OPAMP

OPAMP is an "operational amplifier", that means basically it is an amplifier. It is named 'operational' because it can be used to perform many mathematical operations like addition, subtraction, comparison, integration, differentiation etc. Thus OPAMP is an amplifier which is capable of performing many other functions.

OPAMP is a directly coupled high gain amplifier.

The basic building block of all OPAMPs is a differential amplifier circuit.

Drawbacks of RC coupled amplifiers :-

① The gain of RC coupled amplifiers decreases in low frequency range and high frequency range.

② Very low frequency ac signals cannot be amplified.

③ DC (zero frequency) signals cannot be amplified.

These drawbacks can be removed by using direct coupled amplifiers. But these amplifiers have the following drawbacks:-

① The output changes with the age / time and change in supply voltage. This effect is observed even in the absence of an input signal which leads to an output which is unwanted. This is called 'drift'.

② Even if input is ac, a dc component is present in the output.

③ Any noise or unwanted signal appearing at the input of the amplifier becomes appreciable at the output, due to high gain.

Drawbacks of direct amplifiers

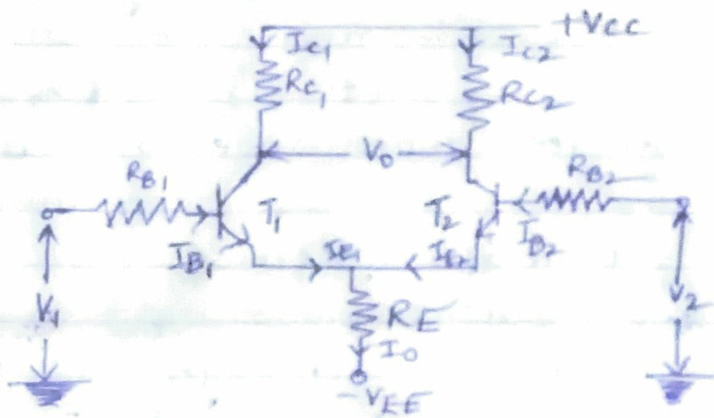
1. Output changes with age or time and change in supply voltage.
2. Noise appearing at the input of the amplifier becomes appreciable at the output due to high gain.

Advantages of differential amplifier

1. It can be used to amplify both ac and dc.
2. It amplifies difference voltage and hence rejects noise or common mode signals.

Differential Amplifier :-

This amplifier amplifies the difference between two input signals and hence called differential amplifier. Its circuit diagram is shown below. It consists of 2 identical CE sections.



Transistors T_1 and T_2 are well-matched in all their characteristics ; $R_{C_1} = R_{C_2}$ and $R_{B_1} = R_{B_2}$. A dual power supply is used for providing transistor biasing. Let V_1 and V_2 denote the externally applied input to T_1 and T_2 respectively. The output voltage V_o is measured between the two collectors of T_1 and T_2.

Suppose there is no externally applied input to the bases of T_1 and T_2 ie $V_1 = V_2 = 0V$. Under this condition, currents through T_1 and T_2 will be equal ie $I_{C_1} = I_{C_2}$; $I_{B_1} = I_{B_2}$ and hence there will be no potential difference between the collectors of the two transistors $\therefore V_o = 0V$. Current I_o that flows through RE is equal to the sum of the emitter currents of the two transistors ie $I_0 = I_{E_1} + I_{E_2}$.

Output voltage will be zero even if V_1 and V_2 are finite, so long as they are equal. ie if $V_1 = V_2$, $V_0 = 0$.

If $V_1 > V_2$, T_1 conducts more and current through it increases. T_2 conducts less, it's emitter current decreases by the same amount by which emitter current of T_1 increased and the current through R_E remains equal to I_0. With collector current of T_1 greater than collector current of T_2 the collector voltage of T_1 is less than that of T_2. Hence a potential difference is developed between the two collectors.

If $V_2 > V_1$, current through T_2 increases. At the same time, current through T_1 decreases equally, maintaining current through R_E, equal to I_0. Once again, a potential difference is developed between the two collectors due to different collector currents.

This circuit amplifies the difference in the two input voltages and hence it is called a differential amplifier ie if $V_1 - V_2 = 0$, $V_0 = 0$. If $V_1 - V_2$ has a finite value, then $V_0 = A_d(V_1 - V_2)$ where A_d is the differential gain of the amplifier.

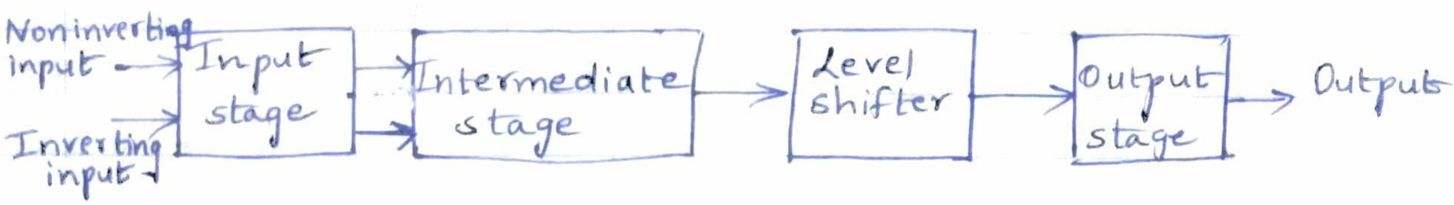
Differential Amplifier Configurations:—

There are four types of differential amplifier configurations:

(1) The dual input ~~inpu~~, differential or balanced output
(2) The dual input, single-ended or unbalanced output
(3) The single input, differential output.
(4) The single input, single-ended output.

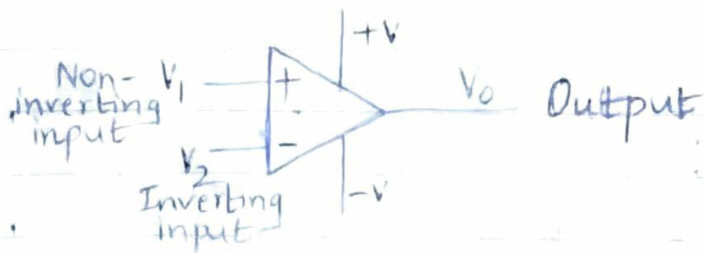
These configurations are defined according to the number of input signals used and the way output is measured. When we use two inputs, the configuration is said to be dual input; otherwise it is a single input. If the output voltage is measured between the two collectors, the configuration is referred to as a balanced or differential output. On the other hand, if the output is measured at either collector with respect to ground, the configuration is said to be unbalanced or single-ended output.

Block diagram of an OPAMP:—



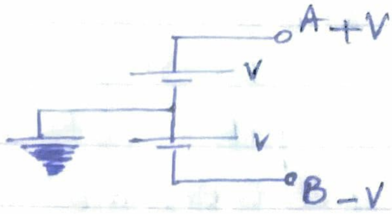
An OPAMP is a multistage amplifier which can be represented by the above block diagram. The input stage is a dual input, differential output differential amplifier. This stage generally provides most of the voltage gain of the amplifier and also establishes the other characteristics of an OPAMP, such as input impedance, slew rate, bandwidth and rejection of common-mode signals. The intermediate stage is usually another differential amplifier, which is driven by the output of the first stage. In most amplifiers, the intermediate stage is a dual-input ~~signa~~ single-ended output and it provides further gain. The dc voltage at the output of the intermediate stage is well above ground potential. Therefore, generally, the level translator or shifting circuit is used after the intermediate stage to shift the dc level at the output of this stage downward to zero volts with respect to ground. The final stage is a power amplifier whose function is to provide maximum power output.

Symbol :-



The voltage to the noninverting input is V_1 volts and voltage to the inverting input is V_2 volts. V_0 is the output voltage. Note that all these voltages are measured with respect to ground. The two inputs of the OPAMP are the noninverting input (indicated by the '+' sign), the inverting input (indicated by the '−' sign). The non-inverting input is so named because an ac signal or dc voltage applied to this input produces an in phase or same polarity signal at the output. On the other hand, the (−) input or inverting input is so called because an ac signal or dc voltage applied to this input produces an 180° out of phase or opposite polarity signal at the output.

OPAMPs normally use a dual power supply consisting of 2 supplies connected in series as shown below.



Terms and parameters used with an OPAMP:

① Open loop gain A_{OL}:

In case of amplifiers, the term open loop indicates that no connection, either direct or through another network, exists between the output and input terminals. ie. the output signal is not fed back in any form as part of the input signal and the loop that would have been formed with feedback is open. Since the OPAMP amplifies the difference voltage between the two input terminals, the open-loop voltage gain is defined as the ratio of the output voltage to the differential input voltage. ie $A_{OL} = \dfrac{V_o}{V_1 - V_2}$

where V_0 is the output voltage and V_1, V_2 are the voltages at the non-inverting and inverting inputs respectively of the amplifier. A_{OL} is very large, of the order of 10^4.

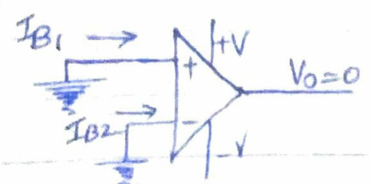
2) Offset voltage :

An ideal OPAMP gives zero output when the input voltages are zero. But practical OPAMPs behave differently. Due to a slight mismatch in the transistor characteristics, the output voltage is not zero for zero input voltages and has a certain finite value. This value of the output voltage is called the output offset voltage. Such an output offset voltage is an error voltage and is therefore undesirable.

Input offset voltage is the voltage that must be applied between the two input terminals of an OPAMP to reduce the output voltage to zero.

3) Input Offset current :

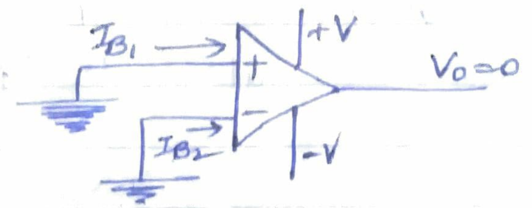
For a balanced OPAMP ie output zero for zero input voltages, if I_{B_1} and I_{B_2} are the currents flowing into the non-inverting and inverting terminals respectively of an OPAMP, then the algebraic difference between the currents is referred to as input offset current I_{io}. In the form of an equation, $I_{io} = |I_{B_1} - I_{B_2}|$



Smaller the offset current, better the OPAMP. In the ideal case, $I_{io} = 0$.

4). Input bias current:

For a balanced OPAMP ie output zero for zero input voltages, if I_{B_1} and I_{B_2} are the currents flowing into the non-inverting and inverting terminals respectively of the OPAMP, then the average of the currents is referred to as input bias current I_B. In equation form, $I_B = \frac{I_{B_1} + I_{B_2}}{2}$



5) Common-mode rejection ratio (CMRR):

This is an important parameter for an OPAMP. It is an index of the ability of the amplifier to reject common-mode signals. Common-mode signals are signals common to both the inputs. For eg. noise signals. Unwanted signals or noise signals affect the performance of an OPAMP and must be rejected ~~th~~ by the amplifier. CMRR indicates this ability of the OPAMP.

It is defined as the ratio of the differential voltage gain (A_d) to the common-mode voltage gain (A_{cm})

ie $CMRR = \frac{A_d}{A_{cm}}$

Common-mode voltage gain (A_{cm}) is the ratio of the output common-mode voltage V_{ocm} to the input common-mode voltage(V_{cm}): A_d is same as A_{OL}

$$A_{cm} = \frac{V_{ocm}}{V_{cm}}$$

From the above equations, it is clear that, to have ~~a very good~~ total rejection of noise signals, $A_{cm} = 0$ and therefore $CMRR = \infty$.
CMRR is normally expressed in decibels as

$$CMRR(db) = 20 \log\left(\frac{A_d}{A_{cm}}\right).$$

Higher the value of CMRR, better is the ability of the OPAMP to reject common-mode signals such as noise signals. Ideally, $CMRR = \infty$

6) Slew Rate :

When input to an OPAMP changes, the output also changes. But this change in output does not occur instantly. It takes some time. The rate of change of output with respect to time is called 'slew rate', expressed in $V/\mu secs$.

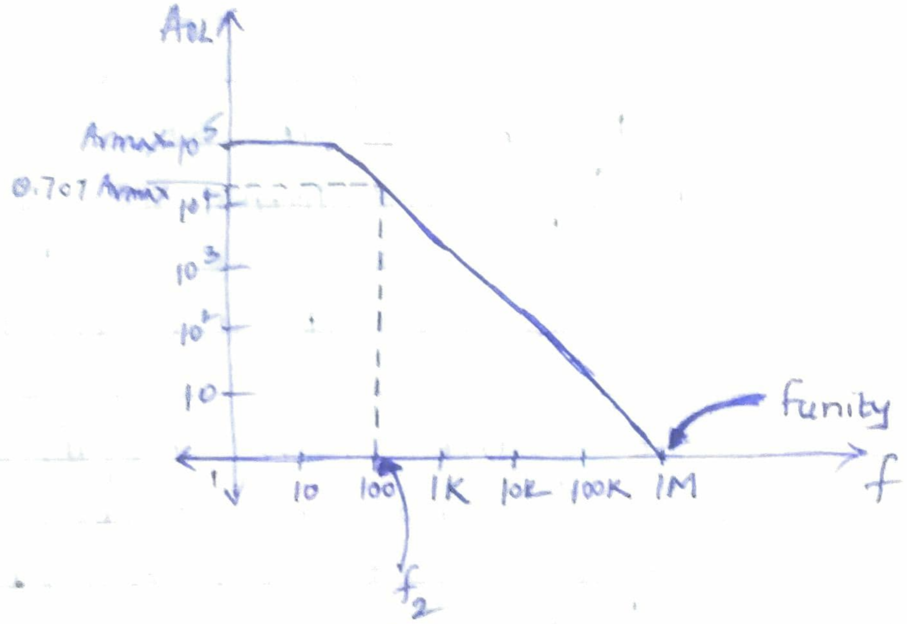
ie Slew rate $= \frac{dV_o}{dt}$

High slew rate value indicates that output voltage changes rapidly with input voltage changes. Ideally, slew rate is infinity.

7) Frequency Response :

The variation of the open-loop voltage gain of the amplifier with the frequency of the input signal is termed frequency response of the amplifier.

The frequency response curve of an OPAMP is shown below.



It is observed that the open-loop voltage gain at DC and low frequencies is very high, of the order of 10^5. But as the frequency of the input signal increases, the gain falls at a regular rate. The frequencies at which the gain is 0.707 times or 70.7% of the maximum gain are called cut-off frequencies. Here, the lower cut-off frequency is 0 Hz and upper cut-off frequency is f_2. The frequency at which voltage gain falls to unity is called unity-gain frequency (f_{unity}).

Bandwidth of an amplifier is the frequency range over which the gain is greater than or equal to 0.707 times the maximum gain.

Bandwidth $= f_2$ since lower cut-off frequency is zer

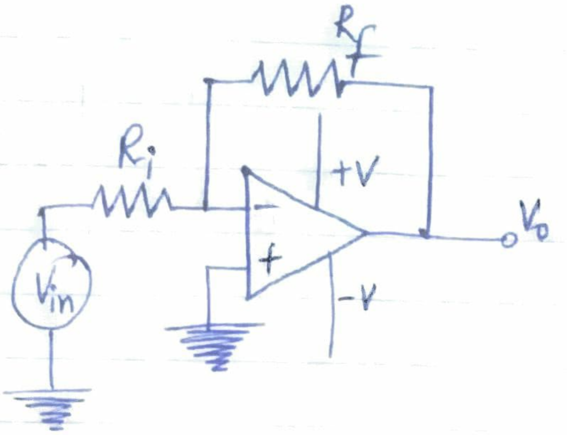
The product of gain and upper cut-off frequency is called 'Gain Bandwidth Product'. For IC 741, its value is 1 MHz ie equal to funity.

Ideal OPAMP characteristics

1. Infinite open-loop gain
2. Zero output voltage when input voltage is zero.
3. Resistance offered by an OPAMP at its input terminals is called input resistance. An ideal OPAMP has infinite input resistance so that any signal source can drive it and there is no loading.
4. Just like a voltage source, an amplifier also has a certain internal resistance referred to as output resistance. An ideal OPAMP has zero output resistance.
5. An ideal OPAMP has infinite bandwidth so that all frequency signals from 0 to ∞ Hz are amplified to the same extent.
6. An ideal OPAMP has infinite CMRR value so that the output common-mode noise voltage is zero.
7. An ideal OPAMP has infinite slew rate so that output voltage changes occur simultaneously with change in input voltage.
8. Zero input offset current.

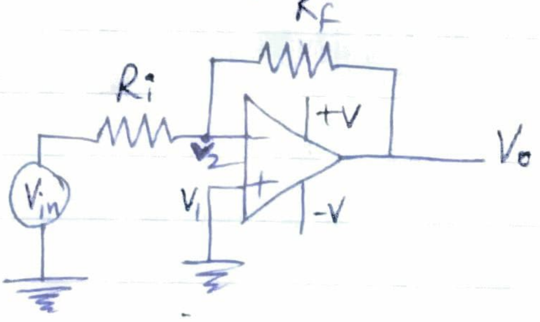
Q) Closed loop gain A_{CL} :

The voltage gain of an amplifier with feedback is called the closed loop gain of the amplifier. In the figure below, the feedback resistor R_f forms a closed loop between the input and the output.



Here the closed loop gain of the OPAMP is defined as $A_{CL} = \frac{V_o}{V_{in}} = -\frac{R_f}{R_i}$

9) Concept of virtual ground:



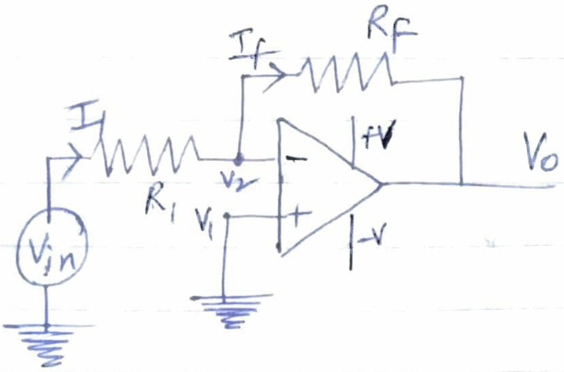
If V_1 is the voltage at non-inverting input and V_2 is the voltage at inverting input, then the differential voltage gain ~~of~~ of an OPAMP is given by $A_d = \frac{V_o}{V_1 - V_2}$ where V_o is the output voltage.

For an ideal OPAMP, A_d is infinite. $\therefore V_1 - V_2 = 0$
ie $V_1 = V_2$ —①
Thus inverting input and noninverting input voltages are equal, but no current flows between them as input impedance is infinite, ideally. The two inputs are hence called virtually short. Many times, the non-inverting input is grounded, ie $V_1 = 0$. From eqn ①

we can conclude that $V_2 = 0$. But the inverting terminal is not an actual ground since it cannot sink or source any amount of current.
∴ the inverting input is said to be at virtual ground.

Applications :-

Inverting amplifier



For the inverting amplifier, the input voltage V_{in} is applied to the inverting input terminal through input resistance R_1. The non-inverting input is grounded. A resistor R_f is connected in the feedback network between the output terminal and the inverting input terminal. (negative feedback)

With input resistance of OPAMP very high, ideally infinite, all the current flowing through R_1 flows through R_f.

$$\therefore I_1 = I_f$$

$$\frac{V_{in} - V_2}{R_1} = \frac{V_2 - V_0}{R_f}$$

However $V_2 = 0$ by the virtual ground concept.

$$\therefore \frac{V_{in}}{R_1} = -\frac{V_o}{R_f}$$

$$\therefore \frac{V_o}{V_{in}} = -\frac{R_f}{R_1}$$

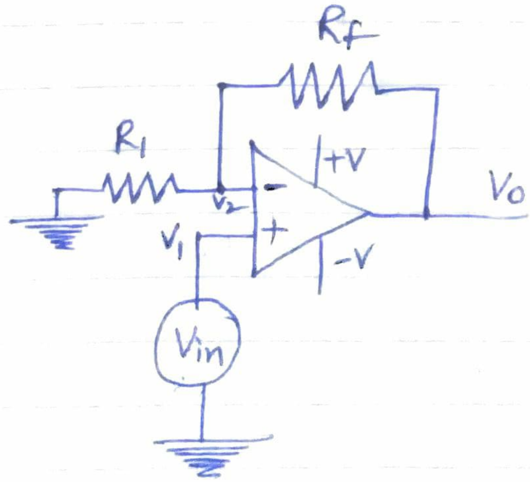
$A_{CL} = \frac{V_o}{V_{in}} = -\frac{R_f}{R_1}$ is the gain of the amplifier in the inverting configuration.

- Output voltage $V_o = -\frac{R_f}{R_1} V_{in}$

ie output voltage is $\frac{R_f}{R_1}$ times the applied input V_{in}.

The negative sign in the above expression indicates that the input and output signals are out of phase by 180° or of opposite polarities.

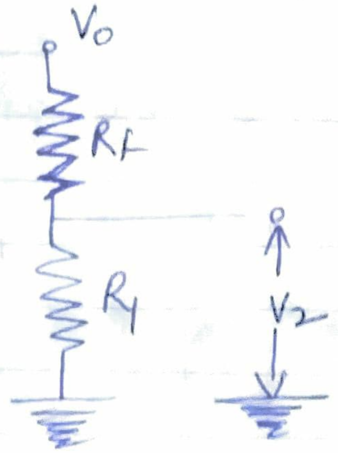
Non inverting amplifier

- 

For ~~an~~ noninverting amplifier, the signal to be amplified V_{in} is applied to the noninverting terminal.

The inverting input terminal is grounded through a resistor R_1. A feedback resistor R_f is connected between inverting input and output terminals. (negative feedback)

R_f and R_1 form a potential divider chain and the inverting input therefore receives a voltage V_2 which is a fraction of the output V_o and is given by $V_2 = \frac{R_1}{R_1+R_f} \times V_o$ — ①



V_2 is the feedback voltage.

Also $V_1 = V_{in}$ — ② from above circuit.

Since open-loop gain of the amplifier is very high ideally infinite, $V_1 = V_2$ — ③

From eqns ①, ②, ③

$$V_{in} = \frac{R_1}{R_1+R_f} V_o$$

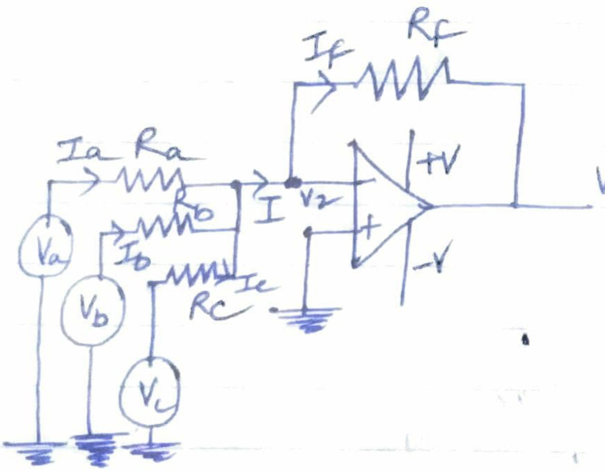
$$\therefore \frac{V_o}{V_{in}} = \frac{R_1+R_f}{R_1} = 1 + \frac{R_f}{R_1}$$

$A_{CL} = \frac{V_o}{V_{in}} = 1 + \frac{R_f}{R_1}$ is the gain of the amplifier in the non-inverting configuration.

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

ie output voltage is $1+\frac{R_f}{R_1}$ times the applied input and in phase with it. Therefore the circuit is called a non-inverting amplifier.

Inverting adder / Summing amplifier:-



The above figure shows the inverting configuration with three inputs V_a, V_b, V_c, which are to be added by the adder. The voltage V_a is applied to the inverting input terminal through input resistor R_a while voltages V_b and V_c are given to the inverting input through input resistors R_b and R_c respectively.

In this circuit, $I_a + I_b + I_c = I$ and $I = I_f$ since input resistance of OPAMP is very high, ideally infinite.

$$\therefore I_a + I_b + I_c = I_f$$

$$\frac{V_a - V_2}{R_a} + \frac{V_b - V_2}{R_b} + \frac{V_c - V_2}{R_c} = \frac{V_2 - V_o}{R_f}$$

By the virtual ground concept, $V_2 = 0$.

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

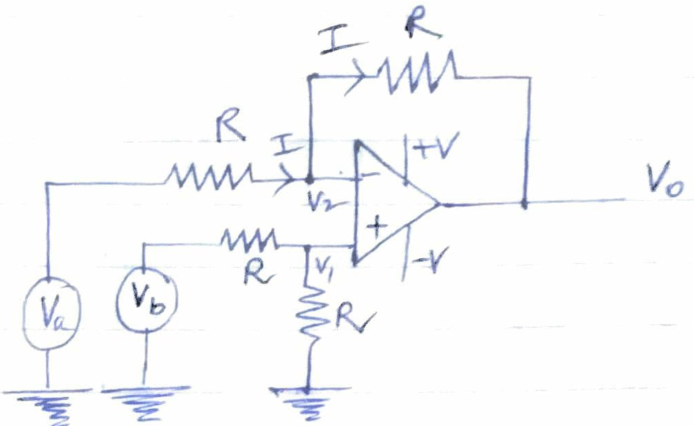
$$\therefore V_o = -\left(\frac{R_F}{R_a} V_a + \frac{R_F}{R_b} V_b + \frac{R_F}{R_c} V_c\right)$$

If $R_a = R_b = R_c = R$, then $V_o = -\frac{R_F}{R}(V_a + V_b + V_c)$

This means that the output voltage V_o is the sum of the input voltages multiplied by the gain of the amplifier.

If $R_f = R$, then $V_o = -(V_a + V_b + V_c)$

Subtractor :-



In this circuit, neither of the OPAMP input terminal is connected directly to ground. Input voltage V_a is applied to the inverting input and input voltage V_b is applied to the non-inverting terminal.

Now $V_1 = \frac{R}{R+R} \times V_b = \frac{V_b}{2}$ —— (1)

and $\frac{V_a - V_2}{R} = \frac{V_2 - V_o}{R}$ ($\because$ input resistance is high)

ie $V_a - V_2 = V_2 - V_o$

$V_a + V_o = 2V_2$

$$\therefore V_2 = \frac{V_a + V_o}{2} \quad \text{—— (2)}$$

Since open-loop gain of OPAMP is very high, ideally infinite, $V_1 = V_2$

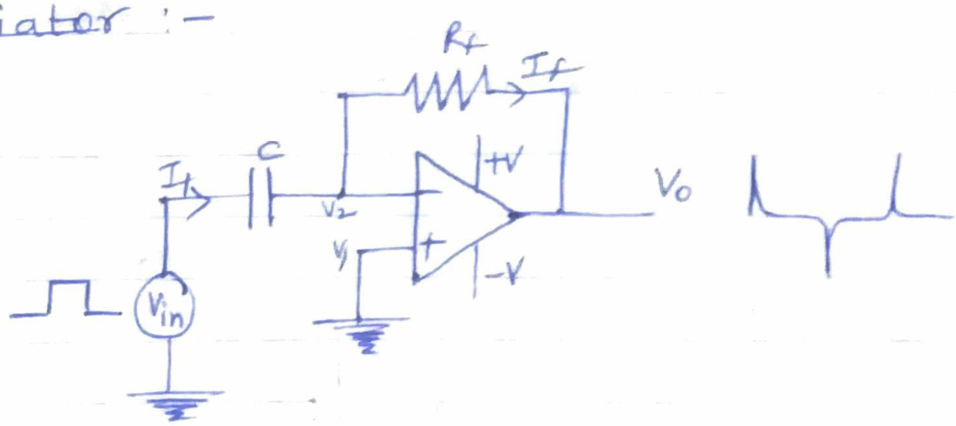
$$\therefore \frac{V_b}{2} = \frac{V_a + V_o}{2}$$

$$V_b = V_a + V_o$$

$$\text{or} \quad V_o = V_b - V_a$$

Thus the output voltage V_o is equal to the difference between the voltages V_b and V_a applied at the non-inverting and inverting input terminals respectively.

Differentiator :-



In this circuit, the input voltage V_{in} is applied to the inverting input through the capacitor C. A resistor R_f is connected between the inverting input terminal and the output terminal. The noninverting input is grounded.

$I_1 = I_f$ since input resistance of OPAMP is ideally infinite.

$$I_1 = C\frac{d}{dt}(V_{in} - V_2) \quad \text{and} \quad I_f = \frac{V_2 - V_o}{R_F}$$

$$\therefore \; C\frac{d(V_{in}-V_2)}{dt} = \frac{V_2-V_o}{R_f}$$

$V_2=0$ by the virtual ground concept

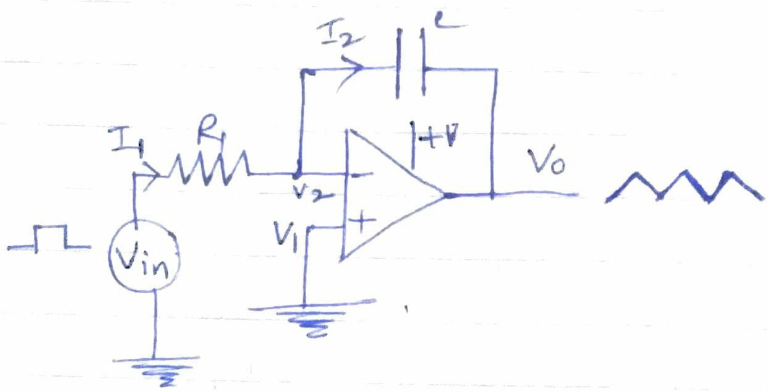
$$\therefore \; C\frac{dV_{in}}{dt} = \frac{-V_o}{R_f}$$

ie $$V_o = -R_f C \frac{dV_{in}}{dt}$$

Thus output V_o is equal to $R_f C$ times the derivative of the input voltage V_{in}. ie the output voltage is proportional to the derivative of the input voltage and therefore this circuit is called a differentiator.

If input to a differentiator is a square wave, output is a spike waveform.

Integrator



In this circuit the input voltage Vin is applied to the inverting input terminal through resistor R_1. The noninverting terminal is grounded. A capacitor is connected between the inverting input and output terminal.

Current $I_1 = I_2$ since input resistance of OPAMP is high, ideally infinite.

$$I_1 = \frac{V_{in} - V_2}{R_1} \quad \text{(Input current)}$$

and $$I_2 = C\frac{d}{dt}(V_2 - V_0)$$

$$\therefore \frac{V_{in} - V_2}{R_1} = C\frac{d}{dt}(V_2 - V_0)$$

Since $V_2 = 0$ by the virtual ground concept,

$$\frac{V_{in}}{R_1} = -C\frac{dV_0}{dt}$$

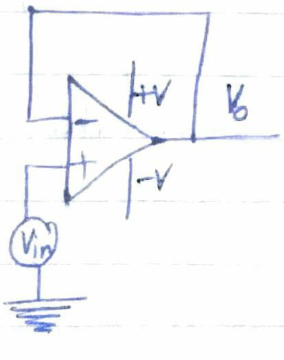
ie $$\frac{dV_0}{dt} = -\frac{1}{R_1 C} V_{in}$$

$$\therefore V_0 = \frac{-1}{R_1 C}\int V_{in}\, dt$$

The above equation implies that the output voltage is proportional to the time integral of the input voltage.

- If input is a square wave, then output is a triangular wave

Voltage follower :-



Voltage follower is a special case of the non-inverting amplifier. For a noninverting amplifier, gain $= 1 + \frac{R_f}{R_1}$

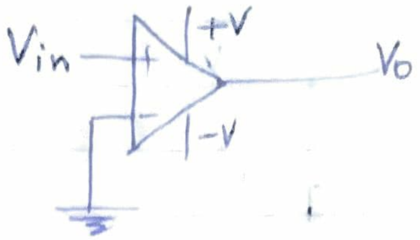
In the above circuit, $R_f = 0$, $R_1 = \infty$. Therefore, gain equals one and output voltage is equal to and in phase with the input. In other words, output follows the input and hence it is called a voltage follower. The voltage follower is also called a noninverting buffer. This circuit has a very very high input resistance and a very low output resistance. When placed between two networks, it removes the loading on the first network.

Comparator :-

A comparator is a circuit with two inputs and one output. It compares an unknown voltage with a known reference voltage and indicates which of the two is greater.

It is an open-loop application of OPAMP. Hence for even a small differential input, the output equals saturation voltage, ~~that~~ $+V_{sat}$ or $-V_{sat}$. The saturation voltage is normally 2 V less than the applied supply voltage.

Comparator with zero reference.



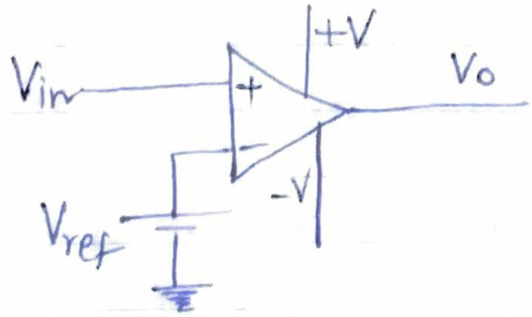
Reference voltage is zero volts, which is the inverting terminal voltage.

When the unknown voltage $V_{in} > 0$, $V_o = +V_{sat}$ since the non-inverting terminal voltage is then greater than inverting terminal voltage.

If $V_{in} < 0$, $V_o = -V_{sat}$ since the non-inverting voltage is less than inverting voltage.

Thus if output is positive, unknown voltage is more than zero and if output is negative, unknown voltage is less than zero.

Comparator with positive reference

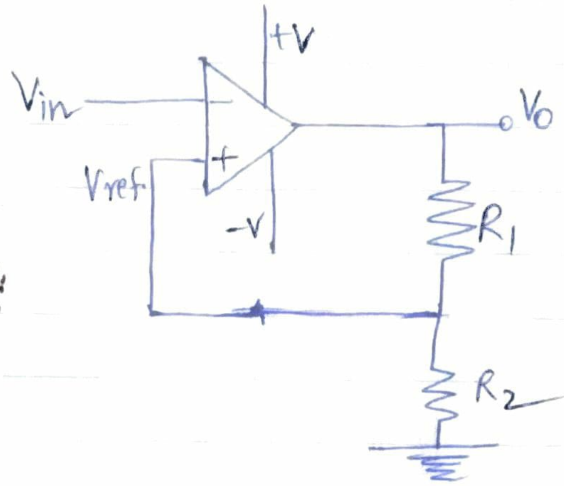


Reference voltage V_{ref} is given to the inverting terminal of OPAMP. Therefore when unknown voltage(V_{in}) is greater than V_{ref}, output is positive.

When V_{in} is less than V_{ref}, output is negative

Thus V_{in} is compared with a positive voltage V_{ref} and output indicated as either $+V_{sat}$ or $-V_{sat}$

Schmitt Trigger or Sine to square convertor



This circuit employs positive feedback and the feedback voltage given to the noninverting input of the OPAMP is given by the equation $V_f = V_{ref} = \frac{R_2}{R_1+R_2} \times V_o$

$$= B\,V_o$$

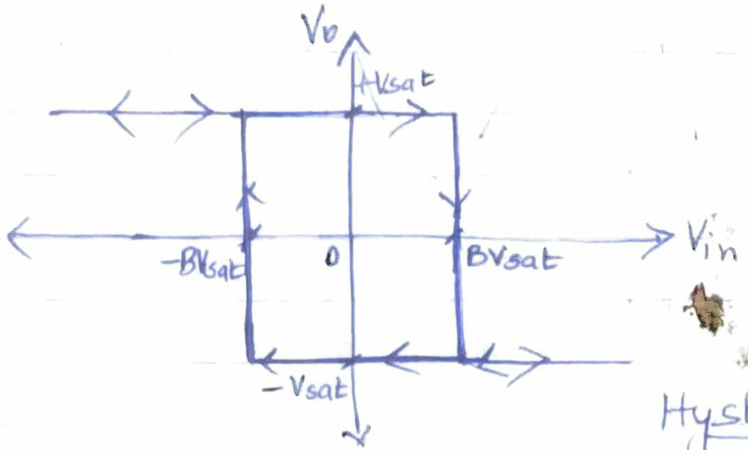
where B is called the feedback fraction.

Hence if the output voltage equals $+V_{sat}$ then $V_{ref} = +B\,V_{sat}$ and if output voltage equals $-V_{sat}$, then $V_{ref} = -B\,V_{sat}$.

Suppose the OPAMP is in positive saturation. ∴ the noninverting input voltage $V_{ref} = +BV_{sat}$. ~~If~~ As long as V_{in} is less than V_{ref}, V_o continues to equal $+V_{sat}$. However when V_{in} exceeds V_{ref}, the output switches to negative saturation.

With output now equal to $-V_{sat}$, V_{ref} equals $-BV_{sat}$. Only when V_{in} takes a

Value more negative than $-BV_{sat}$, the output once again changes to $+V_{sat}$.



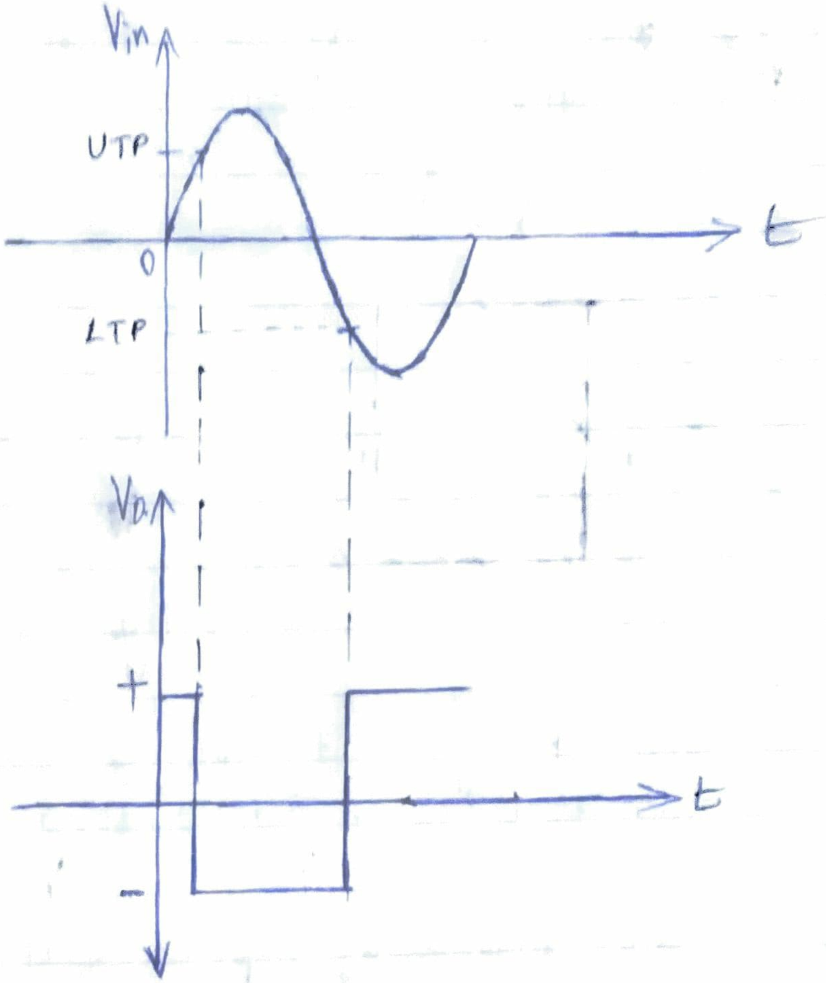
Hysterisis curve

Thus the output goes from positive to negative at only one positive input voltage called the upper trip point or UTP. LTP or lower trip point is the negative input voltage at which the output voltage switches from negative to positive value.

$UTP = +BV_{sat}$ and $LTP = -BV_{sat}$.

The difference between UTP and LTP is called hysterisis. It prevents noise from causing false triggering.

Suppose Vin is a sine wave as shown below. At a certain positive value of Vin (= UTP), output goes from high to low and at a certain negative value of Vin (= LTP), output changes from low to high. Due to this, a sine wave at input produces a square wave at output. Hence called a sine-to square wave converter.



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