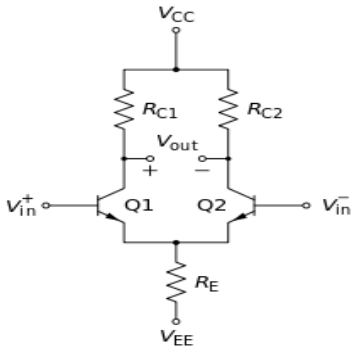
OPERATIONAL AMPLIFIER

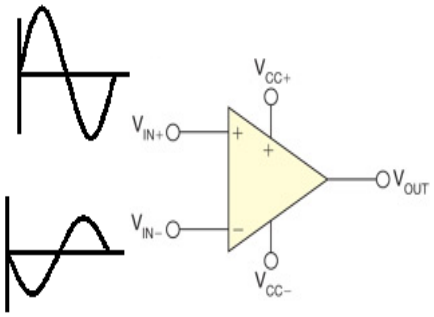
We know that the basic building block of an OP-AMP is a differential amplifier, so we must know the idea working of differential amplifier. *Differential amplifier amplifies the difference between two input signals*. The inputs are applied to the two separate terminals called as differential inputs $V_{id} = V_1 - V_2$.



The differential amplifier circuit is symmetrical in nature. The two transistors T_1 and T_2 are connected to a common supply + V_{EE} & -V_{CC}, equal collector resistors R_{c1} & R_{c2} are connected. The input & output voltage are with respect to ground. Differential amplifier has two inputs and one output therefore it can be operated in three different modes as,

1. Differential input mode.
2. Common input mode.
3. Single ended input mode.

1. Differential input mode –



In this mode the input signal is applied between terminal V_1 and V_2 and output is taken across output terminal and ground. It is called as differential input single ended output mode. Output is taken across either of collectors. Its output is given by equation,

$$V_0 = A\,(V_1 - V_2)$$

Where A = Gain of amplifier.

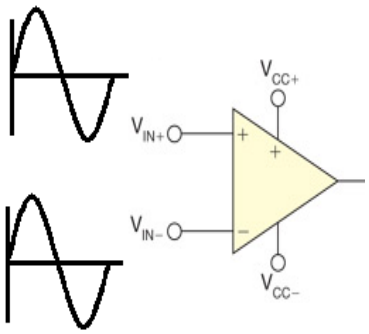
V_1 is 180^0 out of phase with input, $V_1 = V_2$

$$V_0 = A\,[(V_1 - (-V_2)]$$

$$V_0 = 2\,V_1\,A$$

Thus in differential amplifier the maximum gain is two times input voltage multiplied by gain. Differential input gain is $A_{DM.}$

2. Common input mode –



In this mode the same (common) signal is applied to both input terminals, that is

$V_1 = V_2$, then

$$V_0 = A\,(V_1 - V_2)$$

$$V_0 = 0$$

Common mode gain is $A_{CM.}$

Thus there should be high gain for differential mode, it amplifies desired input voltage and rejects unwanted common mode signal like noise, hum etc.

Common Mode Rejection Ratio (CMMR) – The ratio of differential mode gain to the common mode gain is called as Common Mode Rejection Ratio.

It gives the quality of an OP – AMP, How much amount of noise or hum is rejected by an OP-AMP.

$$CMMR = \frac{Differential\ mode\ gain}{common\ mode\ gain} = \frac{A_{DM}}{A_{CM}}$$

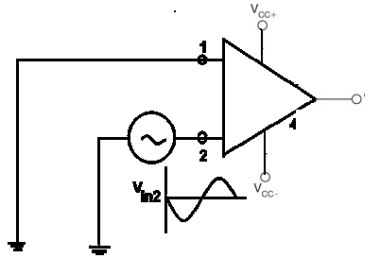
Higher the C. M. M.R. better is the quality of an OP-AMP.

The two leads of OP AMP acts as antenna which picks up the signal of atmosphere, which appears as common signal to both inputs.

Example – Ignition of spark of vehicle, lightning etc.

The differential gain is useful; it amplifies the desired input signal and rejects common unwanted signals like noise or hum etc.

3. Single ended input mode –



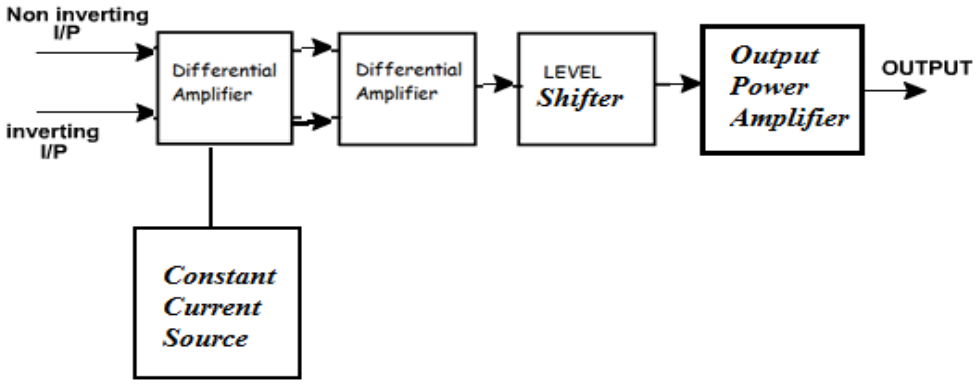
In this mode input is applied to one of its input terminal and other input is made grounded. When output is single ended it is called as an OP – AMP.

Operational Amplifier (OP-AMP) –

Operational amplifier or *OP-AMP refers to a class of high gain DC coupled amplifier that has differential inputs (two inputs) and single ended output*. OP-AMP is basically

a differential amplifier whose basic function is to amplify the difference between two input signals.

Block diagram of OP-AMP –



The internal circuitry of OP – AMP is mainly divided into three parts

1. Input stage
2. Intermediate stage
3. Output stage

1. Input stage – This stage consists of differential amplifier with double ended output. The amplifier provides with constant current source. This stage provides large and stable gain, high input impedance. The constant current source reduces noise and provides high C. M. R. R.

2. Intermediate stage – This stage consists of one or more differential amplifier with single ended output. Due to two or more stages large gain and C. M. R. R. can be obtained. A emitter follower is used so that there is no phase shift between input and output. Hence it gives low output impedance. The outputs of second stage are normally increases due to direct coupling and finally it may be equal to the supply voltage, also in absence of input, output may not be zero. The output is shifted to ground with level shifter circuit.

3. Output stage – Its output impedance is low and it provides sufficient current to load without any distortion. It helps to supply larger output voltage without distortion.

Characteristics of OP –AMP – The ideal and practical characteristics of OP – AMP are as follows

1. **Infinite open loop gain** ($A_v = \infty$)- The gain of OP –AMP when no feedback is provided is called as open loop gain. In ideal condition is value is infinite.

$$A_v = \frac{V_0}{V_{id}}$$

$$A_v \rightarrow \infty, \qquad V_{id} \rightarrow 0$$

Practically the value of open loop gain is about 10^5.

2. Infinite input impedance ($\boldsymbol{Z_{in} = \infty}$) **–** Infinite input impedance ensures that no current flows through the input terminals.

$$Z_{in} = \frac{V_{in}}{I_{in}}$$

$$Z_{in} \rightarrow \infty, \qquad I_{in} \rightarrow 0$$

Practically the value of input impedance is about 20 MΩ.

3. Zero output impedance ($\boldsymbol{Z_0 = 0}$) **–** It is the resistance at the output stage. It gives how much maximum current flow through the output terminals.

$$Z_0 = \frac{V_0}{I_0}$$

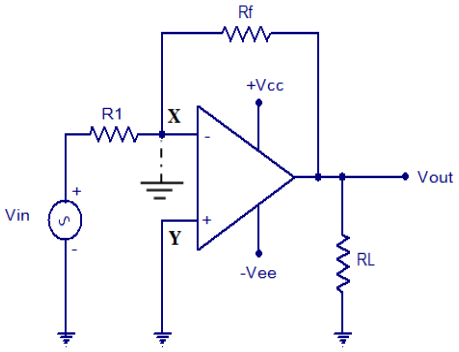
$$Z_0 \rightarrow 0, \qquad I_0 \rightarrow \infty$$

Practically the value of output impedance is about 75 Ω.

4. Infinite band width ($\boldsymbol{\Delta F = \infty}$) **-** The range of frequency for which OP –AMP works properly with maximum gain is called bandwidth. OP – AMP band width is infinite in ideal case and practically it is in MHz

5. Perfect balance - OP – AMP produces linear relationship between input and output.

Que. Explain the concept of virtual ground.



We know that input impedance of OP – AMP is very high therefore no current flows through input resistance R_i. Hence no current flows through points X and Y. As no current flows through these points, they must be at equal potential. The point Y is at ground potential so point X must be also at ground potential. The point X is not physically ground still the potential at X is ground. Hence it is called as virtual ground. Open loop gain is infinite practically very large,

$$A_v = \frac{V_0}{V_i}$$

$$A_v \rightarrow \infty, \qquad V_i \rightarrow 0$$

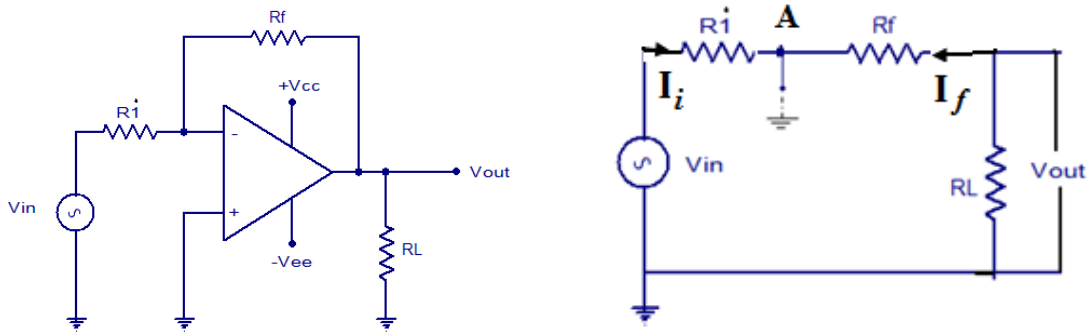
$$V_i = V_1 - V_2 = 0$$

$$V_2 = 0 \; therefore \; V_1 = 0$$

Since V_i is zero thus virtually point X is at zero or ground. When non inverting terminal is grounded inverting terminal is also grounded. But there is no actual short between these two terminals, there is very high input impedance hence it is known as virtual ground.

OP – AMP as an inverting amplifier (Inverting mode) –

Que. Draw circuit diagram of OP – AMP in an inverting mode and derive expression for its output voltage (or gain).



The input is applied to the inverting terminal and non inverting terminal is grounded then OP – AMP is said to be in an inverting mode. The phase shift between input and output is in 180^0.

The output voltage is,

$$V_0 = I_f R_f \quad or \; I_f = \frac{V_0}{R_f}$$

The input voltage is,

$$V_i = I_i R_i \quad or \; I_i = \frac{V_i}{R_i}$$

$$\frac{V_0}{V_i} = \frac{I_f R_f}{I_i R_i}$$

$$But, \quad I_i = -I_f$$

$$\frac{V_0}{V_i} = -\frac{R_f}{R_i}$$

$$\frac{V_0}{V_i} = Gain = A$$

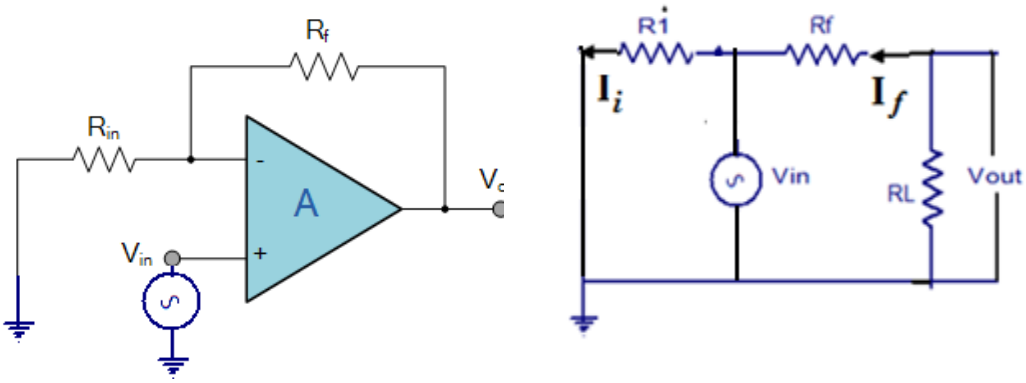
$$\boldsymbol{Gain = A = -\frac{R_f}{R_i}}$$

$$\boldsymbol{V_0 = -\frac{R_f}{R_i} V_i}$$

The negative sign indicates that output signal is inverted with input signal.

OP – AMP as non inverting amplifier (Non Inverting mode) –

Que. Draw circuit diagram of OP – AMP as non inverting amplifier and derive expression for its output voltage (or gain).



The input is applied to the non inverting terminal and inverting terminal is grounded then OP – AMP is said to be in a non inverting mode. The input and output are in phase with each other.

The input impedance of OP – AMP is infinite.

$$I_i = I_f$$

$$\frac{V_{in}}{R_{in}} = \frac{V_o - V_{in}}{R_f}$$

$$V_o - V_{in} = \frac{R_f}{R_{in}} V_{in}$$

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

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

$$\boldsymbol{Gain = A = \frac{V_0}{V_{in}} = \left(\frac{R_f}{R_{in}} + 1\right)}$$

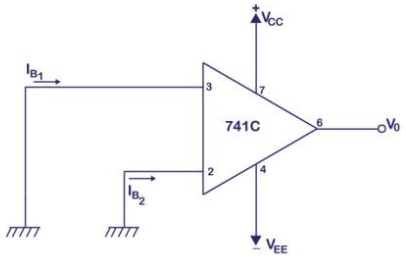
This equation shows that output is in phase with input. The gain of non inverting amplifier cannot be less than one.

Specifications of OP – AMP –

1. Input bias current – *It is the biasing current required at either input to provide zero output voltage with zero input signals.*

Generally OP – AMP has differential amplifier at the input stage. The differential amplifier is a transistor circuit, which is current operated device. The current flowing through the bases of two transistors must be equal. When these currents are unequal, current flows through

external resistance and it produces small differential input voltage which produces an offset output voltage.



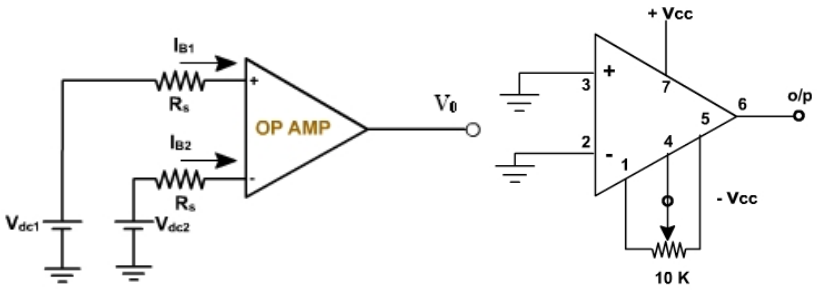
Normally because of mismatch of two transistors, input bias current produces. In general purpose OP – AMP the value of input bias current is 40 nA.

input bias current is also defined as,

$$I_B = \frac{|I_{B1} + I_{B2}|}{2}$$

2. Input offset current – The base currents of input transistors are never equal because of difference between biasing current of inverting and non inverting input is called input offset voltage. It is maximum 20 nA. Smaller the offset current; greater the OP – AMP performance. *It is the difference between two bias currents.*

3. Input offset voltage –

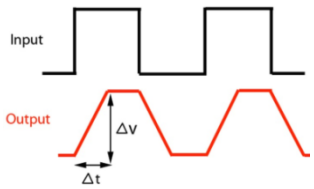


When input voltages to OP – AMP are zero, the output must be zero. But there is small error voltage appeared at output due to mismatch in base to emitter voltages of transistors. This is called input offset voltage. This voltage must apply to particular input terminal to obtain zero output voltage. Practically it may be few millivolts. This is called as offset compensation voltage.

4. Slew rate – When OP – AMP is used for *AC applications* this parameter is very important. *Slew rate is the maximum rate of change of output voltage per unit time.*

The low slew rate produces distortion, it must be high. Slew rate is measured in terms of ***micro volts / second.*** For IC – 741 slew rates is 0.5 volt / millisecond.

$$S = \frac{dV_0}{dt}$$



5. Drift – Drift is related with temperature. When operating temperature of OP – AMP is changes, the output is also changes. The variation in output due to change in temperature is called drift. All OP – AMP parameters are specified at 25^0 C.

6. Open loop gain (A_v) – Internal gain of OP – AMP without feedback is called open loop gain. Practically open loop gain is very high. *It is defined as the ratio of output voltage to the differential input voltage.*

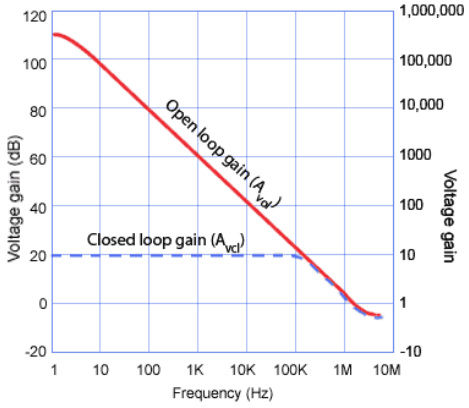
$$A_v = \frac{V_o}{V_{in}}$$

Open loop gain is extremely high. It is defined as the ratio of output voltage to the differential input voltage.

7. Close loop gain – The overall gain of OP – AMP with feedback is called as close loop gain. OP – AMP is generally used with feedback, the gain is adjusted by feedback resistor which has a range of 10^3 to 10^5.

8. Frequency response –

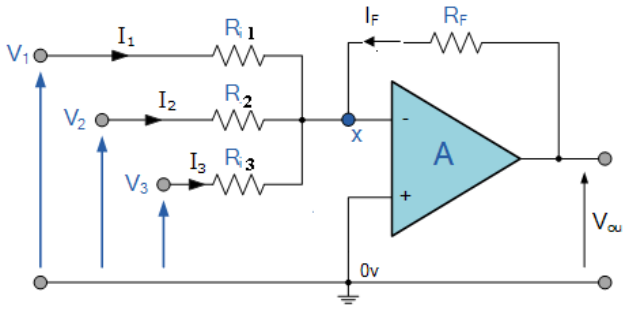
The gain of OP – AMP depends on operating frequency. The frequency response of OP – AMP is given in terms of gain. OP – AMP shows good response for wide range of frequency. It falls beyond certain frequency about few MHz.



Applications of OP – AMP –

1. OP – AMP as summing amplifier (Adder) –

Figure shows circuit of OP – AMP as an inverting adder.V_1, V_2 and V_3 are three inputs fed to the inverting terminals through input resistors R_1, R_2 and R_3.



$$I_f = -I_{in}$$

$$I_{in} = I_1 + I_2 + I_3$$

$$But,\quad I_1 = \frac{V_1}{R_1},\quad I_2 = \frac{V_2}{R_2},\quad I_3 = \frac{V_3}{R_3}\ and\ I_f = \frac{V_0}{R_f}$$

$$I_{in} = I_1 + I_2 + I_3$$

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

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

The negative sign shows that there is 180^0 phase shift between input and output.

$$If\ R_1 = R_2 = R_3 = R_f = R$$

$$\boldsymbol{V_0 = -(V_1 + V_2 + V_3)}$$

In general,

$$\boldsymbol{V_0 = -(V_1 + V_2 + V_3 + V_4 + \ldots\ldots + V_n)}$$

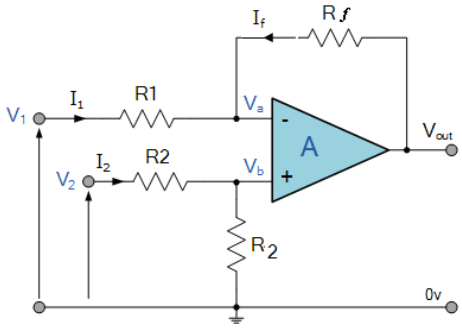
The gain of OP – AMP is given as,

$$A = \frac{V_0}{V_i}$$

$$\boldsymbol{A = \frac{R_f}{R_i}}$$

2. OP – AMP as subtractor –

Figure shows circuit of OP – AMP as subtractor. When OP – AMP is used as subtractor it is used as a differential amplifier. V_1 and V_2 are two inputs fed to the inverting terminal and non inverting terminal of OP – AMP.

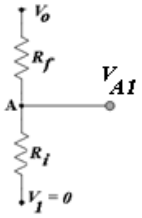


As we know that input impedance of OP – AMP is very high, no external current flows through it. Hence no current flows through points A and B. Thus points A and B must be at equi-potential.

Potential at point A – The potential at point A is the sum of potentials, when voltage sources are grounded one by one.

$$V_A = V_{A1} + V_{A2}$$

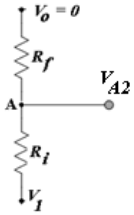
By Thevenin's theorem, first ground V_1, the equivalent circuit becomes,



$$V_{A1} = \left(\frac{R_i}{R_i + R_f}\right) V_0$$

Now V_0 is grounded,

$$V_{A2} = \left(\frac{R_f}{R_i + R_f}\right) V_1$$

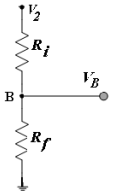


The potential at A is,

$$V_A = V_{A1} + V_{A2}$$

$$V_A = \left(\frac{R_i}{R_i + R_f}\right) V_0 + \left(\frac{R_f}{R_i + R_f}\right) V_1 \quad \ldots\ldots (1)$$

The potential at point B –



$$V_B = \left(\frac{R_f}{R_i + R_f}\right) V_2$$

$$V_A = V_B$$

$$\left(\frac{R_i}{R_i + R_f}\right)V_0 + \left(\frac{R_f}{R_i + R_f}\right)V_1 = \left(\frac{R_f}{R_i + R_f}\right)V_2$$

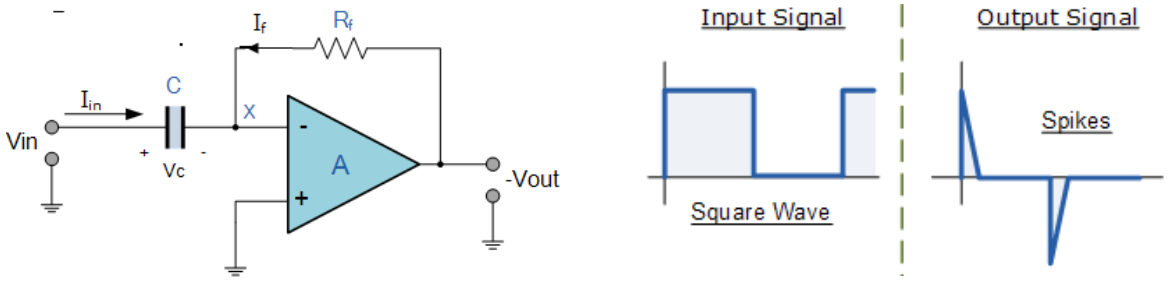
$$\left(\frac{R_i}{R_i + R_f}\right)(V_2 - V_1) = \left(\frac{R_i}{R_i + R_f}\right)V_0$$

$$V_0 = \frac{R_f}{R_i}(V_2 - V_1)$$

$$If\ R_i = R_f$$

$$\boldsymbol{V_0 = (V_2 - V_1)}$$

3. OP – AMP as differentiator - An inverting differentiator circuit is shown in figure. The output voltage is derivative of input voltage.



$$I_f = -I_{in}$$

We know that,

$$Q \propto V$$

$$Q = C\,V$$

But current is the rate of flow of charge.

$$I = \frac{dQ}{dt}$$

$$I_{in} = C\,\frac{dV_{in}}{dt}$$

$$I_f = \frac{V_0}{R_f}$$

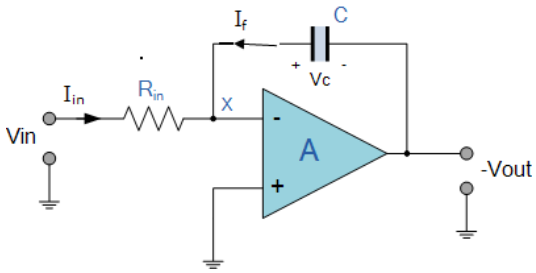
$$\frac{V_0}{R_f} = -\,C\,\frac{dV_{in}}{dt}$$

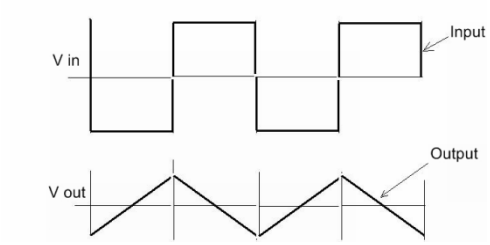
$$\boldsymbol{V_0 = -R_f\,C\,\frac{dV_{in}}{dt}}$$

$$If\quad R_f\,C = 1$$

$$\boldsymbol{V_0 = -\frac{dV_{in}}{dt}}$$

4. OP – AMP as integrator - An inverting integrator circuit is shown in figure. The output voltage is integration of input voltage. OP – AMP integrator is obtained from differentiator by just interchanging the position of R and C.





$$I_f = -I_{in}$$

We know that,

$$Q \propto V$$

$$Q = C\,V_0$$

But current is the rate of flow of charge.

$$I = \frac{dQ}{dt}$$

$$I_f = C\,\frac{dV_0}{dt}$$

$$I_{in} = \frac{V_{in}}{R_i}$$

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

Take integration on both sides,

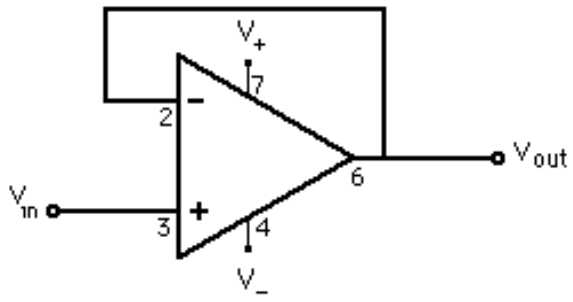
$$\boldsymbol{V_0 = -\frac{1}{R_i C}\int V_{in}\,dt}$$

$$If \quad \frac{1}{R_i\,C} = 1$$

$$\boldsymbol{V_0 = -\int V_{in}\,dt}$$

5. OP – AMP as buffer (Unity gain amplifier / Voltage follower circuit) –

Figure shows OP – AMP as buffer. In this circuit inverting terminal is directly connected to the output and input V_{in} is given to the non inverting terminal.



$$V_0 = \left(1 + \frac{R_f}{R_i}\right) V_{in}$$

As feedback resistance is zero $R_f = 0$,

$$V_0 = (1 + o)\, V_{in}$$

$$\boldsymbol{V_0 = V_{in}}$$

$$\boldsymbol{A = \frac{V_0}{V_i} = 1}$$

As OP – AMP is used in non inverting mode; the output voltage is given by,

Thus it acts as unity gain amplifier. It has two main features,

1. It produces very high input impedance and
2. It produces very low output impedance.

Hence, it is used to connect two circuits as well as to isolate two circuits, that is for maximum power transfer from one circuit to another circuit buffer is used.

6. OP – AMP as comparator –

Comparator is a high gain (open loop) circuit which compares the voltages coming at two input terminals. Generally fixed reference voltage is applied to one of the input terminal of OP – AMP. Accordingly there are two types of comparators as, 1) Inverting comparator & 2) non inverting comparator.

1) Inverting comparator -

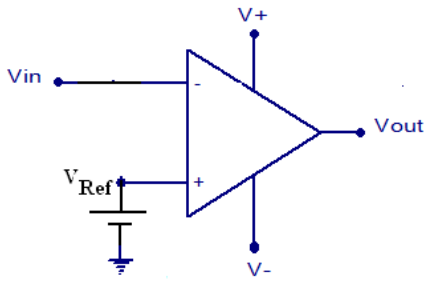
In this comparator circuit, input is applied to the inverting terminal and reference voltage is applied to the non inverting terminal. The input voltage V_{in} is compared with reference voltage V_{ref} and it gives corresponding output voltage. The output voltage of comparator is either $V_{0\,sat}^{+}$ *or* $V_{0\,sat}^{-}$.

If input voltage V_{in} is less than V_{ref} (that is voltage at negative terminal is less than positive terminal), the output will be $V_{0\,sat}^{+}$.

$$\boldsymbol{V_{in} < V_{ref}\ then\ output = \ V_{0\,sat}^{+}}$$

If input voltage V_{in} is greater than V_{ref} (that is voltage at negative terminal is greater than positive terminal), the output will be $V_{0\,sat}^{-}$.

$$\boldsymbol{V_{in} > V_{ref}\ then\ output = \ V_{0\,sat}^{-}}$$



2) Non - inverting comparator -

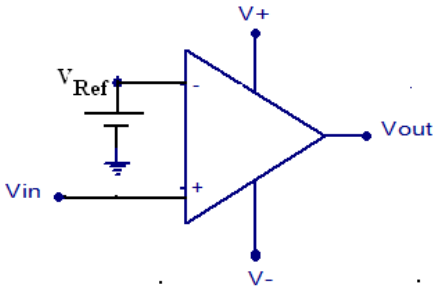
In this comparator circuit, input is applied to the non inverting terminal and reference voltage is applied to the inverting terminal. The input voltage V_{in} is compared with reference voltage V_{ref} and it gives corresponding output voltage. The output voltage of comparator is either $V_{0\,sat}^{+}$ *or* $V_{0\,sat}^{-}$.

If input voltage V_{in} is less than V_{ref} (that is voltage at negative terminal is less than positive terminal), the output will be $V_{0\,sat}^{-}$.

$$\boldsymbol{V_{in} < V_{ref}\ then\ output = \ V_{0\,sat}^{-}}$$

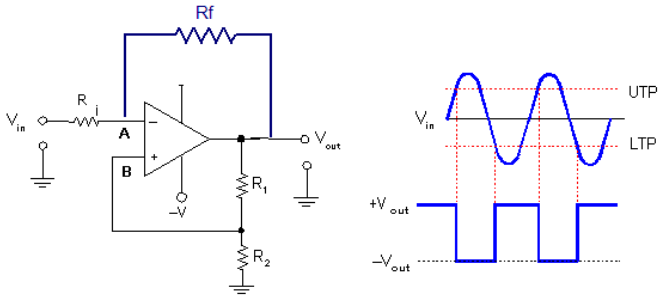
If input voltage V_{in} is greater than V_{ref} (that is voltage at negative terminal is greater than positive terminal), the output will be $V_{0\,sat}^{+}$.

$$\boldsymbol{V_{in} > V_{ref}\ then\ output = \ V_{0\,sat}^{+}}$$



7. OP – AMP as Schmitt trigger (Regenerative comparator) –

Figure shows the comparator circuit having positive feedback. It converts any waveform into square wave. A voltage divider arrangement is made at output by using two resistors (R_1, R_2) and is given to non inverting terminal that is voltage across R_2 is given to non inverting terminal.



Suppose that output voltage is at positive saturation ($V_{0\,sat}^{+}$) then the voltage across R_2 (Voltage across point B) becomes,

$$V_{R2} = \left(\frac{R_2}{R_1 + R_2}\right) \; V_{0\,sat}^{+}$$

The voltage at point A is V_i which is less than voltage at point B is called *Upper Trip Point (UTP).* So when input voltage is less than UTP, the output of Schmitt trigger is $V_{0\,sat}^{+}$.

But when input voltage V_i exceeds UTP, the output immediately switches to $V_{0\,sat}^{-}$. The voltage at point B becomes,

$$V_{R2} = \left(\frac{R_2}{R_1 + R_2}\right) \; V_{0\,sat}^{-}$$

This voltage is called *Lower Trip Point (LTP).* When the voltage Vi becomes less than LTP; the output of Schmitt trigger changes to $V_{0\,sat}^{-}$. Hence any waveform can converted into square wave.