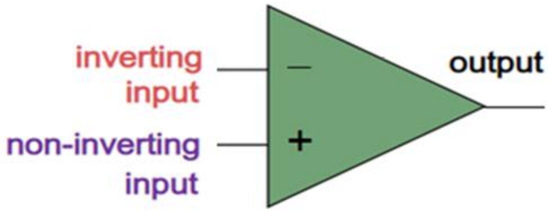
Unit 02: Operational Amplifier

- What is OP-AMP?
- Block diagram of OP-AMP
- OP-AMP Parameters
- Ideal and Practical Characteristics of OP-AMP
- Study of IC 741
- Concept of Virtual Ground
- Applications of OP-AMP
    - Inverting Amplifier
    - Non-inverting Amplifier
    - Summing Amplifier
    - Subtractor
    - Comparator

What is OP-AMP?

OP-AMP is a multistage high gain differential amplifier. It is extensively used in signal conditioning, filtering or to perform mathematical operations (such as addition, subtraction, integration and differentiation). An Operational Amplifier is basically a three-terminal device which consists of two high impedance inputs and one output.



Schematic symbol of OP-AMP

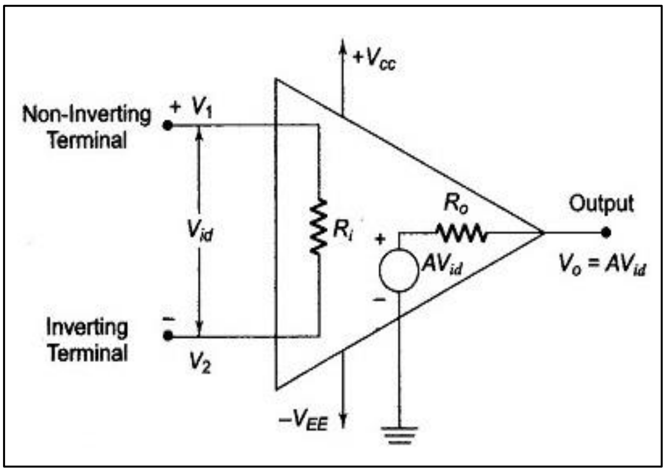
Let, the open loop gain of op-amp is denoted by 'A'
V_1 = Voltage at non-inverting terminal &
V_2 = Voltage at inverting terminal

$V_{id} = V_1 - V_2$ ➔ Differential input voltage

V_o = Output Voltage

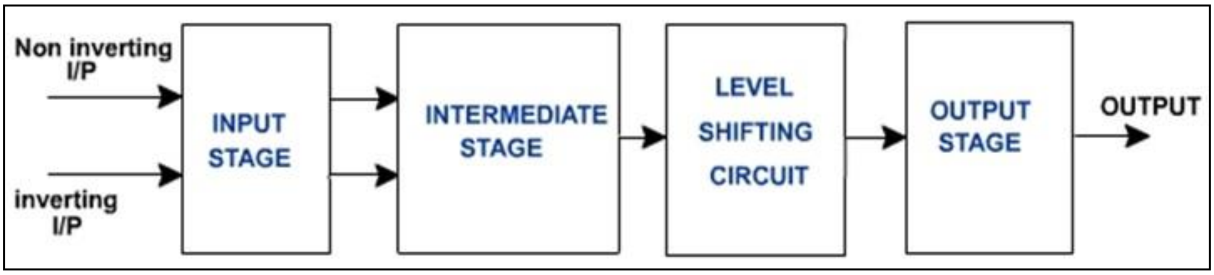
$$\therefore V_o = A\,V_{id} = A\,(V_1 - V_2)$$

i] when, $V_1 = 0$ ➔ $V_0 = -AV_2$
ii] when, $V_2 = 0$ ➔ $V_0 = AV_1$



Block diagram of OP-AMP

An operational amplifier is a direct-coupled high gain amplifier usually consisting of one or more differential amplifiers followed by a dc level shifter and output stage [push pull amplifier]. Since, an op-amp is a multistage amplifier, it can be represented by a block diagram as shown in figure:



1. Input Stage: The first stage is double ended high gain differential amplifier (i.e., dual input balanced output differential amplifier). This stage is generally responsible for most of the gain of op-amp. Also, this stage determines the input resistance of op-amp.

2. Intermediate Stage: The second stage is called as Intermediate stage. This is usually another differential amplifier. It is driven by output of input stage. This stage is dual input unbalanced (single ended) output differential amplifier. This stage provides additional voltage gain to the input signals.

3. Level Shifting Stage: Third stage is called as level shifting stage (or Level Translator). Usually, an emitter follower circuit is used in order to shift the DC level at the output. Because of direct coupling between first two stages, the DC level at the output of intermediate stage is well above ground potential. This increase in DC level limits the output voltage swing or may distort the output signal. To overcome this problem, Level shifting stage is used to bring this DC level to a zero volt with respect to ground.

4. Output Stage: The final stage is called output stage. This is normally complementary push-pull amplifier. This stage increases the output voltage swing and current supplying capacity of the op-amp. A well-designed output stage also provides low output resistance.

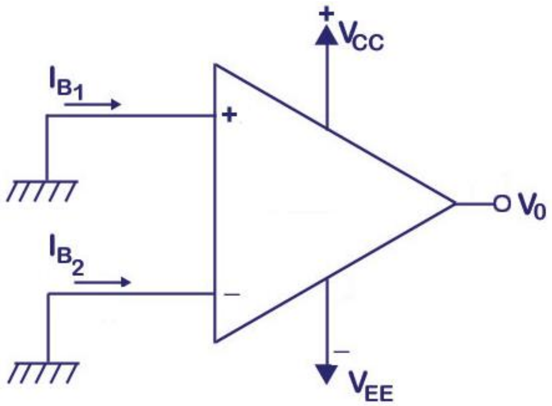
OP-AMP Parameters:

1. Input Bias Current: The input bias current (I_B) is the average of the currents enter into the two input terminals with the output at zero volts. Typically, the input bias current is around 80 nA. Ideally, input bias current should be ZERO !

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

2. Input Offset Current: The input offset current is the difference between the two input currents of the op-amp with the output at zero volts. Typically, the input offset current for a 741 op-amp is 20 nA.

$$I_{offset} = |\, I_{B1} - I_{B2} \,|$$



3. Input Offset Voltage: In the ideal op-amp when both inputs are at zero volts the output should be zero volts. But, due to imbalances within the device a small amount of voltage will appear at the output. This extra voltage can be eliminated by giving a small voltage called Input offset voltage (V_{OS}) to the amplifier. Typically, the input offset voltage for a 741 op-amp is around 1 mV.

4. Common Mode Rejection Ratio (CMRR): In OP-AMP, output voltage is proportional to the difference between the voltages applied to its two input terminals [$V_o = A\,V_{id} = A\,(V_1 - V_2)$]. When the two input voltages are equal, ideally the output voltages should be zero. A signal which is applied to both input terminals of the op-amp is called as Common Mode Signal. Usually, common mode signal is an unwanted noise voltage.

The ability of an op-amp to suppress common-mode signals is expressed in terms of its common-mode rejection ratio (CMRR). CMRR is defined as the ratio of differential voltage gain to common-mode voltage gain

$$\text{CMRR} = \frac{A_d}{A_c} = \frac{\text{Differential voltage gain}}{\text{Common Mode voltage gain}}$$

In dB it is given by the expression,

$$\text{CMRR} = 20\,\log_{10}\left(\frac{A_d}{A_c}\right)\ \text{dB}$$

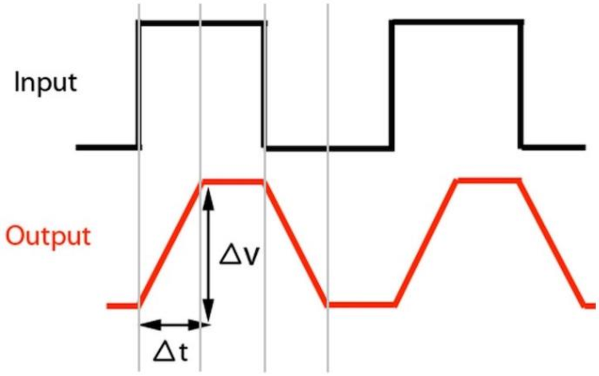
where, $A_d =$ Differential Voltage Gain and $A_c =$ Common Mode Gain
*High value of CMRR means op-amp has better ability to reject common mode signals like electrical NOISE. Ideally, CMRR should be infinite !

5. Slew Rate (SR): The slew rate is the maximum rate of change in output voltage per unit of time. The slew rate indicates how fast the output of an op-amp can change in response to changes in input frequency.

It is expressed in volts per microseconds and typical value for the slew rate is 0.5 V/μs.

$$SR = \left.\frac{dV_{out}}{dt}\right|_{max}$$

Ideally, Slew Rate should be ∞

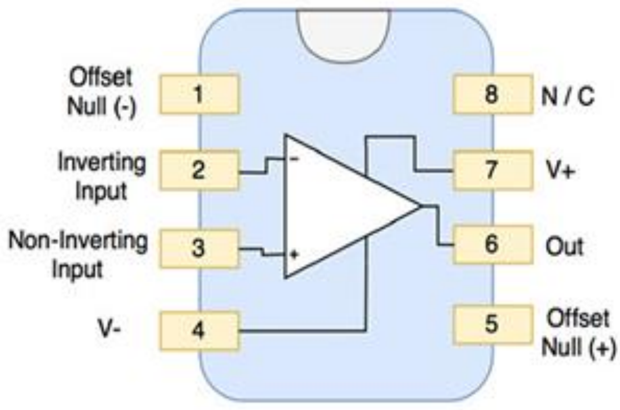


Ideal and Practical characteristics of OP-AMP:

Sr. No.	Characteristics	Ideal	Typical value for IC 741
1.	Voltage gain (open loop), A	∞	2×10^5
2.	Input Impedance, Ri	∞	2 MΩ
3.	Output Impedance, Ro	0	75 Ω
4.	Bandwidth, BW	∞	1 MHz
5.	Common Mode Rejection Ratio (CMRR)	∞	90 dB
6.	Slew rate, SR	∞	0.5 V/μs
7.	Input offset voltage	0	1 mV
8.	Input offset current	0	20 nA
9.	Input bias current	0	80 nA

Study of IC 741

- The 741 OP-AMP IC was first manufactured by Fairchild semiconductors in the year 1968. The number 741 itself has no such meaning
- It can be remembered as IC having 7 functional pins, 4 pins capable of taking input and 1 output pin. The main intention of this 741 op-amp is to strengthen AC & DC signals and for mathematical operations.

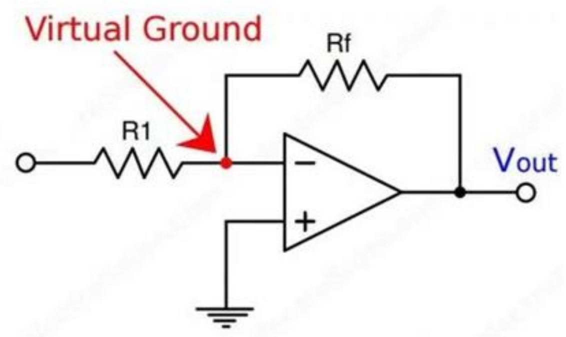


Concept of Virtual Ground

As the name indicates it is virtual, not real ground. In op-amp the term virtual ground means that the voltage at that particular node is almost equal to ground voltage (0V). It is not physically connected to ground. This concept is very useful in analysis of op-amp circuits and it will make a lot of calculations very simple.

We know that an ideal op-amp will provide infinite voltage gain.

$$\text{Gain (A)} = \frac{V_{out}}{V_{in}} = \infty$$



When gain is infinite, the input voltage Vin must be zero.

Here, input voltage is nothing but the difference between voltages at inverting and non-inverting terminals.

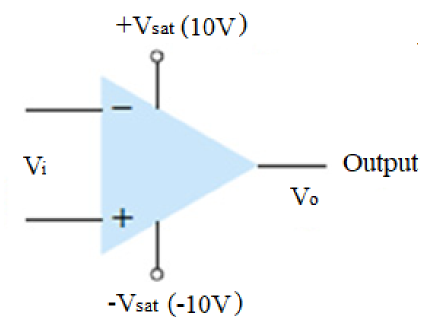
Thus, $V_{in} = V_{id} = V_1 - V_2$
i.e.,

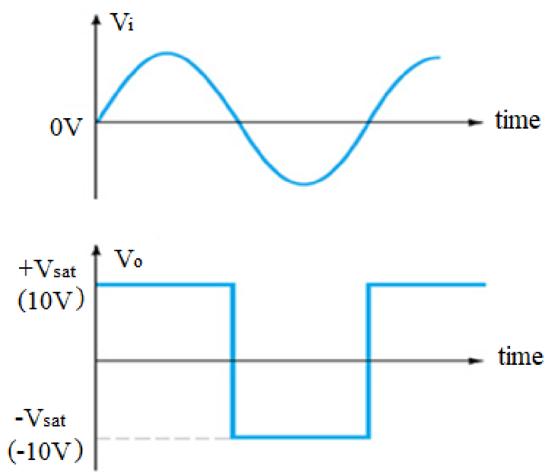
$$0 = V_1 - V_2$$
$$\therefore V_1 = V_2$$

"The simple meaning of virtual ground is that the potential at inverting and non-inverting terminal is always same. If anyone of these two terminals is grounded then the second terminal will also have ground potential."

Negative Feedback Amplifier using op-amp:

Open Loop Gain [A] of an operational amplifier can be very high, as much as 1,00,000 or more. However, this very high gain is of no real use to us as it makes the amplifier both unstable and hard to control !





As the open loop DC gain of an operational amplifier is extremely high we can therefore afford to lose some of this high gain by connecting a suitable resistor from the output terminal back to the inverting input terminal to both reduce and control the overall gain of the amplifier. This then produces and effect known commonly as Negative Feedback, and thus produces a very stable Operational Amplifier based system.

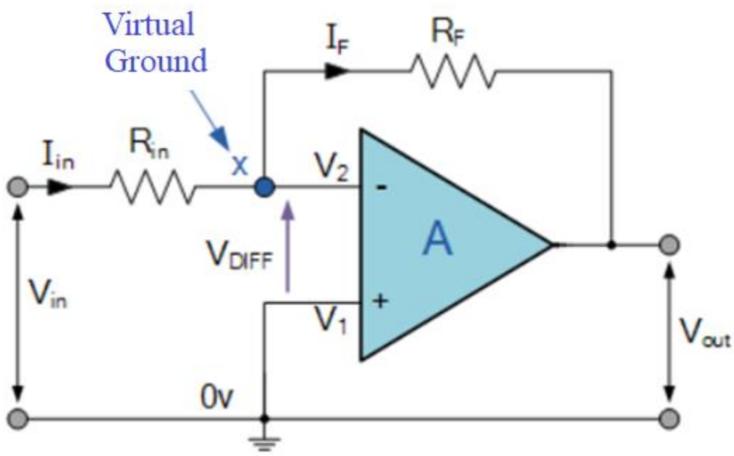
Applications of OP-AMP:

- OP-AMP applications can be classified into two types:
    1. Linear applications and
    2. Non-Linear applications
- A circuit is said to be linear, if there exists a linear relationship between its input and the output. Similarly, a circuit is said to be non-linear, if there exists a non-linear relationship between its input and output.
- In Linear applications, op-amp works in Amplifier mode [Example: Non-inverting & Inverting amplifier, Voltage Follower, Summing Amplifier, Subtractor etc.]
- Whereas, in Non-Linear applications op-amp works in Switching Mode [Example: Comparator, Zero crossing detector etc.]

Inverting Amplifier:

In the Inverting Amplifier circuit the operational amplifier is connected with feedback to produce a closed loop operation. When dealing with operational amplifiers there are two very important rules to remember about inverting amplifiers, these are:

1. No current flows into input terminal
2. V1 always equals V2 [by the concept of Virtual ground]



By using these two rules we can derive the equation for calculating the closed-loop gain of an inverting amplifier:

$$I_{in} = \frac{V_{in} - V_X}{R_{in}} \quad \text{and} \quad I_F = \frac{V_X - V_{out}}{R_F}$$

Also, we have

$$I_{in} = I_F$$

$$\therefore \frac{V_{in} - V_X}{R_{in}} = \frac{V_X - V_{out}}{R_F}$$

$\because$ X is virtual ground

$$i.e., \quad V_X = 0V$$

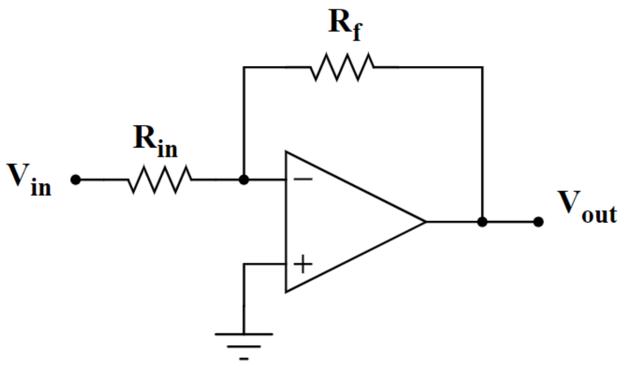
$$\frac{V_{in}}{R_{in}} = \frac{-V_{out}}{R_F}$$

$$\frac{V_{out}}{V_{in}} = -\left(\frac{R_F}{R_{in}}\right)$$

$$\therefore \text{Voltage Gain } (A_V) = -\left(\frac{R_F}{R_{in}}\right)$$

This is closed loop gain of op-amp when used in inverting configuration. Negative sign shows phase shift of 180 degrees between output and input voltages.

Ex: For the inverting amplifier as shown in fig. R_F = 20 KΩ, R_{in} = 10 KΩ and V_{in} = 2V (peak-to-peak). Find output voltage V_{out}. Draw input output waveforms.



Solution:

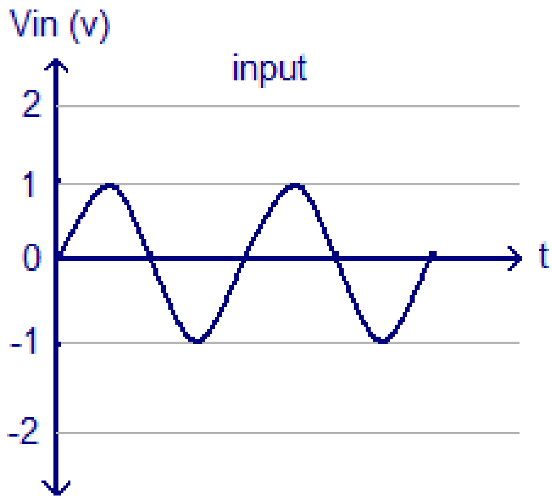
We know that the gain of inverting amplifier is given by,

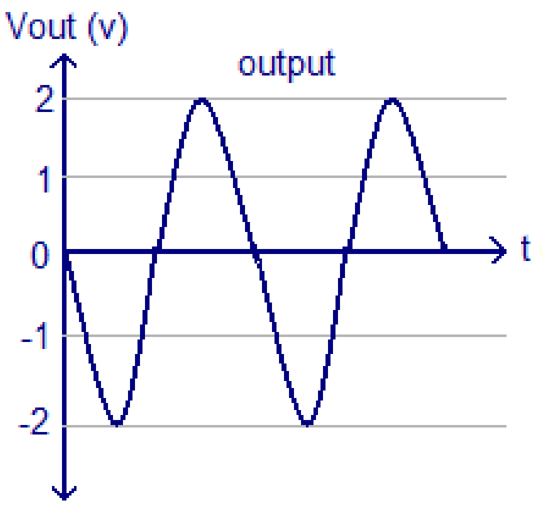
$$A_V = \frac{V_{out}}{V_{in}} = -\left(\frac{R_F}{R_{in}}\right)$$

i.e.,

$$V_{out} = -\left(\frac{R_F}{R_{in}}\right) V_{in} = -\left(\frac{20\ K\Omega}{10\ K\Omega}\right) 2V = -4V \text{ (peak to peak)}$$

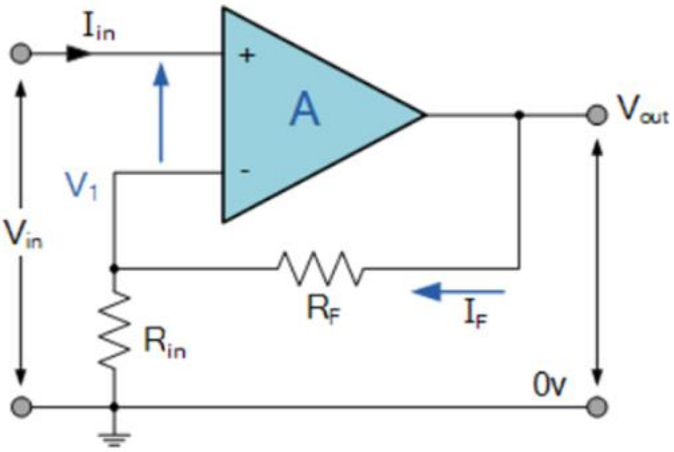
Input Output Waveform for the given inverting amplifier is as follows:





Non-inverting Amplifier:

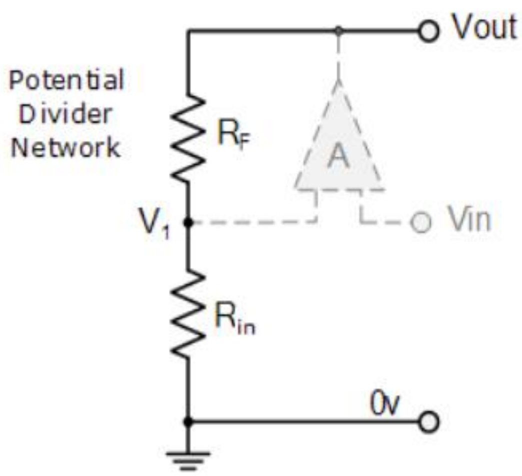
In this configuration, the input voltage signal, (V_{in}) is applied directly to the non-inverting (+) input terminal which means that the output gain of the amplifier becomes "Positive" in value in contrast to the "Inverting Amplifier" circuit whose output gain is negative in value.



Two important rules to remember about non-inverting amplifier are:

1. No current flows into input terminal
2. Vinv always equals to Vnon-inv [by the concept of Virtual ground]

Because of this virtual earth node the resistors, RF and Rin form a simple potential divider network across the non-inverting amplifier as shown below:



By using the formula to calculate the output voltage of a potential divider network, we have:

$$V_1 = \left(\frac{R_{in}}{R_{in} + R_F}\right) V_{out}$$

But $V_{in} = V_1$

$$\therefore V_{in} = \left(\frac{R_{in}}{R_{in} + R_F}\right) V_{out}$$

$$\frac{V_{out}}{V_{in}} = \left(\frac{R_{in} + R_F}{R_{in}}\right)$$

$$i.e., \quad \frac{V_{out}}{V_{in}} = \left(1 + \frac{R_F}{R_{in}}\right)$$

$$\text{Voltage Gain } (A_V) = \left(1 + \frac{R_F}{R_{in}}\right)$$

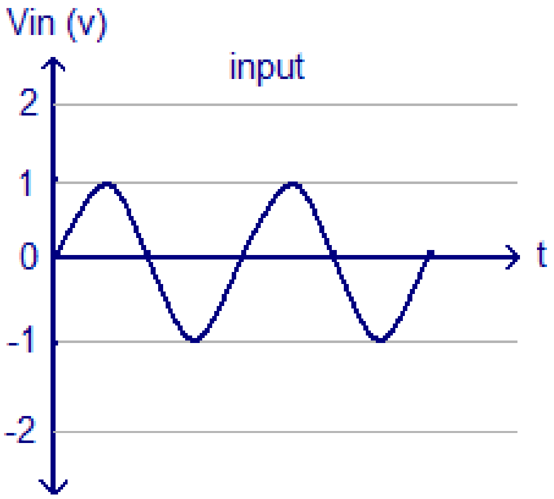
This is closed loop gain of op-amp when used in non-inverting configuration

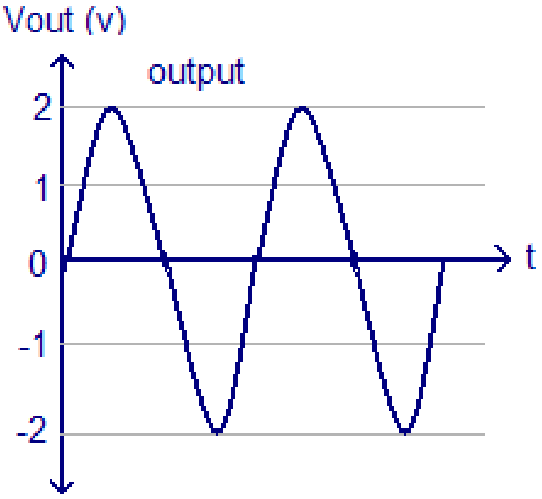
Ex: For the non-inverting amplifier R_f = 10 KΩ, R_{in} = 10 KΩ and V_{in} = 2V (peak-to-peak). Find output voltage V_{out}. Draw input output waveforms.

Solution: We know that the gain of non-inverting amplifier is given by,

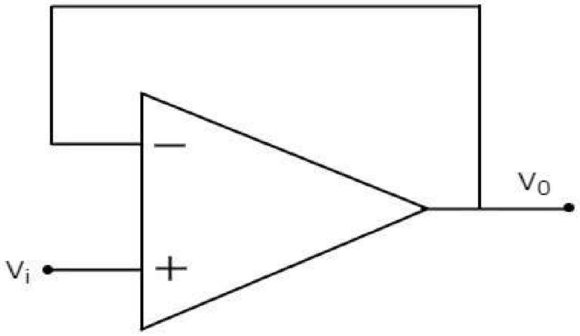
$$A_V = \frac{V_{out}}{V_{in}} = \left(1 + \frac{R_F}{R_{in}}\right)$$

$$V_{out} = \left(1 + \frac{R_F}{R_{in}}\right) V_{in} = \left(1 + \frac{10\ K\Omega}{10\ K\Omega}\right) 2V = 4V \text{ (peak to peak)}$$





Voltage Follower:



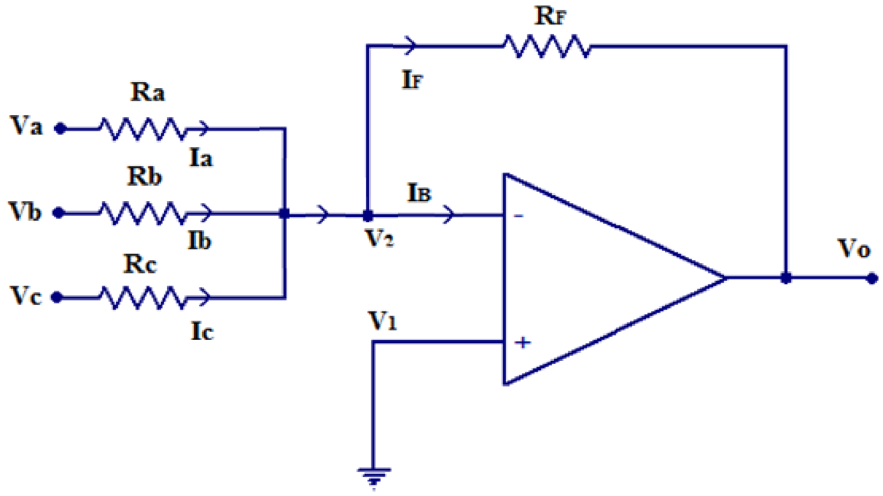
- A voltage follower is an electronic circuit, which produces an output that follows the input voltage. It is a special case of non-inverting amplifier. If we consider the value of feedback resistor, R_F as zero ohms, then a non-inverting amplifier becomes a voltage follower.
-
- The circuit diagram of a voltage follower is shown in the figure.

- The output voltage Vo of a voltage follower is equal to its input voltage Vi. Thus, the gain of a voltage follower is equal to one since, both output voltage Vo and input voltage Vi of voltage follower are same.

- The voltage follower circuit is ideal to serve as buffer (or isolation unit). It is also used in sample & hold circuit, filters etc.

Summing Amplifier:

Many applications in electronic circuits require two or more signals to be added or combined into a single output. The summing amplifier does the exact same thing. For this reason, summing amplifier is also called as 'Voltage Adder' since its output is the addition of voltages present at its input terminal. The summing amplifier uses an inverting amplifier configuration i.e. the input is applied to the inverting input terminal of the op-amp, while the non-inverting input terminal is connected to ground. Due to inverting configuration, the output of Summing amplifier is out of phase with respect to the input by 180°. Circuit shown in figure below will work as summing amplifier:



By applying KCL we get, $I_a + I_b + I_c = I_F$ ... since, $I_B = 0$

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

By the concept of virtual ground we have: $V_1 = V_2 = 0\text{ V}$

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

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

when $R_a = R_b = R_c = R$, equation becomes:

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

This means that the output voltage is equal to the negative sum of all the inputs times the gain of the circuit; hence, the circuit is called Summing amplifier. When $R_F = R$ the gain of circuit will be 1 and the output voltage is equal to the negative sum off all input voltages. Thus,

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

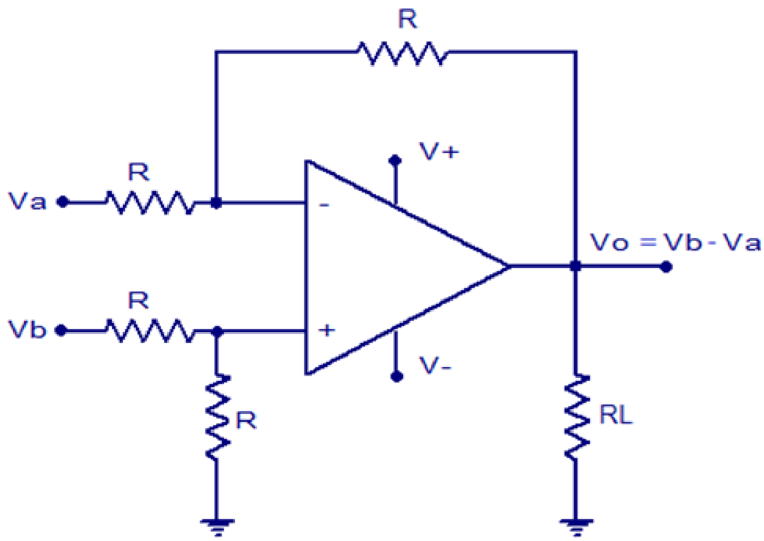
Subtractor:

A basic differential amplifier can be used as a subtractor as shown in the figure. Here, neither input is grounded. A close examination of the circuit reveals that it is a combination of inverting and non-inverting amplifiers. When V_b is zero, the circuit appears as an inverting amplifier while when V_a is zero the circuit becomes non-inverting amplifier. Since, the circuit has two inputs V_a & V_b, Superposition Theorem [SPT] will be used to determine the voltage gain of amplifier.

SPT: The output of a linear circuit when multiple independent sources are acting at the same time is equivalent to the sum of the outputs due to each independent source acting at a time.

Case[i]: When $V_b = 0V$, circuit becomes an inverting amplifier and thus, output voltage due to input V_a is V_{oa} and it is given by:

$$V_{oa} = -\left(\frac{R_F}{R_{in}}\right)V_{inv} = -\frac{R}{R}V_a = -V_a$$



Case [ii]: When $V_a = 0V$, the circuit becomes non-inverting amplifier having voltage divider network consisting of two resistors at the non-inverting terminal. Therefore,

$$V_{non-inv} = \frac{R}{R+R}V_b = \frac{V_b}{2}$$

Thus, output due to input V_b is

$$V_{ob} = \left(1 + \frac{R_f}{R_{in}}\right)V_{non-inv}$$

$$V_{ob} = \left(1 + \frac{R}{R}\right)\frac{V_b}{2} = V_b$$

Thus, the net output voltage

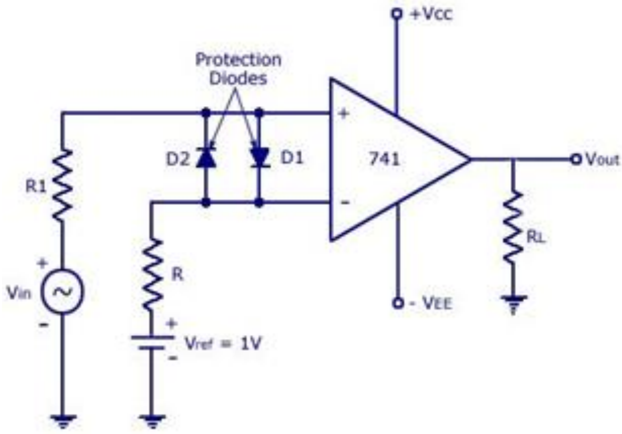
$$V_o = V_{ob} + V_{oa}$$

$$V_o = V_b - V_a$$

Thus, the output voltage V_o is equal to the voltage V_b applied to the non-inverting terminal minus the voltage V_a applied to the inverting terminal; hence, the circuit is called Subtractor.

Comparator:

A comparator, compares a signal voltage on one input of an op-amp with known voltage called the reference voltage on the other input. It is an open loop op-amp with the output may be (+) or (-) saturation voltage, depending upon which input is larger. Comparators are used in Schmitt trigger, level detectors and oscillators. Figure shows an op-amp used as a non-inverting comparator.



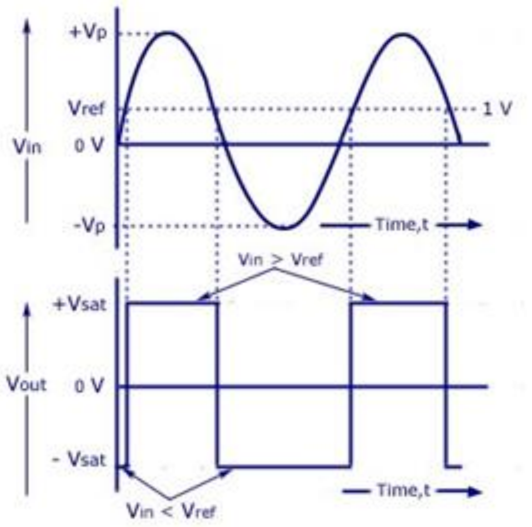
The diodes D1 & D2 protect the op-amp from damage due to excessive input voltage V_{in}. R1 in series with V_{in} is used to limit current through D1 & D2. To reduce offset problems, a resistance R is connected between inverting input and reference voltage.

A fixed reference voltage V_{ref} of 1V is applied to the inverting input and other time varying signal voltage v_{in} is applied to the non-inverting input. Because of this arrangement circuit is also called as Non-inverting Comparator.

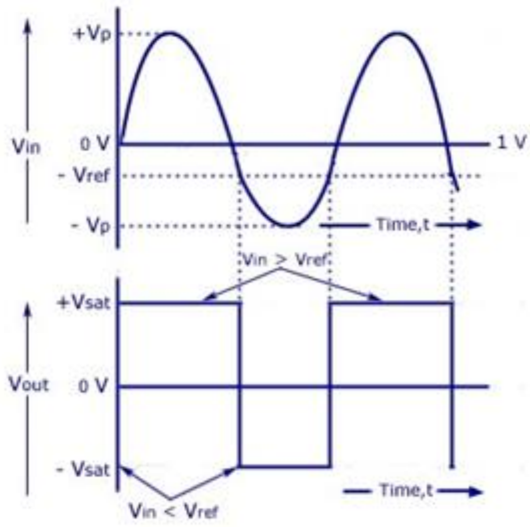
When $V_{in} < V_{ref}$, the output voltage V_o is at $-V_{sat}$ ($\cong -V_{EE}$). Because, voltage at inverting input is higher than that of at non-inverting input.

When $V_{in} > V_{ref}$, the non-inverting input becomes positive with respect to inverting input. Thus, $V_o = +V_{sat}(\cong +V_{CC})$. Thus, output changes from one saturation level to another whenever $V_{in} \cong V_{ref}$.

Following figures show input output waveforms for Non-inverting comparator with different values of V_{ref}.



Input and Output Waveforms
For Positive Vref



Input and Output Waveforms
For Negative Vref

Important Questions:

1. Draw and explain block diagram of Operational Amplifier.
2. Explain the working of inverting amplifier. Derive expression for its gain.
3. Discuss various ideal characteristics of OPAMP.
4. Explain the working of non-inverting amplifier using OPAMP. Derive an expression for its voltage gain.
5. Explain working of Summing Amplifier using OPAMP
6. With the help of suitable diagram explain the working of comparator circuit using OPAMP.