Module - 3

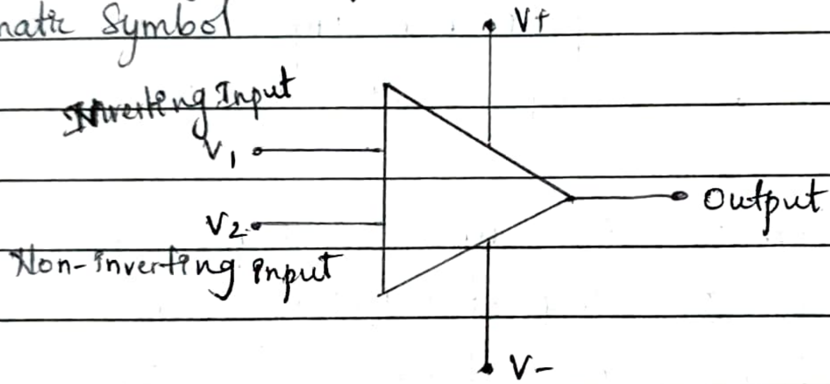
Operational Amplifiers

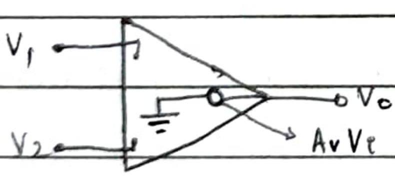
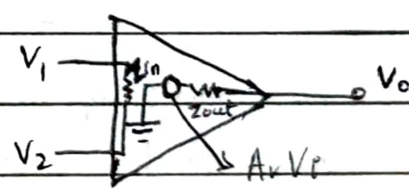
An Operational amplifier is a direct coupled multistaged voltage amplifier with high gain. Its behaviour is controlled by adding suitable feedback. It has very high input impedance and very low output impedance

Op amp is mainly used for performing mathematical operation such as addition, subtraction, integration, differentiation and so on.

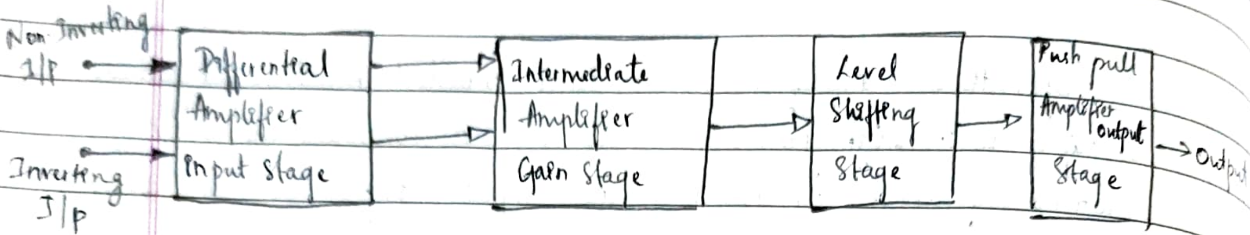
The Standard symbol of Op amp is shown below

Schematic Symbol



Ideal Op amp	Practical Op amp
	
- Infinite voltage gain	- Very high voltage gain
- Infinite Bandwidth	- Very high bandwidth
- Infinite input impedance	- Very high input impedance
- Zero output impedance	- Low output impedance

* Block diagram of Operational Amplifier



* Input Stage - This stage consists of dual input, balanced output differential amplifier. This stage provides most of the voltage gain and also influences the input impedance of operational amplifier.

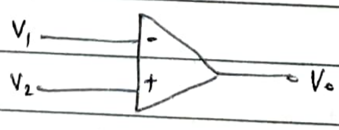
- Intermediate Stage - This stage is dual input, unbalanced output differential amplifier. This stage provides additional gain.

- Level shifting stage - Since direct coupling is used in Op amp there will be non-zero DC voltage at output of intermediate stage. This DC voltage should be removed. Hence the level shifting stage is used to remove any DC voltages.

- Output Stage - The output stage is a push-pull class B ~~[illegible]~~ complementary amplifier. This stage provides high efficiency and offers low output resistance.

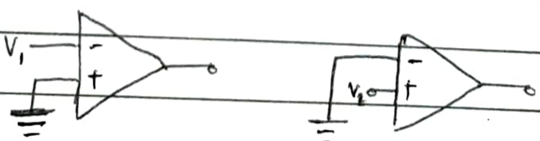
* Op amp input modes

a) Differential Mode

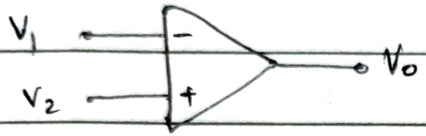


$V_1 \neq V_2$

9) Single ended differential mode



ii) Double ended



$V_1 \neq V_2$

b) Common Mode ($V_1 = V_2$)

- ~~Ind~~ In differential mode the input signals are not in phase where as in common mode, the two signal are of same phase, frequency and amplitude
- In common mode since both inputs are same, they cancel each other resulting in zero input voltage. This is called as Common mode rejection
- Generally we assume noise signals will appear equally at both the inputs. Since the Op amp output is proportional to difference of inputs, there is no output.

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S.No	Parameter	Symbol	Ideal Value	Typical value for μA741
1.	Gain (open loopgain)	A_{OL}	∞	Min = 50,000 Max = 2×10^5
2.	Input impedance	Z_i	∞	Min = 0.3 MΩ Max = 2MΩ
3.	Output impedance	Z_o	0	75 Ω
4.	Band Width	$BW(f_2-f_1)$	∞	1MHz
5.	Input voltage range	V_i	$\pm\infty$	± 13V
6.	CMRR	ρ	∞	90dB
7.	Input offset current	I_{os}/I_{io}	0	20nA
8.	Input offset voltage	V_{io}	0	2mV
9.	Input bias current	V_{io}	0	80nA
10.	Slew Rate	SR	∞	0.5 V/μ sec
11.	Power supply rejection ratio	PSRR	0	30μV/V

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* Op Amp Parameters

1. Common mode rejection ratio (CMRR)

- CMRR is measure of ability of Op amp to reject the common mode signals. That is signals which appear both at inverting and non-inverting input terminals such as noise.
- Ideally the Op amp provides very high gain for differential signals. However practically very low common voltage gain (less than 1) is exhibited by Op Amp and open loop differential voltage gain is in order of several thousands.

$$CMRR = \frac{A_{OL}}{A_{cm}} = \frac{\text{Open loop differential voltage gain}}{\text{Common voltage gain}} = \infty$$

Higher the CMRR much better. It is usually expressed in decibel (dB)

$$CMRR = 20 \log_{10}\left(\frac{A_{OL}}{A_{cm}}\right)$$

Q. A certain Op Amp has open loop differential voltage gain of 100000 and common voltage gain 0.2. Determine the CMRR in dB

$$CMRR = 20 \log_{10}\left(\frac{100000}{0.2}\right) = 20 \log_{10}(500000)$$

$$CMRR = 113.97 \text{ dB}$$

2. Gain: It is defined as ratio of output by input

$$Gain = \frac{V_o}{V_{in}}$$

Ideally gain should be infinite but practically gain will be very high

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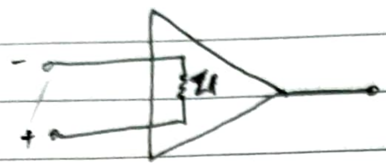
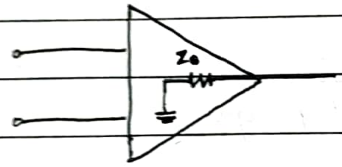
3. Input Resistance/Impedence



The input impedance is the net impedance present between inverting and non-inverting terminals. Ideally it should be infinite but the typical value is $2M\Omega$.

4. Output Impedence/Resistance



Output Impedance is total impedance which appears at output terminal of Opamp. Ideally it should be 0 and typical value is 75Ω

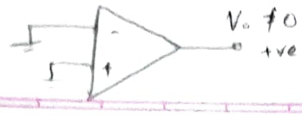
5. Slew Rate
The maximum rate of change of output voltage in response to the change in input voltage is called as Slew Rate. It depends on high frequency response of amplifier stages within the Op Amp. Typically it will be $0.5V/\mu sec$

$$\text{Slew Rate (SR)} = \frac{\Delta V_o}{\Delta t} \quad V/\mu sec$$

6. Band Width - It is defined as Range of frequencies over which the signals will be ~~amplified~~ amplified with same gain. Ideally it is infinite

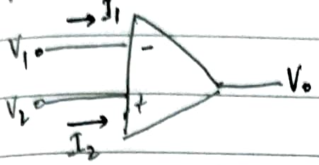
$$BW = f_2 - f_1$$

7. Input offset voltage - for ideal Op amp when the input voltage is 0, then the output will also be zero. However, in practical Op Amp there will be a small DC voltage at the output though the input is zero. In order to make output voltage zero, we apply the



differential DC between the inputs which is called as Input offset voltage.

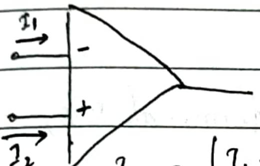
8. Input biased Current



$$I_B = \frac{I_1 + I_2}{2}$$

Input biased current is the average of both the input currents. It is the DC current required by the input of amplifier to operate the first stage.

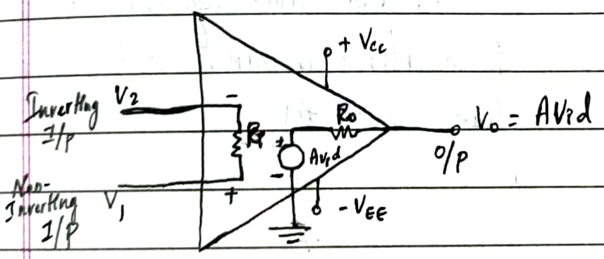
9. Input offset current



$I_{os} = |I_1 - I_2|$

Input offset current is difference of input biased currents. Ideally the biased current are equal, however for pratical Op amp, they are not equal. The offset voltage which appears at output is due to input offset current

10. Equivalente circuit of an Opamp



Equivalente circuit of an Op amp consists of 3 main parameters that is Input resistance, Output resistance and the open loop gain

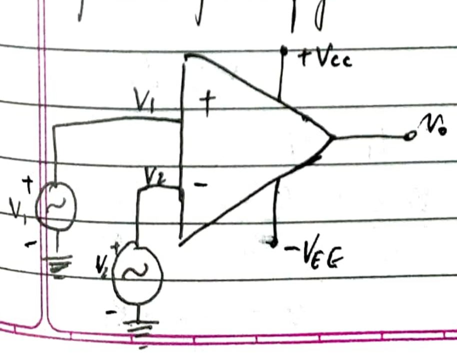
$V_o = AVid$

$V_o = A(V_1 - V_2)$.

A → Open loop gain of Op amp

Vid → Difference input voltage.

Open loop configurations.

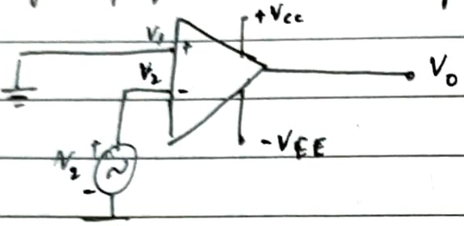


3 Types of open loop configurations.

1. Differential Amplifier where $V_1 \neq V_2$

$$V_o = A(V_1 - V_2)$$

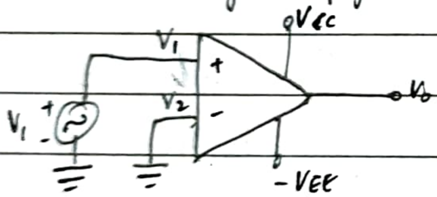
2. Inverting Amplifier - In this configuration $V_1 = 0$



$$\boxed{V_o = -AV_2}$$

Since the voltage to non-inverting terminal is 0, we have the equation ~~Vo = -AVin above equat~~

3. Non-inverting configuration

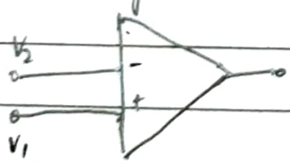


$V_o = AV \rightarrow$ Output voltage

In non-inverting configuration, voltage to inverting terminal will be zero, ∴ we have $V_o = AV$

* Application of Op amp

1. Virtual ground (virtual short)

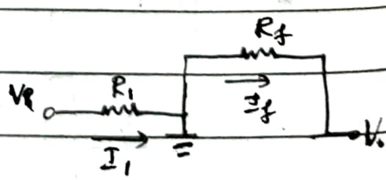


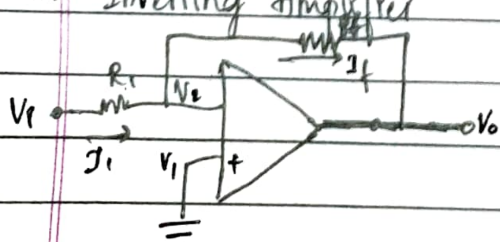
$$V_o = A(V_1 - V_2)$$

$$V_1 - V_2 = \frac{V_o}{A} = \frac{V_o}{\infty} = 0$$

$$V_1 = V_2$$

2. Inverting Amplifier





$$I_1 = I_f$$

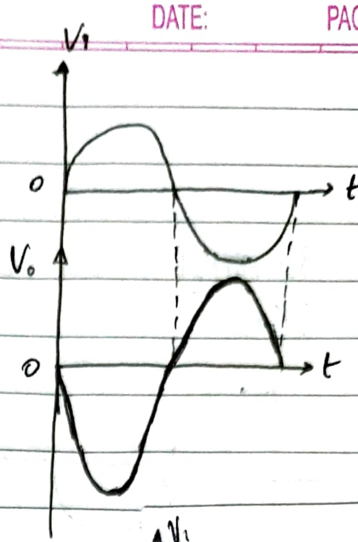
$$\frac{V_i - 0}{R_1} = \frac{0 - V_o}{R_f} \therefore \frac{V_i}{R_1} = \frac{-V_o}{R_f}$$

$$V_o = \frac{-V_i}{R_1} \times R_f = -\left(\frac{R_f}{R_1}\right) \times V_i$$

$V_o = -\left(\frac{R_f}{R_1}\right) \times V_i$

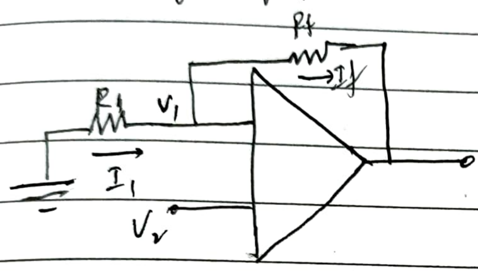
$V_o = -AV_i$ ← In inverting amplifier

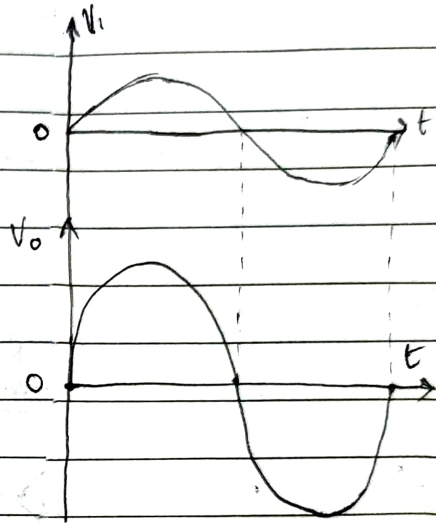
$\therefore A = \frac{R_f}{R_1}$ → which is the gain offered by amplifier. The negative sign indicates that output 180° out of phase w.r.t input. As can be seen in waveform



CLOSED LOOP

3 Non-inverting amplifier





$I_1 = I_f$

$$\frac{0 - V_i}{R_1} = \frac{V_i - V_o}{R_f}$$

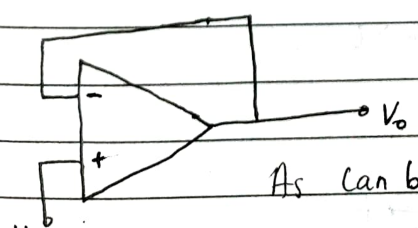
$$V_o = -\left(\frac{R_f}{R_1}\right) V_i + V_i = \left(1 + \frac{R_f}{R_1}\right) V_i = V_o$$

$V_o = AV_i$

where $A = \left(1 + \frac{R_f}{R_1}\right)$, the gain of non-inverting amplifier is $1 + \frac{R_f}{R_1}$

$A > 1$. As can be seen from expression, Output will be in phase with input with amplification. As can be seen in waveforms

4 Voltage follower.



The above circuit in ~~known~~ non inverting configuration, we know that $A = 1 + \frac{R_f}{R_1}$

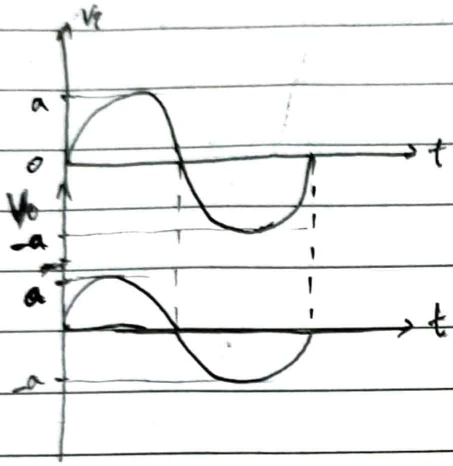
As can be seen in circuit $R_f = 0$, $R_1 = \infty$

$\therefore A = 1$

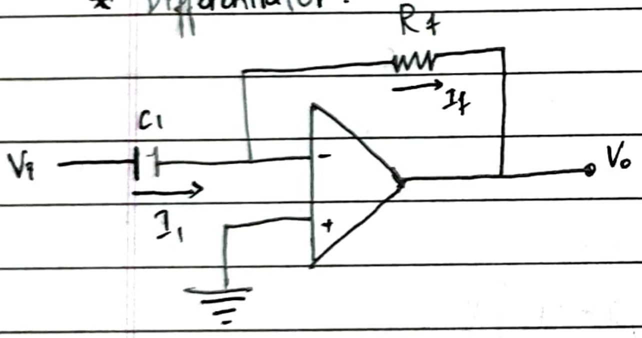
$V_o = AV_i$

$V_o = 1(V_i)$

The output is same as input, ∴ It is voltage follower or buffer



★ Differentiator.



$I_1 = I_f$

$I = C\frac{dv}{dt}$

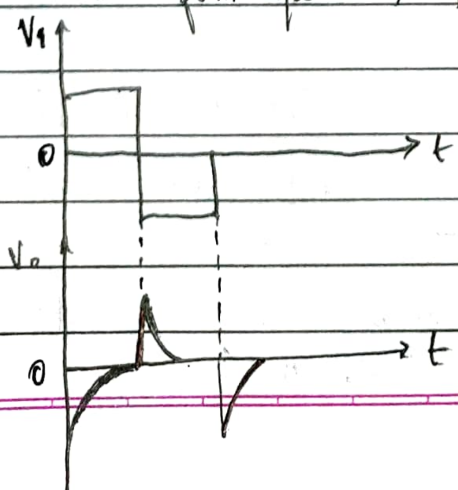
$C_1\frac{dV_i}{dt} = \frac{0 - V_o}{R_f}$

$$\boxed{V_o = -R_fC_1\frac{dV_i}{dt}}$$

The above circuit is differentiator when the input is applied to capacitor. and R_f is in feedback loop. Therefore we have

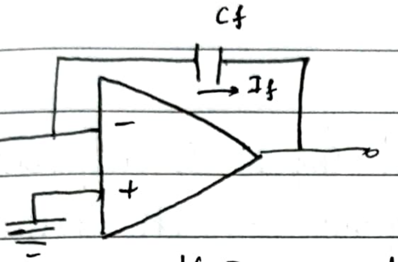
$$V_o = -R_fC_1\frac{dV_i}{dt}$$

As can be seen from equation, the output is differentiation of input



As can be seen in waveform, if input is square wave then output of differentiator will have spikes of very high voltage.

* Integrator



$$I_1 = I_f$$

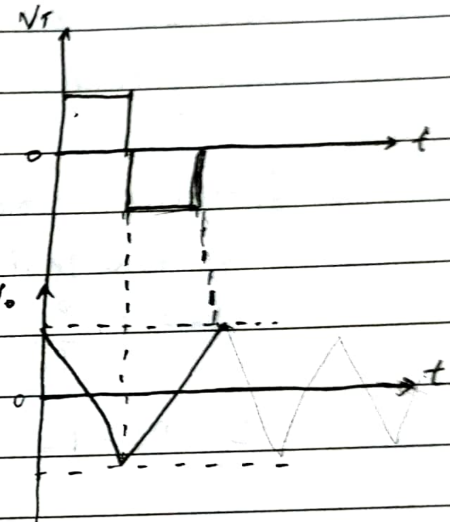
$$\frac{V_i - 0}{R_1} = C_f \frac{d}{dt}(0 - V_o)$$

$$\frac{V_i}{R_1} = -C_f \frac{dV_o}{dt}$$

$$dV_o = \frac{-1}{R_1 C_f} V_i dt$$

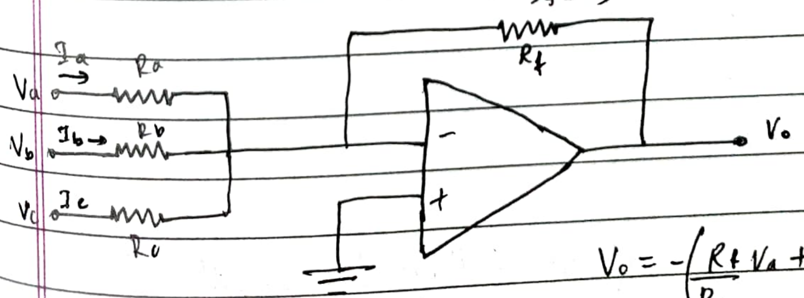
Applying integration on both sides

$$V_o = \frac{-1}{R_1 C_f} \int V_i dt$$



In Integrator we have a resistor at the input and capacitor in the ~~feed back~~ feedback loop. As can be seen from final expression. The output is integral of input. If a square wave is applied as input to integrator then the output will be a triangular wave.

* Inverting Configuration



$$I_a + I_b + I_c = I_f$$

$$\frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_c}{R_c} = \frac{0 - V_o}{R_f}$$

$$\cancel{V_o = -\frac{R_f}{R_a} V_a}$$

$$V_o = -\left(\frac{R_f}{R_a} V_a + \frac{R_f}{R_b} V_b + \frac{R_f}{R_c} V_c\right)$$

a) Scaling ~~Amp~~ Amplifier or Weightage Amplifier

$$V_o = -\left(\frac{R_f}{R_a} V_a + \frac{R_f}{R_b} V_b + \frac{R_f}{R_c} V_c\right)$$

If $\frac{R_f}{R_a} \neq \frac{R_f}{R_b} \neq \frac{R_f}{R_c}$

Since the coefficient of each input is different, the impact of each input on the output depends on its respective coefficient. Hence such a circuit is called as Scaling circuit.

b) Summing Amplifier / Adder

We know that

$$V_o = -\left(\frac{R_f}{R_a} V_a + \frac{R_f}{R_b} V_b + \frac{R_f}{R_c} V_c\right)$$

If $R_f = R_a = R_b = R_c$

$$V_o = -(V_a + V_b + V_c)$$

That is, the output is inverted summation of the inputs.

c) Averaging circuit

We know that

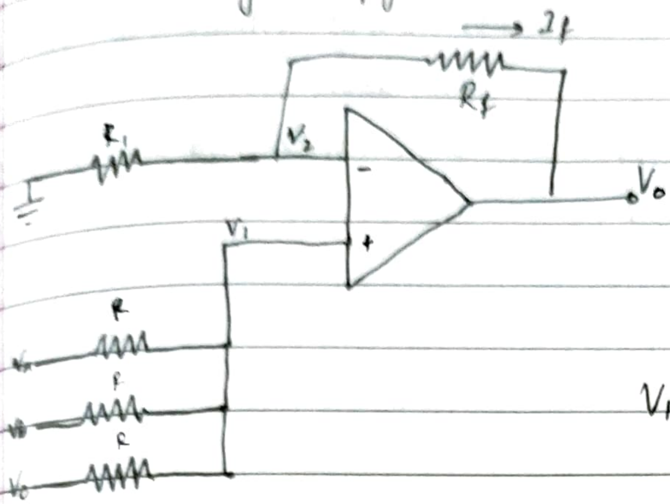
$$V_o = -\left(\frac{R_f}{R_a} V_a + \frac{R_f}{R_b} V_b + \frac{R_f}{R_c} V_c\right)$$

If $\frac{R_f}{R_a} = \frac{R_f}{R_b} = \frac{R_f}{R_c} = \frac{1}{3}$

$$V_o = -\frac{(V_a + V_b + V_c)}{3}$$

If $\frac{R_f}{R} = \frac{1}{n}$ where n = No. of inputs then the circuit behaves as averaging circuit.

Non-inverting Configuration.



Using the principle of superposition we have

$$V_1 = \frac{V_a R/2}{R_1 + R_2} + \frac{V_b R/2}{R_1 + R_2} + \frac{V_c R/2}{R_1 + R_2}$$

$$V_1 = \frac{V_a + V_b + V_c}{3}$$

The circuit is in non-inverting configuration, ∴ we have

$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_1 = \left(1 + \frac{R_f}{R_1}\right)\left(\frac{V_a + V_b + V_c}{3}\right)$$

a) Summing amplifier

We know that $V_o = \left(1 + \frac{R_f}{R_1}\right)\left(\frac{V_a + V_b + V_c}{3}\right)$

If $\left(1 + \frac{R_f}{R_1}\right) = 3$ then

$V_o = V_a + V_b + V_c$ → output is summation of input.

b) Averaging circuit

We know that $V_o = \left(1 + \frac{R_f}{R_1}\right)\left(\frac{V_a + V_b + V_c}{3}\right)$

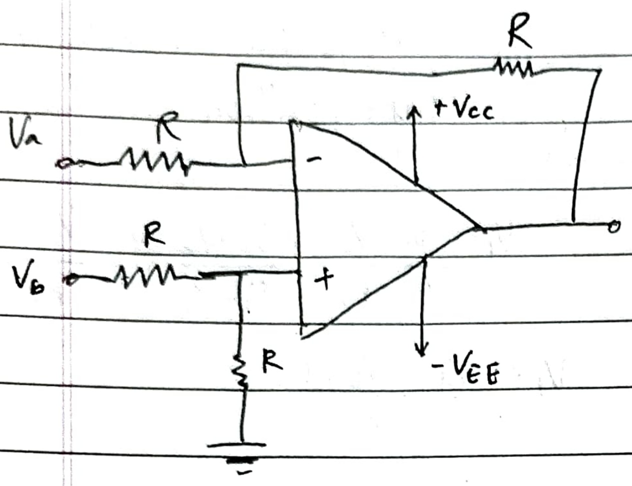
If $\left(\frac{R_f}{R_1}\right) = 0$, then $V_o = \frac{V_a + V_b + V_c}{3}$ → output is average of input

* Differential Configurations.

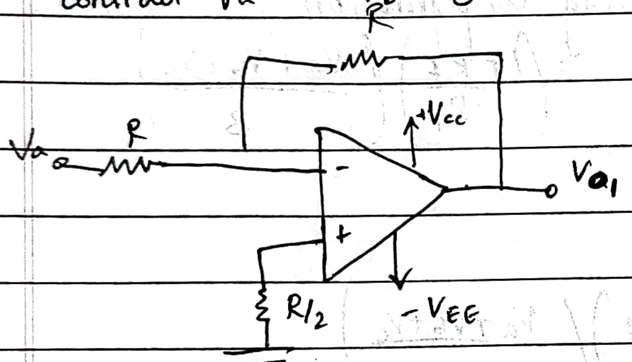
1. Subtractor.

Using principle of superposition we have

~~1. Consider V_a and $V_b = 0$~~



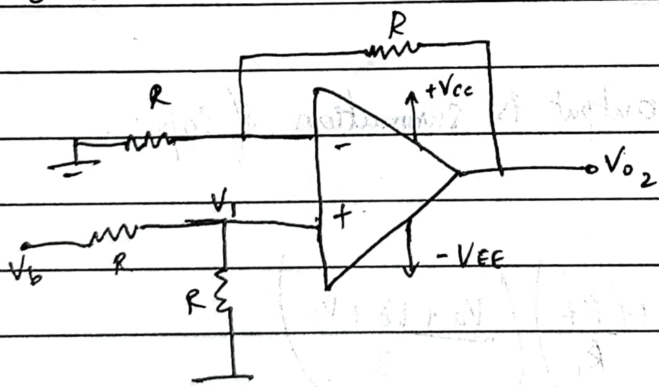
a. Consider V_a and $V_b = 0$

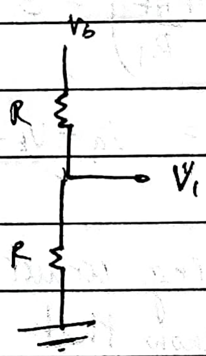


$$V_{o1} = \frac{-R}{R} V_a = -V_a$$

~~V_{o1}~~

b. Consider V_b and $V_a = 0$





$$V_1 = \frac{V_b R}{R+R} = \frac{V_b}{2}$$

$$V_{o_2} = \left(1 + \frac{R}{R}\right) . V_1 .$$

$$V_{o_2} = \frac{2V_b}{2} = V_b$$

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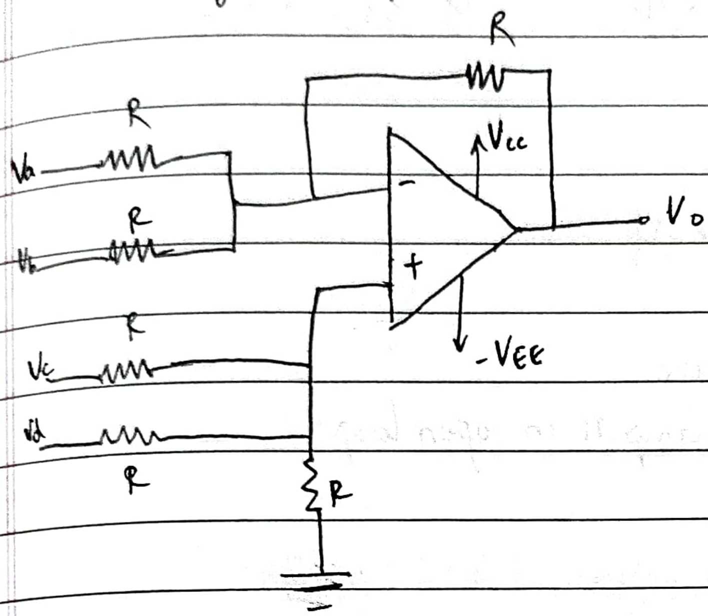
Using principle of superposition :

The output voltage → $V_o = V_{o1} + V_{o2}$

$V_o = V_b - V_a$

2. Summing Amplifier



a) Consider Va, therefore $V_b = V_c = V_d = 0$ then we have ~~Vo~~

$V_{o1} = -V_a$

Similarly

Consider V_b, where $V_a = V_c = V_d = 0$ then

$V_{o2} = -V_b$

llly $V_{o3} = V_c$ and $V_{o4} = V_d$ ∴ we have final output as

$V_o = -V_a - V_b + V_c + V_d$

Q. Determine the output voltage if

a) $V_{in} = 20\,mV$ dc

b) $V_{in} = -50\,\mu V$ peak sine wave

Assume $A = 2 \times 10^5$ (The op amp is in open loop)

For inverting

$V_{in} = -50\mu V$

a) $V_o = -AV_i$

$V_o = 50 \times 10^{-3} \times 2 \times 10^5$

$V_o = -2 \times 10^5 \times 20 \cancel{\times} 10^{-3}$

$= 100 \times 10^2 = 10^4\,V$

$V_o = -2 \times 10^2 \times 20$

$V_o = -40 \times 10^2\,V = -4 \times 10^3$

$V_{in} = +10$

b) $V_o = -2 \times 10^5 \times -50 \times 10^{-6}$

Ideally we get -15, practically -14 not -4×10^3

$= 100 \times 10^{-1}$

$= 10\,V$

NOTE: The output voltage of amplifier will always be limited by DC power supply. For op amp we have $+V_{cc} = 15V$ & $-V_{EE} = -15V$

∴ The maximum negative voltage for op amp can be $-15V$. But the saturation voltage for op amp will be 1 volt less than supply voltage

∴ $V_o = -14V$

Q. Assume Op amp is in closed loop connected as non-inverting amplifier given $V_o = 0.1V$, $R_f = 100k$, $R_1 = 1k$. Find V_i, also if R_1 changes from 1k to 10k find corresponding V_i

— $A = 1 + \frac{R_f}{R_1} = 1 + \frac{100}{1} \Rightarrow A = 101$

$V_o = 0.1 = 101 \times V_i$

$V_i = \frac{0.1}{101} = 9.900 \times 10^{-4}$

$= 0.99mV$

— $A = 1 + \frac{100}{10} = 11$

$V_o = 11 \times V_i = 0.1$ $\qquad V_i = \frac{0.1}{11} = 9.09 \times 10^{-3} = 9.09mV$

Q. Given CMRR = 30dB and open loop differential voltage gain is 100K. Find the common mode voltage gain

$CMRR = 20\log_{10}\left(\frac{A_d}{A_{cm}}\right) dB$

$30 = 20\log_{10}\left(\frac{100000}{A_{cm}}\right)$

$\frac{30}{20} = \log_{10}\left(\frac{100000}{A_{cm}}\right)$

$\text{antilog}(1.5) = \frac{100000}{A_{cm}}$

$31.6227 = \frac{100000}{A_{cm}}$

~~$A_{cm} = 3162.28532\ dB$~~

$A_{cm} = \frac{100000}{31.62} = 3162.55\ dB$