# OPERATIONAL AMPLIFIER

UDOSHI BASAVARAJ

## Introduction:

*) It is a high gain, directly coupled, differential amplifier.

*) It can amplify signal frequency ranging between 0 & 1MHz i.e OP-AMP can amplify both AC & DC signals

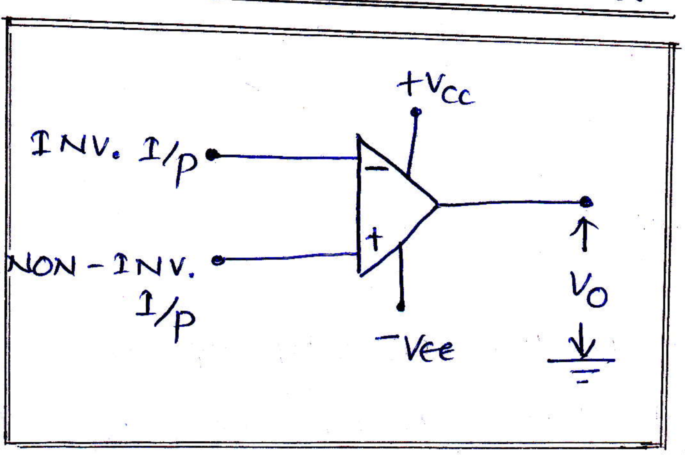
*) Response of OP-AMP is controlled by passive component like resistor.

*) OP-AMP is available in IC package

*) OP-AMP has no effect of temperature variations.

*) It can perform mathematical operations such as, Addition, Subtraction, Multiplication, Differentiation, Integration & Comparison of signals hence it is called as Operational Amplifier [OP-AMP]

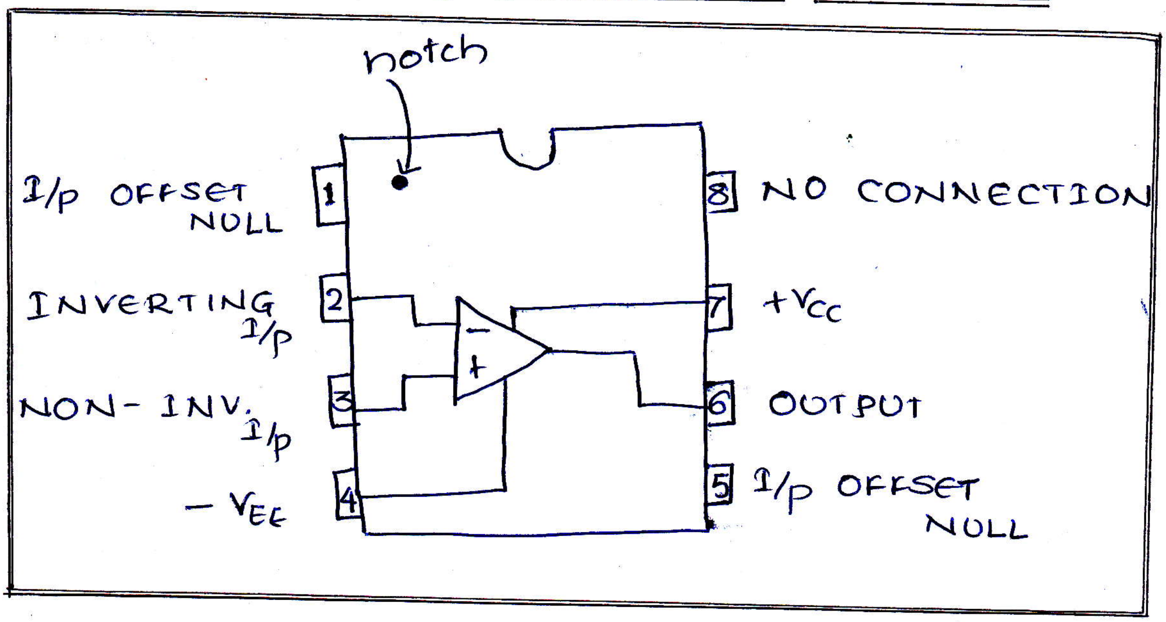
## Symbol of OP-AMP:




✓ Inverting I/p: If the signal is applied to inverting I/p terminal, output signal will be inverted part of applied i/p signal. i.e I/p & O/p signals are out of phase by 180°.

✓ Non-Inverting I/p: If the signal is applied to non-inv. i/p, output & i/p signal are inphase. i.e phase difference is zero

*) PIN-OUT DIAGRAM OF IC 741

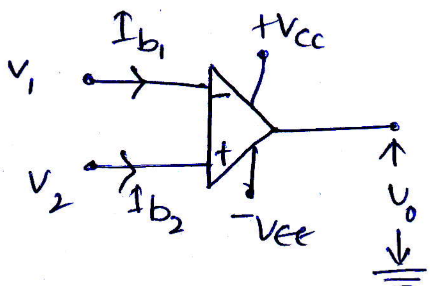



*) CHARACTERISTICS OP-AMP

i) Input OFFSET Voltage: It is the amount of Voltage must be applied across input terminals of an OP-AMP to nullify whose output.

ii) Input offset Current ; It is the algebraic difference between Currents entering the input terminals of an OP-AMP.

i.e Input Offset Current = $[I_{b_1} - I_{b_2}]$




iii) Output Offset Voltage; It is the ability of an OP-AMP to produce O/p signal even though i/p's are maintained with zero potential.

*) **Slew Rate (S):** Rate of change of Maximum output voltage with time is called slew rate.

i.e $S = \frac{d(V_{o\,max})}{dt}$ Unit of slew rate is $V/\mu s$

*) **Common Mode Rejection Ratio [CMRR]:** It is ratio of differential gain [$A_d$] to the common mode gain [$A_c$]

i.e $CMRR = \frac{A_d}{A_c}$

*) **Power Supply Rejection Ratio [PSRR]** or **Supply Voltage Rejection Ratio [SVRR]**

It is the ratio of change in input offset voltage to the change in supply voltage.

Ideally PSRR or SVRR is zero

*** Unit of it is $\mu V/V$

## Ideal characteristics of an OP-AMP

i) Input Impedance is infinity i.e $Z_{in} = \infty$

ii) Open loop Voltage gain is infinity i.e $A_v = \infty$

iii) Band width is infinity i.e $BW = \infty$

iv) Slew rate is infinity i.e $S = \infty$

v) CMRR is infinity i.e $CMRR = \infty$

vi) Output Impedance is zero i.e $Z_{out} = 0$

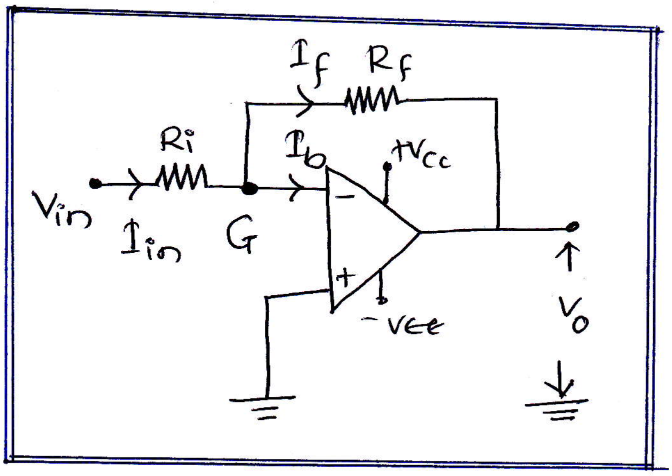
vii) Difference input Voltage to an op-Amp is zero, i.e $V_1 \sim V_2 = 0$

viii) No effect of temperature

## *) Concept of Virtual Ground :

Defn: A node which has zero potential w.r.to ground but not connected to ground is called as Virtual Ground.

Concept :




Let
- $V_1$ is voltage drop across inverting terminal.
  i.e $V_1 = V_G$
- $V_2$ is voltage drop across non-inverting terminal

✓ but non-inverting terminal is grounded hence $V_2 = 0$

(*) According to ideal characteristics of OP-AMP is

$V_1 \sim V_2 = 0$ or $V_1 - V_2 = 0 \Rightarrow V_1 = V_2$ since $V_2 = 0$

$\boxed{\therefore V_1 = 0}$ i.e $V_G = 0$ potential across node G is zero $\rightarrow$ (i)

(*) $|||^{rly}$ According to ideal characteristics of OP-Amp.

$Z_{in} = \infty$ hence $I_b = 0$

$\Rightarrow$ Current accepting or sinking capability of node G zero $\rightarrow$ (ii)

$\therefore$ from case (i) & (ii) Node G is called virtual ground.

(*) Real Ground or Ground i.e earth: whose current sinking capability is infinity but potential is zero.

#) OP-AMP's mode of OPERATION as an AMPLIFIER

1> INVERTING Amplifier

2> NON-INVERTING Amplifier

## #> APPLICATIONS OF OP-AMP

i> OP-AMP Adder [3 i/p signals]

ii> OP-AMP as Differentiator

iii> OP-AMP as Integrator

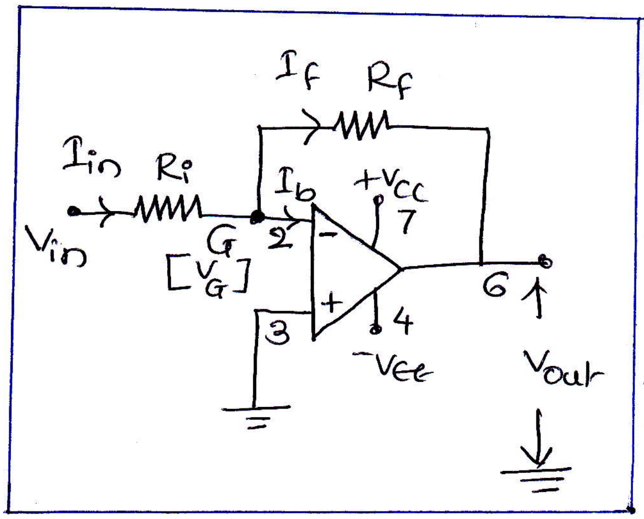
iv> OP-AMP as Buffer Amplifier

v> OP-AMP as Subtractor

## 1> OP-AMP as INVERTING AMPLIFIER:

Defn: An amplifier in which output signal is inverted part of the input signal is called as inverting amplifier i.e input signal & output signal are out of phase by 180°.

Circuit Diagram:




Construction:

→ OP-AMP is operated in inverting mode i.e non-inverting terminal is grounded.

→ Where $R_i$ & $R_f$ are input & feedback resistors respectively

→ OP-AMP is energized by applying DC Sources $-V_{EE}$ & $+V_{CC}$

→ O/p is measured across Pin # 6 with respect to ground.

## Derivation:

✓ Apply KCL to node 'G'

$$I_{in} = I_b + I_f \rightarrow (1)$$

but $I_b = 0$ $\because$ $Z_{in} = \infty$

$$\therefore \quad I_{in} = I_f \rightarrow (2)$$

✓ Express Currents as ratio of voltage drop to opposition.

$$(2) \Rightarrow \quad \frac{V_{in} - V_G}{R_{in}} = \frac{V_G - V_o}{R_f}$$

where $V_G = 0$ due to the concept of virtual ground

$$\Rightarrow \quad \frac{V_{in}}{R_{in}} = -\frac{V_o}{R_f} \quad \text{or} \quad \boxed{V_o = \left[-\frac{R_f}{R_{in}}\right] V_{in}} \rightarrow (3)$$

[where '−' sign indicates inverting mode of operation]

eqn (3) is called o/p Voltage expression for inverting amplifier.

$|||^{rly}$

Gain of the inverting mode of operation is,

$$(3) \Rightarrow \quad \frac{V_o}{V_{in}} = A_v = \left[-\frac{R_f}{R_{in}}\right]$$

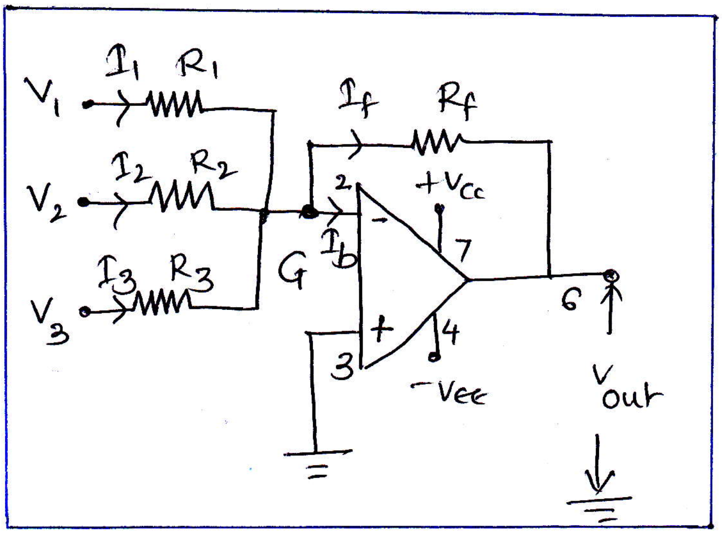
## 2) OP-AMP as Summing Amplifier or Adder:

**Defn:** An amplifier in which output is sum of all the applied input signals.

i.e $V_0 = -[V_1 + V_2 + V_3]$

where $V_1$, $V_2$ & $V_3$ are i/p signals,
"-ve" indicates OP-Amp is operated in inverting mode.

**Circuit Diagram:**




**Derivation:**

✓ Apply KCL to node "G"

$$\Rightarrow \quad I_1 + I_2 + I_3 = I_b + I_f \rightarrow (1)$$

Since $I_b = 0$ ∵ $Z_{in} = \infty$

$$\therefore \quad I_1 + I_2 + I_3 = I_f$$

✓ Express currents as ratio of voltage drops to opposition.

i.e
$$\frac{V_1 - V_G}{R_1} + \frac{V_2 - V_G}{R_2} + \frac{V_3 - V_G}{R_3} = \frac{V_G - V_0}{R_f} \rightarrow (2)$$

where $V_G = 0$ due to the concept of virtual ground.

$$(2) \Rightarrow \quad \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_0}{R_f}$$

Or $\boxed{V_0 = -R_f\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]} \rightarrow (3)$

where eqn (3) ⇒ O/p voltage expression for 3 i/p OP-Amp Adder,

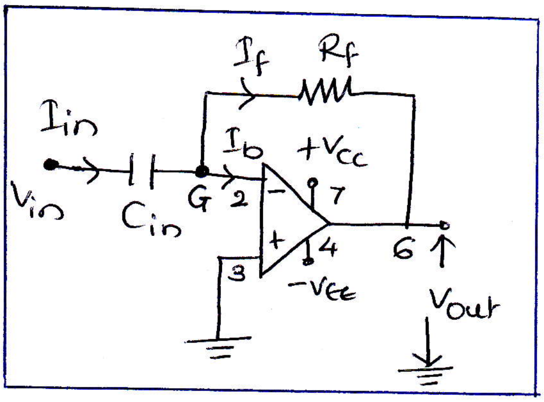
if $R_f = R_1 = R_2 = R_3 = R$

$$(3) \Rightarrow \quad V_0 = -[V_1 + V_2 + V_3]$$

## 3) OP-AMP as Differentiator:

**Defn:** An amplifier in which output is derivative of applied input signal. i.e $V_0 \propto \frac{d[V_{in}]}{dt}$

**Circuit Diagram:**




**Derivation:**

✓ Apply KCL to node "G"

$$I_{in} = I_b + I_f \rightarrow (1)$$

but $I_b = 0$ ∵ $Z_{in} = \infty$

$$(1) \Rightarrow \quad I_{in} = I_f \rightarrow (2)$$

✓ Express Current as ratio of Voltage drops to opposition.

where $I_{in} \rightarrow$ Current flowing Capacitor, hence it is given by $I_{in} = I_c = C \frac{d(V_c)}{dt}$

where $C \rightarrow$ capacitance of Capacitor

$V_c \rightarrow$ Voltage drop across the capacitor.

hence eqn (2) $\Rightarrow$

$$C_{in} \frac{d[V_{in} - V_G]}{dt} = \frac{V_G - V_0}{R_f} \rightarrow (3)$$

where $V_G = 0$ due to the concept of Virtual Ground

eqn (3) $\Rightarrow$

$$C_{in} \frac{dV_{in}}{dt} = -\frac{V_0}{R_f} \quad \text{or} \quad \boxed{V_0 = [-C_{in} \cdot R_f] \frac{d(V_{in})}{dt}} \rightarrow (4)$$

Eqn (4) is called as output voltage expression for OP-Amp Differentiator.

✓ where $(C_{in} \cdot R_f)$ is a constant, can be replaced by proportionality.

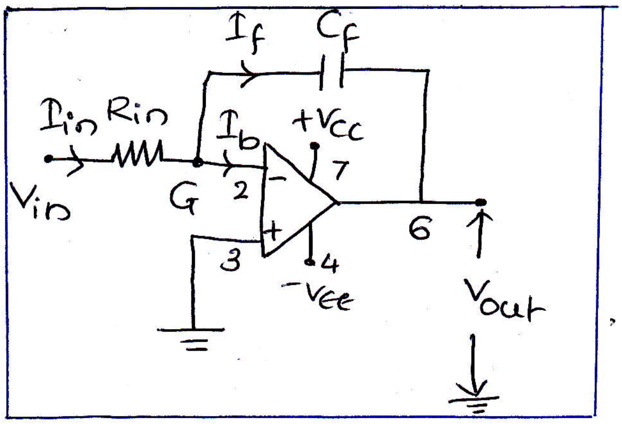
Hence $V_0 \propto \frac{d(V_{in})}{dt}$

## 4> OP-AMP as Integrator

**Defn:** An amplifier in which o/p signal is directly proportional to the integral part of the input signal.

i.e $V_o \propto \int V_{in} \cdot dt$

**Circuit Diagram:**




**Derivation:**

✓ Apply KCL to node "G"

$I_{in} = I_b + I_f \rightarrow (1)$

but $I_b = 0 \because Z_{in} = \infty$

$\therefore (1) \Rightarrow I_{in} = I_f \longrightarrow (2)$

where $I_f = I_{C_f}$ i.e current flowing through capacitor "$C_f$"

✓ Express currents as ratio of voltage drops to opposition

hence eqn (2) $\Rightarrow$

$$\frac{V_{in} - V_G}{R_{in}} = C_f \cdot \frac{d[V_G - V_o]}{dt} \rightarrow (3)$$

where $V_G = 0$ due to the concept of virtual ground,

$$(3) \Rightarrow \frac{V_{in}}{R_{in}} = C_f \frac{d[-V_o]}{dt} \quad \text{or} \quad -dV_o = \left[\frac{1}{C_f R_{in}}\right] V_{in}\, dt$$

or $$dV_o = \left[-\frac{1}{C_f \cdot R_{in}}\right] V_{in}\, dt \rightarrow (4)$$

Integrate eqn (4) on both hand sides

$$\int dV_o = \left[-\frac{1}{C_f \cdot R_{in}}\right] \int V_{in}\, dt$$

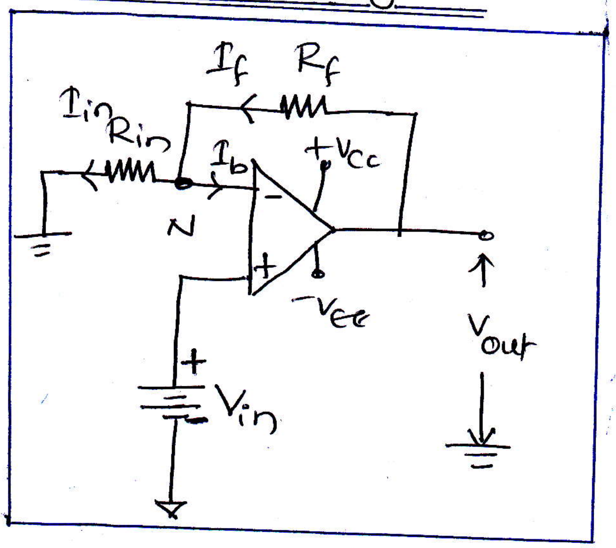
or $$\boxed{V_o = \left[-\frac{1}{C_f \cdot R_{in}}\right] \int V_{in}\, dt} \rightarrow (5) \Rightarrow V_o \propto \int V_{in}\, dt$$

eqn (5) is called o/p voltage expression for "Op-Amp Integrator."

5> OP-AMP as NON-INVERTING AMPLIFIER:

**Defn:** An amplifier in which o/p signal is in phase with input signal.

**Circuit Diagram:**




where $V_{in} \rightarrow$ is voltage drop across non-inverting terminal

i.e $V_2 = V_{in}$

$V_1 = V_N$

$V_1 \rightarrow$ Voltage drop across inverting terminal i.e $V_1 = V_N$

According to ideal characteristics of an OP-AMP is,

$V_1 \sim V_2 = 0$ or $V_1 - V_2 = 0$

but $V_2 = V_{in}$

$V_1 = V_2 = V_{in}$

$\therefore$ Voltage drop across inverting terminal is also "$V_{in}$"

✓ Apply KCL to node "N"

$I_{in} + I_b = I_f$ but $I_b = 0$ $\therefore$ $Z_{in} = \infty$

$\Rightarrow I_{in} = I_f$ Express Currents as ratio of voltage drops to opposition,

Hence $\dfrac{0 - V_{in}}{R_{in}} = \dfrac{V_{in} - V_o}{R_f} \Rightarrow -\dfrac{V_{in}}{R_{in}} = \dfrac{V_{in}}{R_f} - \dfrac{V_o}{R_f}$

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

$$\frac{V_o}{R_f} = V_{in}\left[\frac{1}{R_f} + \frac{1}{R_{in}}\right]$$

or $$V_o = V_{in}\left[\frac{R_f}{R_f} + \frac{R_f}{R_{in}}\right]$$

$$\therefore \boxed{V_o = V_{in}\left[1 + \frac{R_f}{R_i}\right]} \rightarrow (1)$$

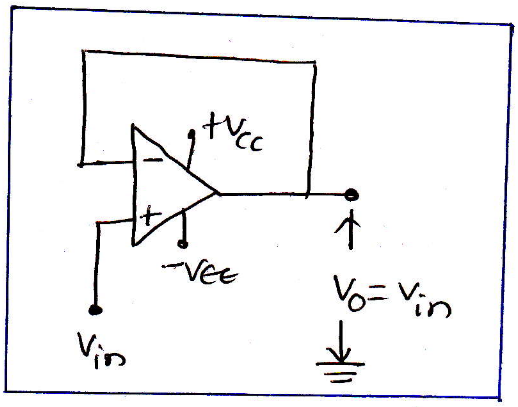
eqn (1) is called o/p voltage expression for OP-Amp inverting amplifier.

or $$A_v = \frac{V_o}{V_{in}} = \left[1 + \frac{R_f}{R_i}\right] \Rightarrow$$ Voltage gain Expression.

## 6> OP-AMP as Buffer Amplifier:

**Defn:** An amplifier whose output is equals to applied input both in magnitude & phase.

**Circuit Diagram:**




**Circuit construction:**

→ OP-Amp Buffer Amplifier is operated in non-inverting mode.

✓ Gain of non-inverting amplifer is given by,

$$A = \left[1 + \frac{R_f}{R_i}\right]$$

According circuit Diagram $R_f = 0$

$$\therefore A = \frac{V_o}{V_{in}} = 1 \quad \text{or} \quad V_o = V_{in}$$

Hence Buffer amplifier is called as "unity gain Amplifier."

## 7> OP-AMP SUBTRACTOR:

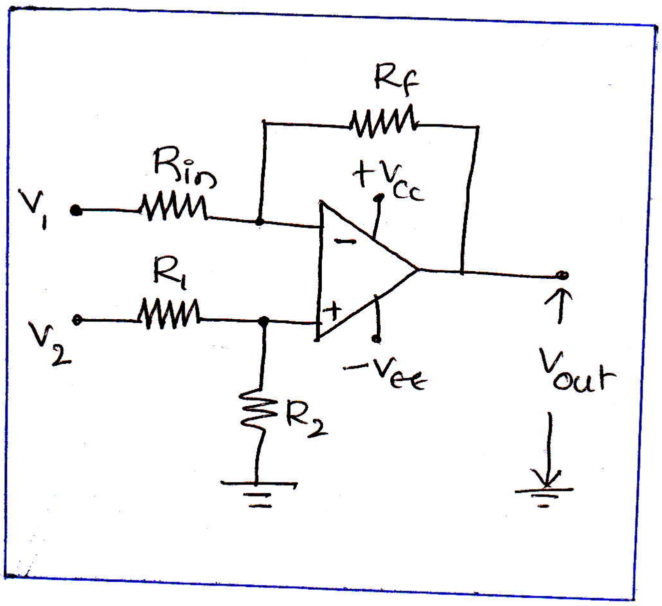
**Defn:** An amplifier in which output signal is difference of applied input signals.

i.e $V_{out} = V_2 - V_1$

where $V_2 \rightarrow$ Voltage applied to non-inverting terminal

$V_1 \rightarrow$ Voltage applied to inverting terminal

**Circuit Diagram:**




OP-AMP is operated in both inverting mode & non-inverting hence combined effectiveness of inverting mode output & non-inverting mode output generates difference b/w applied input signal.

i.e $V_{out} = V_{o1} + V_{o2} \rightarrow (1)$

where $V_{out} \rightarrow$ output of Subtractor i.e output because of combined effect of input signal $V_1$ & $V_2$

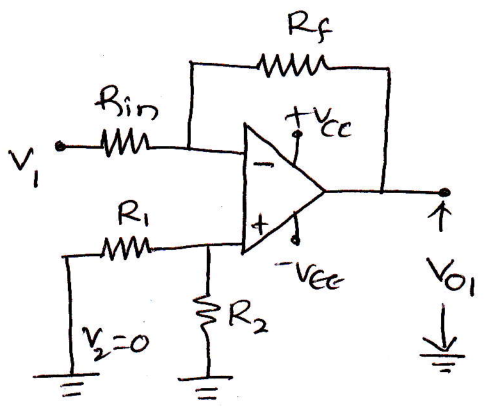
$V_{o1} \rightarrow$ Output due to only inverting mode of operation

$V_{o2} \rightarrow$ Output due to only non-inverting mode of operation

Hence study on subtractor circuit is conducted in two cases. One is inverting mode & case two is non-inverting mode. Therefore combined effectiveness of case(i) & case(ii) will be OP-AMP SUBTRACTOR.

Case i) OP-AMP is operated only in inverting mode

i.e non-inverting terminal is grounded $\therefore V_2 = 0$

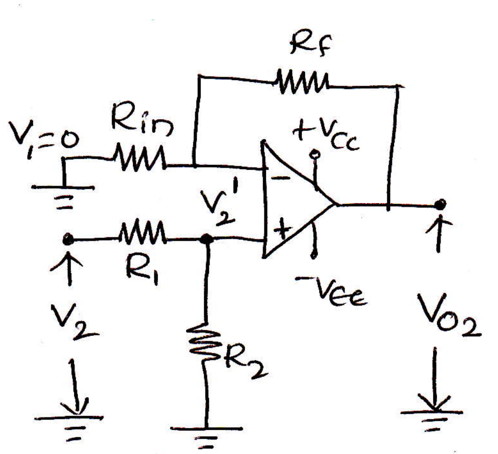



Output voltage expression for inverting mode of OP-Amp is,

$$V_{o1} = \left[-\frac{R_f}{R_{in}}\right] V_1 \rightarrow (2)$$

Case ii) OP-AMP is operated only in non-inverting mode

i.e $V_1 = 0$




where $V_2'$ is input voltage to non-inverting terminal, To determine $V_2'$ apply voltage divider rule across resistor $R_2$
[$R_1$ & $R_2$ are connected in series]

$$\Rightarrow \quad V_2' = \frac{V_2 R_2}{R_1+R_2} \rightarrow (3)$$

[VDR is $V_x = \frac{V_T R_x}{R_1+R_2}$]

Output Voltage expression for non-inv. OP-Amp is,

$$V_{o2} = \left[1+\frac{R_f}{R_i}\right] V_2' \rightarrow (4)$$ Substitute eqn (3) in eqn (4)

$$(4) \Rightarrow \quad V_{o2} = \left[1+\frac{R_f}{R_i}\right] \frac{V_2 R_2}{R_1+R_2} \rightarrow (5)$$

✓ Substitute eqns (2) & (5) in eqn (1)

eqn (1) $\Rightarrow$

$$\boxed{V_o = \left[-\frac{R_f}{R_{in}}\right] V_1 + \left[1+\frac{R_f}{R_{in}}\right] \frac{V_2 R_2}{R_1+R_2}} \rightarrow (6)$$

eqn(6) indicates output voltage expression for OP-Amp Subtractor

if $R_f = R_{in} = R_1 = R_2 = R$

Then $\boxed{V_o = V_2 - V_1}$

# OP-AMP

# PROBLEMS

## List of Formulae :

*> Output voltage Expression for INVERTING AMPLIFIER is,

$$V_o = \left[-\frac{R_f}{R_i}\right]V_{in}$$

*> Output voltage expression for NON-INVERTING AMPLIFIER is,

$$V_o = \left[1+\frac{R_f}{R_i}\right]V_{in}$$

*> Output voltage expression for 3 i/p's OP-AMP INVERTING ADDER is,

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

if $R_f = R_1 = R_2 = R_3 = R$

Then $V_o = -[V_1 + V_2 + V_3]$

*> Output voltage expression for OP-AMP DIFFERENTIATOR is,

$$V_o = \left[-R_f C_{in}\right]\frac{d(V_{in})}{dt}$$

*> Output voltage expression for OP-AMP INTEGRATOR is,

$$V_o = -\left[\frac{1}{R_i C_f}\right]\int V_{in}\, dt$$

*> Output voltage expression for OP-AMP BUFFER AMP. is

$V_o = V_{in}$ or $A_v$ is unity

*> Calculate the output voltage of a three input Summing amplifier : Given $R_1 = 200k\Omega$, $R_2 = 250k\Omega$, $R_3 = 500k\Omega$ & $R_f = 1M\Omega$, $V_1 = 2V$, $V_2 = 2V$, $V_3 = 1V$ [6 marks]

<u>Soln:</u> $V_{out}$ for 3 input Summing amplifier is,

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

$$= -\left[\frac{(1\times10^{+6})}{(200\times10^3)}(2) + \frac{(1\times10^6)}{(250\times10^3)}(2) + \frac{(1\times10^6)}{(500\times10^3)}(1)\right]$$

$$= -\left[10 + 8 + 2\right]$$

$$V_o = -20V$$

*> Design an adder circuit using OP-AMP to obtain an output expression $V_o = -(0.1V_1 + 0.5V_2 + 20V_3)$, where $V_1$, $V_2$ & $V_3$ are the inputs. Select $R_f = 10k\Omega$ [5 Marks]

<u>Soln:</u> $V_{out}$ for 3 i/p adder is,

$$V_o = -\left[\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right] \quad \text{Given } R_f = 10k\Omega$$

$$\therefore V_o = -\left[\frac{10K}{R_1}V_1 + \frac{10K}{R_2}V_2 + \frac{10k}{R_3}V_3\right] \longrightarrow (1)$$

Given $V_o = -[0.1V_1 + 0.5V_2 + 20V_3] \longrightarrow (2)$

compare eqns (1) & (2),

$$\frac{10k}{R_1}\cancel{V_1} = 0.1\cancel{V_1} \;;\quad \frac{10K}{R_2}\cancel{V_2} = 0.5\cancel{V_2} \;;\quad \frac{10K}{R_3}\cancel{V_3} = 20\cancel{V_3}$$

$$\therefore R_1 = 100k\Omega \;;\quad R_2 = 20k\Omega \;;\quad R_3 = 500\Omega$$

Draw the circuit Diagram of 3 i/p Adder Substitute $R_1$, $R_2$ & $R_3$ values

*) Design an Inverting adder circuit using an OP-AMP to the given output expression. [8marks]

$V_o = -[3V_1 + 4V_2 + 5V_3]$, given $V_1$, $V_2$ & $V_3$ are input Voltages & $R_f = 100k\Omega$

Soln: Output voltage expression for 3 i/p OP-Amp Adder is,

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

Given $R_f = 100k$

$$\therefore V_o = -\left[\frac{100k}{R_1}V_1 + \frac{100k}{R_2}V_2 + \frac{100k}{R_3}V_3\right] \rightarrow (1)$$

Given $v_o = -[3V_1 + 4V_2 + 5V_3] \rightarrow (2)$

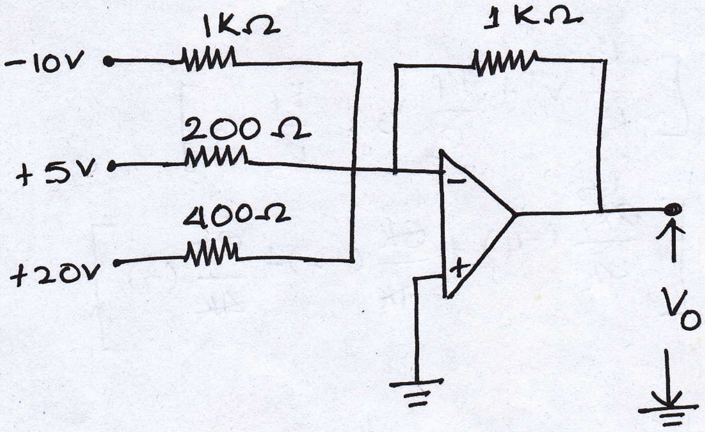
Compare eqns (1) & (2)

$\frac{100k}{R_1}\cancel{V_1} = 3\cancel{V_1}$ ; $\frac{100k}{R_2}\cancel{V_2} = 4\cancel{V_2}$ ; $\frac{100k}{R_3}\cancel{V_3} = 5\cancel{V_3}$

$\therefore R_1 = 33.33k\Omega$ ; $R = 25k\Omega$ ; $R_3 = 20k\Omega$

• Draw the circuit Diagram of OP-Amp three i/p Adder & Substitute $R_1, R_2$ & $R_3$ values

*) Find the output voltage for the circuit shown below. [6Marks]




Soln: Vout for 3 i/p OP-AMP Adder is,

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

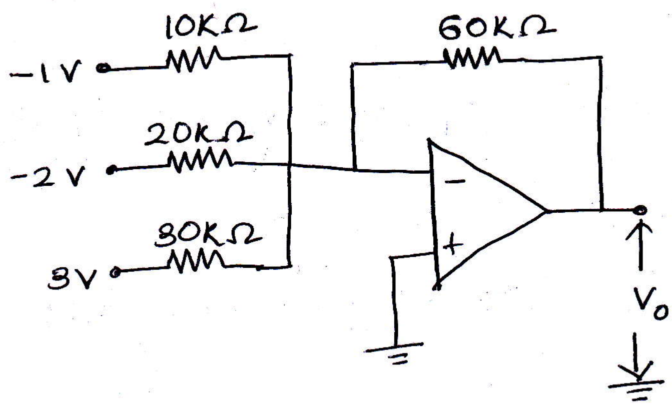
$$= -\left[\frac{\cancel{1k}}{\cancel{1k}}(-10) + \frac{\overset{5}{\cancel{1k}}}{\cancel{200}}(5) + \frac{\overset{2.5}{\cancel{1k}}}{\cancel{400}}(20)\right]$$

$$= -\left[-10 + 25 + 50\right]$$

$$\underline{\underline{V_o = -65V}}$$

*) Calculate the output voltage $[V_o]$ for the Given circuit.

[6 Marks]




Soln: Vout for 3 i/p Adder is,

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

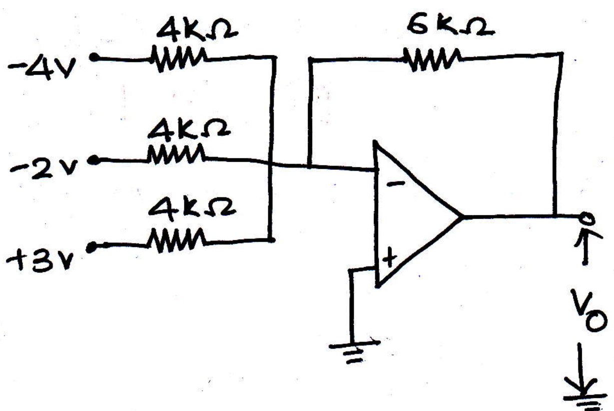
$$= -\left[\frac{\overset{6}{\cancel{60K}}}{\cancel{10K}}(-1) + \frac{\overset{3}{\cancel{60K}}}{\cancel{20K}}(-2) + \frac{\cancel{30k}}{\cancel{30k}}(3)\right]$$

$$= -[-6-6+3]$$

$$\therefore V_o = -3V$$

*) Find the output voltage of the 3-input adder circuit shown below

[8 Marks]




Soln:

Vout for 3 i/p Adder is,

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

$$= -\left[\frac{\overset{1.5}{\cancel{6k}}}{\cancel{4k}}(-4) + \frac{\overset{1.5}{\cancel{6k}}}{\cancel{4k}}(-2) + \frac{\overset{1.5}{\cancel{6k}}}{\cancel{4k}}(3)\right]$$

$$= -[-6-3+4.5]$$

$$V_o = -4.5V$$