Faculty of Engineering and Technology

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B.Tech –II Sem

Basic Electronics Engineering (EC-201)

Unit-3 OPERATIONAL AMPLIFIER

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Introduction

→ The operational amplifier most commonly referred as op-amp was introduced in 1940's. The first op-amp was designed in 1948 using vaccum tubes.

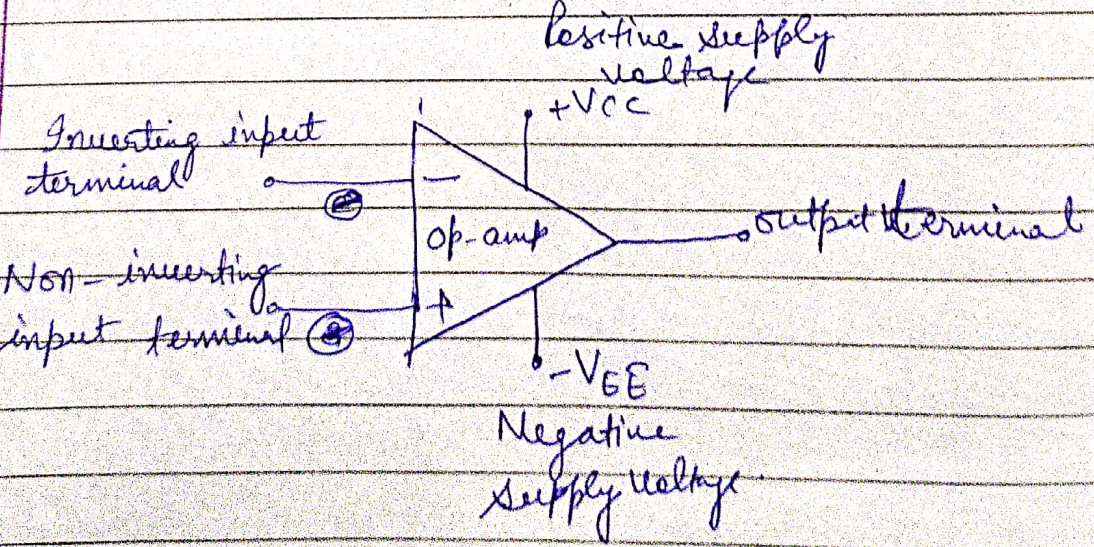
→ Due to the use of vaccum tubes, the early op-amps were bulky, power consuming and expensive.

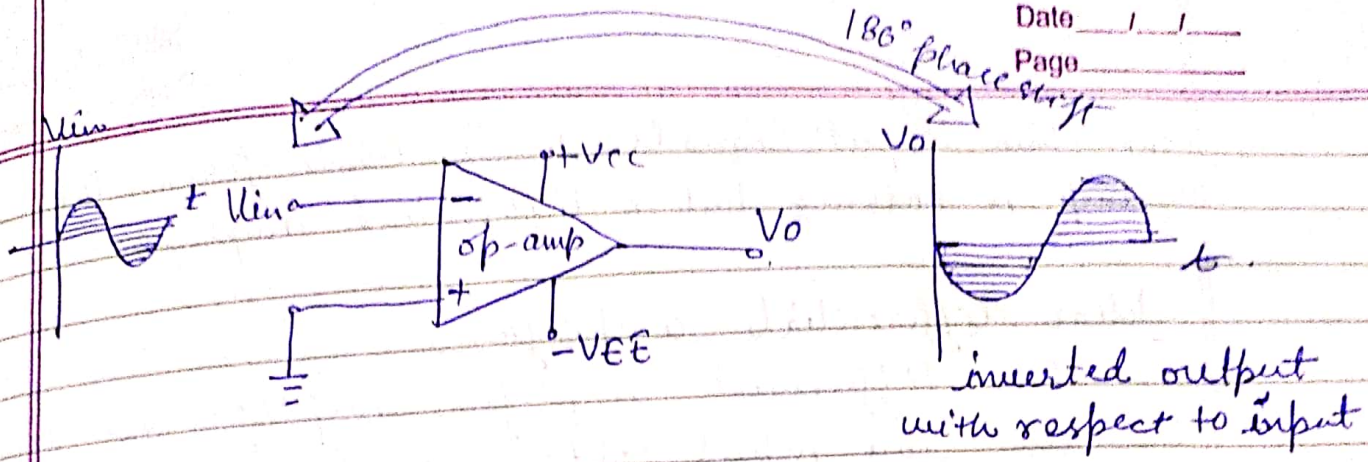
→ Due to its use in performing mathematical operations it has been a name operational amplifier.

→ Robert J. Widlar at Fairchild brought out the popular 741 integrated (IC) opamp between 1964 to 1968. The IC version of opamps uses BJTs and FETs which are fabricated along with the other supporting components, on a single Semiconductor chip or wafer which is pinhead size.

→ With the help of IC op-amp, the circuit design becomes very simple.

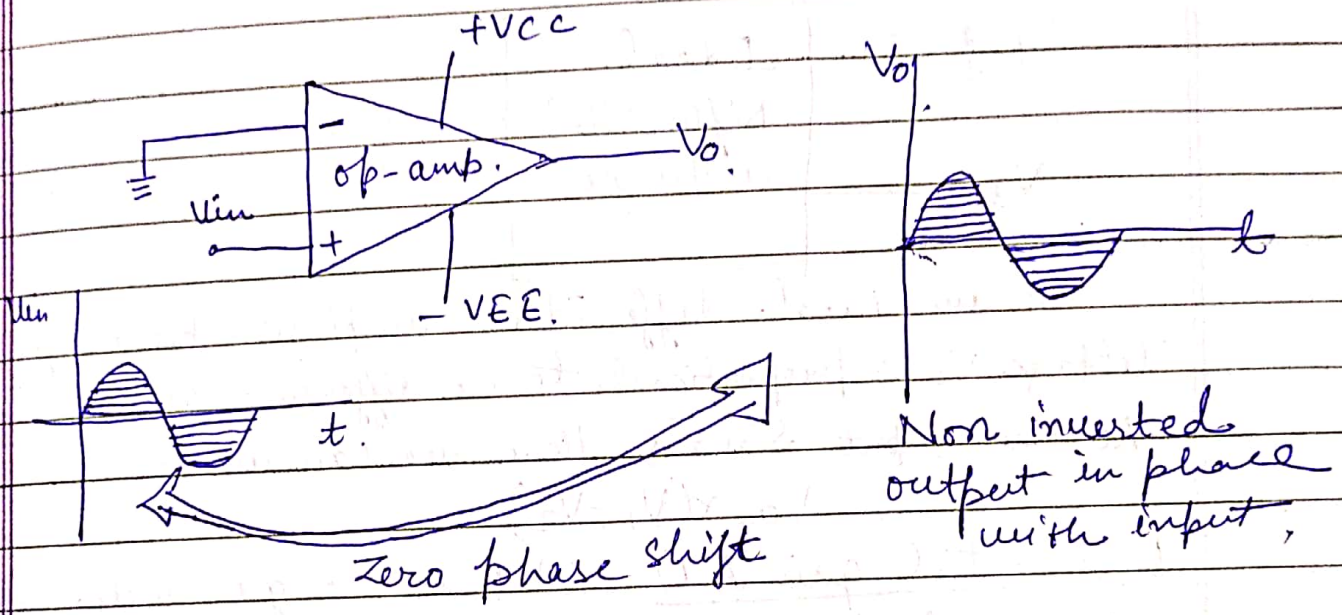
Op Amp symbol & terminals





inverted output with respect to input

a) input applied to inverting terminal.



Non inverted output in phase with input.

b) input applied to non inverting terminal.

Saturable property of op-amp

The open loop gain of opamp is very high. while every op-amp has property that its output can swing between two levels decided by supply voltages +Vcc & -VEE. Thus if output tries to rise more than +Vcc or less than -VEE then it gets clipped & get saturated at the levels almost equal to +Vcc & -VEE on positive & negative side respectively.

Ideal op-Amp :- The ideal op-amp is basically an amplifier which amplifies the difference between

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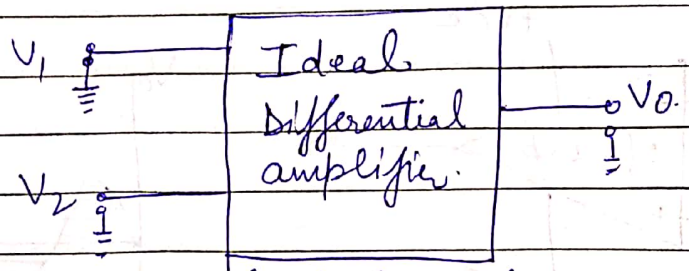
the two input Signals. In its basic form, the opamp is nothing but a differential amplifier.

Ideal differential amplifier

The differential amplifier amplifies the difference between two input voltage signals. Hence it is also called difference amplifier.



In an ideal differential amplifier the output voltage V_o is proportional to the difference between the two input Signals, Hence we can write,

$$V_o \propto (V_1 - V_2)$$

Differential gain (A_d). → A_d is the gain with which differential amplifier amplifies the difference between two input Signals.

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

$$A_d = \frac{V_o}{V_d}$$

$$A_d = 20 \log_{10} A_d \text{ in } dB.$$

Common mode gain (A_c)

if we apply two input voltages which are equal in all respects to differential amplifier i.e. $V_1 = V_2$ then ideally $V_o = (V_1 - V_2) A_d$ must be zero. But O/P of practical differential amplifier depends on the average common level of two inputs. Such an average level of two input signal is called Common mode Signal.

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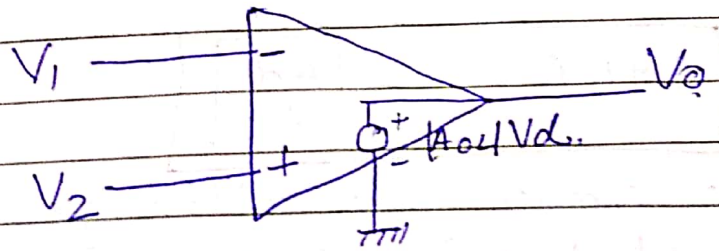
$$V_c = \frac{V_1 + V_2}{2}$$

$$V_o = A_c V_c$$

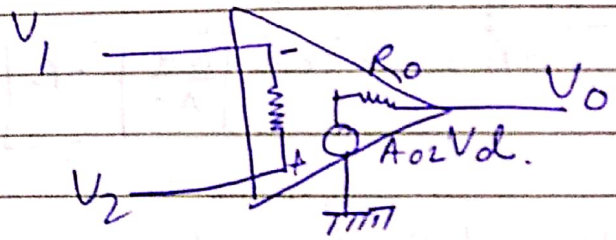
Total o/p of any differential amplifier

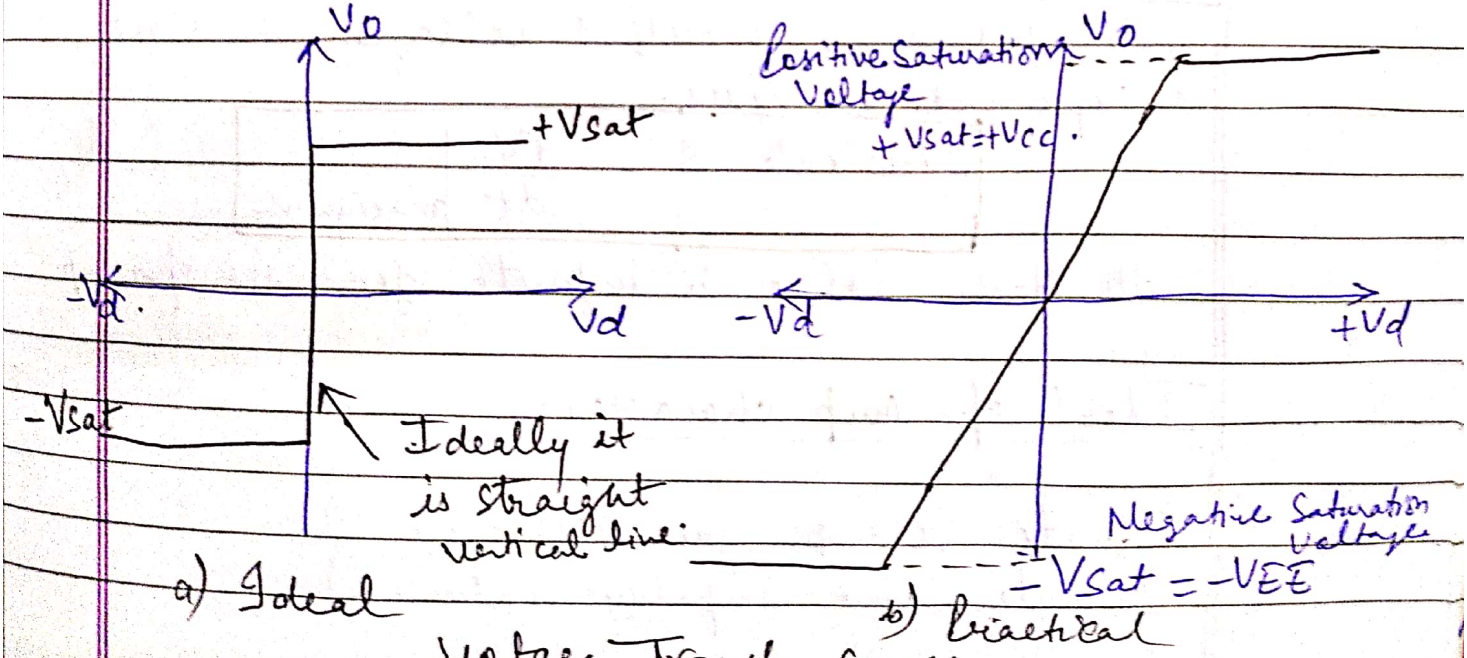
$$\boxed{V_o = A_d V_d + A_c V_c}$$

Ideal op-amp:



Practical op-amp





Voltage Transfer Curves

CMRR (Common Mode Rejection Ratio)

The ability of a differential amplifier to reject a common mode signal is expressed by a ratio called common mode Rejection Ratio denoted as CMRR or ρ.

it is defined as the ratio of the differential voltage gain A_d to common mode voltage gain A_c

$$CMRR = \rho = \left|\frac{A_d}{A_c}\right|$$

* Ideally the common mode voltage gain is zero, hence the ideal value of CMRR is ∞.
* For a practical differential amplifier A_d is large & A_c is small hence the value of CMRR is also very large.

$$CMRR \text{ in } dB = 20 \log \left|\frac{A_d}{A_c}\right| dB$$

Slew Rate → It is defined as the maximum rate of change of output voltage with time & expressed in V/μs.

$$\text{Slew rate } S = \left.\frac{dV_o}{dt}\right|_{\text{maximum}}$$

Its ideal value is infinite for the opamp.

Ideal Op-Amp characteristics

1) Infinite Voltage gain ($A_{OL} = \infty$)
2) Infinite Input Impedance ($R_{in} = \infty$)

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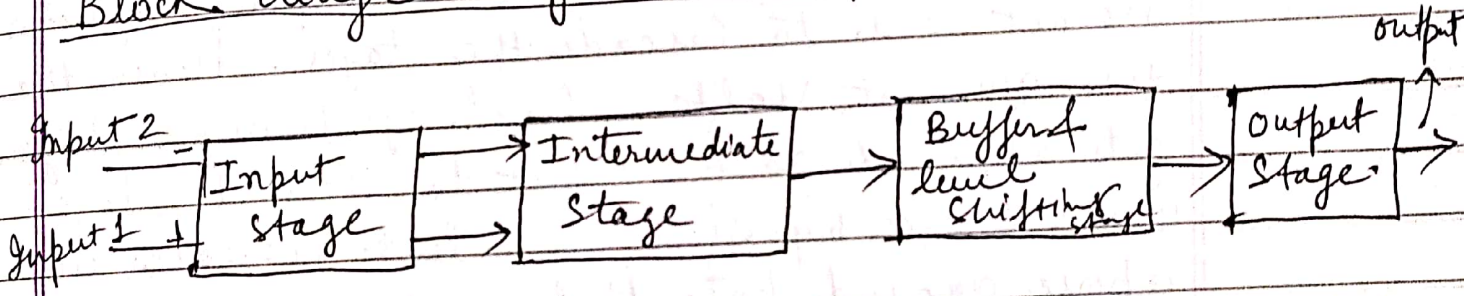
3) Zero output impedance ($R_o = 0$)
4) Zero offset voltage ($V_{ios} = 0$)
5) Infinite Bandwidth
6) infinite CMRR ($\rho = \infty$)
7) infinite Slew rate ($S = \infty$)
8) Power supply rejection ratio ($PSRR = 0$)

It is defined as the ratio of change in input offset voltage due to change in supply voltage producing it, keeping other power supply voltage constant.

$$PSRR = \frac{\Delta V_{IOS}}{\Delta V_{CC}} \quad V_{EE} \text{ constant}$$

Block diagram of I.C. op-Amp.



Now, a days op-amps are available in an integrated circuit form. Commercial integrated circuit op-amps usually consists of four cascaded blocks.

1) **Input Stage :-** The Input stage requires high Input impedance to avoid loading on the sources. it requires two input terminals. it also requires low output impedance. All such requirements are achieved by using the dual input, balanced output differential amplifier as the input stage. This stage provides most of the voltage gain of the amplifier.

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2) Intermediate stage :- The output of the input stage drives the next stage which is an intermediate stage. This is another differential amplifier with dual input, unbalanced i.e. Single ended output. The overall gain requirement of the opamp is very high. The input stage alone cannot provide such a high gain. The main function of the intermediate stage is to provide additional voltage gain required.

3) Level Shifting Stage :- All the stages are directly coupled to each other. As the op-amp amplifies d.c. signals also, the coupling capacitors are not used to cascade the stages. Hence the d.c. quiescent voltage level of perivious stage gets applied as the input to the next stage. Hence stage by stage d.c. level increases well above ground potential. Such a high d.c. voltage level may drive the transistor into Saturation. This further may cause distortion in the output due to clipping. This may limit the maximum dc output voltage Swing without any distortion.

The level shifter stage brings the d.c. level down to ground potential, when no signal is applied at the input terminals. Then signal is given to last stage which is output stage.

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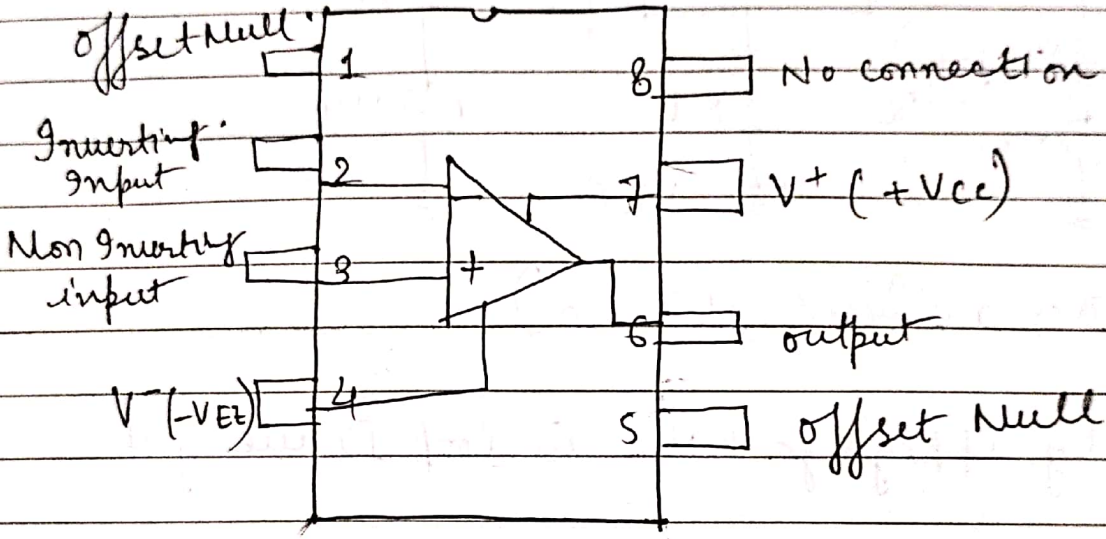
4) **Output Stage** :- The basic requirements of an output stage are low output impedance, large a.c. output voltage swing & high current sourcing & sinking capability. The push-pull complementary amplifier meets all these requirements & hence used as an output stage.

Op-amp IC 741 pin diagram



Virtual Ground

This means the differential input voltage V_d between the non inverting & inverting input terminals is essentially zero.

Ideally $\begin{cases} R_i = \infty . \\ A_d = \infty . \end{cases}$

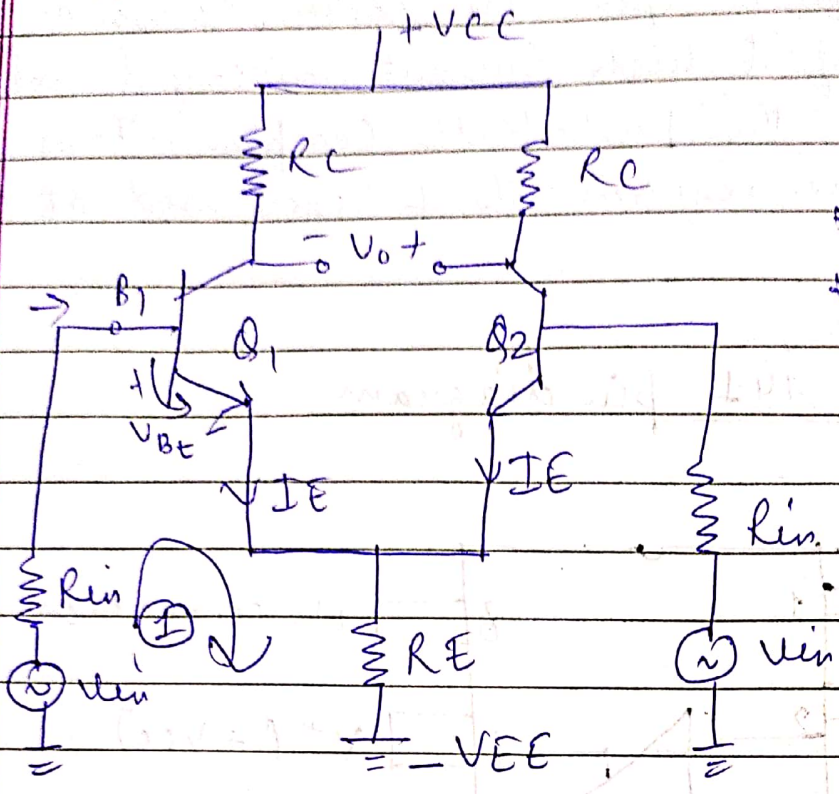
$$A_d = \frac{V_o}{V_d}.$$

$$V_d = \frac{V_o}{A_d} \quad (\text{putting } A_d = \infty)$$

$$V_d = \frac{V_o}{\infty} = 0, \qquad V_1 - V_2 = 0$$

$$\boxed{V_1 = V_2}$$

Differential amplifier circuit (DC analysis I_C, V_{CE})



* Q_1 & Q_2 are matched.
* those β values must be exactly equal. internal resistances are equal.

DC analysis ($V_{in} = 0$)

By applying KVL in loop (1) we get.

$$-I_B R_{in} - V_{BE} - 2I_E R_E + V_{EE} = 0 \quad -1$$

($I_C \approx I_E$) Since $\beta \gg 1$.

$$V_{EE} = \frac{I_E}{\beta} R_{in} + V_{BE} + 2I_E R_E = 0 \quad -2$$

$$I_E = \frac{V_{EE} - V_{BE}}{\frac{R_{in}}{\beta} + 2R_E} \quad -3$$

$$\boxed{I_E = \frac{V_{EE} - V_{BE}}{2R_E}} \quad -4 \quad (\text{Since } \beta \gg 1)$$

applying KVL at o/p side we get.

$$\boxed{V_{CE} = V_C - V_E} \quad -5$$

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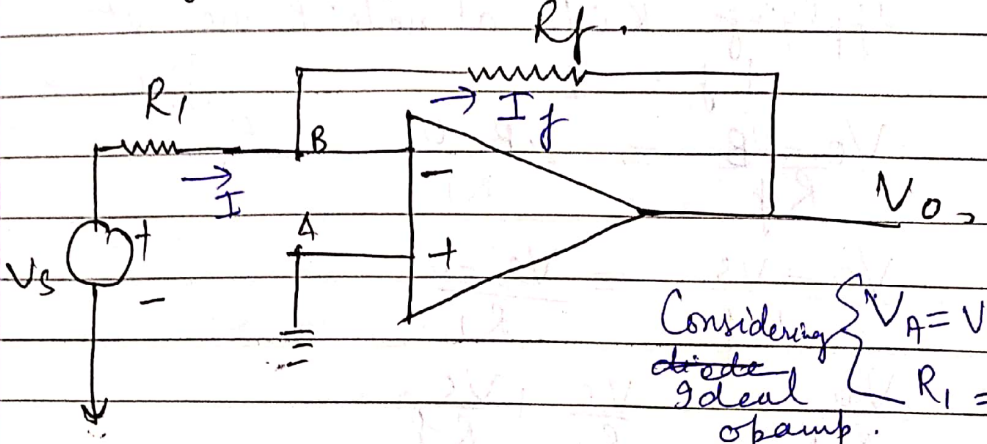
$V_C = V_{CC} - I_C R_C$ — 6

putting eqn 6 in eqn 5 we get

$$\boxed{V_{CE} = V_{CC} - I_C R_C - V_E} \quad -7.$$

Op-Amp Applications

1) Inverting amplifier



Considering ideal opamp $\begin{cases} V_A = V_B = 0 \text{ (virtual ground concept)} \\ R_1 = \infty. \end{cases}$

Applying KCL at node B, we get.

$$I = I_f$$

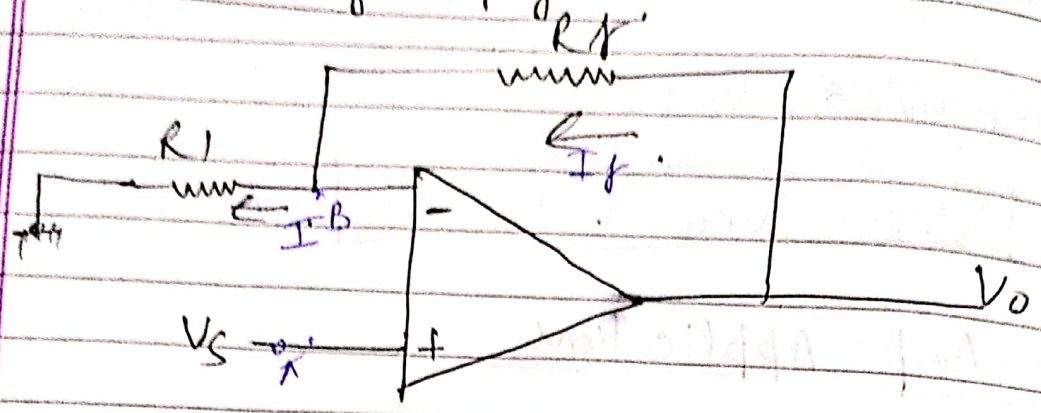
$$\frac{V_s - 0}{R_1} = \frac{0 - V_o}{R_f}$$

$$\frac{V_s}{R_1} = \frac{-V_o}{R_f}$$

$$\frac{V_s}{V_o} = -\frac{R_f}{R_f}$$

$$\boxed{\frac{V_o}{V_s} = -\frac{R_f}{R_1}}$$

2) Non inverting amplifier



Applying KCL at node 'B' we get

$I_f = I$

$VA = VB = Vs$

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

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

$$\frac{V_o}{R_f} = \frac{V_s}{R_1} + \frac{V_s}{R_f}$$

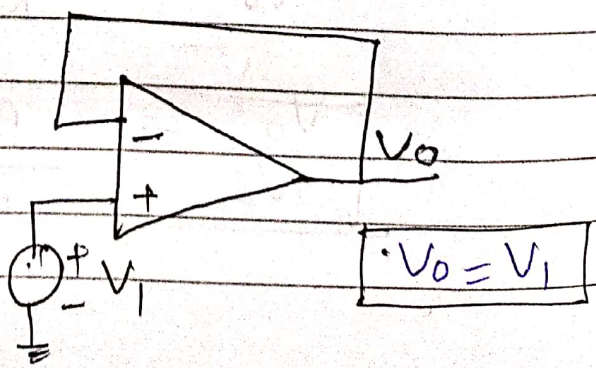
$$\frac{V_o}{R_f} = V_s\left(\frac{1}{R_1} + \frac{1}{R_f}\right)$$

$$\frac{V_o}{V_s} = R_f\left(\frac{R_f + R_1}{R_f R_1}\right)$$

$$= \frac{R_f + R_1}{R_1}$$

$$\boxed{\frac{V_o}{V_s} = 1 + \frac{R_f}{R_1}}$$

3) Voltage follower



$\boxed{V_o = V_1}$

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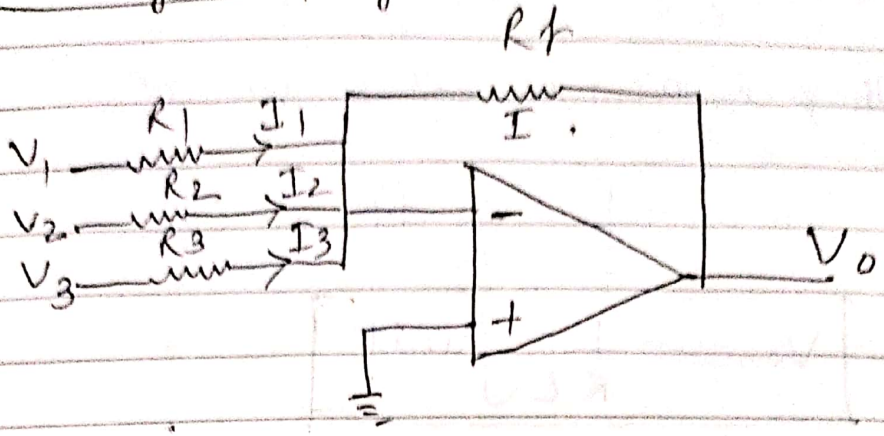
4) Summing Amplifier



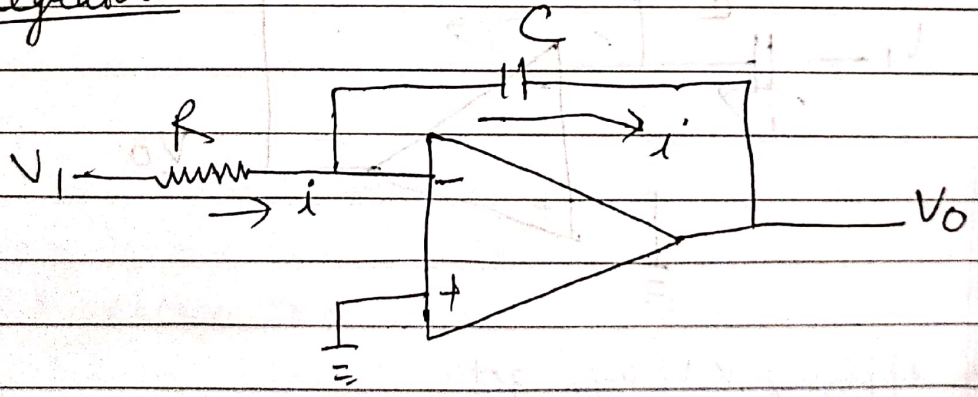
Applying KCL we get

$$I = I_1 + I_2 + I_3$$

$$\frac{0 - V_o}{R_f} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

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

5) Integrator



Applying KVL we get

$$V_1 - iR = 0$$

$$i = \frac{V_1}{R} \quad -(1)$$

Applying KVL we get

$$0 - \frac{1}{C}\int i\,dt - V_o = 0$$

$$V_o = -\frac{1}{C}\int i\,dt \quad -(2)$$

putting eqn (1) in eqn 2 we get

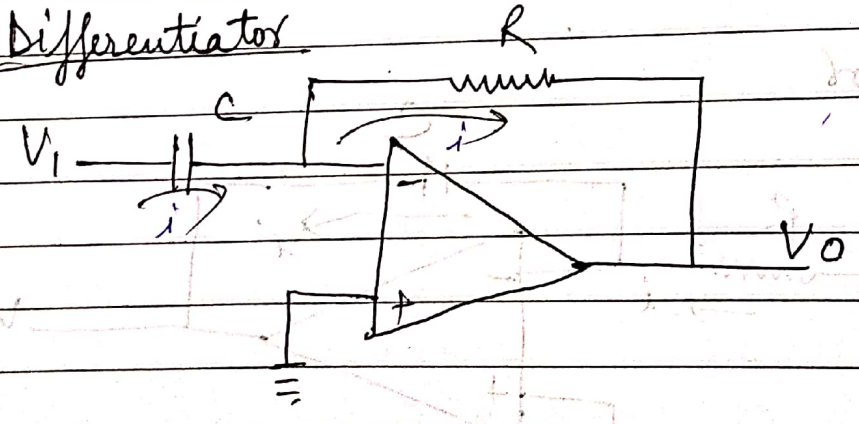
$$V_o = -\frac{1}{C}\int \frac{V_i}{R}\,dt$$

$$\boxed{V_o = -\frac{1}{RC}\int v_i\,dt}$$

applications of practical integrator

1) In the analog computers
2) In solving the differential equations
3) In analog to digital Converters
4) Various signal wave shaping circuits
5) In ramp generators.

6) **Differentiator**



applying KVL we get

$$V_1 - \frac{1}{C}\int i\,dt = 0$$

$$V_1 = \frac{1}{C}\int i\,dt \quad -(1)$$

differentiating eqn (1) w.r.t. dt we get.

$$\frac{dV_1}{dt} = \frac{1}{C} i \quad -(2)$$

$$\boxed{i = C\frac{dV_1}{dt}}$$

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applying KVL we get

$$0 - iR = V_o \quad -(3)$$

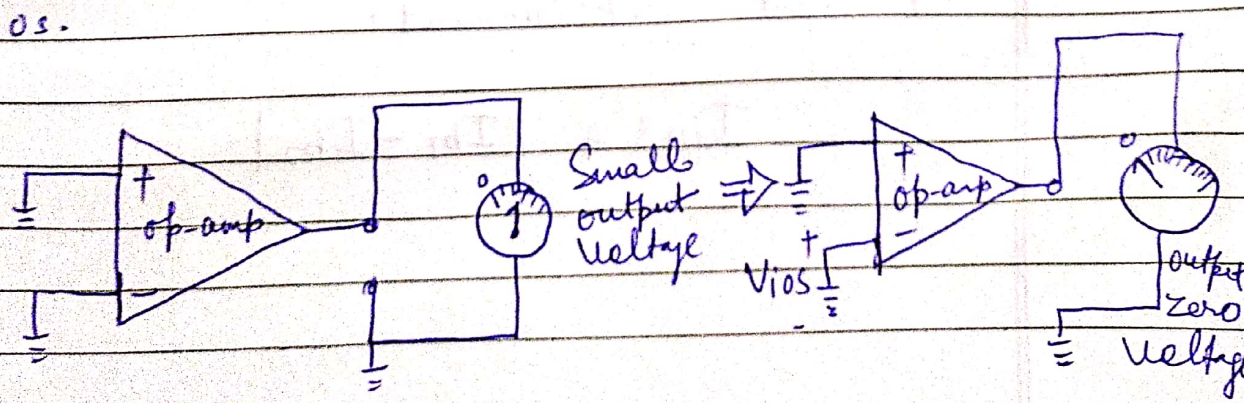
putting eqn (2) in eqn (3) we get :-

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

applications of practical differentiator

1) In the wave shaping circuits to detect high frequency components in the input signal.
2) As a rate of change detector in FM demodulators.

Input offset Voltage :- Whenever both the input terminals of the op-amp are grounded, Ideally, the output voltage should be zero. However, in this condition, the practical op amp shows a small non zero output voltage. To make this output voltage zero, a small voltage in millivolts is required to be applied to one of the input terminals. Such a voltage makes the output exactly zero. This dc voltage, which makes the output voltage zero, when the other terminal is grounded is called input offset voltage denoted as V_{IOS}.

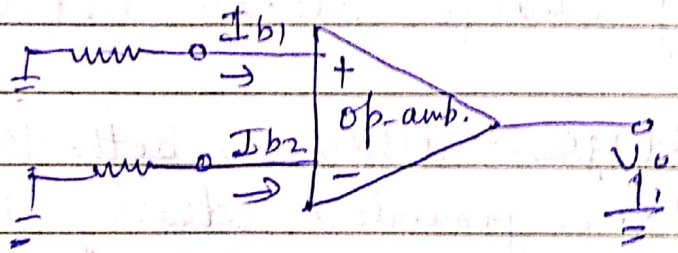


Input bias Current

For ideal op-amp, no current flows into the input terminals. so input bias current can be defined as the current flowing into each of two input terminals when they are biased to the same voltage level i.e. when the op-amp is balanced.

The two bias currents are never same hence the manufactures specify the average input bias current I_b, which is found by adding the magnitudes of I_{b1} & I_{b2} and dividing the sum by 2.

$$I_b = \frac{|I_{b1}| + |I_{b2}|}{2}$$



Input offset Current :-

If we supply equal d.c currents to the two inputs, output voltage of op-amp must be zero. But practically, there exists some voltage at the output. To make it zero, the two input currents are made to differ by small amount. This difference is nothing but the input offset current.

$$I_{ios} = |I_{b1} - I_{b2}|$$

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Output offset voltage

Ideally when both the inputs of op amp are at zero potential, output must be zero. But both input offset voltage & bias current contribute to produce output voltage with zero inputs. The voltage existing at the output when inputs are zero is called output offset voltage & denoted as Voos.