Electronic Circuits

Operational Amplifier

Lecture 3

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Op-Amp Applications

Linear Applications

1- The Inverting Amplifier

2-The Noninverting Amplifier

3- Summing Amplifier

4- Subtractor

5- Voltage Follower

6- Controlled Sources

7- Integrator

8- Differentiator

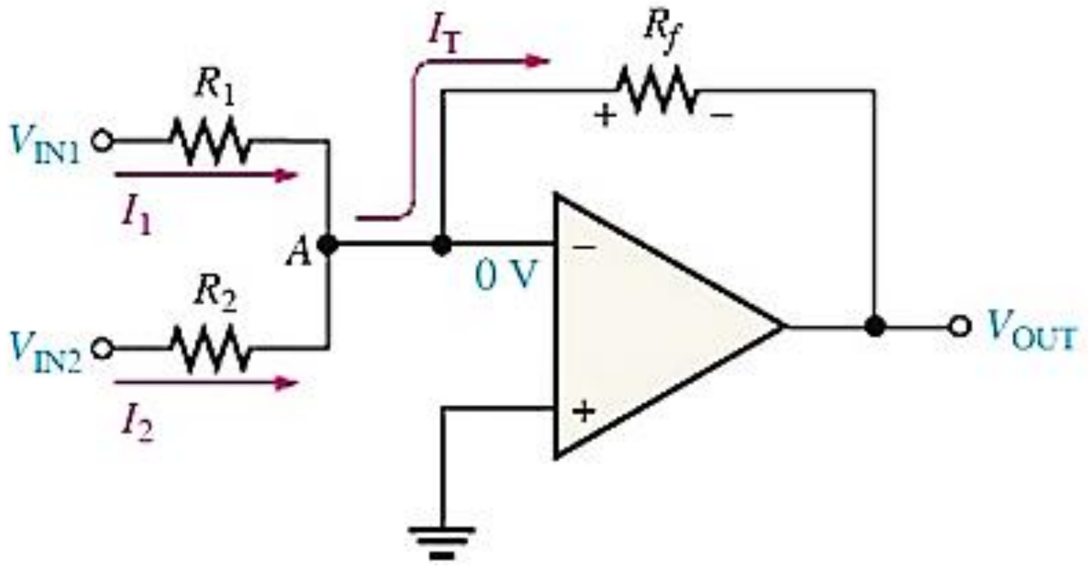
3- Inverting Summing Amplifier

- A **summing amplifier** has two or more inputs; normally all inputs have unity gain. The output is proportional to the negative of the algebraic sum of the inputs.

$$I_T = I_1 + I_2$$

$$V_{OUT} = -I_T R_f$$

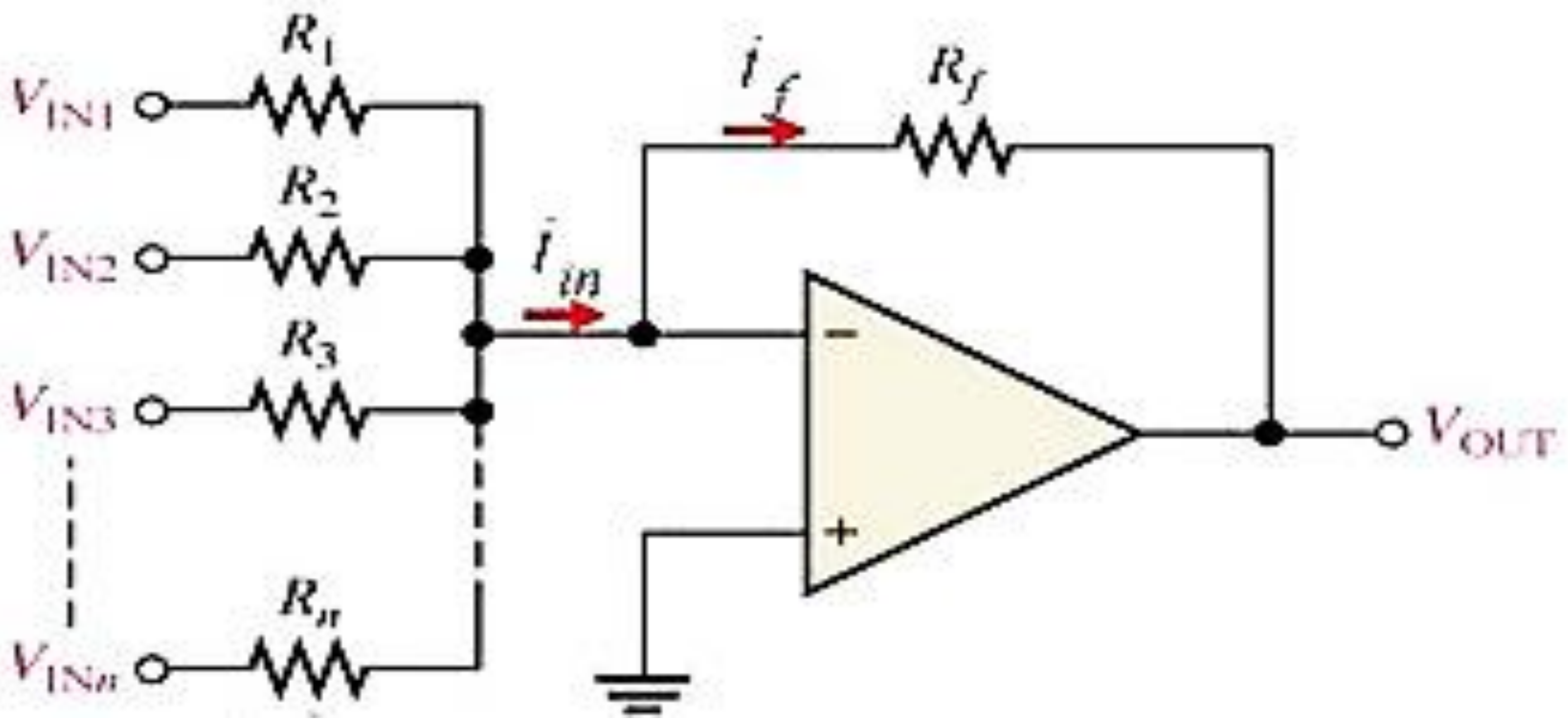
$$V_{OUT} = -(I_1 + I_2)R_f = -\left(\frac{V_{IN1}}{R_1} + \frac{V_{IN2}}{R_2}\right)R_f$$



If all three of the resistors are equal ($R_1 = R_2 = R_f = R$), then

$$V_{OUT} = -\left(\frac{V_{IN1}}{R} + \frac{V_{IN2}}{R}\right)R = -(V_{IN1} + V_{IN2})$$

3- Inverting Summing Amplifier



$$V_{out} = -i_{in}R_f \quad = -\left(V_1\frac{R_f}{R_1} + V_2\frac{R_f}{R_2} + \ldots + V_N\frac{R_f}{R_N}\right)$$

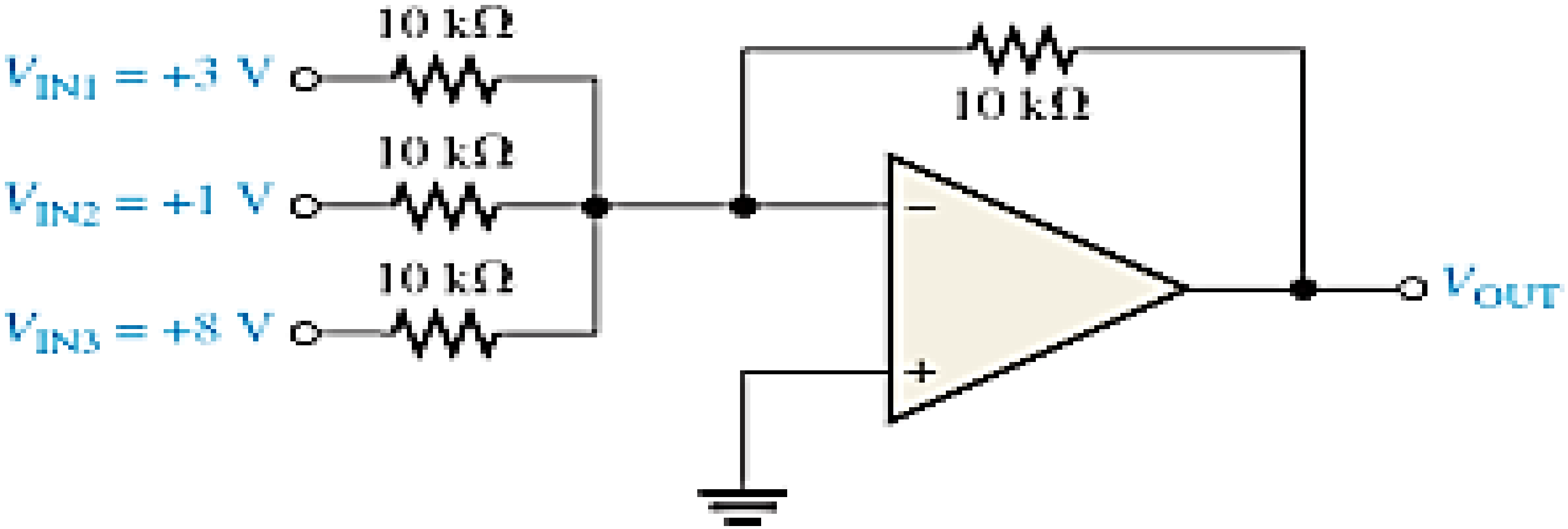
Summing Amplifier Equation

$$-V\text{out} = \frac{R_F}{R_{IN}}\left(V1 + V2 + V3 \ldots .\text{etc}\right)$$

3- Inverting Summing Amplifier examples

Summing Amplifier with Unity Gain: Example

Determine the output voltage in Figure



$$V_{OUT} = -(V_{IN1} + V_{IN2} + V_{IN3}) = -(3\text{ V} + 1\text{ V} + 8\text{ V}) = \mathbf{-12\ V}$$

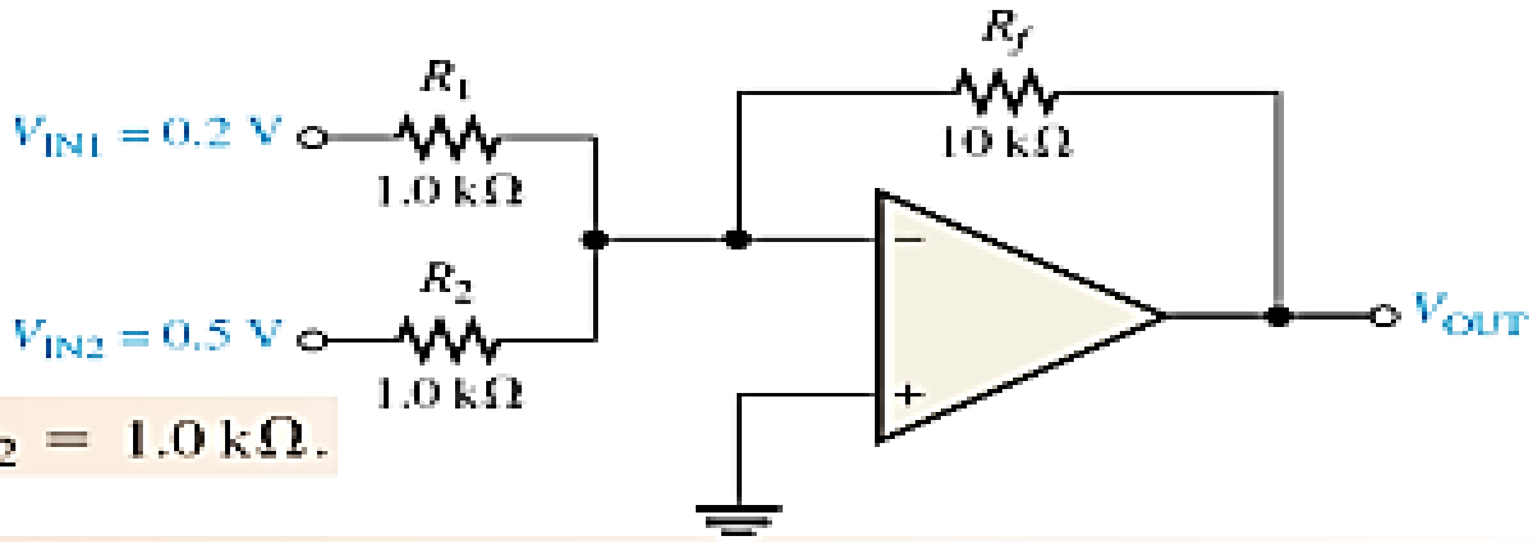
3- Inverting Summing Amplifier examples

Summing Amplifier with Gain Greater Than Unity

■ When R_f is larger than the input resistors, the amplifier has a gain of R_f/R, where R is the value of each equal-value input resistor. The general expression for the output is

$$V_{OUT} = -\frac{R_f}{R}(V_{IN1} + V_{IN2} + \cdots + V_{INn})$$

Example: Determine the output voltage for the summing amplifier shown



$R_f = 10\ \text{k}\Omega$ and $R = R_1 = R_2 = 1.0\ \text{k}\Omega$.

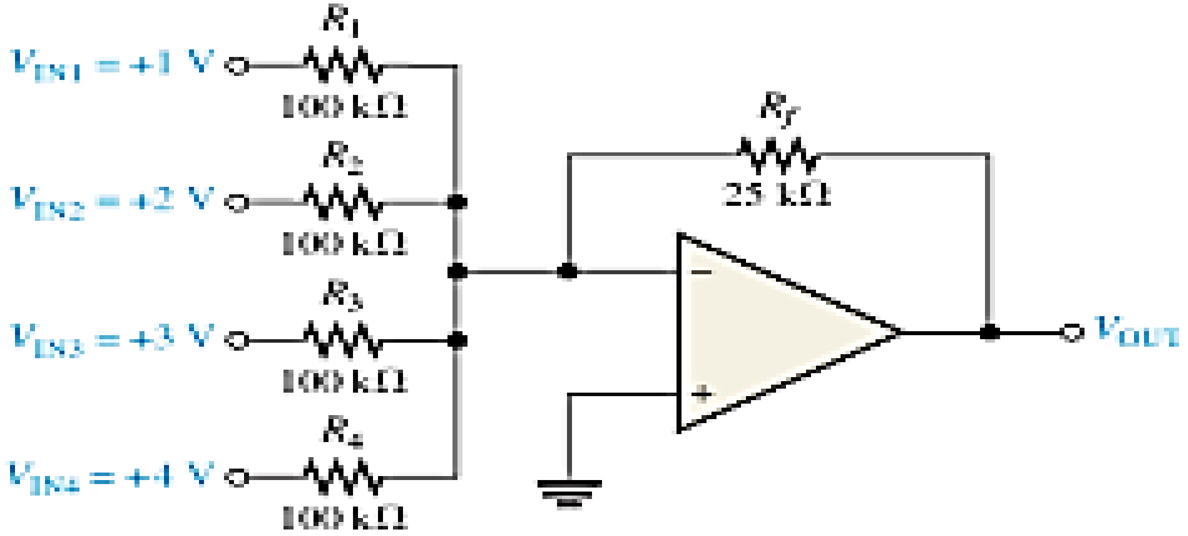
$$\rightarrow \quad V_{OUT} = -\frac{R_f}{R}(V_{IN1} + V_{IN2}) = -\frac{10\ \text{k}\Omega}{1.0\ \text{k}\Omega}(0.2\ \text{V} + 0.5\ \text{V}) = -10(0.7\ \text{V}) = -7\ \text{V}$$

3- Inverting Summing Amplifier examples

Averaging Amplifier

- An **averaging amplifier** is basically a summing amplifier with the gain set to $R_f/R = 1/n$ (n is the number of inputs). The output is the negative average of the inputs.

Example: Show that the amplifier in Figure produces an output whose magnitude is the mathematical average of the input voltages.



$$V_{OUT} = -\frac{R_f}{R}(V_{IN1} + V_{IN2} + V_{IN3} + V_{IN4})$$

$$= -\frac{25\text{ k}\Omega}{100\text{ k}\Omega}(1\text{ V} + 2\text{ V} + 3\text{ V} + 4\text{ V}) = -\frac{1}{4}(10\text{ V}) = -2.5\text{ V}$$

$$V_{IN(avg)} = \frac{1\text{ V} + 2\text{ V} + 3\text{ V} + 4\text{ V}}{4} = \frac{10\text{ V}}{4} = 2.5\text{ V}$$

3- Inverting Summing Amplifier examples

Scaling Adder

■ **A scaling adder** has two or more inputs with each input having a different gain. The output represents the negative *scaled* sum of the inputs. the output voltage can be expressed as

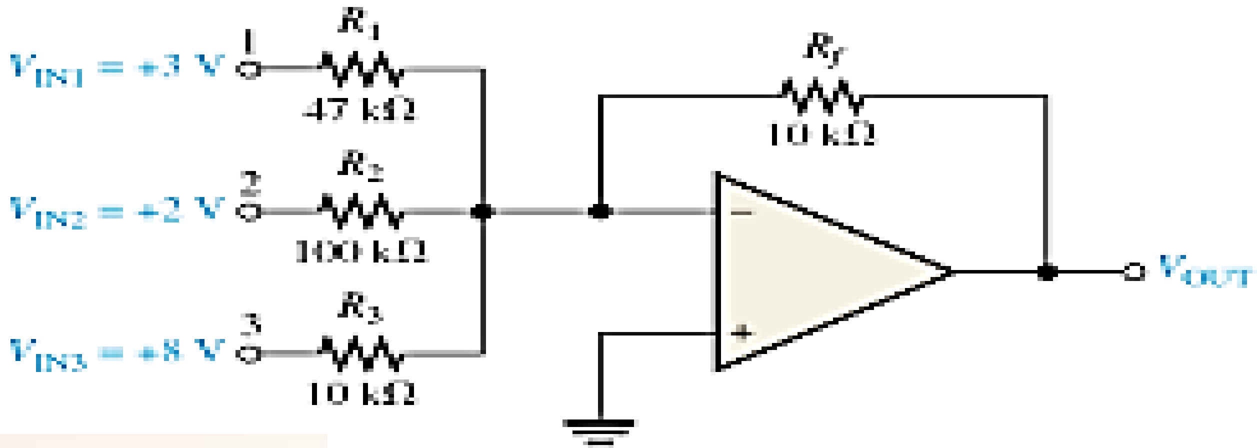
$$V_{OUT} = -\left(\frac{R_f}{R_1}V_{IN1} + \frac{R_f}{R_2}V_{IN2} + \cdots + \frac{R_f}{R_n}V_{INn}\right)$$

Example: Determine the weight of each input voltage for the scaling adder in Figure and find the output voltage.

$$\text{Weight of input 1: } \frac{R_f}{R_1} = \frac{10\ \text{k}\Omega}{47\ \text{k}\Omega} = 0.213$$

$$\text{Weight of input 2: } \frac{R_f}{R_2} = \frac{10\ \text{k}\Omega}{100\ \text{k}\Omega} = 0.100$$

$$\text{Weight of input 3: } \frac{R_f}{R_3} = \frac{10\ \text{k}\Omega}{10\ \text{k}\Omega} = 1.00$$



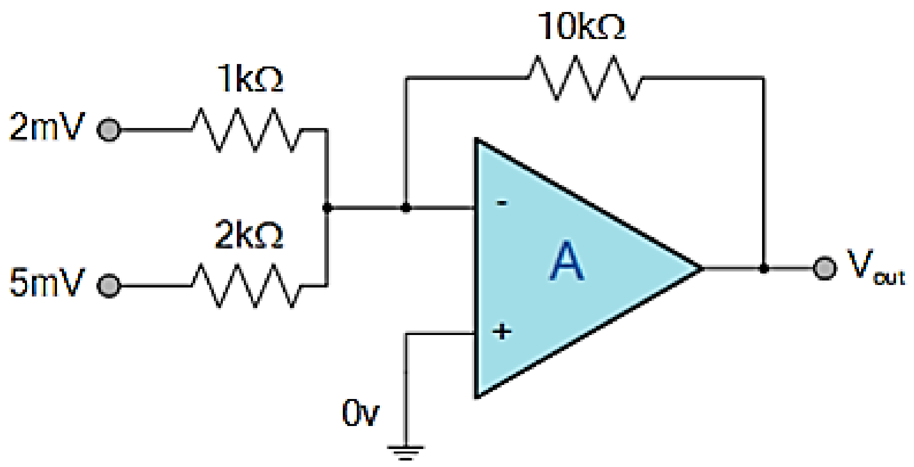
$$V_{OUT} = -\left(\frac{R_f}{R_1}V_{IN1} + \frac{R_f}{R_2}V_{IN2} + \frac{R_f}{R_3}V_{IN3}\right)$$

$$= -[0.213(3\ \text{V}) + 0.100(2\ \text{V}) + 1.00(8\ \text{V})]$$

$$= -(0.639\ \text{V} + 0.2\ \text{V} + 8\ \text{V}) = -8.84\ \text{V}$$

3- Inverting Summing Amplifier examples

Find the output voltage of the following *Summing Amplifier* circuit.



$$\text{Gain (Av)} = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$$

$$A_1 = \frac{10k\Omega}{1k\Omega} = -10$$

$$A_2 = \frac{10k\Omega}{2k\Omega} = -5$$

$$Vout = (A_1 \times V_1) + (A_2 \times V_2)$$

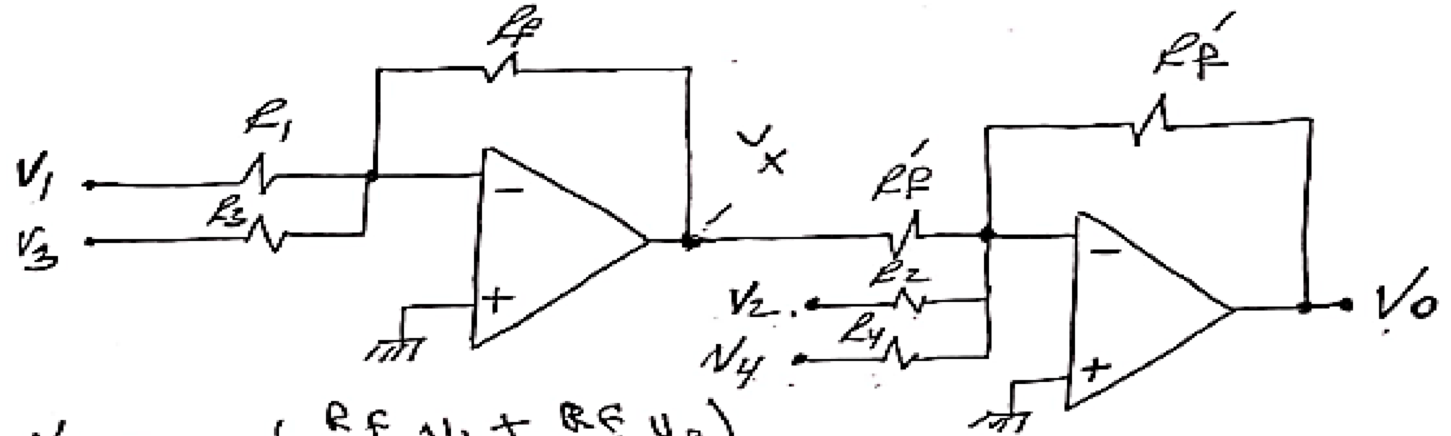
$$Vout = (-10(2mV)) + (-5(5mV)) = -45mV$$

3- Inverting Summing Amplifier examples

ex: design an op. amp. circuit to get :

$$V_o = 2V_1 - 6V_2 + 5V_3 - 3V_4$$

Sol. $$V_o = (2V_1 + 5V_3) - (6V_2 + 3V_4)$$



$$V_x = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_3}V_3\right)$$

$$V_o = \underbrace{\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_3}V_3\right)}_{V_x} - \left(\frac{R_f'}{R_2}V_2 + \frac{R_f'}{R_4}V_4\right)$$

but $V_o = (2V_1 + 5V_3) - (6V_2 + 3V_4)$

3- Inverting Summing Amplifier examples

$$V_o = \underbrace{\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_3} V_3\right)}_{V_x} - \left(\frac{R_f'}{R_2} V_2 + \frac{R_f'}{R_4} V_4\right)$$

but $V_o = (2 V_1 + 5 V_3) - (6 V_2 + 3 V_4)$

then $\frac{R_f}{R_1} = 2$, $\frac{R_f}{R_3} = 5$

, $\frac{R_f'}{R_2} = 6$, $\frac{R_f'}{R_4} = 3$

Let $\boxed{R_f = 10k\Omega} \Rightarrow \boxed{R_1 = 5k\Omega}$, $\boxed{R_3 = 2k\Omega}$

& Let $\boxed{R_f' = 12k\Omega} \Rightarrow \boxed{R_2 = 2k\Omega}$, $\boxed{R_4 = 4k\Omega}$

3- Inverting Summing Amplifier examples

ex: design an op. amp. Circuit :

a) to provide : $V_o = -(4V_1 + V_2 + 0.1\,V_3)$

b) sketch the output signal if :

$V_1 = 2 \sin \omega t$

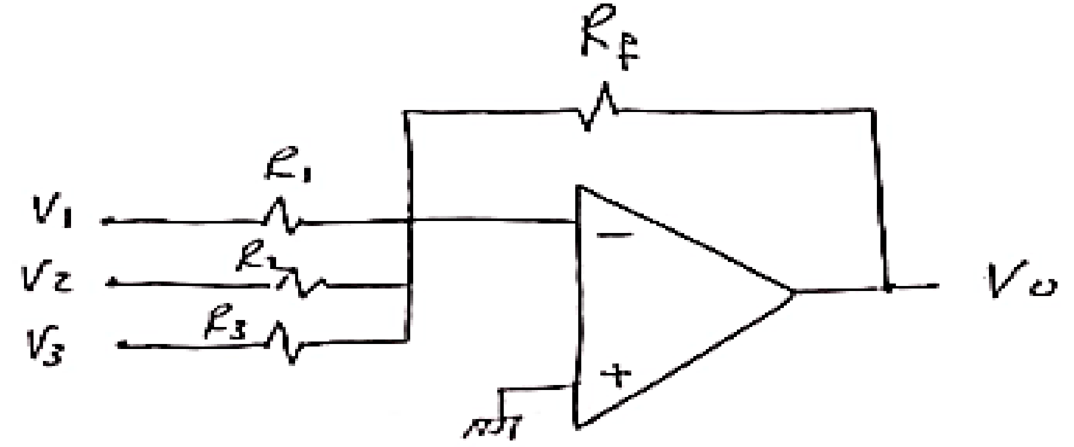
$V_2 = 5\,v$

$V_3 = -100\,v$

3- Inverting Summing Amplifier examples

Solution:

(a)



$$V_o = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right)$$

$$, \quad V_o = -(4 V_1 + V_2 + 0.1 V_3)$$

$$\frac{R_f}{R_1} = 4 , \quad \frac{R_f}{R_2} = 1 , \quad \frac{R_f}{R_3} = 0.1$$

Let $\boxed{R_f = 8 k\Omega}$ $\Rightarrow$ $\boxed{R_1 = 2 k\Omega}$

$, \boxed{R_2 = 8 k\Omega}$

$, \boxed{R_3 = 80 k\Omega}$

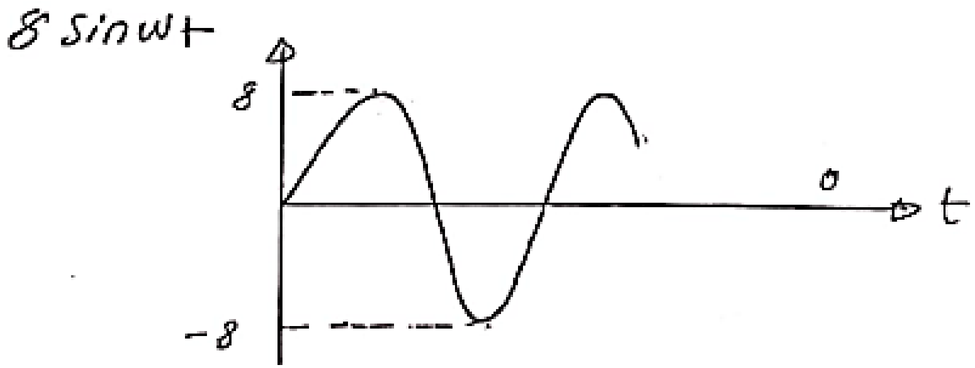
3- Inverting Summing Amplifier examples

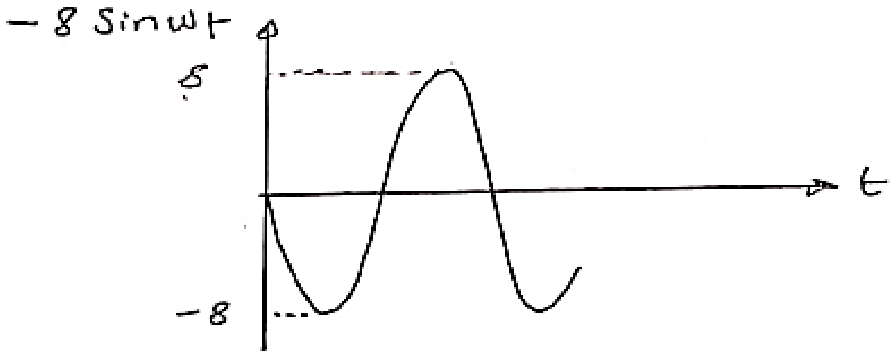
(b) $V_o = -(4V_1 + V_2 + 0.1V_3)$

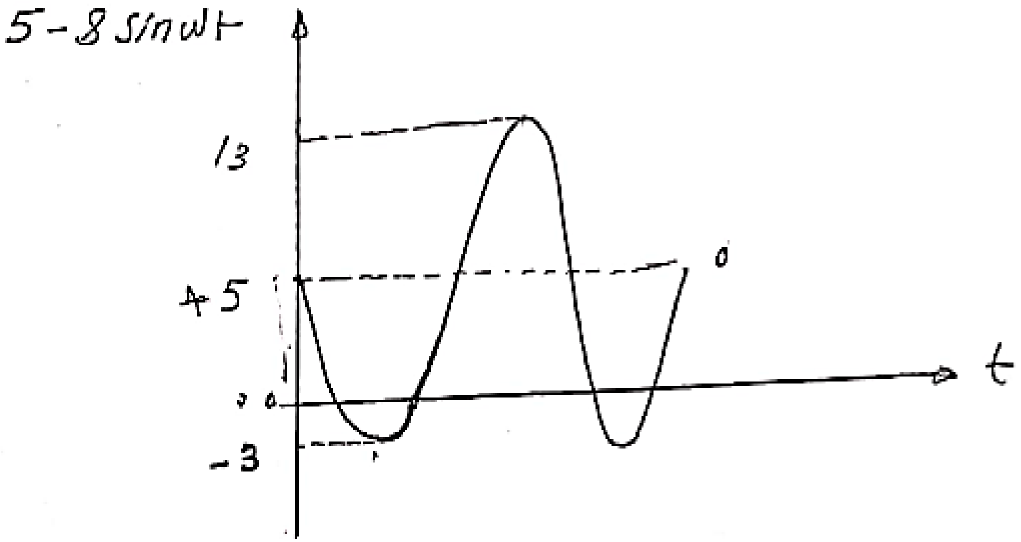
$= -[4(2\sin\omega t) + 5 + 0.1(-100)]$

$= -[8\sin\omega t + 5 - 10]$

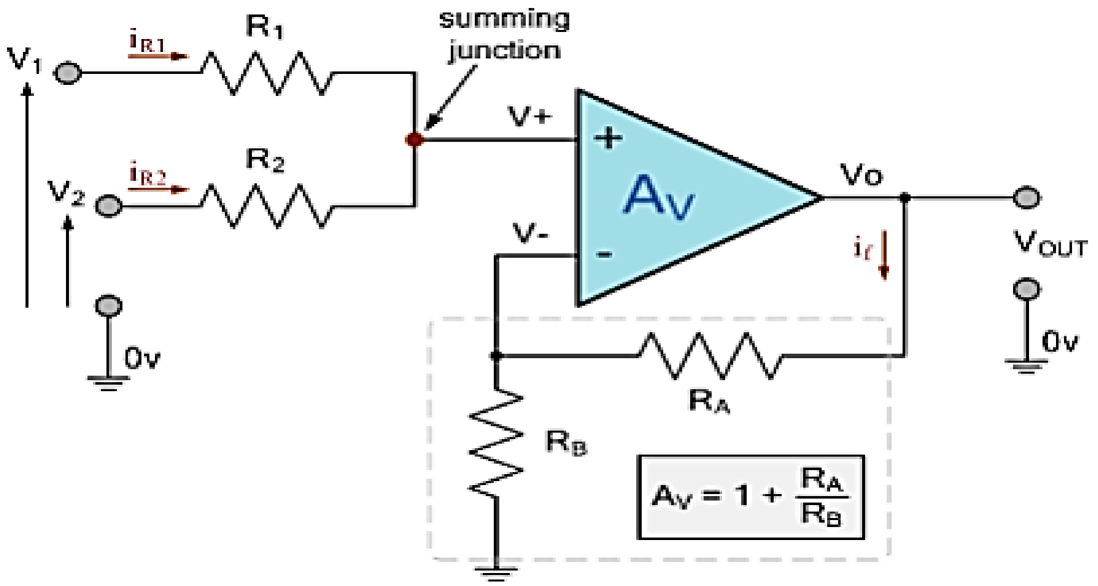
$V_o = \underbrace{5}_{DC} - \underbrace{8\sin\omega t}_{ac}$







3- Non inverting Summing Amplifier



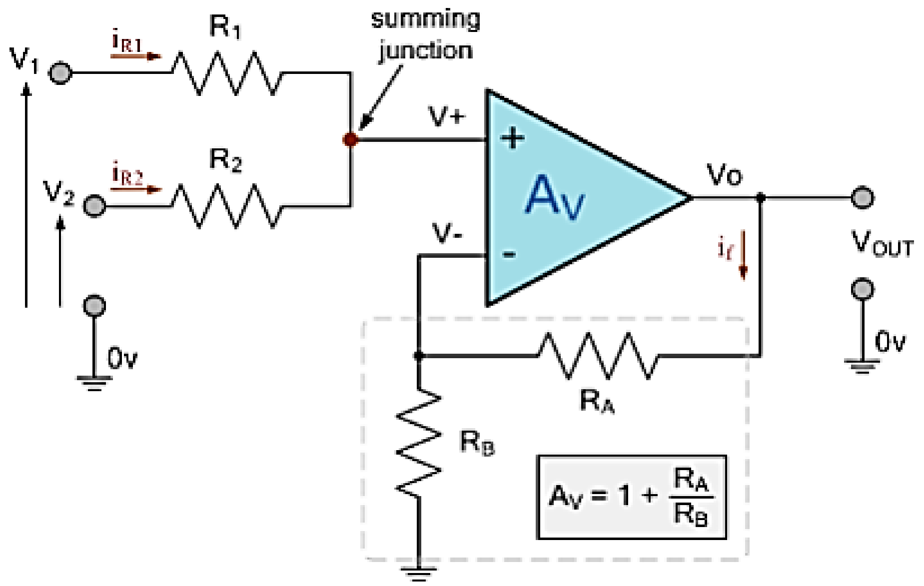
- The advantage of the non-inverting configuration compared to the inverting summing amplifier configuration. Besides the most obvious fact that the op-amps output voltage Vout is in phase with its input, and the output voltage is the weighted sum of all its inputs which themselves are determined by their resistance ratios, the biggest advantage of the non-inverting summing amplifier is that because there is no virtual earth condition across the input terminals, its input impedance is much higher than that of the standard inverting amplifier configuration.

3- Non inverting Summing Amplifier

$$I_{R1} + I_{R2} = 0 \quad (KCL)$$

$$\frac{V_1 - V+}{R_1} + \frac{V_2 - V+}{R_2} = 0$$

$$\therefore \left(\frac{V_1}{R_1} - \frac{V+}{R_1}\right) + \left(\frac{V_2}{R_2} - \frac{V+}{R_2}\right) = 0$$



If we make the two input resistances equal in value, then R1 = R2 = R

$$V+ = \frac{\frac{V_1}{R} + \frac{V_2}{R}}{\frac{1}{R} + \frac{1}{R}} = \frac{\frac{V_1 + V_2}{R}}{\frac{2}{R}}$$

$$\text{Thus} \quad V+ = \frac{V_1 + V_2}{2}$$

3- Non inverting Summing Amplifier

The standard equation for the voltage gain of a non-inverting summing amplifier circuit is given as:

$$A_V = \frac{V_{OUT}}{V_{IN}} = \frac{V_{OUT}}{V+} = 1+\frac{R_A}{R_B}$$

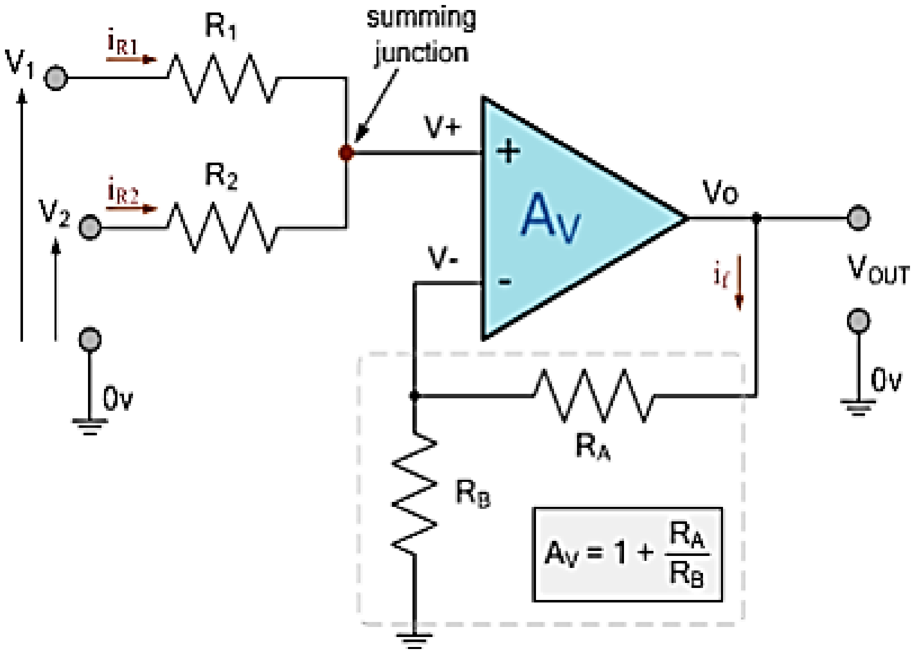
$$\therefore \quad V_{OUT} = \left[1+\frac{R_A}{R_B}\right]V+$$

$$\text{Thus:} \quad V_{OUT} = \left[1+\frac{R_A}{R_B}\right]\frac{V_1+V_2}{2}$$

$$\text{If } \; R_A = R_B$$

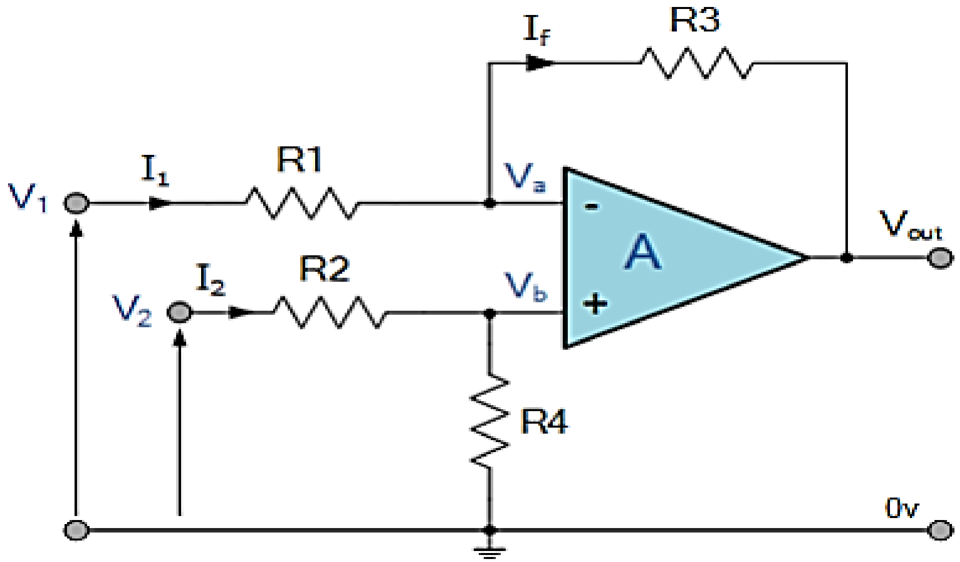
$$V_{OUT} = [1+1]\frac{V_1+V_2}{2} = \cancel{2}\,\frac{V_1+V_2}{\cancel{2}}$$

$$\therefore \; V_{OUT} = V_1 + V_2$$



4- Subtractor

- All op-amps are “Differential Amplifiers” due to their input configuration, But by connecting one voltage signal onto one input terminal and another voltage signal onto the other input terminal the resultant output voltage will be proportional to the “Difference” between the two input voltage signals of V1 and V2.
- Then differential amplifiers amplify the difference between two voltages making this type of operational amplifier circuit a Subtractor unlike a summing amplifier which adds or sums together the input voltages. This type of operational amplifier circuit is commonly known as a Differential Amplifier configuration.



4- Subtractor

$$I_1 = \frac{V_1 - V_a}{R_1}, \quad I_2 = \frac{V_2 - V_b}{R_2}, \quad I_f = \frac{V_a - (V_{out})}{R_3}$$

$$\text{Summing point } V_a = V_b$$

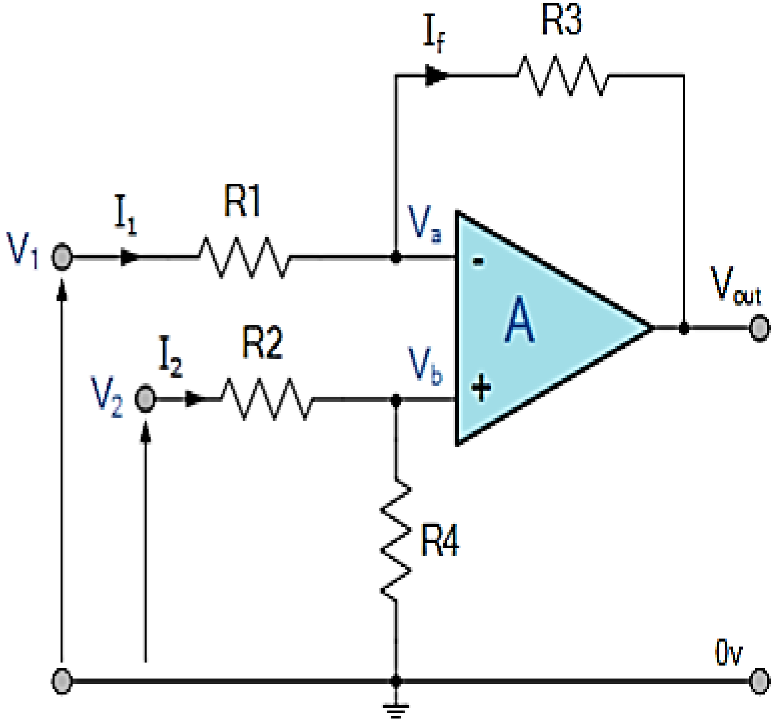
$$\text{and } \quad V_b = V_2\left(\frac{R_4}{R_2 + R_4}\right)$$

$$\text{If } V_2 = 0, \text{ then: } V_{out(a)} = -V_1\left(\frac{R_3}{R_1}\right)$$

$$\text{If } V_1 = 0, \text{ then: } \quad V_{out(b)} = V_2\left(\frac{R_4}{R_2 + R_4}\right)\left(\frac{R_1 + R_3}{R_1}\right)$$

$$V_{out} = -V_{out(a)} + V_{out(b)}$$

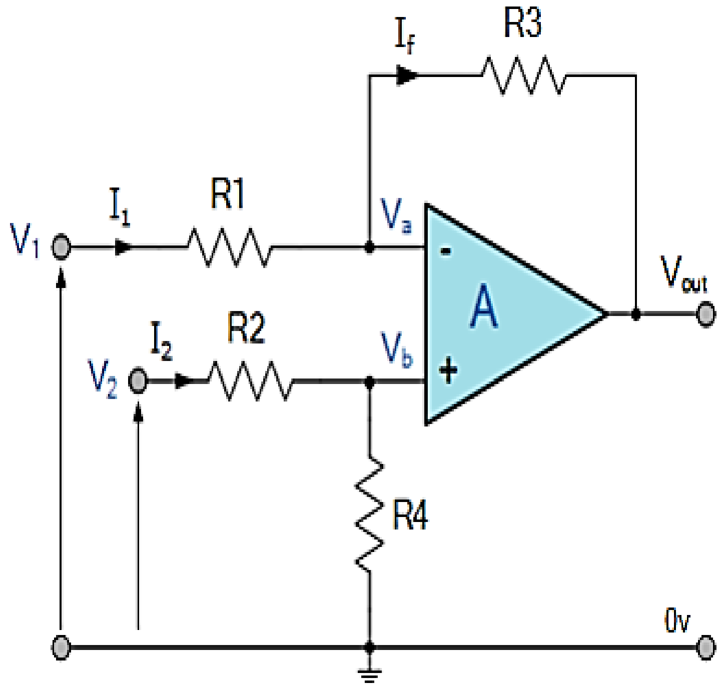
$$\boxed{\therefore \ V_{out} = -V_1\left(\frac{R_3}{R_1}\right) + V_2\left(\frac{R_4}{R_2 + R_4}\right)\left(\frac{R_1 + R_3}{R_1}\right)}$$



4- Subtractor

- When resistors, R1 = R2 and R3 = R4 the above transfer function for the differential amplifier can be simplified to the following expression:
- Differential Amplifier (Subtractor) Equation:

$$V_{OUT} = \frac{R_3}{R_1}\left(V_2 - V_1\right)$$



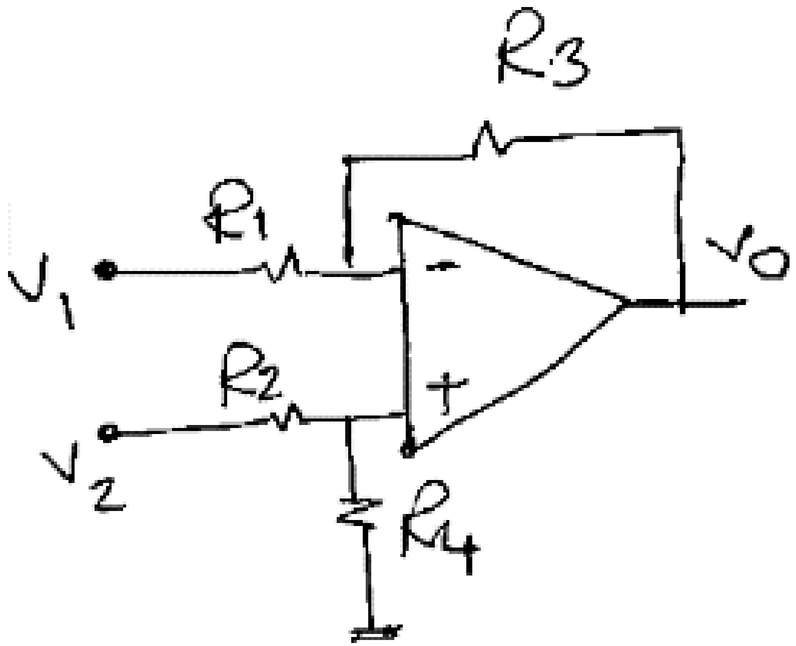
- If all the resistors are all of the same ohmic value, that is: R1 = R2 = R3 = R4 then the circuit will become a Unity Gain Differential Amplifier and the voltage gain of the amplifier will be exactly one or unity. Then the output expression would simply be Vout = V2 – V1

4- Subtractor example

Design an opamp Circuit for

$$V_o = 0.6 V_2 - 0.5 V_1$$

using subtractor



Solution

$$V_o = -V_1 \underbrace{\left(\frac{R_3}{R_1}\right)}_{a_1} + V_2 \underbrace{\left(\frac{R_4}{R_2+R_4}\right)\left(\frac{R_1+R_3}{R_1}\right)}_{a_2}$$

$$V_o = -a_1 V_1 + a_2 V_2$$

$$V_o = -0.5 V_1 + 0.6 V_2$$

4- Subtractor example

$$* \quad a_1 = \frac{R_3}{R_1} = 0.5 = \frac{1}{2}$$

$$\text{let } \boxed{R_1 = 10K\Omega} \Rightarrow \boxed{R_3 = 5K\Omega}$$

$$* \quad a_2 = \left(\frac{R_4}{R_2+R_4}\right)\left(\frac{R_1+R_3}{R_1}\right) = 0.6$$

$$\left(\frac{R_4}{R_2+R_4}\right)\left(1+\cancel{\frac{R_3}{R_1}}^{\,0.5}\right) = \frac{6}{10}$$

$$\frac{R_4}{R_2+R_4} = \frac{\cancel{6}}{10} \times \frac{2}{\cancel{3}} = \frac{4}{10}$$

$$\text{let } \boxed{R_4 = 10K} \Rightarrow \frac{10}{R_2+10} = \frac{4}{10}$$

$$R_2 + 10 = \frac{100}{4} = 25 \Rightarrow \boxed{R_2 = 15K\Omega}$$

Another example using summator

ex: design an op. amp. Circuit for

$$V_o = 0.5 V_1 - 2 V_2$$

$$V_o = \frac{R_f}{R_1} V_1 - \frac{R_f'}{R_2} V_2$$

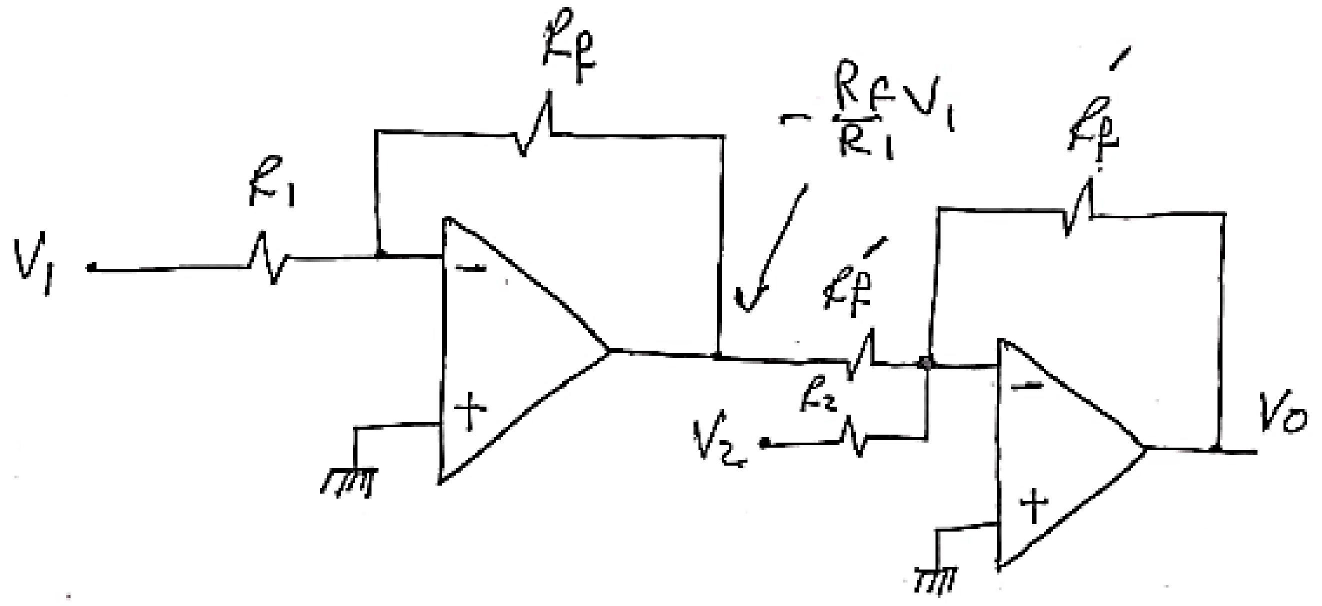
$$= 0.5 V_1 - 2 V_2$$

$$\therefore \frac{R_f}{R_1} = 0.5 \qquad \& \qquad \frac{R_f'}{R_2} = 2$$

Let $R_f = R_f' = 10 k\Omega$

$$\Rightarrow \boxed{R_1 = 20 k\Omega}$$

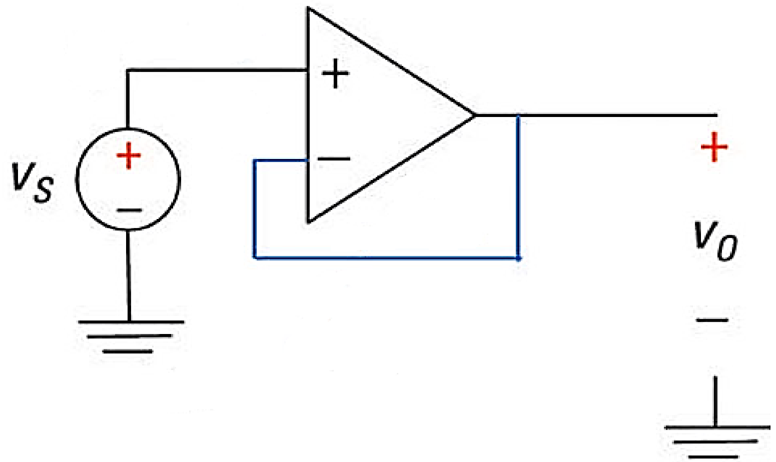
$$\boxed{R_2 = 5 k\Omega}$$



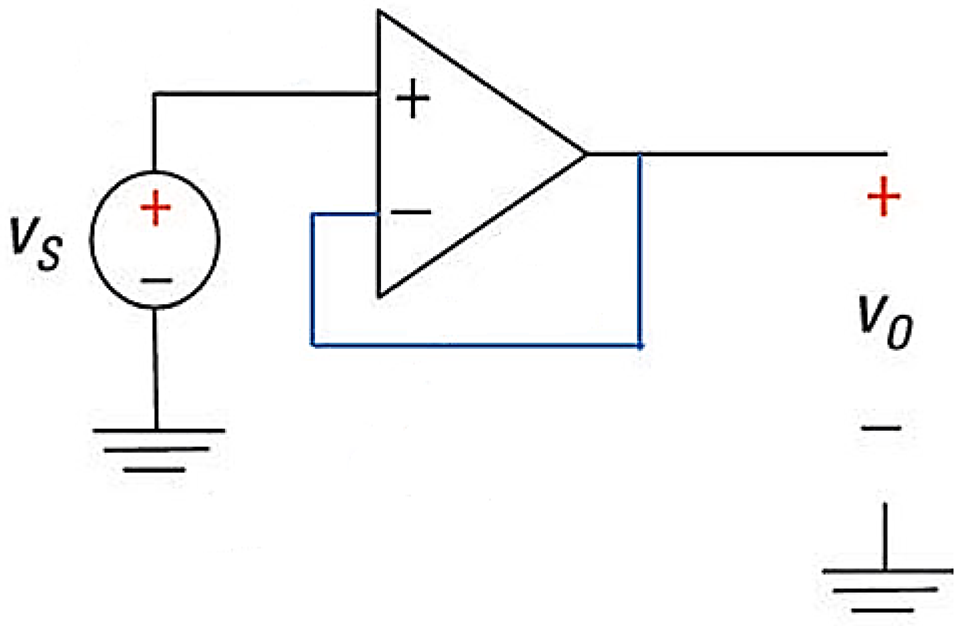
5- Voltage Follower (Buffer)

- The voltage follower (or buffer) is an op-amp circuit that has its inverting input connected directly to the output without a feedback resistor. Since the input always equals the output, the gain of a voltage follower equals one.

- The benefit of using a voltage follower is the high input impedance and low output impedance of the op-amp that allows almost all of the voltage from a previous source to be dropped across it. The op-amp can, in turn, feed the rest of the circuit with the higher desired voltage.



5- Voltage Follower (Buffer)



- Again, V+ = V-, and in this case V+ also equals the voltage source (Vs). Furthermore, the output (Vout) is equal to V-.
- V- = Vout, and V+ = Vs, therefore, Vs = Vout

$$\text{A (Gain)}= \frac{V_{out}}{V_s} = 1$$