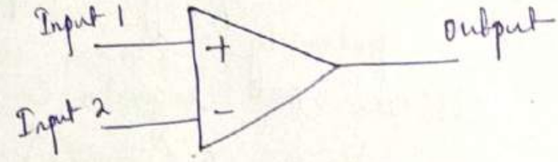
Module - III Operational Amplifier (Op-amp)

Def: An operational amplifier or op-amp is a very high gain differential amplifier with high input impedance and low output impedance.

→ The word operational stands for various mathematical operations such as addition, subtraction, multiplication, differentiation, integration, etc and amplifier is one which boosts or amplifies the signal. Since this circuit performs both mathematical operations and amplification, it is called operational amplifier (Op-amp).

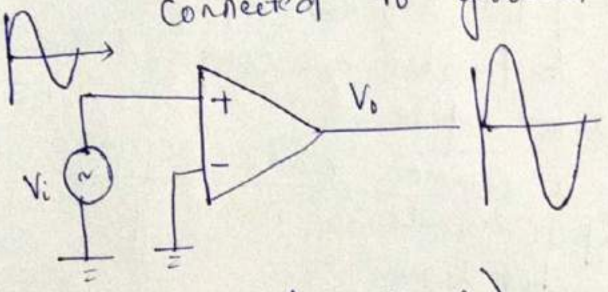
- Application :- voltage amplitude changes (amplitude and polarity), Oscillators, filter circuits and many types of instrumentation circuits.

Basic op-amp

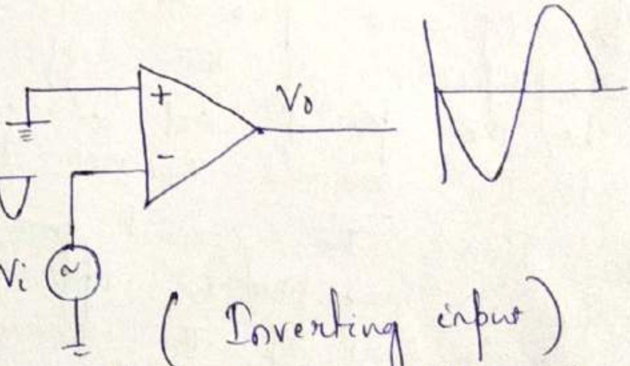


Single - Ended Input

→ Single - ended input operation means when the input is connected to one input with the other input connected to ground.

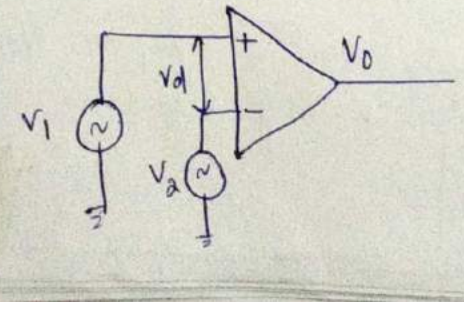


(Non - inverting input)
(The input is applied to the (+) input)



(Inverting input)
(The input is applied to the ~~...~~ (−) input)

Double - Ended (Differential) Input :-



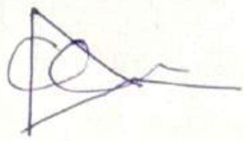
V_1 = Non - inverting input
V_2 = Inverting input
A = voltage gain

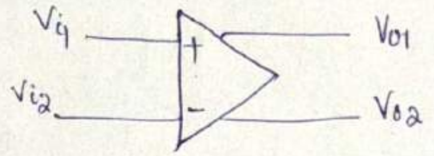
The differential input is

$$V_{in} \text{ or } V_d = V_1 - V_2$$

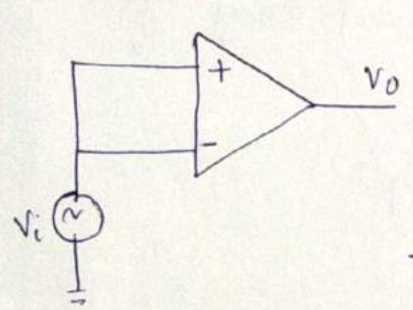
~~Outp~~ Output voltage $V_{out} = A\,V_{in} = A(V_1 - V_2)$

Double - Ended Output :-





Common - Mode operation



When the same input signals are applied to both inputs, the signals are equally amplified but in opposite polarity signals at the output.
Hence the signals cancel.

$$V_{out} = A(V_1 - V_2) = A \cdot 0 = 0 \quad (V_1 = V_2).$$

* But, practically V_{out} is very small.

Differential and common mode operation :-

→ An op-amp provides an output component due to the amplification of the difference of the signals applied to the ~~po~~ '+' and '-' inputs and also a component due to the signals common to both inputs.

→ Since the circuit provides a common mode rejection that is amplification the opposite input signals is much greater than that of the common input signals.
This is called the common-mode rejection ratio (CMRR).

* Differential Inputs :- When separate inputs are applied to the Op-amp, the resulting signal is

$$\boxed{V_d = V_{i_1} - V_{i_2}}$$

* Common Inputs :- When both input signals V_{i_1} and V_{i_2} are the same, the resulting signal is

$$\boxed{V_c = \frac{1}{2}(V_{i_1} + V_{i_2})}$$

* **Output voltage** :- Since any signals applied to an op-amp have both in-phase and out-of-phase components, the resulting output is

$$\boxed{V_0 = A_d V_d + A_c V_c}$$

V_d = difference voltage
V_c = common voltage
A_d = Differential gain of the amplifier
A_c = Common-mode gain of the amplifier.

* **Opposite Polarity Inputs** :-

when $v_{i_1} = -v_{i_2} = V_s$

Then
$$V_d = V_{i_1} - V_{i_2} = v_{i_1} - (-v_{i_2}) = 2V_s$$
$$V_c = \frac{1}{2}(v_{i_1} + V_{i_2}) = \frac{1}{2}(V_{i_1} - V_{i_1}) = 0\,V$$

Hence $$\boxed{V_0 = 2 A_d V_s}$$

* **Same polarity Inputs** :-

When $V_{i_1} = V_{i_2} = V_s$

Then
$$V_d = V_{i_1} - V_{i_2} = V_s - V_s = 0$$
$$V_c = \frac{1}{2}(v_{i_1} + V_{i_2}) = \frac{1}{2}(V_s + V_s) = V_s$$

Then $$\boxed{V_0 = A_c V_s}$$

* **Common-mode Rejection Ratio**

→ A measure of rejection of signals common to both inputs is referred to as the common-mode rejection of the amplifier and the numerical value is known as Common-mode rejection ratio (CMRR).

→ It is defined as the ratio of differential voltage gain to common-mode voltage gain and it is given as

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

In ~~an~~ an ideal differential amplifier, the output signal V_{out} is

$$V_{out} = A(V_{i_1} - V_{i_2}) = A V_d$$

But practically, $V_{out} = A_d V_d + A_c V_c$

where $V_d = V_{i_1} - V_{i_2}$

$$V_c = \frac{1}{2}(V_{i_1} + V_{i_2})$$

Let the output voltage V_{out} is expressed as a linear combination of two input voltages V_{i_1} and V_{i_2}.

Then $\cancel{V_{i_1} = V_c + \frac{1}{2} V_d}$

$\cancel{V_{i_2} = V_c - \frac{1}{2} V_d}$

~~Then Vout is~~ $V_{out} = A_1 V_{i_1} + A_2 V_{i_2}$

where $A_1 \to$ the voltage gain for input V_{i_1} with V_{i_2} is grounded.

$A_2 \to$ voltage gain for input V_{i_2} with V_{i_1} is grounded.

Solving V_d and V_c for V_{i_1} and V_{i_2} is

$$V_{i_1} = V_c + \frac{1}{2} V_d$$

$$V_{i_2} = V_c - \frac{1}{2} V_d$$

Substituting these values in V_{out}

$$V_{out} = A_1\left(V_c + \frac{1}{2} V_d\right) + A_2\left(V_c - \frac{1}{2} V_d\right)$$

$$= \frac{1}{2}(A_1 - A_2) V_d + (A_1 + A_2) V_c$$

$$= A_d V_d + A_c V_c$$

Where $A_d = \frac{A_1 - A_2}{2}$

$$A_c = (A_1 + A_2)$$

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

$$\boxed{CMRR(\log) = 20 \log \frac{A_d}{A_c}}$$

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$$V_0 = A_d V_d + A_c V_c = A_d V_d \left(1 + \frac{A_c V_c}{A_d V_d}\right)$$

$$\boxed{V_0 = A_d V_d \left(1 + \frac{1}{CMRR} \frac{V_c}{V_d}\right)}$$

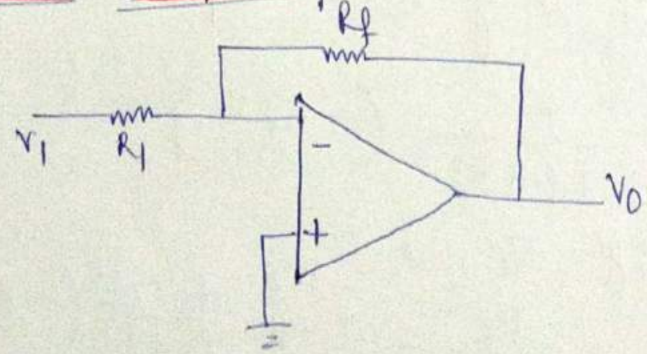
Hence, it is clearly shown that even when both V_d and V_c components of signals are present, for large values of CMRR, the output voltage will be mostly due to the difference signal.

Ideal Op-amp :- Characteristics

The op-amp is said to be ideal having the following characteristics

- → Its open-loop gain A is ∞.
- → Its input resistance (i.e the resistance measured between inverting and non-inverting terminal) R_{in} is ∞.
- → Its output impendance R_{out} is 0.
- → Infinite frequency bandwidth.
- → Drift of characteristics with temperature is nil.
- → CMRR is ∞.
- → Slew rate is ∞.

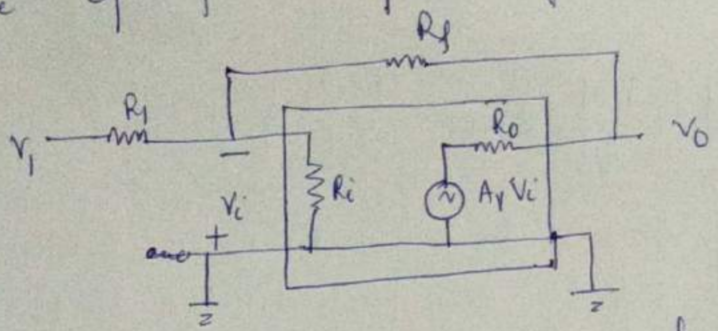
Basic Op-amp



(the resulting output is opposite in phase to the input signal.)

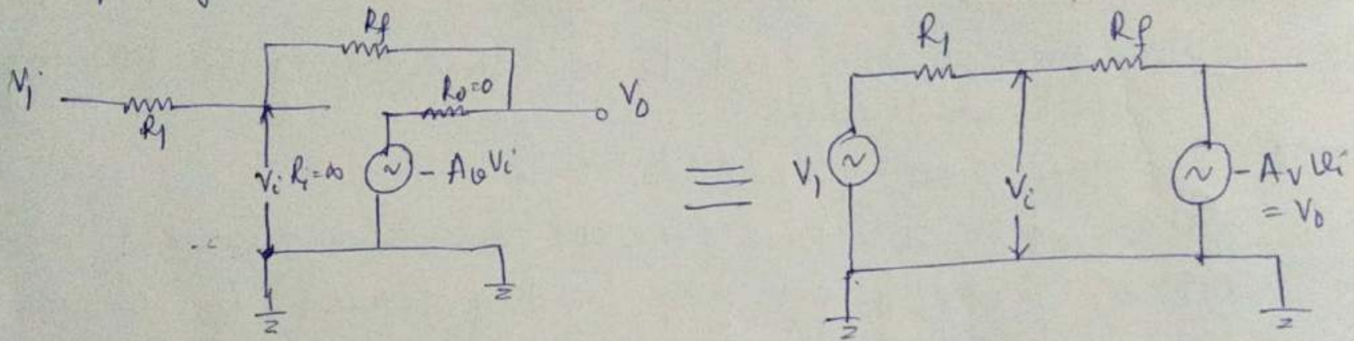
(Basic op-amp connection)

If the op-amp is replaced by its ac equivalent circuit then



(op-amp ac equivalent circuit)

Replacing $R_i = \infty$ and $R_o = 0\,\Omega$.



(ideal op-amp circuit)

Using superposition theorem for solving V_1 in terms of the components making $-A_V V_i$ set to zero.

$$V_{i_1} = \frac{R_f}{R_1 + R_f} V_1$$

For the source $-A_V V_i$ only making V_1 set to zero

$$V_{i_2} = \frac{R_1}{R_1 + R_f} \left(-A_V V_i\right)$$

Hence, the total voltage V_i is

$$V_i = V_{i_1} + V_{i_2} = \frac{R_f}{R_1 + R_f} V_1 + \frac{R_1}{R_1 + R_f}\left(-A_V V_i\right)$$

$$\Rightarrow \left(1 + \frac{R_1}{R_1 + R_f} A_V\right) V_i = \frac{R_f}{R_1 + R_f} V_1$$

$$\Rightarrow \left(\frac{R_1 + R_f + R_1 A_V}{\cancel{R_1 + R_f}}\right) V_i = \frac{R_f}{\cancel{R_1 + R_f}} V_1$$

$$\boxed{V_i = \frac{R_f}{R_f + (1+A_v)R_1} V_1}$$

if $A_v >> 1$, hence $A_v R_1 >> (1+R_f)$.

So

$$V_i = \frac{R_f}{A_v R_1} V_1$$

So,

$$\frac{V_0}{V_i} = \cancel{\frac{-A_v V_i}{R_f V_1} \cdot A_v R_1 \cdot \frac{R_f}{A_v R_1} V_1}$$

$$= -\frac{A_v V_i}{V_i} = -\frac{A_v}{V_i} \frac{R_f V_1}{A_v R_1}$$

$$\Rightarrow \frac{V_0}{V_i} = -\frac{\cancel{A_v} R_f}{R_1} \cdot \frac{V_1}{V_i}$$

$$\Rightarrow \boxed{\frac{V_0}{V_1} = -\frac{R_f}{R_1}}$$

Hence, $\boxed{V_0 = \left(-\frac{R_f}{R_1}\right) V_1}$

depends on only R_f and R_1.

Unity gain

if $R_f = R_1$, then

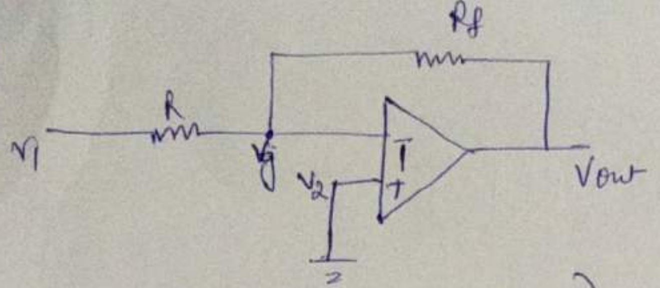
$$\boxed{\frac{V_0}{V_1} = -\frac{R_f}{R_1} = -1}$$

- The circuit provides a unity voltage gain with 180° phase inversion.

Virtual Ground

Virtual ground is making a node on a connection virtually ground i.e it is not physically connected to the ground but voltage at that point/ node is 0V.
- Therefore, it is refered as ground.

eg



In an ideal op-amp open loop gain A is ∞.

(inverting amplifier) $A = \dfrac{V_{out}}{(v_2 - v_g)} = \dfrac{V_{out}}{(V_{noninv} - V_{inv})}$

if $A = \infty$, $V_g - V_2 = 0$

As v_2 is connected to ground $v_2 = 0$, hence $v_g = 0$

Though v_g is not connected to the ground, but $v_g = 0$.

In the practical op-amp, the gain is very very large.

Let $A = 10^5$.

The output voltage Vout is to be limited to the supply voltage Vcc, which is of the order 10 or 15 V.

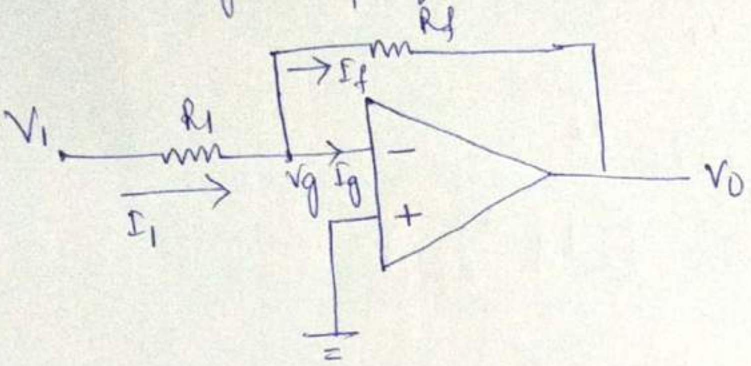
Then $V_{in} = (V_{noninv} - V_{inv}) = \dfrac{V_{out}}{10^5} = \dfrac{10}{10^5} = 0.0001\ V$

Hence $V_{noninv} - V_{inv} = 0.0001\,V \cong 0$

As ~~$V_2 = V_{noninv} = 0$~~ Hence, there is a virtual short in between noninverting input and inverting input.

Practical Op-amp Circuits

1) Inverting Amplifier :-



(Inverting constant-gain multiplier)

It is the most widely used constant-gain amplifier circuit.

As we know

$$V_0 = -A_d V_g$$

$$\Rightarrow V_g = -\frac{V_0}{A_d}$$

For ideal op-amp $A_d = \infty$, hence $V_g = 0$

So $i_g = \frac{V_g}{R_i} = \frac{V_g}{\infty} = 0$ $\left(\because \text{for ideal opamp } R_i = \infty \right)$

Applying KCL at the node

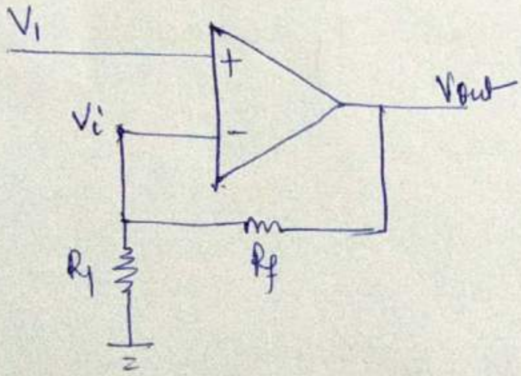
$$I_1 = I_g + I_f$$

$$\Rightarrow \frac{V_1 - V_g}{R_1} = 0 + \frac{V_g - V_0}{R_f}$$

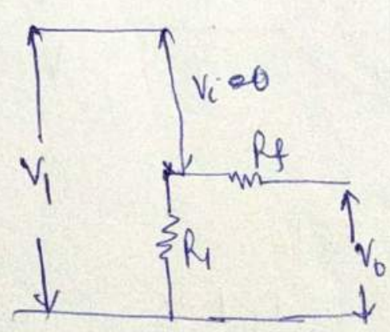
$$\Rightarrow \frac{V_1}{R_1} = -\frac{V_0}{R_f} \Rightarrow \boxed{\frac{V_0}{V_1} = -\frac{R_f}{R_1}}$$

The output is inverted from the input.

2) Non Inverting Amplifier :-



(Non inverting constant-gain multiplier)



(Equivalent circuit)

From the potential divider network

$$V_i = \frac{R_1}{R_1 + R_f} V_0$$

As $I_g = 0$ & virtual ground

$$V_i = V_1$$

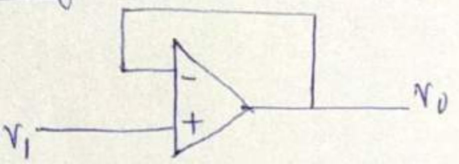
$\Rightarrow$ Hence $V_1 = \frac{R_1}{R_1 + R_f} V_0$

$$\Rightarrow \frac{V_0}{V_1} = \frac{R_1 + R_f}{R_1} = \left(1 + \frac{R_f}{R_1}\right)$$

$$\Rightarrow \boxed{V_0 = \left(1 + \frac{R_f}{R_1}\right) V_1}$$

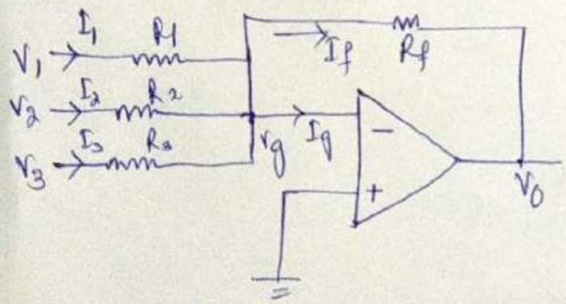
So, the overall closed-loop gain of a non-inverting amplifier will always be greater than one.

3) Unity Follower



$$\boxed{V_0 = V_1}$$

4) Summing Amplifier



This circuit provides a algebraically summing of three voltages, each multiplied by a constant-gain factor.

We know that $I_g = 0$ and $V_g = 0$.

Applying KCL

$$I_1 + I_2 + I_3 = I_g + I_f$$

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

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

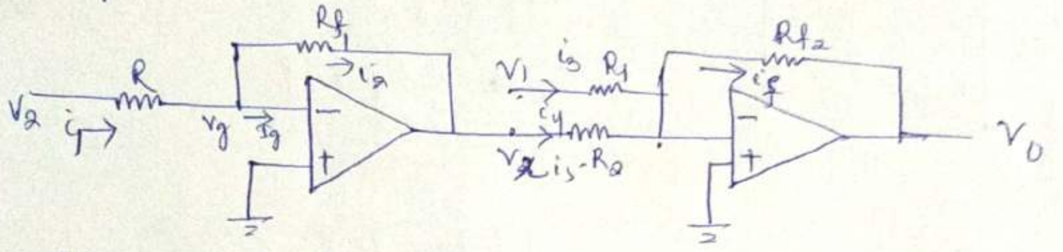
$$\Rightarrow \boxed{V_0 = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right)}$$

If $R_1 = R_2 = R_3 = R_f$

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

The output is the summation of the inputs.

5) <u>Op-amp as Subtractor</u>



$V_g = 0$ & $I_g = 0$

$$\frac{V_2 - V_g}{R} = \frac{V_g - V_x}{R_{f_1}} \Rightarrow \frac{V_2}{R} = -\frac{V_x}{R_{f_1}}$$

$$\Rightarrow V_x = -V_2 \quad (R = R_{f_1})$$

Applying KCL to the second part

$$i_4 + i_5 = i_f \Rightarrow \frac{V_1 - V_g}{R_1} + \frac{V_x - V_g}{R_2} = \frac{V_g - V_0}{R_{f_2}}$$

$$\Rightarrow \frac{V_1}{R_1} + \frac{V_x}{R_2} = -\frac{V_0}{R_{f_2}}$$

But $V_x = -V_2$

Replacing the same

$$\Rightarrow \frac{V_1}{R_1} - \frac{V_2}{R_2} = -\frac{V_0}{R_{f_2}} \Rightarrow V_0 = -\left(\frac{R_{f_2}}{R_1} V_1 - \frac{R_{f_2}}{R_2} V_2\right)$$

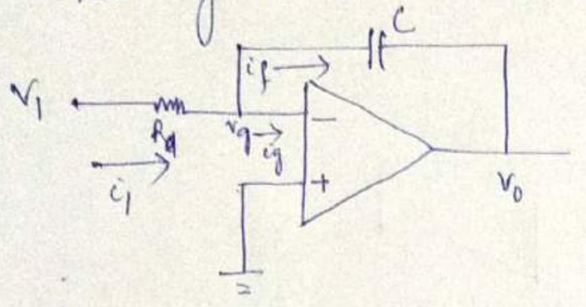
if $R_1 = R_2 = R_f$, then

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

Since, the output voltage is the difference of two input voltages, it is known as subtractor.

6) Integrator

→ If the feedback component used is a capacitor, then the resulting circuit is called an integrator.



Applying

$i_1 = i_g + i_f$

$$\Rightarrow \frac{V_1 - V_g}{R} = i_g + C\frac{d(V_g - V_0)}{dt}$$

$$\Rightarrow \frac{V_1}{R} = -C\frac{dV_0}{dt} \Rightarrow \frac{dV_0}{dt} = -\frac{1}{RC}V_i$$

Integrating both sides w.r.t t we get

$$V_0(t) = -\frac{1}{RC}\int_0^t V_1(t)\,dt$$

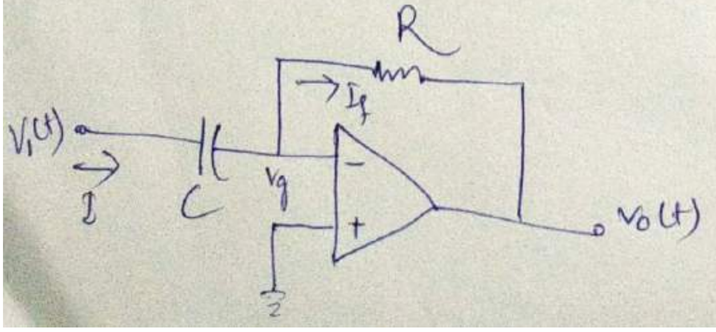
$$\boxed{V_0 \propto \int_0^t V_1\,dt}$$

Since the output is directly proportional to the integration of the input, it is known as integrator.

★ If more than one input is applied to an integrator, then the resulting operation is

$$V_0(t) = -\left[\frac{1}{R_1 C}\int V_1(t)\,dt + \frac{1}{R_2 C}\int V_2(t)\,dt + \frac{1}{R_3 C}\int V_3(t)\,dt\right]$$

7) Differentiator



$I = I_g + I_f$

$$C\frac{d(V_1 - V_g)}{dt} = \frac{V_g - V_0}{R}$$

$$\Rightarrow C \frac{dv_1}{dt} = -\frac{V_0}{R}$$

$$\Rightarrow V_0(t) = -RC \frac{dv_1(t)}{dt} \Rightarrow \boxed{V_0(t) \propto \frac{d v_1(t)}{dt}}$$

Since the output voltage is proportional to the differentiation of the input, it is known as differential Amplifier.

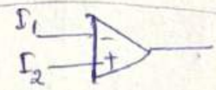
Some Important Op-amp Specifications.

1) Output offset voltage :- It is the dc voltage present at the output terminal when the two input terminals are grounded.

2) Input offset voltage :- It is defined as the resultant difference in voltage required at the input of op-amp to make the output voltage to zero.

3) Input offset current :- It is defined as the difference between the two currents entering the input terminals of a balanced amplifier for Vout = 0.

$$\boxed{I_{in}(\text{offset}) = I_1 - I_2 \text{ for } V_{out} = 0}$$



4) Input Bias current :- It is defined as the average of the current across the two terminals of the op-amp to make the output voltage zero.

$$\boxed{I_B = \frac{I_1 + I_2}{2} \text{ for } V_{out} = 0}$$

5) ~~Info~~ Input offset current drift :- It is defined as the ratio of change in input offset current to the change in temperature.

6) Input offset voltage drift :- It is defined as the ratio of change in input offset voltage to the change in temperature.

7) Slew Rate :- It is the opamp's ability to handling varying signals.

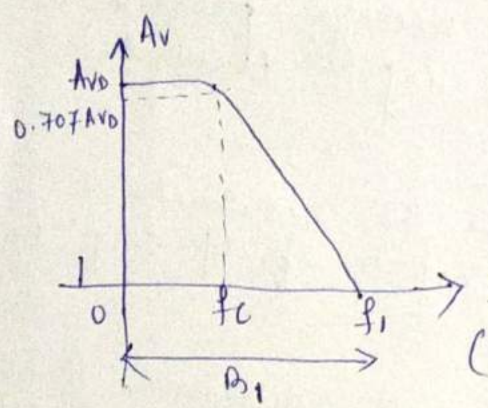
→ It is defined as the maximum rate of change of output voltage per microsecond (V/μsec).

$$\boxed{SR = \frac{\Delta V_o}{\Delta t} \quad V/\mu sec}$$

8) Power supply Rejection Ratio :- It is defined as the ratio of change in output offset voltage to the change in power supply voltage

$$\boxed{PSRR = \frac{\Delta V_{CO}}{\Delta V_{CC}}}$$

9) Gain – Bandwidth :–



(gain Vs frequency of a typical op-amp)

As the frequency of the input signal increases the open loop gain drops off until it reaches the value of 1.

– The frequency range at which this unity gain is achieved is known as unity-gain bandwidth.

– The cut-off frequency of the op-amp f_c is defined as the freq frequency range, when the gain ~~is~~ drops by 3 dB or 0.707 A_{VD}.

– The unity-gain frequency (f_1) and cutoff frequency is related by

$$\boxed{f_1 = A_{VD} f_c}$$

gain

Hence, the unity gain frequency (f_1) may also be called the gain – bandwidth product of the op-amp.

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