Samiran

Operational Amplifier

→ The significance of the term 'operational' is that the OP AMP can perform mathematical operations such as summation, subtraction, integration, and differentiation.

→ The IC OP AMP was developed by Robert Widlar in 1964.

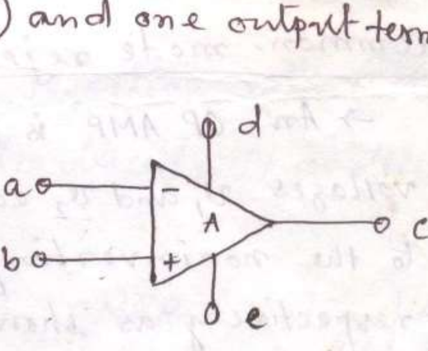
→ Such operations are important in analog computers.

→ The OP-AMPs can be used in signal amplification, wave forming, servocontrols, impedance transformation, active filters, oscillators, voltage regulators, analog to digital and digital-to-analog converters, to mention but a few.

Circuit Symbol

→ Fig. shows the circuit representation of an operational amplifier.

→ It has two input terminals (marked a and b) and one output terminal (marked c).



→ Terminal a is known as the inverting input terminal and is labelled '−'. The significance of the negative sign is that a signal applied at the terminal a appears at the terminal c with its polarity reversed.

→ Terminal b is called the noninverting input terminal and is labelled '+'. A signal applied to the terminal b appears at the terminal c with the same polarity.

→ The output voltage at c is proportional to the difference of the two signal voltages applied at the two input terminals simultaneously.

→ The constant of proportionality gives the open loop voltage gain (A) of the operational amplifier. A is a real constant, and for an ideal amplifier A approaches infinity for all frequencies.

→ The power supply voltages which are usually balanced with respe[ct to]
ground are applied to the terminals d and e.

Op-AMP characteristics

The ideal OP AMP has the following properties:

i/ An infinite voltage gain, Practically high voltage gain order of 10^5 or more.

ii/ An infinite input impedance, Practically high input impedance may be as high as 10^{12} ohm.

iii/ Zero output impedance, Practically low output impedance, of order of ~~10~~ ohm.

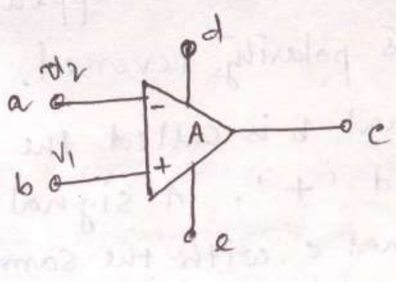
iv/ An infinite bandwidth, practically high bandwidth.

v/ Characteristics not drifting with temperature.

vi/ Perfect balance, i.e., the output voltage is zero when equal voltages are applied to the two input terminals.

Common-mode rejection ratio

→ An OP AMP is basically a differential amplifier with signal voltages v_1 and v_2 each measured with respect to ground, applied to the noninverting terminal b and the inverting terminal a, respectively as shown in fig.



→ The output voltage appearing at the terminal c is v_0, measured with respect to ground.

→ In practice, the difference signal $v_d = (v_1 - v_2)$ and also average signal, called the common-mode signal $v_c = \left(\frac{v_1 + v_2}{2}\right)$

we have

$$v_0 = A_1 v_1 + A_2 v_2 \quad \text{----} (1)$$

There A_1 is the voltage gain when the terminal a is grounded and

2 is that when the terminal b is grounded. Now

$$v_1 = v_c + \frac{1}{2} v_d \quad \text{------ (2)}$$

and $$v_2 = v_c - \frac{1}{2} v_d \quad \text{------ (3)}$$

using eq^{n}s (2) and (3) in (1) we get

$$v_0 = \frac{1}{2}(A_1 - A_2) v_d + (A_1 + A_2) v_c$$

$$= A_d v_d + A_c v_c \quad \text{------ (4)}$$

where
$$A_d = \frac{1}{2}(A_1 - A_2) \quad \text{--- (5)}$$
$$A_c = A_1 + A_2 \quad \text{---- (6)}$$

A_d is the voltage gain for the difference signal and A_c is that for the common-mode signal. In the ideal case, A_d is infinitely large while A_c is zero.

In practice, the situation is not truly ideal, and a figure of merit, called the common-mode rejection ratio (CMRR) of the ~~opamp~~ OP-AMP has to be introduced. It is defined by

$$CMRR = \left|\frac{A_d}{A_c}\right|, \text{ or in dB, } CMRR = 20\log_{10}\left|\frac{A_d}{A_c}\right| \text{ dB.}$$

Since A_d needs to be large and A_c very small, the amplifier must be so designed that the CMRR is much larger than unity. Ideally, the CMRR is infinitely large.

what is the Integrated Circuit (IC)

→ The IC is a complete circuit made up of active components like diode, transistor and passive components like resistor capacitor on a tiny ~~place~~ piece of semiconductor, mainly Silicon.

Advantage and Limitations of IC

The use of ICs offers a lot of advantages as, compared with discrete components interconnected. For instance,

i/ ICs allow batch fabrication, i.e. hundreds of identical circuits can be formed simultaneously on a single silicon wafer. The circuits thus become inexpensive.

ii/ As ICs are much smaller in size and weight, they are useful in applications where weight and space are critical, such as, in aircraft and space vehicles.

iii/ Miniaturization, i.e., realization of small-size devices is the main advantage of IC. Fabrication of more than 10^8 transistors within a chip area of $1\,cm^2$ is now a common feature.

iv/ Due to the miniaturization of components and connecting leads, the high-frequency performance of ICs is better.

→ Despite the above benefits, ICs have several limitations too.

i) Very small resistors (less than a few ohms) and very large resistors (of the order of meg ohm) can not be obtained by IC technology.

ii/ Large capacitances (greater than 200 pF) can not be produced.

iii/ Inductors and transformers can not be fabricated in the ICs.

iv/ The tolarance of the IC passive components is large (typically ±20 percent).

v/ The power dissipation capacity is small.

vi/ The IC components are voltage-sensitive and have large temperature coefficients.

Offset error voltages and current

→ An ideal OP AMP is perfectly balanced, i.e. $V_o = 0$ when $V_1 = V_2$.

→ In practice, an OP AMP shows an unbalance due to a mismatch of the built-in transistors following the inverting and non inverting input terminals. This mismatch gives unequal bias currents flowing through the input terminals. Thus an input offset voltage has to be applied between the two input terminals to balance the output.

1, Input bias current → The input bias current is half the sum of the individual currents entering the two input terminals of a balanced amplifier.

The input bias current is $i_B = (i_{b1} + i_{b2})/2$,

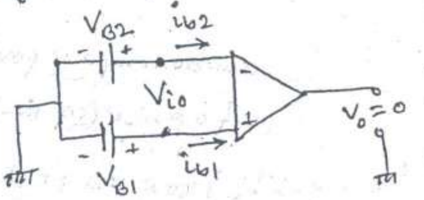
when $V_o = 0$.

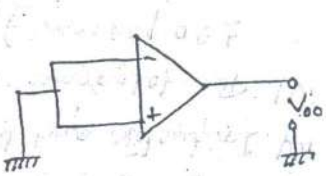
2, Input offset current → The input offset current i_{io} is the difference between the individual currents entering the input terminals of a balanced amplifier.

Thus $i_{io} = i_{b1} - i_{b2}$, when $V_o = 0$

3, Input offset voltage → The input offset voltage V_{io} is the voltage to be applied between the input terminals to balance the amplifier.

4, Output offset voltage → The output offset voltage V_{oo} is the voltage at the output terminal when the two input terminals ~~are~~ are grounded.





The relative sensitivity of an OP-AMP to a difference signal as compared to a common mode signal is called "Common Mode Rejection Ratio" (CMRR) and gives the figure of merit P of a differential amplifier. So CMRR

$$P = \frac{|A_d|}{|A_c|} \quad \text{and is expressed in dB.}$$

The higher the value of CMRR, the better is the OP-AMP.

$$\therefore \quad V_0 = A_d V_d \left(1 + \frac{A_c V_c}{A_d V_d}\right) = A_d V_d \left(1 + \frac{1}{\rho}\frac{V_c}{V_d}\right)$$

* Problem :- determine V_0, when $V_{i1} = 150\ \mu V$, $V_{i2} = 140\ \mu V$
$A_d = 4000$ and $\rho = 100$

* Slew Rate :- It is defined as the maximum rate of change of output voltage when driven by a large step-input voltage.

$$SR = \frac{\Delta V}{\Delta T} \quad V/ms$$

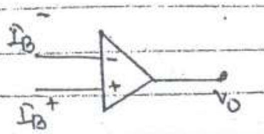
So, $SR = 1\ V/\mu s$ means that the O/P rises or falls by 1V in one μs.

The ideal SR should be ∞, which signifies that the O/P should change instantaneously in response to the I/P step voltage.

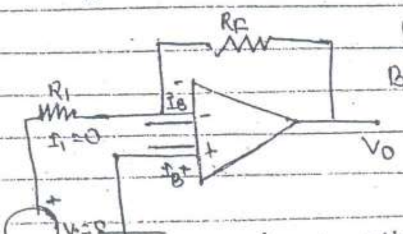
* The non-ideal dc characteristics add error components to the dc output voltage are -

i) Input Bias Current : It is defined as the average of the currents that flow into the inverting and non-inverting terminals of the op-amp.

$$So, \ I_1 = \frac{I_B^- + I_B^+}{2}$$



for a $\qquad I_B = 500\ mA$ or less



Inverting Amplifier with bias current.

For the set. V_0 must be zero for $V_i = 0$
But due to I_B^-, Output

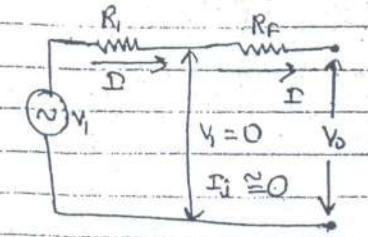
$$V_0 = (I_B^-)R_F = 500\ mA \times 1\ M\Omega$$
$$= 500\ mV$$

an offset value

OP-AMP application :

Before going into the various applications of op-amp. Let have a very important concept of "Virtual Ground" or "Virtual Earth".

In general 'ground' means there exists a short ckt. i.e the voltage is zero and currents flow through, to the ground. The concept of 'virtual ground' implies that although the voltage is nearly 0V there is no current through the short to ground. Consider the ckt below-



"Virtual ground" is a concept only, physically does not exist. It is useful in some application to evaluate the overall gain of the ckt.

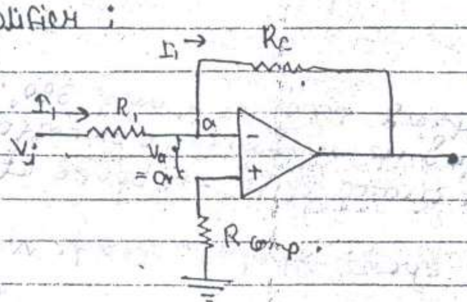
Here,

$$I = \frac{V_1}{R_1} = \frac{-V_0}{R_f}$$

$$\therefore \quad \boxed{V_0/V_1 = -R_f/R_1}$$

* Inverting Amplifier :

Ckt Diagram :



This is the most widely used amplifier among all other op-amp ckts.

Description : A ~~feett~~ feedback of the V_0 is the fed back to the inverting input terminal through R_f. The non-inverting terminal is grounded.

Analysis : The op-amp used is an ideal one (assume)

Let the voltage at pt a ⇒ V_a

∴ Nodal Equation at a gives -

$$\frac{V_i - V_a}{R_1} = \frac{V_a - V_0}{R_f}$$

[As the input impedence is infinite no current does flow through the op-amp but it passes through R_f]

As the +ve terminal is grounded and $A_{OL} = \infty$,

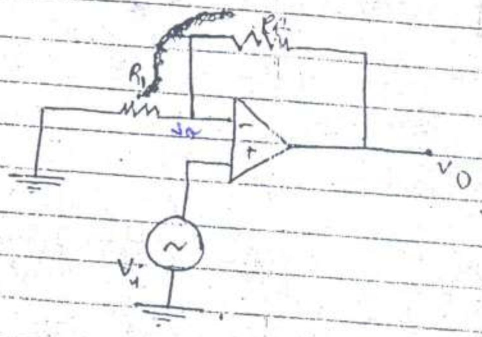
$$\frac{V_0}{V_d} = A_{OL} \quad \text{or} \quad V_d \simeq 0$$

So pt. a is at virtual ground and $V_a = 0$

$$\therefore \frac{V_i}{R_1} = \frac{-V_0}{R_f} \quad \text{or} \quad \boxed{\frac{V_0}{V_i} = -\frac{R_f}{R_1}} \Rightarrow \boxed{A_{CL} = -\frac{R_f}{R_1}}$$

* Non - inverting Amplifier :

Ckt Diagram :



Description :- The input voltage V_i is applied at the positive noninverting terminal of the op-amp. The feed back resistor is used between V_0 and negative inverting terminal

Analysis :- Since the $V_d = 0$, point 'a' is at potential V_i, the same as the input voltage

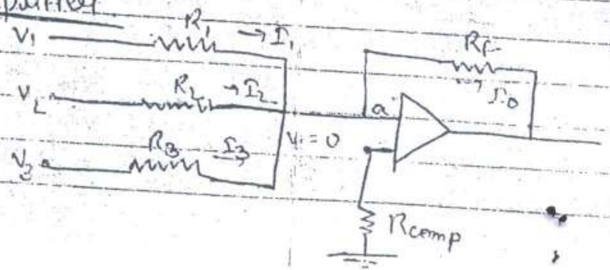
$\therefore$ Applying KCL at node 'a'

$$\frac{V_0 - V_a}{R_f} = \frac{V_a - 0}{R_1} \Rightarrow \frac{V_0}{R_f} = V_i\left(\frac{1}{R_1} + \frac{1}{R_f}\right)$$

$$\text{or} \quad \frac{V_0 - V_i}{R_f} = \frac{V_i}{R_i} \quad \text{or} \quad \boxed{\frac{V_0}{V_i} = \left(1 + \frac{R_f}{R_1}\right)}$$

$$\therefore \boxed{A_{CL} = 1 + \frac{R_f}{R_1}}$$

* Summing Amplifier



Description : A typical summing amplifier with three input voltages V_1, V_2, V_3 will three input resistances R_1, R_2, R_3 respectively are added with the negative terminal of the op-amp. The feedback resistor is R_f.

Analysis :- The point 'a' is at virtual ground, so $V_a = 0$

Now applying KCL at node 'a'

$$I_1 + I_2 + I_3 = I_0$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = \frac{-V_0}{R_f}$$

or $$V_0 = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

if $R_1 = R_2 = R_3 = R$

$$\boxed{V_0 = -\frac{R_f}{R}(V_1 + V_2 + V_3)}$$

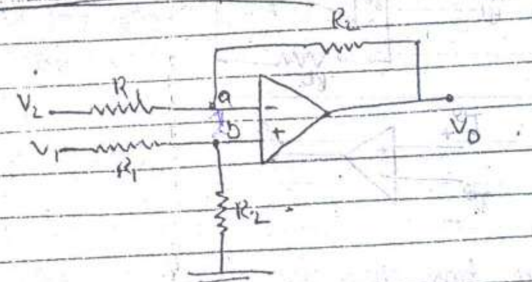
with $R_f = R$

$$\boxed{V_0 = -(V_1 + V_2 + V_3)}$$, (-ve sign shows or signifies inverting amplifier)

This equation shows that the o/p is numerically equal to the algebraic sum of the input voltage, and hence the name.

* Differential or Difference Amplifier :

Ckt Diagram



Description :- A differential amplifier amplifies the difference between the two input voltages. Suppose we are to amplify $(V_1 - V_2)$. So V_2 is applied at negative or inverting terminal, and V_1 is applied at +ve or non-inverting terminal.

Analysis : since, $V_d = 0$, point a and b are at same potential, say V_3.

$\therefore$ Nodal equation at point 'a' – $\frac{V_3 - V_2}{R_1} = \frac{V_o - V_3}{R_2}$ ... (i)

and at point 'b' = $\frac{V_3 - V_1}{R_1} + \frac{V_3}{R_2} = 0$ ... (ii)

From (i) we get

$$\left(\frac{1}{R_1} + \frac{1}{R_2}\right) V_3 - \frac{V_2}{R_1} = \frac{V_0}{R_2} \quad \text{... (iii)}$$

From (ii) we get

$$\left(\frac{1}{R_1} + \frac{1}{R_2}\right) V_3 - \frac{V_1}{R_1} = 0 \quad \text{... (iv)}$$

By (iii) – (iv), we get

$$\frac{1}{R_1}(V_1 - V_2) = \frac{V_0}{R_2}$$

or $$\boxed{V_0 = \frac{R_2}{R_1}(V_1 - V_2)}$$

Differential amplifier has wide use in instrumentation amplifiers.

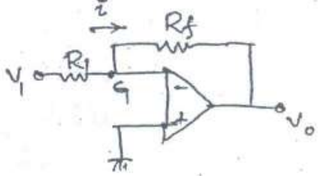
The value of R_2/R_1 is chosen to be very large. So the output can be large for small difference.

e.g. $R_2 = 100R_1$, $V_0 = 100(V_1 - V_2)$; i.e. a small difference is amplified 100 times.

Scale changer

The closed-loop gain of the inverting amplifier is

$$\frac{V_o}{V_1} = -\frac{R_f}{R_1}$$



Let $R_f/R_1 = K$ (a real constant)
in the circuit of fig.
The output voltage can be written as

$$V_o = -KV_1$$

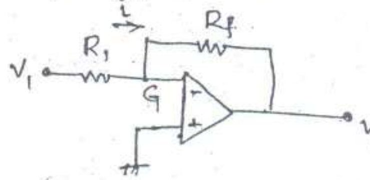
Thus the output voltage scale is obtained by multiplying the input voltage scale by $-K$, called the scale factor.

→ Using precision resistors, accurate values of K can be achieved. The inverting amplifier can then serve as a scale changer.

Phase shifter.

The closed-loop gain of the inverting amplifier is

$$\frac{V_o}{V_1} = -\frac{R_f}{R_1} \quad \text{--- (1)}$$



Let the resistances R_1 and R_f in the circuit of fig be replaced respectively by the impedances Z_1 and Z_f which have equal magnitudes but different phase angles. Hence

$$\frac{V_o}{V_1} = -\frac{Z_f}{Z_1} = -\frac{|Z_f|\exp(j\theta_f)}{|Z_1|\exp(j\theta_1)} = \exp\left[j(\pi+\theta_f-\theta_1)\right] \quad \text{--- (2)}$$

Since $|Z_f| = |Z_1|$ and $\exp(j\pi) = -1$.

→ The angles θ_f and θ_1 are respectively the phase angles of Z_f and Z_1.

→ The eqn (2) shows that V_o leads V_1 by $(\pi+\theta_f-\theta_1)$, but $|V_o| = |V_1|$.

→ Obviously, the circuit shifts the phase of a sinusoidal input voltage leaving its magnitude unaltered. The phase shift can be anything between $0°$ and $360°$.