# UNIT-5

# OP AMP AND ITS APPLICATIONS

## OP AMP

### INTRODUCTION

If multiple electronic components are interconnected on a single chip of semiconductor material, then that chip is called as an **Integrated Circuit**.It consists of both active and passive components.An IC can function as an amplifier,oscillator,timer,counter,computer memory and microprocessor.

The Integrated Circuit was invented in 1958 by Jack Kibly and independently in 1959 by Robert Noyce, revolutionzing electronics by integrating multiple components onto a single chip.

### ADVANTAGES OF IC TECHNOLOGY

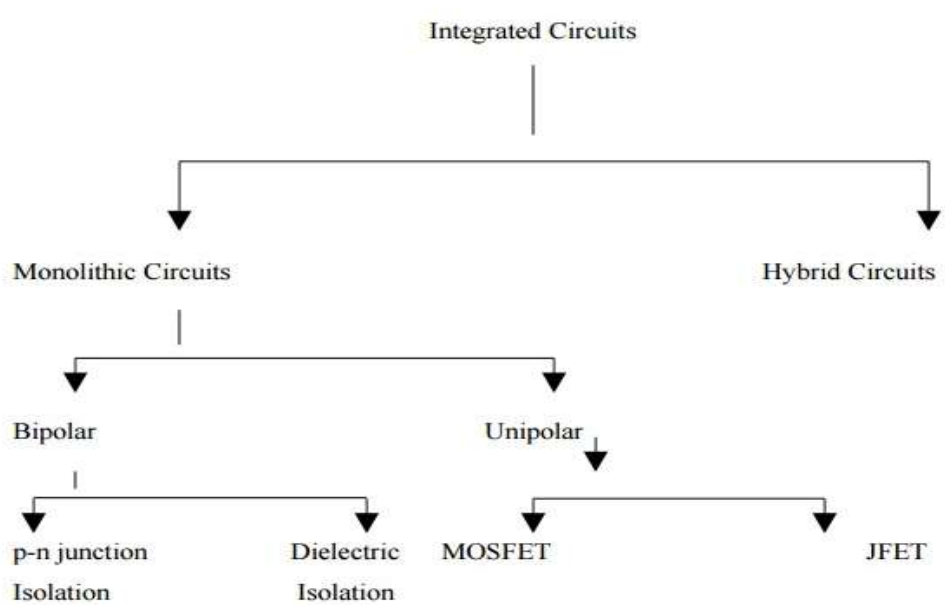
Miniaturization
Cost reduction
Increased system reliability
Improved performance
Matched devices
Increased operating speed
Reduction in power consumption

### CLASSIFICATION OF IC'S

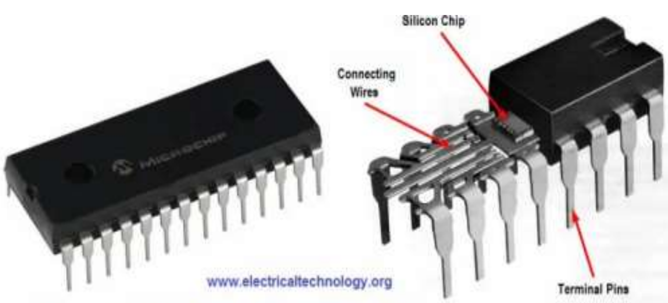
Integrated circuits offer a wide range of applications and could be broadly classified as:

(1.) Digital ICs
(2.) Linear ICs

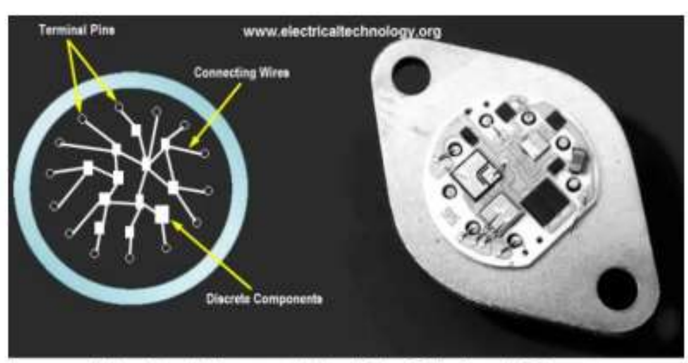
Based on the above requirements, two distinctly different IC technology, namely Monolithic technology and Hybrid technology have been developed.



| | | |
|---|---|---|
| Invention of transistor (Ge) | | 1947 |
| Development of Silicon transistor | | 1955–1959 |
| Silicon Planar Technology | Junction transistor diode | 1959 |
| First ICs, Small Scale Integration (SSI) | 3 to 30 gates/chip approx. or 100 transistors/chip (Logic gates, Flip-flops) | 1960–1965 |
| Medium Scale Integration (MSI) | 30 to 300 gates/chip or 100 to 1000 transistors/chip (Counters, Multiplexers, Adders) | 1965–1970 |
| Large Scale Integration (LSI) | 300 to 3000 gates/chip or 1000–20,000 transistors/chip (8 bit microprocessors, ROM, RAM) | 1970–1980 |
| Very Large Scale Integration (VLSI) | More than 3000 gates/chip or 20,000–10,00,000 transistors/chip (16 and 32 bit microprocessors) | 1980–1990 |
| Ultra Large Scale Integration (ULSI) | $10^6 - 10^7$ transistors/chip (Special processors, Virtual reality) machines, Smart sensors | 1990–2000 |
| Giant-Scale Integration (GSI) | $>10^7$ transistors/chip | |



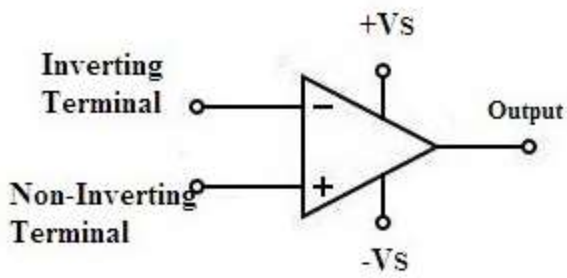

**Monolithic IC in Plastic Package (DIP)**




**Hybrid or Multi-Chip ICs**

**BASIC INFORMATION OF OP AMP**

- An operational amplifier is a direct-coupled high-gain amplifier usually consisting of one or more differential amplifiers and usually followed by a level translator and an output stage.
- An operational amplifier is available as a single integrated circuit package.
- The operational amplifier is a versatile device that can be used to amplify dc as well as ac input signals and was originally designed for computing such mathematical functions as addition, subtraction, multiplication, and integration.
- Thus the name operational amplifier stems from its original use for these mathematical operations and is abbreviated to op-amp.
- With the addition of suitable external feedback components, the modern day op-amp can be used for a variety of applications, such as ac and dc signal amplification, active filters, oscillators, comparators, regulators, and others.




It has two input terminals and one output terminal. The terminal with a (-) sign is called inverting input terminal and the terminal with (+) sign is called the non-inverting input terminal.

**Op-amp pin diagram**

There are 8 pins in a common Op-Amp, like the 741 which is used in many instructional courses.

Pin 1: Offset null
Pin 2: Inverting input terminal
Pin 3: Non-inverting input terminal
Pin 4: -VCC (negative voltage supply)
Pin 5: Offset null
Pin6: Output voltage
Pin 7: +VCC (positive voltage supply)
Pin 8: No Connection

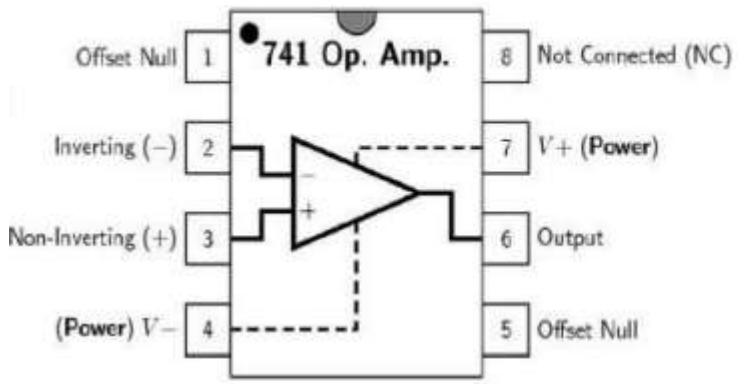



Figure : Pin connection, LM741.

**Pins 1 & 5: Offset Null**: These pins are used to "null" or zero the output of the op-amp, often by connecting them to a potentiometer, to eliminate any residual output voltage when there is no intentional input.
**Pin 2: Inverting Input (-)**: A signal applied to this pin will result in an output signal with the opposite polarity (180° phase shift).
**Pin 3: Non-Inverting Input (+)**: A signal applied here will result in an output signal with the same polarity as the input.
**Pin 4&7: Power Supply pins**: This pin connects to the negative power supply and positive power supply of the circuit.
**Pin 6: Output**: This is the main output terminal where the amplified signal is available.
**Pin 8: NC**: It is just a pin that is used to fill up the empty pin in the IC 741 Op Amp. It has no connection with any of the internal or external circuits.

**Packages**

3 popular packages are

1. Metal can(TO) package
2. Dual in line package(DIP)
3. Flat package(or)Flat pack

## FEATURES OF 741 OP-AMP:

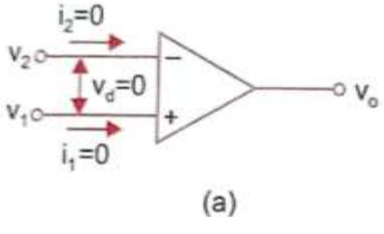
The IC 741 is high performance monolithic op-amp IC.It is available in 8pin, 10pin or 14pin configuration. It can operate over a temperature of -55º C to 125º C.

**Features:**

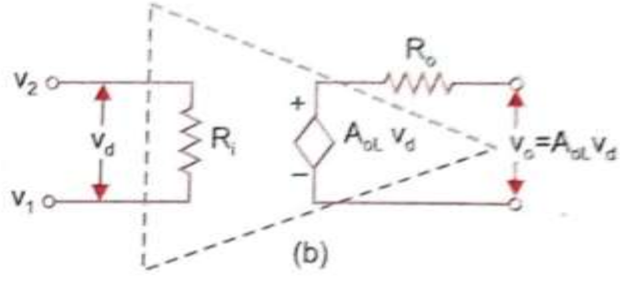
- i) No frequency compensation required
- ii) Short circuit protection provided
- iii) Offset Voltage null capability
- iv) Large common mode and differential voltage range
- v) No latch up
- vi) It consumes low power

## IDEAL AND PRACTICAL OP AMP

### 1.Ideal op amp



Ideal op-amp



Equivalent op-amp

An Ideal operational amplifier is shown in the figure,In an ideal op amp,

1. The currents entering the input terminals 1 and 2, $i_1$ and $i_2$ respectively, shall be zero. $i_1=i_2=0$.
2. The voltages between reference and the input terminals 1 and 2, $V_1$ and $V_2$ respectively, shall be equal. $V_1=V_2$.
3. The difference between input terminal voltages, $V_a$ shall be zero. $V_a=V_2 - V_1$.

As per the figure shown as equivalent circuit, input resistance $R_i$, output resistance $R_o$ and open loop gain $A_{oL}$ shall be explained further.

4. Input resistance $R_i$ shall be very high (Ideally $Ri=\infty$)
5. Output resistance $R_o$ shall be very low (Ideally $R_o=0$)
6. Open loop gain $A_{oL}$ shall be very high (Ideally $A_{OL}=\infty$)

| Ideal OPAMP | Practical OPAMP |
|---|---|
| An Ideal OPAMP has | In a Practical OPAMP |
| Infinite voltage gain, so that it can amplify input signals of any amplitude. | Voltage gain is not infinite, but typically 10^5 to 10^8, so it is not able to amplify input signals smaller than 100 uV. |
| Infinite input resistance, so that almost any signal source can drive it and there is no loading of preceding stage. | Input resistance is typically 10^6 to 10^12 ohm (for FET input Op-Amps such as uAF771), so still it draws some current and not all source can drive it. |
| Zero output resistance, so that output can drive an infinite number of other devices. | Output resistance is typically 75 ohm for standard Op-Amps, so it has limit to deliver current to output devices. |
| Zero output voltage when input voltage is zero. | It is not able to give zero at output when input is zero, due to mismatching of input transistors. |
| Infinite bandwidth, so that any frequency signal can be amplified without attenuation. | Op-Amp has its own Gain-Bandwidth product, so input frequency should not exceed from that particular frequency range at desired gain. |
| Infinite common-mode rejection ratio, so that the output common-mode noise voltage is zero. | CMRR is typically 90 dB, so still it gives output voltage even if both input terminals are shorted. |
| Infinite slew rate, so that output voltage changes occur simultaneously with input voltage changes. | Slew rate is typically 0.5 to 90 V/uS(for improved Op-Amp such as LM318), so output cannot be change simultaneously with input, there is some delay. |

## DC Characteristics

### INPUT BIAS CURRENT

The op-amp's input is differential amplifier which may be made of BJT or FET. In an ideal op-amp, we assumed that no current is drawn from the input terminals (the base currents entering into the inverting and non-inverting terminals ($I_B^-$ & $I_B^+$) respectively). Even though both the transistors are identical $I_B^-$ and $I_B^+$ are not exactly equal due to internal imbalance between the two inputs. Input bias current and inverting amplifier with bias currents is shown in figure. Manufacturers specify the input bias current $I_B$.

If input voltage $V_i = 0V$. The output voltage $V_o$ should also be ($V_o = 0$) but for $I_B$=500nA , We find that the output voltage is offset by Op-amp with a 1 M feedback resistor

$$V_o = 500nA*1M=500mV$$

The output is driven to 500mV with zero input, because of the bias currents.

i.e. to compensate for bias current, the compensating resistor, Rcomp should be equal to the parallel combination of resistor $R_1$ and Rf

### INPUT OFFSET CURRENT

i. Bias current compensation will work if both bias currents $I_B^+$ and $I_B^-$ are equal.
ii. Since the input transistor cannot be made identical. There will always be some small difference between $I_B^+$ and $I_B^-$. This difference is called the offset current

$$|I_{os}| = I_B^+ - I_B^-$$

### INPUT OFFSET VOLTAGE

In spite of the use of the above compensating techniques, it is found that the output voltage may still not be zero with zero input voltage [$V_o \neq 0$ with $V_i = 0$]. This is due to unavoidable imbalances inside the op-amp and one may have to apply a small voltage at the input terminal to make output ($V_o$) = 0 figure shown below is the op-amp showing input offset voltage. This voltage is called input offset voltage $V_{os}$. This is the voltage required to be applied at the input for making output voltage to zero ($V_o = 0$).

### THERMAL DRIFT

Bias current, offset current, and offset voltage change with temperature. A circuit carefully nulled at 25°C may not remain. So when the temperature rises to 35°C. This is called drift. Offset current drift is expressed in nA/°C. These indicate the change in offset for each degree Celsius change in temperature.

## AC Characteristics

### SLEW RATE

The slew rate of an amplifier is the maximum rate of change of voltage at its output. It is expressed in V/s (or more probably, V/μs). Op amps may have different slew rates during positive and negative going transitions, due to circuit design. For this analysis, we shall assume that good fast op amps have reasonably symmetrical slew rates.

### Common Mode Rejection Ratio - CMRR

When the same voltage is applied to both the terminals of op amp then the op amp is said to be operated in common mode configuration. Op amp is to be operated only differential mode and common mode signals shall be noise or disturbance signal. The ability of differential amplifier is to reject the common mode signal and expressed as a ratio termed as Common mode rejection ratio (CMRR).

It is defined as ratio of the differential voltage gain (Ad) to common mode voltage gain (Ac).

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

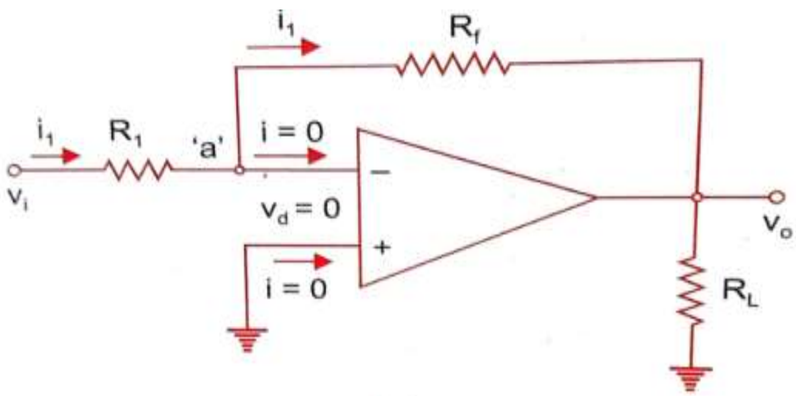
$$CMRR\ in\ dB = 20 log \left|\frac{A_d}{A_c}\right|\ in\ dB$$

Practically CMMR should be larger and ideally it shall be ∞

### MODES OF OPERATION

- The configuration in which output depends on input, but output has no effect on the input is called open loop configuration.
- No feedback from output to input is used in such configuration.
- The op-amp can be used in three modes in open loop configuration.They are
  1. Inverting amplifier
  2. Non inverting amplifier
  3. Differential amplifier

### INVERTING AMPLIFIER




(a) Inverting amplifier

- This is perhaps the most widely used of all the op-amp circuits.
- The circuit is shown in an above figure.
- The output voltage Vo is fed back to the inverting input terminal through the $R_f$-$R_i$ network where $R_f$ is the feedback resistor.
- Input signal $V_i$ (ac or dc) is applied to the inverting input terminal through $R_i$ and non-inverting input terminal of op-amp is grounded

$$i_1 = \frac{V_i}{R_1} \longrightarrow (1)$$

$$V_0 = -i_1 R_f \longrightarrow (2)$$

$$(2) - (1), \quad A_{CL} = \frac{V_0}{V_i} = \frac{-i_1 R_f}{i_1 R_1}.$$

⇒ Here '–' indicates 180° phase shift

$$\boxed{A_{CL} = \frac{-R_f}{R_1}}$$

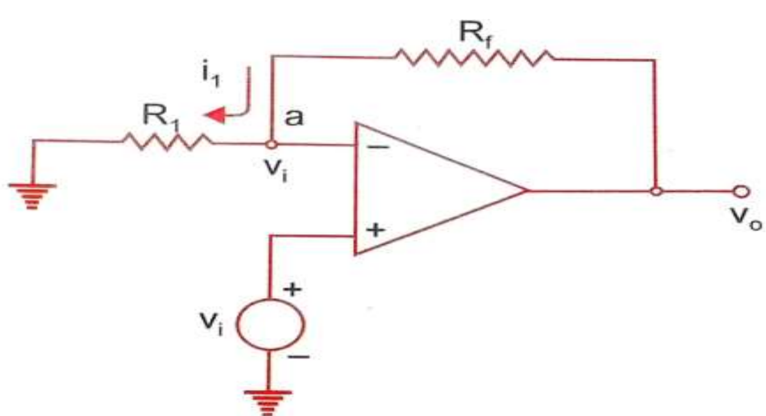
Applying Nodal Analysis,

$$\frac{V_a^{\to 0} - V_i}{R_1} = \frac{V_0 - V_a^{\to 0}}{R_f}$$

$$\boxed{A_{CL} = \frac{V_0}{V_i} = \frac{-R_f}{R_1}}$$

* To avoid the loading conditions, we are using the '$R_L$' resistance.

**NON INVERTING AMPLIFIER**




(a) Non-inverting amplifier

If a signal (ac or dc) is applied to the non-inverting input terminal and feedback is given as shown in the figure, the circuit amplifies without inverting the input signal. Such a circuit is called non-inverting amplifier. It may be noted that it is also a negative feed-back system as output is being fed back to the inverting input terminal.

As the differential voltage $V_d$ at the input terminal of op-amp is zero, the voltage at node 'a' in figure is $V_i$, same as the input voltage applied to non-inverting input terminal. Now $R_f$ and $R_1$ forms a potential divider. Hence

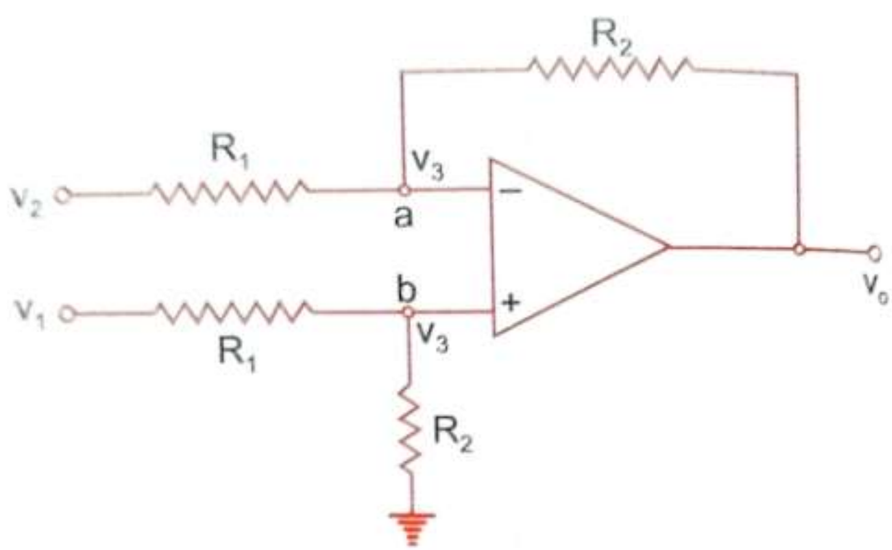
Applying voltage divider rule,

$$V_i = \frac{V_o \cdot R_1}{R_1 + R_f}$$

$$A_{CL} = \frac{V_o}{V_i} = \frac{R_1 + R_f}{R_1}$$

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

**DIFFERENTIAL AMPLIFIER**




A differential amplifier

A circuit that amplifies the difference between two signals is called a difference or differential amplifier. This type of amplifier is very useful in instrumentation circuits. A typical circuit is shown in figure. Since the differential voltage at the input terminals of the op-amp is zero, nodes 'a' and 'b' are at the same potential, designated as $V_3$.

Applying Nodal Analysis at Node 'a',

$$\frac{V_3 - V_2}{R_1} = \frac{V_0 - V_3}{R_2}$$

$$\frac{V_3 - V_2}{R_1} + \frac{V_3 - V_0}{R_2} = 0 \rightarrow (1)$$

Applying Nodal equation at Node 'b',

$$\frac{V_3 - V_1}{R_1} = \frac{0 - V_3}{R_2}$$

$$\frac{V_3 - V_1}{R_1} + \frac{V_3}{R_2} = 0 \rightarrow (2)$$

Rearranging (1) and (2) we get,

$$\left(\frac{1}{R_1} + \frac{1}{R_2}\right) V_3 - \frac{V_2}{R_1} = \frac{V_0}{R_2} \rightarrow (3)$$

$$\left(\frac{1}{R_1} + \frac{1}{R_2}\right) V_3 - \frac{V_1}{R_1} = 0 \rightarrow (4)$$

equating (3) and (4) we get;

(subtracting)..

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

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

$$\boxed{V_0 = \frac{R_2}{R_1}(V_1 - V_2)} \rightarrow (5).$$

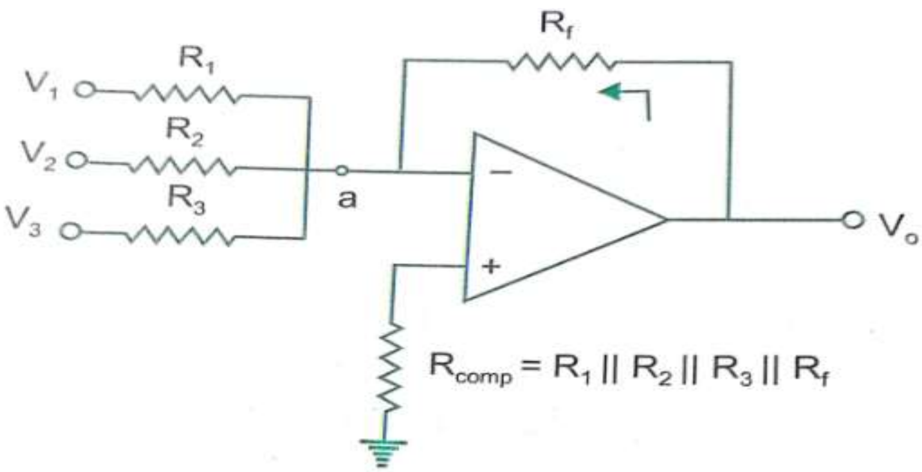
$\frac{R_2}{R_1}$ → gain of the amplifier.

# APPLICATIONS OF OP AMP

## SUMMING AMPLIFIER

Op-amp may be used to design a circuit whose output is the sum of several input signals. Such a circuit is called a summing amplifier or a summer. An inverting summer or a non-inverting summer may be obtained as discussed now.

### Inverting Summing Amplifier




(a) Inverting summing amplifier

A typical summing amplifier with three input voltages $V_1$, $V_2$ and $V_3$, three input resistors $R_1$, $R_2$, $R_3$ and a feedback resistor $R_f$ is shown in figure. The following analysis is carried out assuming that the op-amp is an ideal one, that is, $A_{OL} = \infty$ and $R_i = \infty$. Since the input bias current is assumed to be zero, there is no voltage drop across the resistor $R_{comp}$ and hence the non-inverting input terminal is at ground potential.

The voltage at node 'a' is zero as the non-inverting input terminal is grounded.

Apply KCL at node 'a'

$$I_1 + I_2 + I_3 = I_f$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \frac{V_0}{R_f} = 0$$

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

$$\Rightarrow V_0 = -\left[\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right] \rightarrow (1)$$

Case 1: If $R_f = R_1 = R_2 = R_3$,

then $V_0 = -(V_1 + V_2 + V_3)$

$\therefore$ It is summing output.

**SCALING AND AVERAGING AMPLIFIER**

Case 2: If $R_1 = R_2 = R_3 = 3R_f$

from equ ①,

$$V_0 = -\left(\frac{V_1}{3} + \frac{V_2}{3} + \frac{V_3}{3}\right)$$

$$V_0 = -\left(\frac{V_1 + V_2 + V_3}{3}\right)$$

$\therefore$ It is averaging output.

Case 3: If $R_f \neq R_1 \neq R_2 \neq R_3$

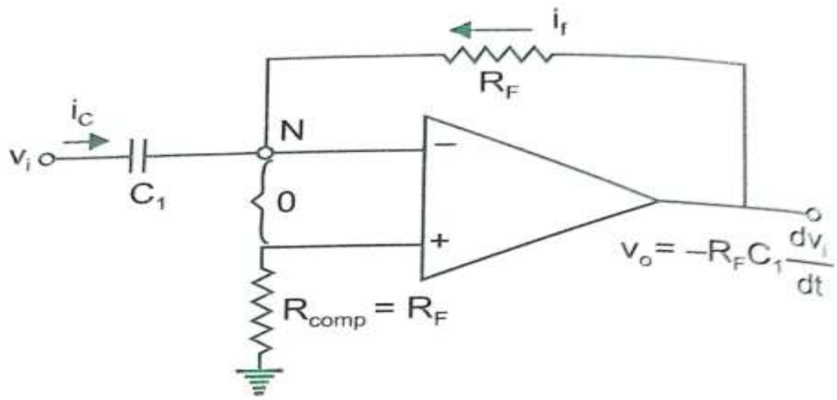
then $$V_0 = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right)$$

$\therefore$ It is scaling output.

**DIFFERENTIATOR**

One of the simplest of the op-amp circuits that contain capacitor is the differentiating amplifier or differentiator. As the name suggests, the circuit performs the mathematical operation of differentiation, that is, the output waveform is the derivative of the input waveform. A differentiator circuit is shown in Fig.

The node N is at virtual ground potential, i.e., $V_N = 0$.




(a) Op-amp differentiator

The output function of the Differentiator is the input function of the difference.

— Applying Nodal analysis,

$$i_c + i_f = 0$$

$$C_1 \frac{d}{dt}(V_i - V_a) + \frac{V_o - V_a}{R_f} = 0 \quad (V_a = 0)$$

$$C_1 \frac{d}{dt}(V_i) + \frac{V_o}{R_f} = 0$$

$$C_1 \frac{d}{dt}(V_i) = -\frac{V_o}{R_f}$$

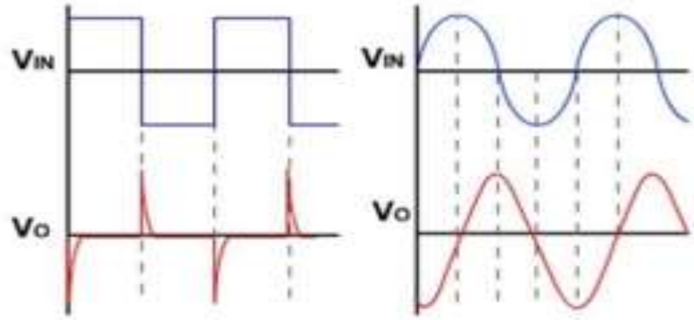
$$-V_o = R_f C_1 \frac{d}{dt}(V_i)$$

$$\boxed{V_o = -R_f C_1 \frac{d}{dt}(V_i).}$$ → Ideal differentiator

(−) → phase difference (180° phase shift)

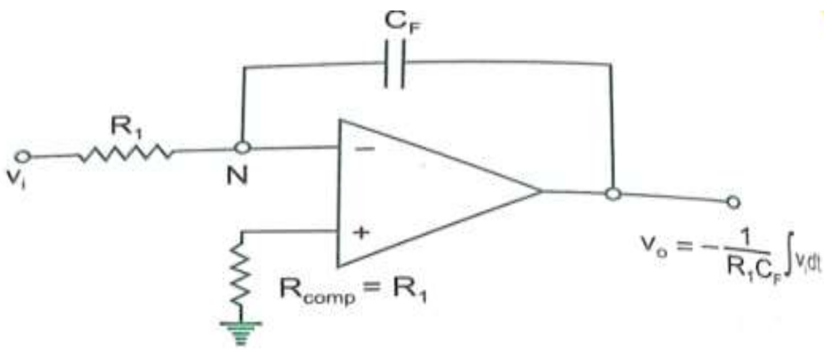
A cosine wave input produces sine output

The input signal will be differentiated properly if the time period T of the input signal is larger than or equal to $R_f C$.




## INTEGRATOR

If we interchange the resistor and capacitor of the differentiator, we have the circuit of Figure which as we will see, is an integrator.




(a) Op-amp integrator

Interchanging resistor and capacitor,

Applying Nodal analysis we get,

$$\frac{V_i - V_a}{R_1} = C_f \frac{d}{dt}(V_a - V_o) \quad (V_a \to 0)$$

$$\frac{V_i}{R_1} = -C_f \frac{dV_o}{dt}$$

$$\frac{dV_o}{dt} = \frac{-1}{C_f \cdot R_1} V_i$$

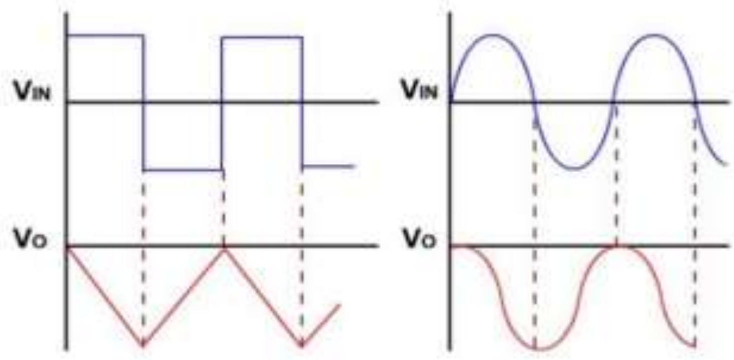
Integrating on both sides we get,

$$\int_0^t \frac{dV_o}{dt} = \frac{-1}{R_1 C_f} \int_0^t V_i(t)$$

$$V_o = \frac{(-)1}{R_1 C_f} \int_0^t V_i(t) + V_o(t) \quad (V_o(t) \to 0)$$

(−) phase difference between input and output.

The output voltage is directly proportional to the negative integral of the input voltage and inversely proportional to the time constant RC. If the input is a sine wave the output will be cosine wave. If the input is a square wave, the output will be a triangular wave.




**RC PHASE SHIFT OSCILLATOR**

Oscillator: Oscillators are amplifiers with feedback. Feedback is the process in which the output signal of the circuit is fed back to the input section. When the amplifier is fed back with its output signal, the characteristics of the circuit change and begin to behave like an oscillator. The signal fed back can be voltage or current, and feedback can be either in series or parallel with the input signal.

Oscillators are used in:

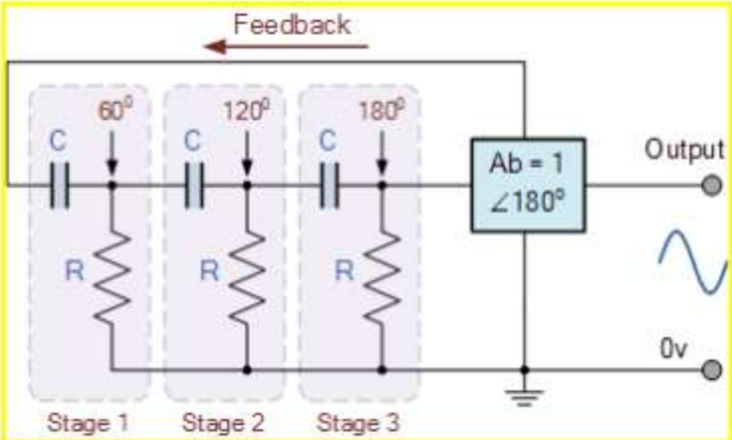
- Radio
- Television
- Computers
- Communication systems

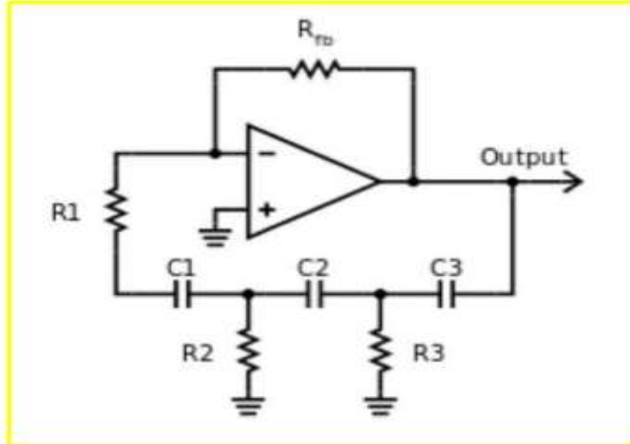
Requirements of an Oscillator

The two main requirements of an oscillator are:

- The magnitude of the gain (A) must be at least 1. (Aß=1)
- The total phase shift of the gain (A) must be either 0° or 360°.

**RC Oscillators** use a combination of an amplifier and an RC feedback network to produce output oscillations due to the phase shift between the stages




- A single stage transistor amplifier can produce $180^o$ of phase shift between its output and input signals when connected as a common-emitter type amplifier and we can use this configuration to produce an RC oscillator circuit.
- Operational amplifier is used to build the oscillator.
- The resistances $R_{feedback}$ and $R_1$ are the input
- Feedback resistances of the inverting amplifier, while $R_1$-$R_3$ and $C_1$-$C_3$ form the phase shift feedback network.
- The feedback factor (ß), defined for the feedback network, is given by

$$B = \frac{V_f}{V_o}$$

## Closed loop gain

where $V_f$ is the output voltage of the feedback section and Vo is the input voltage to the feedback section. It is given by,

$$A_{cl} = \frac{V_o}{V_f}$$

- The phase shift of 180°, the feedback factor must always be 1/29.
- This also implies that the close-loop gain must be at least 29.
- If this closed-loop gain is made less than this, the oscillator will not oscillate and will not produce a sinusoidal output.
- For a closed loop gain slightly larger than 29, the oscillator can give a reasonably pure sinusoid

If **R2 = R3 = R,** and **C1 = C2 = C3 = C**, the oscillation frequency of the oscillator can be shown to be given by

$$f = \frac{1}{2\pi RC\sqrt{6}}$$

**COMPARATOR**

The comparator is a circuit that is used to compare two voltages and provide an output indicating the relationship between those two voltages. Comparators are used to compare

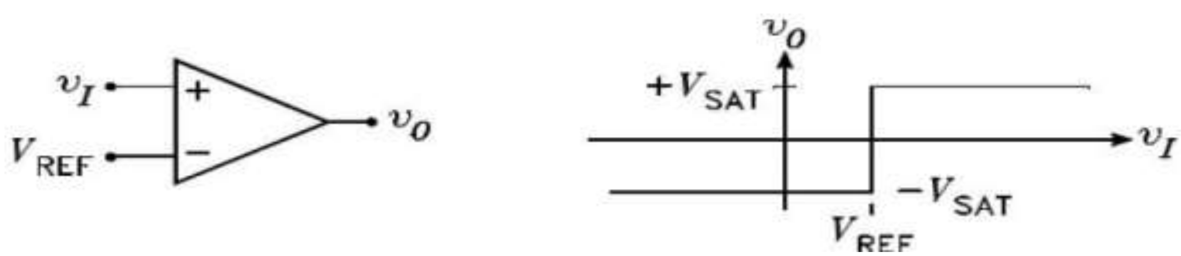
- Two changing voltages to each other, as in comparing two sine waves or
- A changing voltage to a set dc reference voltage.

Figure shows the circuit of an op-amp comparator. There is no feedback path in the circuit. In this circuit, the input voltage is applied to the non-inverting input terminal and a set reference voltage ($V_{ref}$) is applied to the inverting terminal of the op-amp.

Types of Comparators

1. Non-Inverting comparator
2. **Inverting** Comparator

**(1.)Non inverting comparator**




A fixed reference voltage Vref is applied to (-) input and a time varying signal vi is applied to (+) input.The output voltage is at

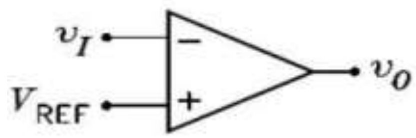
$$V_o = -V_{sat} \text{ for } v_i < V_{ref}$$

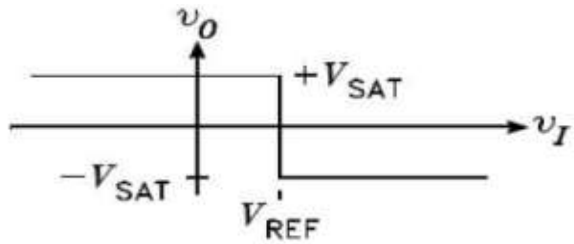
$$= +V_{sat} \text{ for } v_i > V_{ref}.$$

When the noninverting voltage is larger than the inverting voltage the comparator produces a high output voltage (+Vsat). When the non-inverting output is less than the inverting input the output is low (-Vsat).

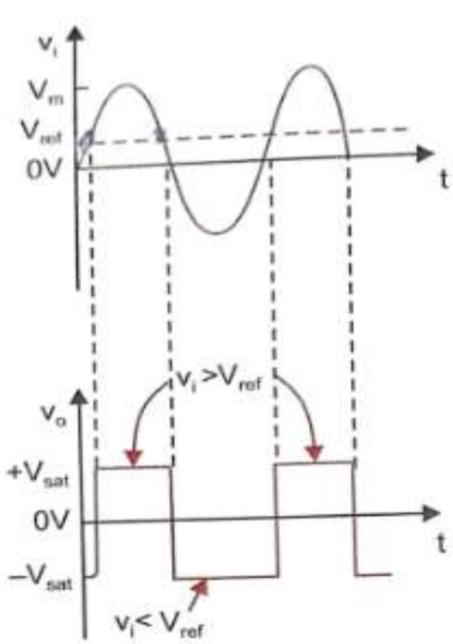
**(2.)Inverting Comparator**

Figure shows a practical inverting comparator in which the reference voltage $V_{ref}$ is applied to the (+) input and $V_i$ is applied to (–) input.

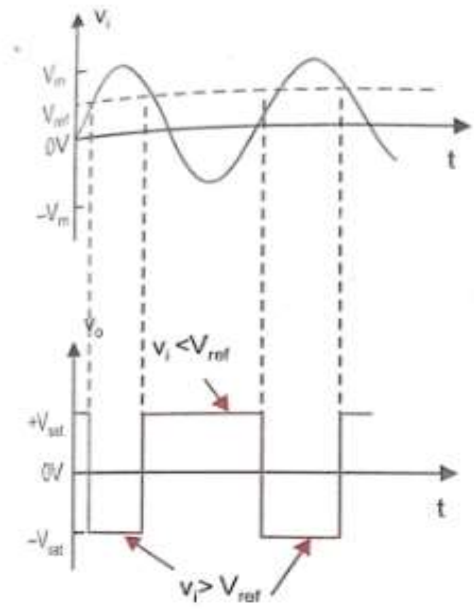



**Input & Output waveforms**:




(1.)Non inverting comparator waveform




(2.) Inverting comparator waveform

**Applications of comparator**

1.Zero crossing detector

2.Window detector

3.Time marker generator

4.Phase detector