frac{4.795}{2.475} \cdot (10k)$

$= 19.4k\Omega$

b)



$\frac{V_a - V_o}{100k} + \frac{V_a - V_{th}}{10k} = 0$

$V_{th} = \frac{28}{100k} \cdot 10k$

$= 2.8\ V$

$R_{th} = \frac{V_{th}}{V_i} (R_i)$

$= \frac{2.8}{2.475} (10k)$

$= 11.3k$

$\therefore$ a) non-invert is higher

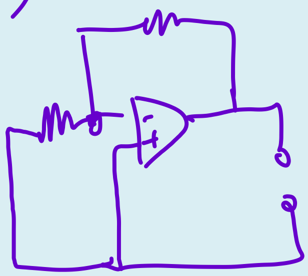
(4) Thevenin Equivalent Output Resistance:

a) Calculate the Thevenin equivalent resistance seen by $v_o(t)$ for the non-inverting configuration shown in Figure 3.0.

b) Calculate the Thevenin equivalent resistance seen by $v_o(t)$ for the inverting configuration shown in Figure 4.0.

c) How does the two equivalent resistances compare?

a)



$$V_{th} = \frac{10}{11} V_o + \frac{10}{11} V_{in}$$

$$= \frac{10}{11}(28) + \frac{10}{11}(2.475)$$

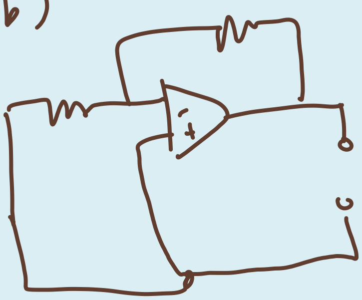
$$V_{th} = 27.7$$

$$R_{th} = \frac{V_{th}}{V_i} R_i$$

$$= \frac{27.7}{2.475}(10k + 100k)$$

$$= 1.231\ M\Omega$$

b)



$$\frac{V_a - V_{th}}{100k} = \frac{V_A - V_i}{10k}$$

$$\frac{V_{th}}{100k} = \frac{V_i}{10k}$$

$$V_{th} = 24.75$$

c) non invert is higher

$$R_{th} = \frac{V_{th}}{V_i}(R)$$

$$= \frac{24.75}{2.475}(10k + 100k)$$

$$= 1.1\ M$$