Syllabus: Introduction to Operational Amplifiers, OP AMP input modes, OPAMP Parameters-CMRR, Input Offset Voltage and Current, Input Bias Current ,Input and Output Impedance,Slew rate, Applications of OP AMP- Inverting Amplifier,Non Inverting Amplifier, Adder, voltage follower, integrator, differentiator, Comparator.

Module-3

Operational Amplifiers

Introduction to Operational Amplifiers

- An Operational Amplifier, or op-amp for short, is fundamentally a voltage amplifying device designed to be used with external feedback components such as resistors and capacitors between its output and input terminals
- An operational amplifier, or op-amp, is the most important and versatile analog IC. ***It is a direct coupled multistage voltage amplifier with an extremely high gain.*** With the help of op-amp, the circuit design becomes very simple. The variety of useful circuits can be built without the necessity of knowing about the complex internal circuitry. Fig. 1 shows circuit symbol and circuit model of an Op-Amp.

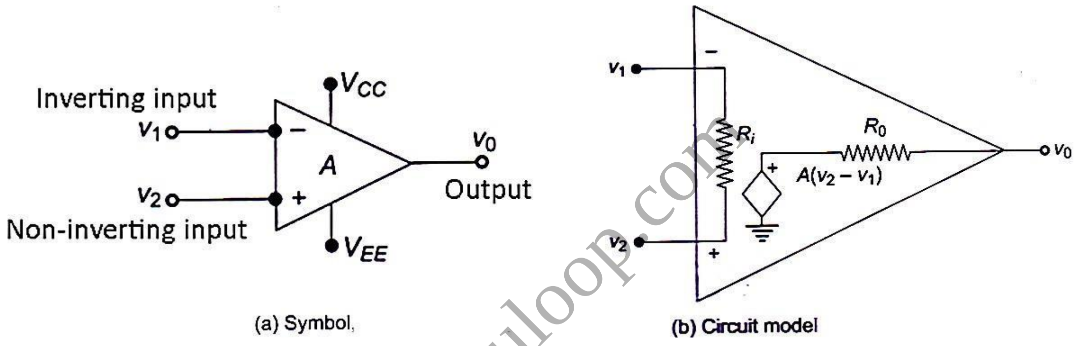


Fig. 1 Circuit symbol and model of an Op-Amp

- An op-amp has two input terminals – an inverting input V_1 and a non-inverting input V_2, and an output V_o. It requires two power supplies: $+V_{CC}$ and $-V_{EE}$. It has a very high input impedance R_{in}, a very low output impedance R_o and a very high gain A.

Infinite gain

$V_0 = A\ (V_2 - V_1)$

$V_2 - V_1 = V_0/A = 0$ where A= infinite

V2=V1

Op-Amp Architecture

The block diagram of an op-amp is as shown in Fig. 2.

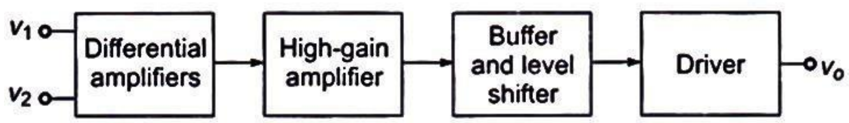


Fig. 2 Block diagram of an op-amp

- The differential amplifier is two BJT or MOSFET amplifiers connected in opposition so as to amplify the difference of two input signals. It has a very high input impedance.

- The high-gain amplifier is another differential amplifier which provides additional voltage gain. Practically, it is not a single amplifier, but a chain of cascaded amplifiers called multistage amplifiers.
- The buffer is an emitter follower used for matching the load. If the output is nonzero for zero input, the level shifter makes it zero.
- Driver is a power amplifier which increases the output voltage swing and keeps the voltage swing symmetrical with respect to ground.

Advantages of Op-Amps

- Low cost
- Small size
- Versatility
- Flexibility
- Dependability

Applications of Op-Amps

- Op-amps have become an integral part of almost every electronic circuit which uses linear integrated circuits.
- Op-amps are used in analog signal processing and analog filtering.
- They are used to perform mathematical operations such as addition, subtraction, multiplication, integration, differentiation, etc.
- They are used in the fields of process control, communications, computers, power and signal sources, displays and measuring systems.
- They are used in linear applications like voltage follower, differential amplifier, inverting amplifier, non-inverting amplifier, etc. and non-linear applications like precision rectifiers, comparators, clampers, Schmitt trigger circuit, etc.

Differential Amplifier

An op-amp is basically a differential amplifier or difference amplifier which amplifies the difference between the two input signals. The output voltage is proportional to the difference between two input voltages. We can write this as

$$V_o \propto (V_2 - V_1)$$

Differential Gain

An op-amp amplifies the difference between the two input signals $\boldsymbol{V_d} = \boldsymbol{V_2} - \boldsymbol{V_1}$. The output voltage is given by

$\boldsymbol{V_o} = \boldsymbol{A_d V_d} = \boldsymbol{A_d}\ (\boldsymbol{V_2} - \boldsymbol{V_1})$ where A_d is the **differential gain** given by $\boldsymbol{A_d} = \mathbf{V0}/\boldsymbol{Vd}$, The differential gain is also called ***open loop voltage gain***

Common Mode Gain

If we apply two input voltages which are equal i.e. if $V_1 = V_2$, then ideally the output must be zero. But practically, the output voltage not only depends on the difference voltage but also depends on the average common level of the two inputs. Such a Common mode signal

$V_c = V_1 + V_2 / 2$

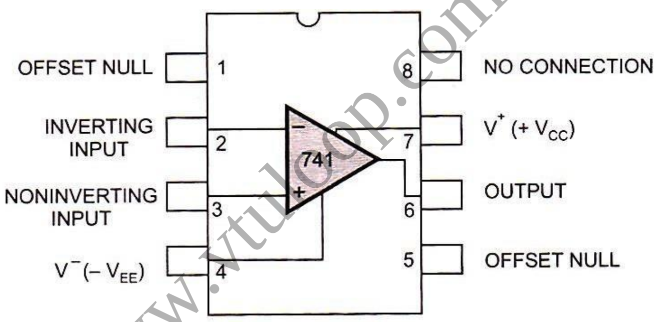
The differential amplifier produces the output voltage proportional to common mode signal and the output voltage is given as $\boldsymbol{V_o = A_c V_c}$

The total output of a differential amplifier is then given by

$$\boxed{\boldsymbol{V_o = A_d V_d + A_c V_c = A_d(V_2 - V_1) + A_c\left(\frac{V_1 + V_2}{2}\right)}}$$

Pin Configuration of 741 OP-AMP

IC 741is the most popular IC version of op-amp. It is an 8-pin IC as shown in Fig. 3.



- Pin 2 is the inverting input terminal and Pin 3 is the non-inverting input terminal
- Pin 6 is the output terminal
- Pin 4 is for $-V_{EE}\,(V^-)$ supply and pin 7 is for $+V_{CC}\,(V^+)$ supply
- Pins 1 and 5 are offset null pins. These are used to nullify offset voltage
- Pin 8 is a dummy pin and no connection is made to this pin

Common Mode Rejection Ratio

Common mode rejection ratio (CMRR) is the ability of an op-amp to reject a common mode signal. **It is defined as the ratio of differential gain $\boldsymbol{A_d}$ to common mode gain $\boldsymbol{A_c}$**CMRR is a large value and is often expressed in decibel as

$$\boxed{\boldsymbol{CMRR = \frac{A_d}{A_c}}}$$

Input offset current

There is a difference in the input current that flows in or out of each of the input pins, even if the output voltage of the operational amplifier is 0 V, due to the fact the pair characteristics (hFE,VBE) of the differential transistor do not match. This difference is known as the input offset current (IIO).

IIO=|IB+-IB-|

INPUT BIAS CURRENT

- One of the golden rules of op amp analysis says this: no current flows into either input terminal. This concept is key for analyzing an amplifier's signal gain.
- However, in reality, a small current flows into both inputs to bias the input transistors. Unfortunately, this bias current gets converted into a voltage by the circuit's local resistors and amplified right along with the signal. The result is an output error in your circuit.
- Depending on the type of input transistor, the bias current can flow in or out of the input terminals. The input current is modeled as current sources, Ib+ and Ib-, in parallel with the positive and negative input terminals.

Ideal Characteristics of Op-Amp

An ideal op-amp has the following characteristics:

1. **Infinite voltage gain (A_{OL} = ∞):** The voltage gain, also known as differential open loop gain is infinite in an ideal op-amp.
2. **Infinite input impedance (R_{in} = ∞):** The input impedance is infinite in an ideal op- amp. This means that no current can flow into an ideal op-amp.
3. **Zero output impedance (R_o = 0):** The output impedance is zero in an ideal op-amp. This means that the output voltage remains the same, irrespective of the value of the load connected.
4. **Zero offset voltage (V_{ios} = 0):** The presence of the small output voltage even when $V_1 = V_2 = 0$ is called offset voltage. In an ideal op-amp, offset voltage is zero. This means the output is zero if the input is zero.
5. **Infinite bandwidth (BW = ∞):** The range of frequencies over which the amplifier performance is satisfactory is called its bandwidth. The bandwidth of an ideal op-amp is infinite.
6. **Infinite CMRR ($CMRR$ = ∞):** The ratio of differential gain to common mode gain is called common mode rejection ratio (CMRR). In an ideal op-amp, CMRR is infinite. This means that the common mode gain is zero in an ideal op-amp.
7. **Infinite slew rate (S = ∞):** Slew rate is the maximum rate of change of output voltage with time. In an ideal op-amp, slew rate is infinite. This means that the changes in the output voltage occur simultaneously with the changes in the input voltage.
8. **No effect of temperature:** The characteristics of an ideal op-amp do not change with the changes in temperature.
9. **Zero PSRR ($PSRR$ = 0):** Power supply rejection ratio (PSRR) is defined as the ratio of the change in input offset voltage due to the change in supply voltage producing it, keeping other power supply voltage constant. In an ideal op-amp, PSRR is zero.

Slew Rate

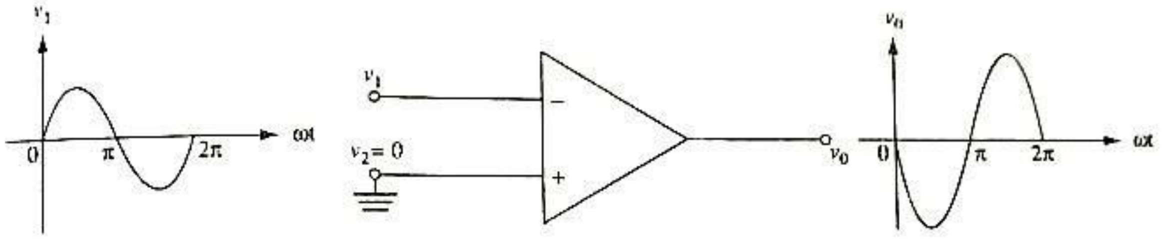
Slew rate is defined as the maximum rate of change of output voltage with time

$$\boxed{Slew\ rate = S = \left.\frac{dV_o}{dt}\right|_{max}}$$

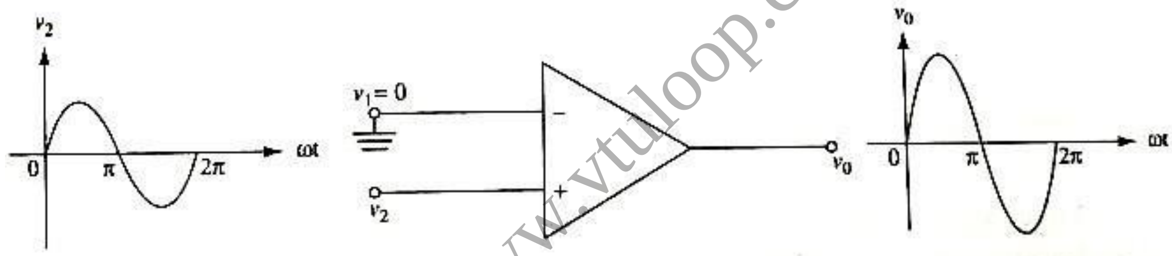
Operation of an Op-Amp

An op-amp is basically differential amplifier which amplifies the difference between the two input signals.

Fig. 4 shows the basic operation of an op-amp as inverting and non-inverting amplifiers.



(a) Inverting amplifier



(b) Non-inverting amplifier

When a voltage V_1 is applied to the inverting input with the non-inverting input grounded ($V_2 = 0$), the output voltage is

$$V_o = A(V_2 - V_1) = A(0 - V_1) = -AV_1$$

This indicates that the output voltage is amplified with a gain A and inverted (phase or polarity reversed) with respect to the input voltage as shown in Fig. 4 (a).

On the other hand, when a voltage V_2 is applied to the non-inverting input with the inverting input grounded ($V_1 = 0$), the output voltage is

$$V_o = A(V_2 - V_1) = A(V_2 - 0) = AV_2$$

This indicates that the output voltage is amplified with a gain A and is in the same phase or polarity as the input voltage as shown in Fig. 4 (b).

Assumptions

While analyzing the operation of op-amp circuits, two assumptions are made:

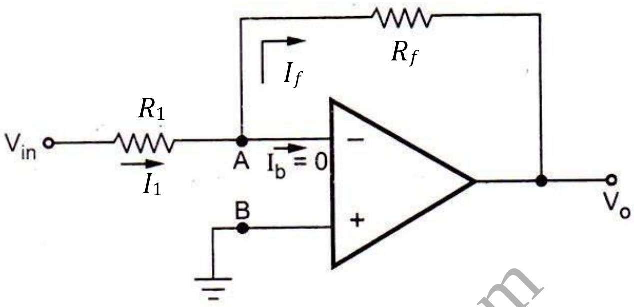
1. **Zero Input Current:** Since the input resistance of an ideal op-amp is infinite, no current flows into an op-amp. This makes the input current zero.

2. This means that the input terminals of an op-amp are always at the same potential. Thus if one terminal is grounded, the other one can be treated to be virtually grounded.

Basic Op-Amp Circuits

Inverting Amplifier

An amplifier which produces a phase shift of 180° between input and output is called ***inverting amplifier.*** Fig. 5 shows an inverting amplifier using op-amp.



From the circuit, the potential at node B, $V_B = 0$. From the concept of virtual ground, the two input terminals are the same potential.

Therefore, the potential at node A, $V_A = V_B = 0$ From the circuit,

$$I_1 = \frac{V_{in} - V_A}{R_1} = \frac{V_{in} - 0}{R_1} \qquad (\because V_A = 0)$$

$$\boldsymbol{I_1 = \frac{V_{in}}{R_1}}$$

$$I_f = \frac{V_A - V_o}{R_f} = \frac{0 - V_o}{R_f}$$

$$\boldsymbol{I_f = -\frac{V_o}{R_f}}$$

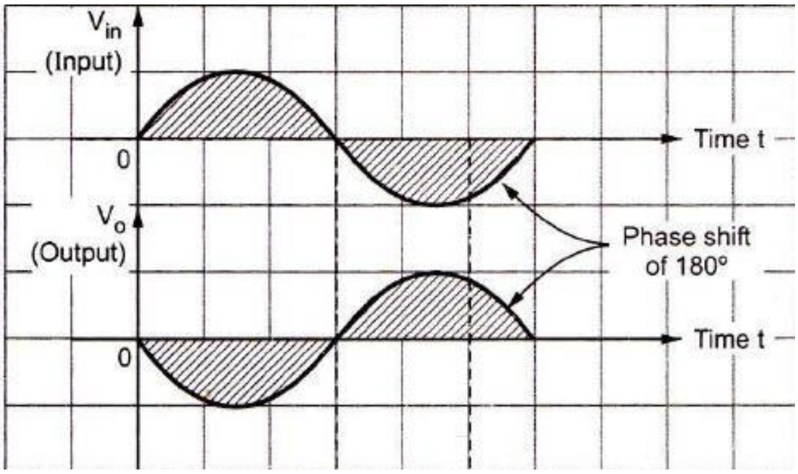
Since op-amp input current is zero, I_1 passes through R_f as I_f. That is,

$$I_1 = I_f$$

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

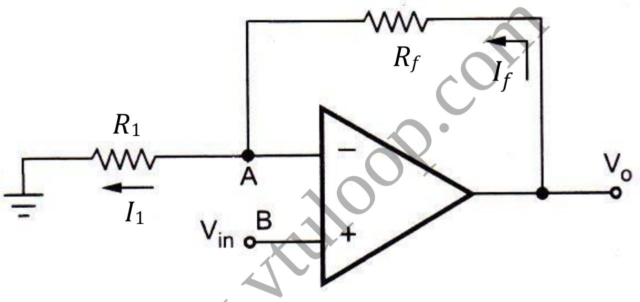
$$\boxed{\boldsymbol{V_o = -\left(\frac{R_f}{R_1}\right) V_{in}}}$$

Here $\frac{R_f}{R_1}$ is called the gain of the amplifier and negative sign indicates that the output is inverted.



Non-Inverting Amplifier

An amplifier which amplifies the input without producing any phase shift between input and output is called ***non-inverting amplifier***. Fig. 7 shows a non-inverting amplifier using op-amp.



From the circuit, the potential at node B, $V_B = V_{in}$.

From the concept of virtual ground, the two input terminals are the same potential. Therefore, the potential at node A, $V_A = V_B = V_{in}$

$$I_1 = \frac{V_A - 0}{R_1} = \frac{V_{in} - 0}{R_1} \qquad (\because V_A = V_{in})$$

$$\boldsymbol{I_1 = \frac{V_{in}}{R_1}}$$

$$I_f = \frac{V_o - V_A}{R_f} = \frac{V_o - V_{in}}{R_f}$$

$$\boldsymbol{I_f = \frac{V_o - V_{in}}{R_f}}$$

Since op-amp input current is zero, I_f passes through R_1 as I_1. That is, $I_1 = I_f$

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

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

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

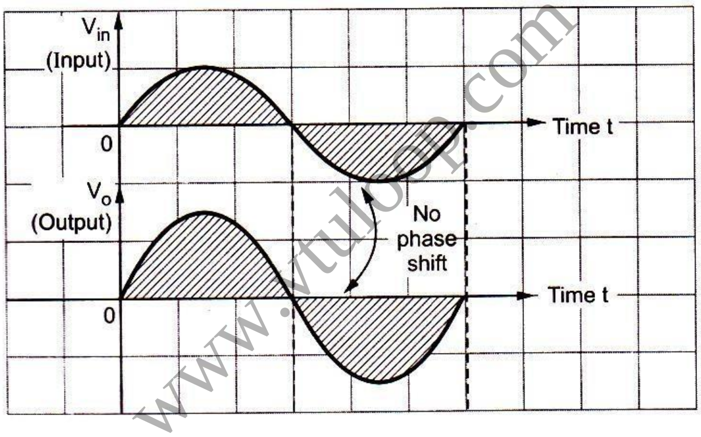
$$\frac{V_o}{R_f} = (\frac{1}{R_1} + \frac{1}{R_f}) V_{in}$$

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

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

$$\boxed{\boldsymbol{V_o = (1 + \frac{R_f}{R_1}) V_{in}}}$$

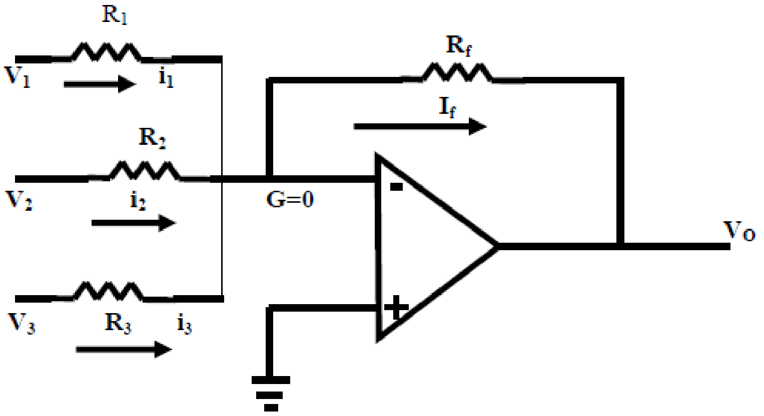
Here $(1 + \frac{R_f}{R_1})$ is called the gain of the amplifier. Fig. 8 shows the input and output waveforms of an inverting amplifier.



Op-Amp Applications

OPAMP Adder (Inverting)

An OPAMP Adder is a circuit which performs addition of two or more input signals which are applied to the inverting input terminal of the OPAMP. In other words an Adder is a circuit which is used to perform addition operation on the signals which are applied to the Inverting input terminal as shown.



By KCL we have

$$i_f = i_1 + i_2 + i_3$$

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

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

$$V_O = -R_f\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]$$

If $R_1 = R_2 = R_3 = R$ then

$$V_O = -\frac{R_f}{R}[V_1 + V_2 + V_3]$$

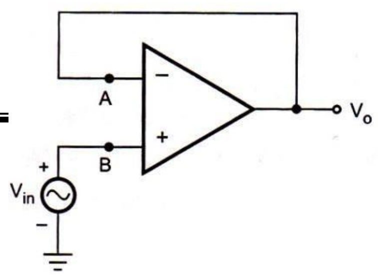
If $R_f = R$ then

$V_O = -[V_1 + V_2 + V_3]$

Hence it can be observed that the output is equal to the inverted sum of the inputs.

Voltage Follower

A circuit in which the output voltage follows the input voltage is called ***voltage follower.***



From the circuit, the potential at node B, $V_B = V_{in}$.

From the concept of virtual ground, the two input terminals are the same potential. Therefore, the potential at node A, $V_A = V_B = V_{in}$.

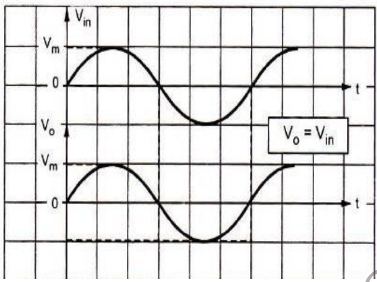
The node A is directly connected to the output. Hence

$$V_o = V_A$$

In a voltage follower gain is unity (A = 1). A voltage follower is also called ***source follower unity gain amplifier***, ***buffer amplifier*** or ***isolation amplifier***.

Now since $V_A = V_{in}$,

$$\boxed{\boldsymbol{V_o = V_{in}}}$$



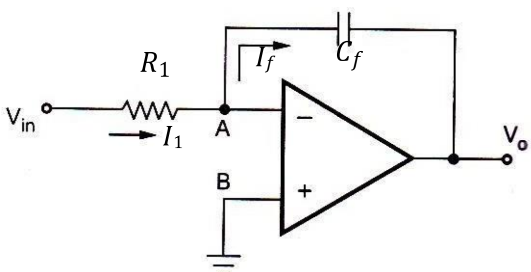
Advantages of Voltage Follower

1. Very large input resistance
2. Very low output resistance
3. Large bandwidth
4. The output follows the input exactly without any phase shift

Summing Amplifier (Adder)

Integrator

In an integrator circuit, the output is the integration of the input voltage. Fig. 15 shows an integrator circuit using an op-amp. From the circuit, the potential at node B, $V_B = 0$. From the concept of virtual ground, the two input terminals are the same potential.



Therefore, the potential at node A, $V_A = V_B = 0$

$$I_1 = \frac{V_{in} - V_A}{R_1} = \frac{V_{in} - 0}{R_1} \qquad (\because V_A = 0)$$

$$\boldsymbol{I_1 = \frac{V_{in}}{R_1}}$$

and

$$I_f = C_f \frac{d(V_A - V_o)}{dt} = C_f \frac{d(0 - V_o)}{dt}$$

$$\boldsymbol{I_f = -C_f \frac{dV_o}{dt}}$$

Since op-amp input current is zero, I_1 passes through R_f as I_f. That is,

$$I_1 = I_f$$

$$\frac{V_{in}}{R_1} = -C_f \frac{dV_o}{dt}$$

$$\frac{dV_o}{dt} = -\frac{V_{in}}{R_1 C_f}$$

Integrating both sides with respect to t,

$$\int \frac{dV_o}{dt} dt = -\frac{1}{R_1 C_f} \int V_{in}\, dt$$

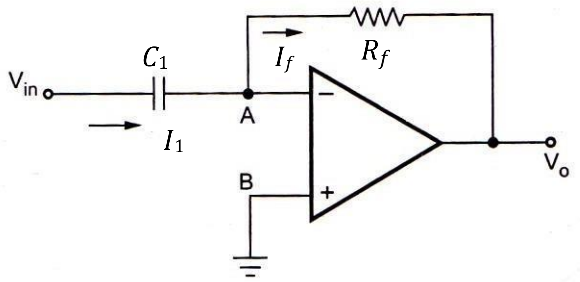
$$\boxed{V_o = -\frac{1}{R_1 C_f} \int V_{in} dt}$$

This shows that the output is the integration of the

input voltage the term indicates the gain of the amplifier

Differentiator

In a differentiator circuit, the output is the differentiation of the input voltage. Fig. 16 shows a differentiator circuit using an op-amp.



From the circuit, the potential at node B, $V_B = 0$.

From the concept of virtual ground, the two input terminals are the same potential. Therefore, the potential at node A, $V_A = V_B = 0$.

From the Circuit

$$I_1 = C_1 \frac{d(V_{in} - V_A)}{dt} = C_1 \frac{d(V_{in} - 0)}{dt} \qquad (\because V_A = 0)$$

$$I_1 = C_1 \frac{dV_{in}}{dt}$$

$$I_f = \frac{V_A - V_o}{R_f} = \frac{0 - V_o}{R_f}$$

$$I_f = -\frac{V_o}{R_f}$$

Since op-amp input current is zero, I_1 passes through R_f as I_f. That is,

$$I_1 = I_f$$

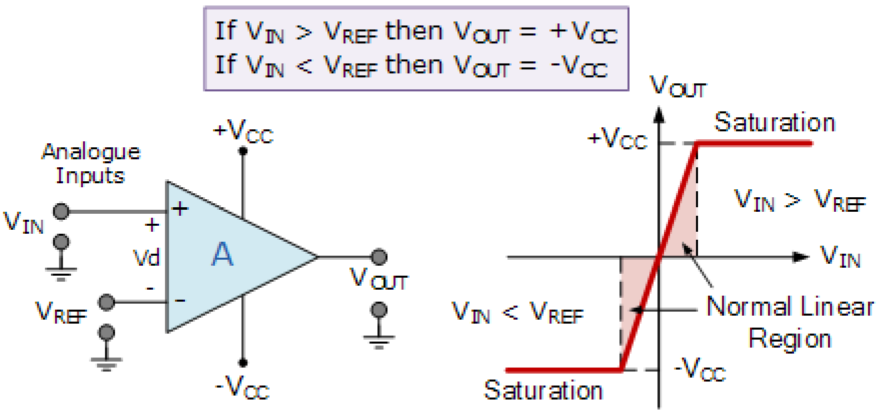
$$C_1 \frac{dV_{in}}{dt} = -\frac{V_o}{R_f}$$

$$\boxed{V_o = -R_f C_1 \frac{dV_{in}}{dt}}$$

This shows that the output is the differentiation of the input voltage. The term $(-R_f C_1)$

This shows that the output is the differentiation of the input voltage. The term $(-R_f C_1)$ Indicates the gain of the amplifier

Comparator



- The Op-amp comparator compares one analogue voltage level with another analogue voltage level, or some preset reference voltage, VREF and produces an output signal based on this voltage comparison. In other words, the op-amp voltage comparator compares the magnitudes of two voltage inputs and determines which is the larger of the two.
- With reference to the op-amp comparator circuit above, lets first assume that VIN is less than the DC voltage level at VREF, (VIN < VREF). As the non-inverting (positive) input of the comparator is less than the inverting (negative) input, the output will be LOW and at the negative supply voltage, -Vcc resulting in a negative saturation of the output.

- If we now increase the input voltage, VIN so that its value is greater than the reference voltage VREF on the inverting input, the output voltage rapidly switches HIGH towards the positive supply voltage, +Vcc resulting in a positive saturation of the output.
- If we reduce again the input voltage VIN, so that it is slightly less than the reference voltage, the op-amp's output switches back to its negative saturation voltage acting as a threshold detector.