SCHOOL OF INFORMATION, COMPUTER, AND COMMUNICATION TECHNOLOGY

SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY

THAMMASAT UNIVERSITY

COURSE	: EES 204 Basic Electrical Engineering Lab
	: ECS 204 Basic Electrical Engineering Lab
TIME	: Wednesday, 09:00 – 12:00 (IE2-Section 1)
	: Wednesday, 13:00 – 16:00 (IE2-Section 2)
EXPERIMENT	: 07 Operational Amplifiers
SEMESTER	: 02/2019

I. OBJECTIVE

To study the use of operational amplifier in amplifiers and integrator.

II. BASIC INFORMATION

II.1 Op-Amp 741

1. In instrumentation circuits, the difficulty often arises in determining how a small dc signal (a few millivolts or less) should be amplified to a more useful signal level. A possible solution is the use of an **operational amplifier (op amp)**. Pin details of op-amp 741 are shown in Figure 1.
2. An op-amp is a two-input single-output device. It is a voltage amplifier with high gain, broad bandwidth, high input impedance and low output impedance. The two inputs are called **inverting** (−) and **noninverting** (+), as shown in Figure 1. Op-amps require two power supplies of the same voltage magnitude but opposite polarities. Practical op-amp has a finite open-loop gain and a low pass frequency response.
3. A few external components (resistors and capacitors) can be connected to an op-amp to form a feedback network, which is capable of controlling the actual (closed-loop) **gain** of the amplification.

Caution: **An op-amp must be treated with special care**. They are powerful but can be easily damaged from wrong circuit wiring. In particular it is abusive to apply AC-signal voltages to the input terminals before providing the power supply (or fully powering up the device), or to exceed certain maximum limits. Therefore, for each section of this experiment, follow the following steps.

i. Set up the circuit with all signal sources turned off.
ii. Double-check your connection.
iii. Enable the power supply (i.e. power up the op amp device).
iv. Turn up the signal source.
v. Op-amps can also be damaged if their outputs are shorted to ground or to the power supply. Please also be very careful with wiring.

op-amp

pin detail of op-amp 741

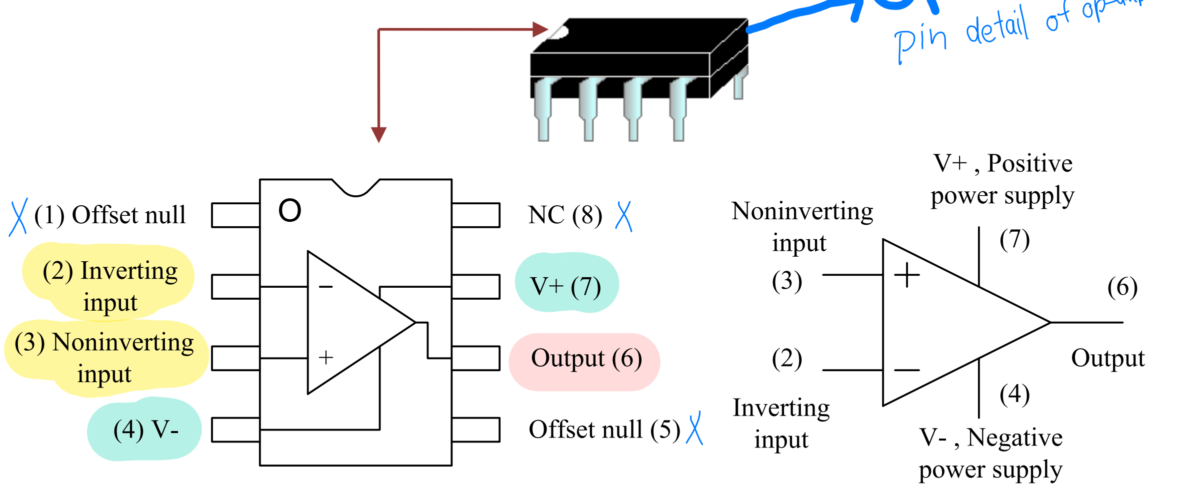
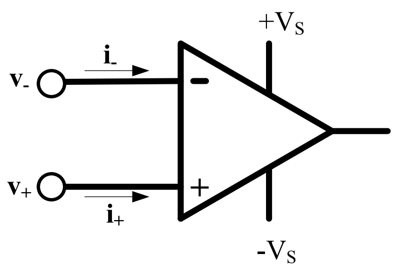


Figure 1: Pin details and configuration of IC 741.

4. Two important characteristics of the ideal op-amp are
   1) The currents into both input terminals are zero:
   $$i_+ = i_- = 0.$$
   2) The voltage across the input terminals is negligibly small:
   $$v_+ \approx v_-.$$

   Remark: Do not assume that $v_+ = v_- = 0$!



II.2 Inverting, Non-Inverting, and Summing Amplifier

1. In **inverting amplifier**, the feedback resistor R_f is connected between the output and the inverting input as shown in Figure 2. The output of the inverting amplifier is

$$v_o = -\frac{R_f}{R_r} v_i$$

Closed-loop gain $= \frac{V_o}{V_i} = -\frac{R_f}{R_r}$ Phase shift 180°
inverting amp.

The minus sign represents a 180° phase shift between the input and the output. The **closed-loop gain** of the inverting amplifier is $\boxed{-(R_f / Rr)}$.

2. Figure 3 shows a circuit of a **noninverting amplifier**. The input signal drives the noninverting input of the op amp. The external resistors R_1 and R_2 form the feedback voltage divider. The output of the noninverting amplifier is

Closed-loop gain $= \frac{V_o}{V_i} = 1 + \frac{R_2}{R_1}$
noninverting amp.

$$v_o = \left(1 + \frac{R_2}{R_1}\right) v_i .$$

The closed-loop gain of the noninverting amplifier is equal to $\boxed{1+(R_2/R_1)}$.

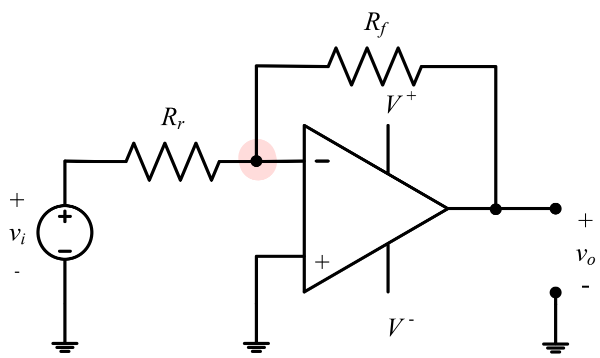


Figure 2: Inverting amplifier.

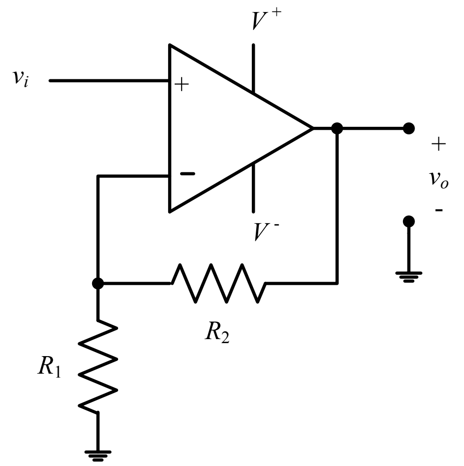


Figure 3: Noninverting amplifier.

3. An example of the **summing amplifier** is shown schematically in Figure 4. The output voltage is the sum of the input voltages with the sign inverted. The output voltage V_0 in Figure 4 is given by

$$V_0 = -\left(\frac{R_F}{R_1} V_1 + \frac{R_F}{R_2} V_2\right)$$

The summer provided in Figure 4 can be modified to provide three or more inputs.

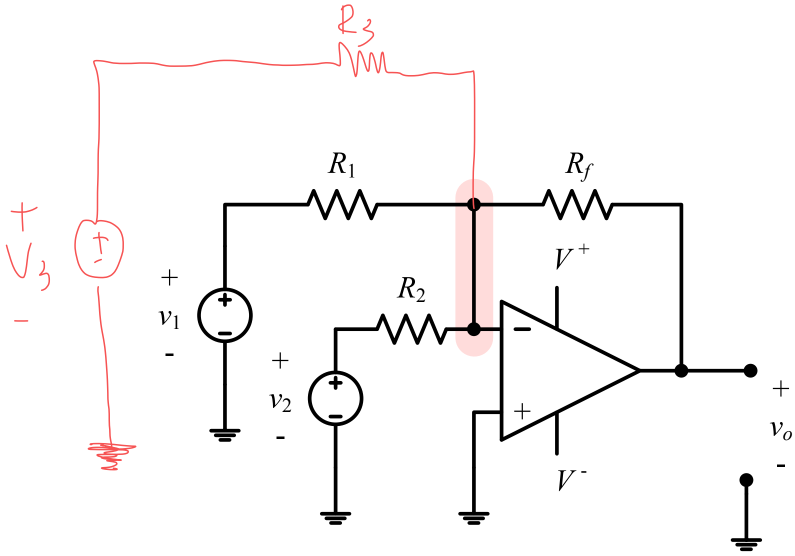


Figure 4**:** Op-amp connected as a summing amplifier.

II.3 Inverting Integrator

1. An inverting integrator is shown in Figure 5. PARTA

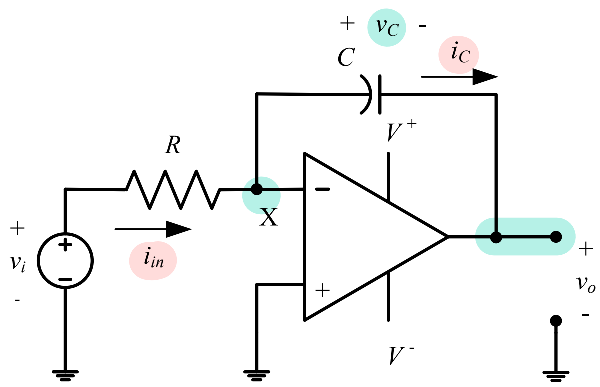


Figure 5: Inverting Integrator

Since no current enters the inverting input of an ideal op-amp, all input currents must flow through the capacitor. Thus, $i_C = i_{in}$. Moreover, for ideal op-amp, we know that the voltage at the two input terminals must be the same. Therefore, $v_X = 0$. This gives $i_{in} = v_i/R$. Recall the relationship between the time-dependent current and voltage for the capacitor:

$$i_C(t) = C\frac{d}{dt}v_C(t).$$

In this case, the current through the capacitor is

$$\boxed{i_C(t) = i_{in}(t) = \frac{v_i(t)}{R}}$$

and the voltage across the capacitor is

$$v_C(t) = v_X - v_o(t) = -v_o(t).$$

Hence,

$$\frac{v_i(t)}{R} = -C\frac{d}{dt}v_o(t).$$

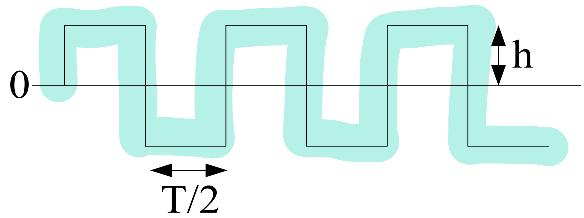
The output voltage then has the following form:

$$v_o(t) = v_o(0) - \frac{1}{RC}\int_0^t v_i(t)\,dt\,,$$

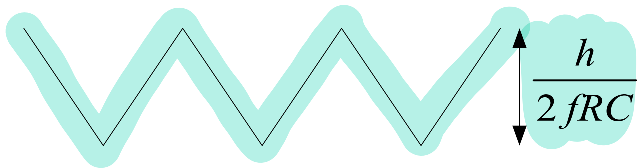
where $v_o(0)$ is the initial value of the output voltage. Note that the change in the output voltage (when considered at two time instants t_1 and t_2) is inversely proportional to the integration of the input voltage.

$$v_o(t_2) - v_o(t_1) = -\frac{1}{RC}\int_{t_1}^{t_2} v_i(t)\,dt\,.$$

Suppose the input voltage waveform v_i is a square wave with frequency f and peak-to-peak voltage $2h$ as shown in Figure 6a.



(a) Input waveform



(b) Output waveform

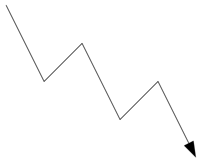
Figure 6: Input and corresponding output waveform to the integrating amplifier in Figure 5.

For half of the period, the input is fixed at $+h$. During this time, the output will decrease. At the end of this interval, the total decrease is

$$\frac{1}{RC}h \times \frac{T}{2} = \frac{h}{2fRC}.$$

Similarly, the output will increase during the time that the input is fixed at $-h$. Because input has equal areas above and below the ground level, the decrease amount is the same as the increase amount and we see a triangular waveform at the output. The peak-to-peak voltage is $h/(2fRC)$ as shown in Figure 6b. In conclusion, **when a square wave drives an op-amp integrator, the output is a triangular wave**.

Remark: For the circuit in Figure 5, an input with nonzero mean (DC offset) can saturate the op-amp. To see this, suppose the range of the square wave input is from -1 to 2 V. Then, during each period of the input, the output will have a $\frac{2}{2fRC}$ decrease and a $\frac{1}{2fRC}$ increase.



Because the amount of decrease is greater, the output will accumulate this difference during each period. It will keep decreasing until it saturates the op amp.

2. The analysis provided earlier is performed in time domain. Alternatively, we can analyze the integrator in Figure 5 in frequency domain via steady-state AC analysis. In particular, suppose the input is sinusoidal with peak V_i and frequency f.

   In AC analysis, we use impedance. The relationship between the current and voltage for the capacitor is

$$V_C = I_C \times Z_C = I_C \times \frac{1}{j\omega C}.$$

   For ideal op-amp, we again have

$$I_C = I_{\text{in}} = \frac{V_i}{R}$$

   and

$$V_C = V_X - V_o = -V_o.$$

   Hence,

$$V_o = -V_C = -I_C \times \frac{1}{j\omega C} = -\left(\frac{V_i}{R}\right) \times \frac{1}{j\omega C}.$$

   Therefore, the gain at frequency f is

$$-\frac{1}{j2\pi fRC}.$$

   In particular, the gain at $f = 0$ is unbounded.

   Recall, from your calculus class, that you can decompose a periodic waveform into a sum of weighted sinusoidal waveforms. If your waveform has a nonzero average, then you have a constant in your sum as well. This constant is the **DC offset**. Our frequency-domain analysis above shows that if the DC offset is nonzero, it will be (theoretically) amplified by an infinite gain! This will saturate the op-amp.

3. In practical circuit, a resistor is usually shunted across the capacitor as shown in Figure 7. In this case,

$$V_C = I_{\text{in}} \times \left(Z_C // R_p\right) = \frac{V_i}{R} \frac{1}{j\omega C + \frac{1}{R_p}} = \frac{V_i}{R} \frac{R_p}{j\omega R_p C + 1}.$$

So,

$$V_o = -V_C = -\frac{V_i}{R} \frac{R_p}{j\omega R_p C + 1}$$

and the gain is

$$\frac{V_o}{V_i} = -\frac{1}{R} \frac{R_p}{j\omega R_p C + 1}.$$

At $f = 0$, the gain is finite.

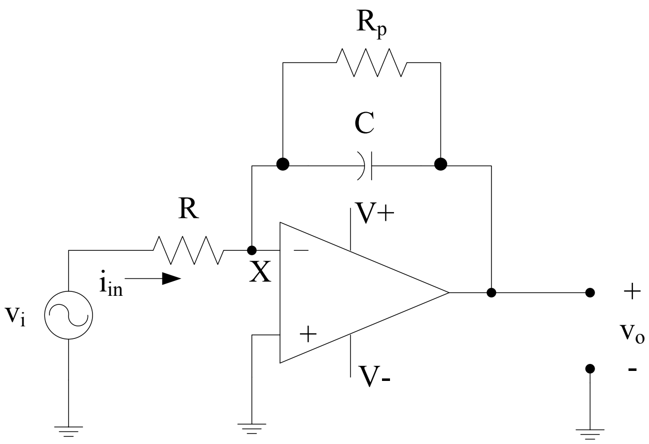


Figure 7: Inverting Integrator with shunt resistor

Large R_p is used so that the overall operation of the circuit is not too different from the original integrating amplifier.

One important effect of adding R_p is that the output will *not* be triangular anymore. You will still observe an output that is very similar to a triangular waveform if the product $R_p C$ is large compared to the half-period time T/2.

It can be shown that if the input is a zero-mean square wave with frequency f and peak-to-peak voltage $2h$ then, the output will be zero-mean waveform with peak-to-peak voltage

$$2h\frac{Rp}{R}\frac{1-r}{1+r},$$

where $r = \exp\left(-\frac{1}{2fR_pC}\right)$.

III. MATERIALS REQUIRED

Power supplies:

± 12V, DC, regulated

Variable 0-15 V

Equipment:

Oscilloscope

Function generator

Multi-meter

Resistors:

two 10-kΩ	one 5-kΩ	one 20-kΩ	one 30-kΩ
one 100-kΩ	one 12-kΩ		

Capacitors:

one 0.001 μF	one 0.01 μF	one 0.047 μF

Semiconductors:

Op amp 741

$$V_0 = -\frac{R_f}{R_r} V_i$$

Pin 7 : +5 means connect red wire + terminal of supply

Pin 4 : -5 means connect black wire - terminal of supply

Pin 4 & 7 use different power supply

IV PROCEDIRE

Part A: Inverting amplifier

$$\text{Gain} = V_o/V_i = -\frac{R_f}{R_r}$$

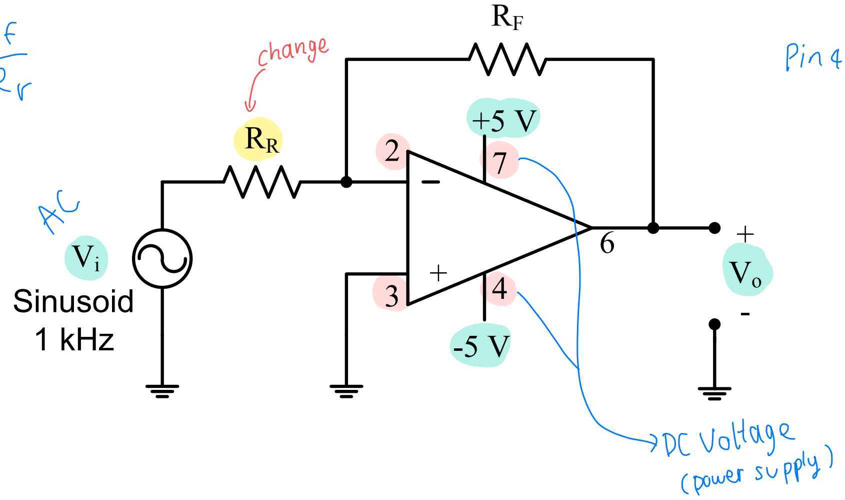


Figure 8: Experimental inverting amplifier.

1. Connect the circuit in Figure 8. Use $R_F = R_R = 10\ k\Omega$. Record the exact values of the resistance in Table 7-1.

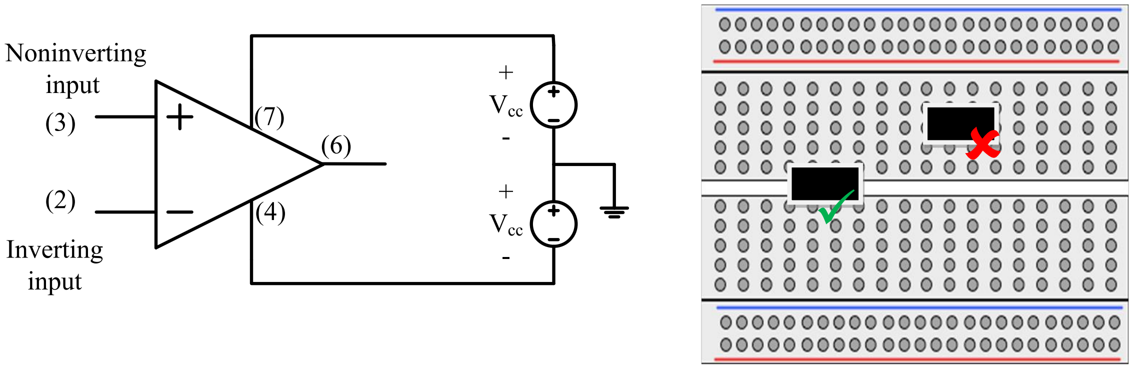
   Caution:

   (a) Do not connect the output (pin 6) of the op-amp directly to the ground.

   (b) Connect ALL the ground nodes together.

   (c) As demonstrated in Figure 9b, plug in op-amp chips so that they straddle the troughs on the proto board. In this way, each pin is connected to a different hole set.

2. The op-amp must be powered by voltage supplies. These supplies are often ignored in op-amp circuit diagrams for the sake of simplicity.
   Figure 9a shows how to power the op-amp with $+V_{cc}$ and $-V_{cc}$.



(a) Powering the op amp

(b) Plugging the 741 chip onto the proto-board

Figure 9: Connecting op-amp 741

Both power supplies in Figure 9a should be set to $V_{cc} = 5$ V which will make $V_7 = +5$ V and $V_4 = -5$ V.

3. Set the sine-wave generator, V_i, to 1 kHz, and then reduce the output of the generator to its smallest value.
4. Connect the Channel 1 of the oscilloscope to the input V_i whilst connect the Channel 2 of the oscillator to the output V_o.
5. Gradually increase the output from signal generator just below the point where the waveform of V_o distorted, i.e., before V_o is no longer a sine wave. Measure the peak-to-peak output voltage and record the value in Table 7-1. This is the **maximum undistorted output signal**.
6. Use the oscilloscope to measure the peak-to-peak voltage of the input signal V_i, and record the results in Table 7-1.
7. Compute and then record the gain of the amplifier (V_o/V_i).
8. Compare the phases of the input and output signal and indicate whether they are in phase or 180° out of phase in Table 7-1.
9. Reduce V_i to its smallest value.
10. Repeat the above procedure by changing the value of R_R to 5 kΩ, 20 kΩ, and 30 kΩ.

Part B: Op-amp Integrator

1. Connect the circuit shown in Figure 10.
2. Read V_{in} and V_{out} of the circuit, by varying the value of C and record the results as listed in Table 7-2.

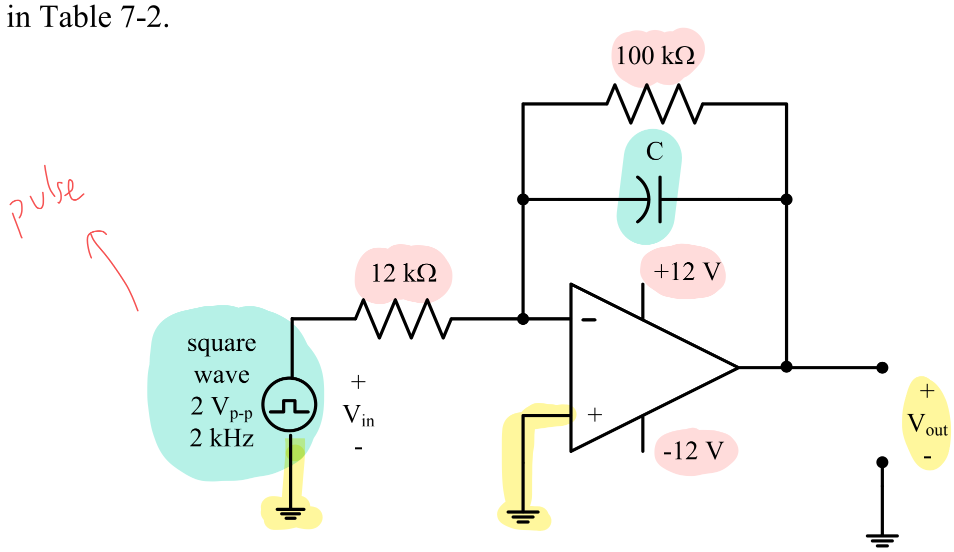


Figure 10: Op amp integrator.

TABLE 7-1: Inverting amplifier

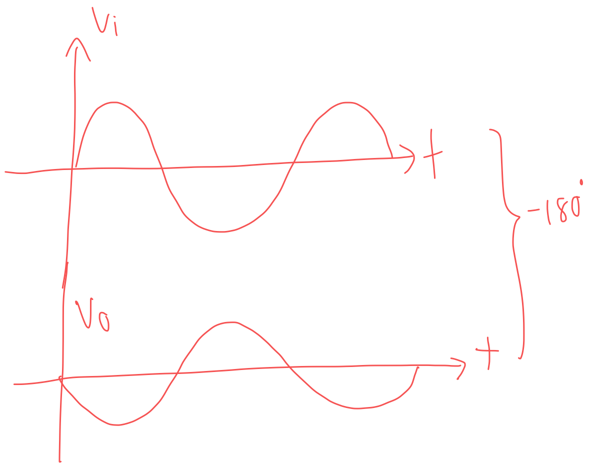
have to find

We don't know V_i (We have to find V_i)
According to V_i we will get V_o out

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

$\varnothing = \frac{d}{D} \times 360$

R_F (Ω)	R_R (Ω)		$V_{p\text{-}p}$		Gain (V_o/V_i)		Phase difference
		Measured	V_i	V_o	$-R_f/R_R$ Calculated	V_o/V_i Measured	
	10 k		4X2 = 8V	3.97+3.97 = 7.94	1	0.993	180
	5 k		2X2 = 4V	3.97+3.97 = 7.94	2	1.985	180
	20 k		8.1X2 = 16.2V	3.97X2 = 7.94	0.5	0.49	180
	30 k		12.2X2 = 24.4	3.97X2 = 7.94	0.333	0.325	180



TA's Signature: ____________________________

30k ; d= 0.5 D= 1
Ø = 180

TABLE 7-2: Op amp integrator

C = 0.047 µF	Waveforms: volts/div = X, time/div = X.
V_{in} = 2 $V_{p\text{-}p}$	
V_{out} = -487.23m $V_{p\text{-}p}$	

C = 0.01 µF	Waveforms: volts/div = ______, time/div = ______.
V_{in} = 2 $V_{p\text{-}p}$	
V_{out} = -2.11 $V_{p\text{-}p}$	

C = 0.001 µF	Waveforms: volts/div = ______, time/div = ______.
V_{in} = 2 $V_{p\text{-}p}$	
V_{out} = -10.04 $V_{p\text{-}p}$	

TA's Signature: ______________________

QUESTIONS

1. The two input terminals of an op amp are labeled as

   (a) high and low. (b) positive and negative.

   (c) active and inactive. (d) inverting and non-inverting.

   (e) differential and non-differential.

2. Find the voltage output of the op amp circuit in Figure 11 when $V_i = 40$ mV.

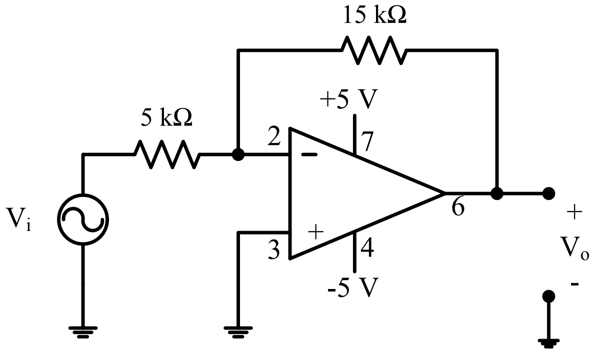
$R_r = 5k\Omega$

$R_f = 15k\Omega$

$Gain = -\frac{R_f}{R_r}$

$= -\frac{15}{5}$

$= -3$



$V_0 = V_i(Gain)$

$= 40(-3) = -120$

Figure 11: An inverting amplifier

(a) -40 mV (b) -60 mV (c) -80 mV (d) -100 mV (e) -120 mV

3. From Figure 11, calculate the current through the feedback resistor.

   (a) 4 μA (b) 6 μA (c) 8 μA (d) 10 μA (e) 12 μA

$i_R = i_C$

$\frac{V_{in}}{R_r} = i_C$

$i_C = \frac{40 \times 10^{-3}}{5 \times 10^3}$

$i_C = 8\mu A$

4. Design a noninverting amplifier in Figure 12 with gain 3.5.

$Gain = 1 + \frac{R_2}{R_1}$

$3.5 = 1 + \frac{R_2}{R_1}$

$\frac{R_2}{R_1} = 2.5$

c $\rightarrow 2.5 = 2.5$ ✓

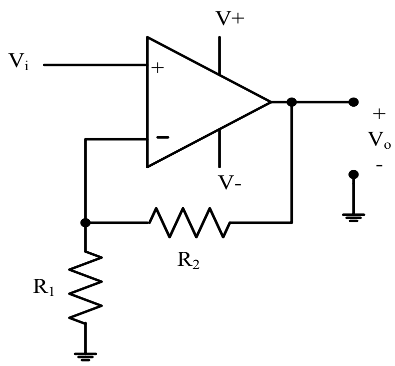


Figure 12: A noninverting amplifier

(a) $R_1 = 2$ kΩ $R_2 = 10$ kΩ → 5 (b) $R_1 = 4$ kΩ $R_2 = 12$ kΩ → 3

(c) $R_1 = 4$ kΩ $R_2 = 10$ kΩ → 2.5 (d) $R_1 = 6$ kΩ $R_2 = 12$ kΩ → 2

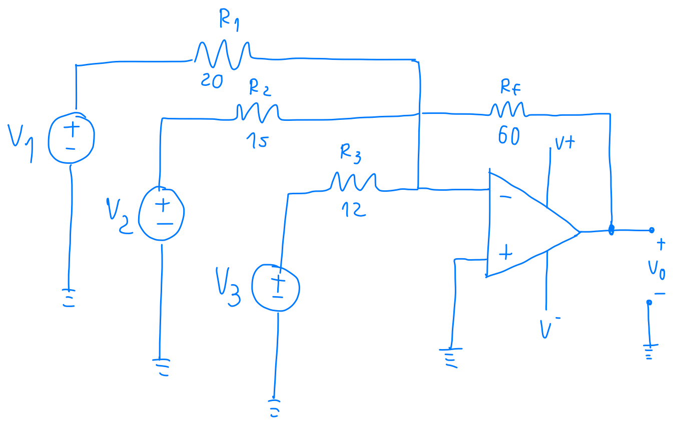
(e) $R_1 = 6$ kΩ $R_2 = 10$ kΩ → $\frac{10}{6}$

$V_0 = \left(1+\frac{R_2}{R_1}\right)V_i = \left(1+\frac{10}{4}\right)4 = \frac{14 \times 4}{4} = 14\ V$

5. From the results in Question 4, find V_o when $V_i = 4$ V.

   (a) 8 V (b) 10 V (c) 12 V (d) 14 V (e) 16 V

6. Design a circuit with an output $V_o = -(3V_1 + 4V_2 + 5V_3)$, where V_1, V_2, and V_3 are the three inputs of the circuit.



$\left.\begin{aligned} \frac{R_f}{R_1} &= 3 \\ \frac{R_f}{R_2} &= 4 \\ \frac{R_f}{R_3} &= 5 \end{aligned}\right\}$ common factor

$R_f = 3 \times 4 \times 5$

$R_f = 60 \rightarrow R_1 = 20$

$R_2 = 15$

$R_3 = 12$