IC741 = opamp

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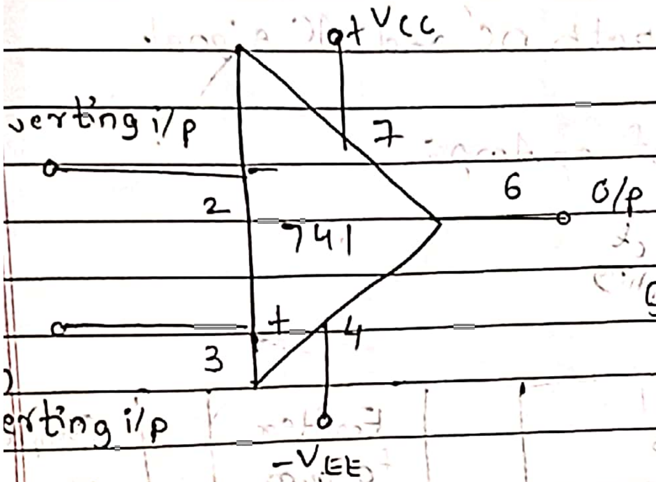
Module 1

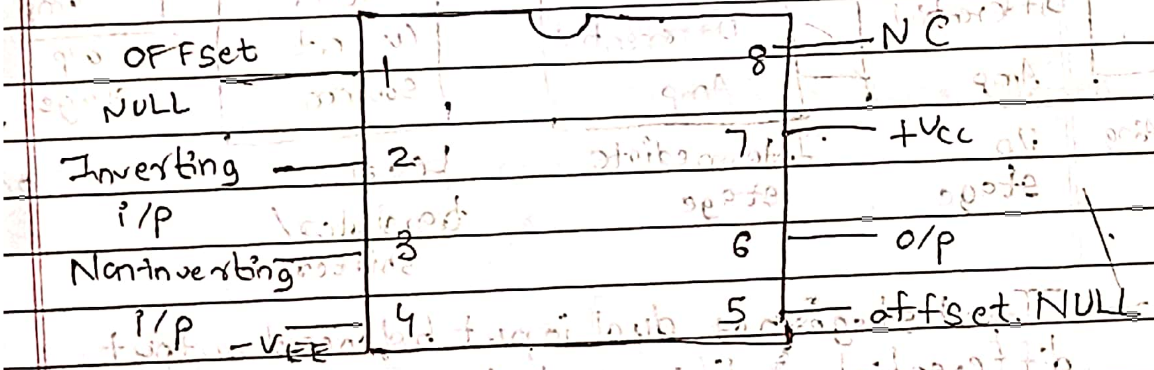
Basics of Operational Amp

Ramakant Gaikwad (opamp and LIC's)

opamp – operational amplifier (performs mathematical operations).



Symbol of IC741



Pin diagram of IC741

→ ① OpAmp is Direct Coupled High Gain Amplifier consist of one or more differential Amplifier followed by level translator and output stage.

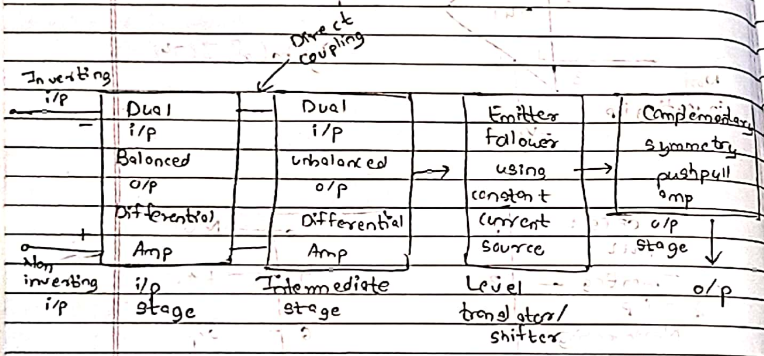
② Output stage is generally push-pull complementary symmetry pair

(1) Why op-Amp is known as operational Amplifier?

→ With the help of opAmp we can perform mathematical functions like addition, subtraction, multiplication, logarithmic, integration, differentiation etc.

It can amplify both DC and AC signal.

* Block Diagram of op Amp:



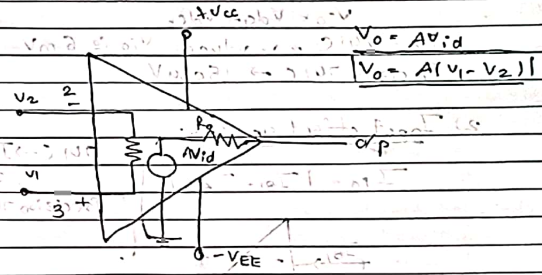
→ Input stage has dual input balanced output differential amplifier and it should have high input impedence.

→ Input stage is directly coupled with dual input unbalanced output diff amplifier which forms intermediate stage.

→ Third stage consists of level shifter (generally emitter follower circuit) which shifts the level to ground.

→ A complementary symmetry pushpull amp forms the output stage which should have low output impedence to giving high voltage gain.

* Equivalent circuit diagram of op-amp:-



$V_o = AV_{id}$

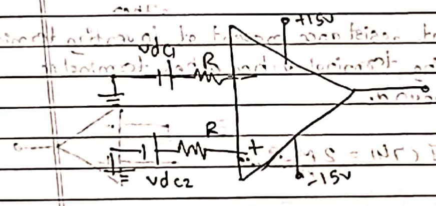
$\boxed{V_o = A(V_1 - V_2)}$

* Features of IC741:-

1. No external frequency compensation required.
2. Short circuit protection.
3. Offset null capability.
4. Large common mode and differential voltage ranges.
5. Low power consumption.
6. No Latchup problems.

* Different parameters of op-amp-

1) Input offset voltage:-



& ↳ commercial temperature range (0 to 70°C)

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Input offset voltage is voltage that must be applied between two input terminals of op-amp to null the output.

$V_{io} = V_{dc1} - V_{dc2}$

For 741C max value of V_{io} is 6 mV

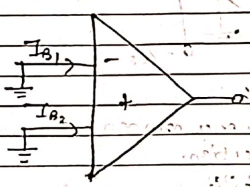
Precision 741C → 150 µV

2) Input offset current -

$I_{io} = |I_{B1} - I_{B2}|$

741C → $I_{io\,max}$ = 200 nA

Precision 741C → 6nA



3) Input bias current -

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

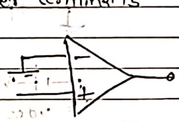
I_B = 500nA. ± 741C

I_B = ±7nA = precision 741C

4) Input Resistance (R_i) -

It's equivalent resistance present at either inverting terminal or non-inverting terminal when other terminal is connected to ground.

$R_i(max)$ = IC741 = 2 MΩ



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5) Input Capacitance:-

It's equivalent capacitance measured at either non-inverting terminal or inverting terminal with other terminal connected to ground.

IC741C = 1.4 pf. ← should be as low as possible

6) Input voltage Range:-

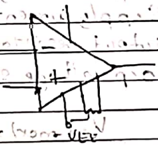
When we apply same input signal at both terminals then it is known as common mode signal and input voltage range is defined under this condition.

Max value for IC741 = ±13V.

7) Offset Voltage Adjustment Range:-

It's capability to null offset voltage. For this potentiometer of 10 kΩ is connected to offset null pins 1 and 5 and variable terminal is connected to $-V_{EE}$. By using a potentiometer, we can reduce offset voltage range.

Max value = ±15mV



8) Common Mode Rejection Ratio (CMRR)

$CMRR = \frac{A_d}{A_c}$ A_d = differential mode gain, A_c = common mode gain

Ideal op-amp = CMRR = ∞

→ It indicates ability to reject common mode signal
→ It should be high as possible.
Max. value 90 dB

9) Supply Voltage Rejection Ratio (SVRR)

$SVRR = \frac{\Delta V_{io}}{\Delta V}$ = $\mu V/V$. It is ratio of change in input offset voltage with variation in supply voltage

741 → 150 $\mu V/V$

10) Large signal voltage gain

$A_d = \frac{V_o}{V_d}$

Max. value = 2×10^5

11) Supply voltage :- Maximum range = ±15V
12) Supply current :- 2 to 3 mA
13) Output resistance: 75 Ω
14) O/P voltage swing:

$V_{sat} = 0.9 V_{cc}$

$V_o(max) = \pm V_{sat}$

If supply voltage is ±15 V_1, $V_{sat} = \pm 13V$

15) Slew Rate

$\boxed{SR = \frac{dV_o}{dt} \quad volts/\mu sec}$ = 0.5 V/μsec

It's defined as maximum rate of change of output voltage with respect to time. It decides capability of op-amp to change its output rapidly.

16) Bandwidth: It is the frequency range of an amplifier over which the signal frequencies are amplified equally.
Bandwidth of 741C = 1 MHz.

17) Gain bandwidth product:- Bandwidth of op amp when gain of amplifier is 1.

18) Output short circuit current:- Max value: 25mA

	Ideal op-amp	Practical value
R_i	∞	2 MΩ
R_o	0	75 Ω
A_v	∞	2×10^5
B.W	∞	1 MHz
CMRR	∞	90 dB
Slew rate	∞	0.5 V/μsec
I/p offset voltage	0	6 mV
SVRR	0	150 μV/V
I/p bias current	0	500 nA
i/p offset current	0	200 nA

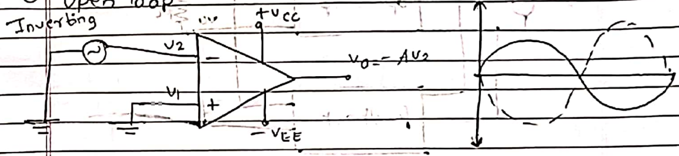
Op-amp configuration

- Open loop
  - Inverting
  - Non inverting
  - Differential
- Closed loop
  - Inverting
  - Non-inverting
  - Differential

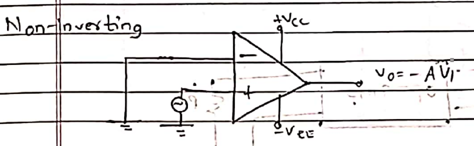
$V_0 = A(V_1 - V_2)$
$= -AV_2$

① Open loop

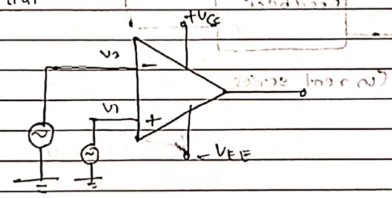
Inverting

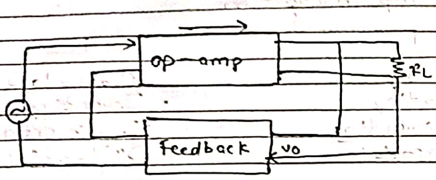


Non-Inverting

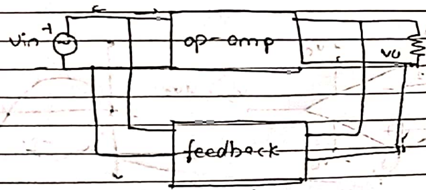


Differential

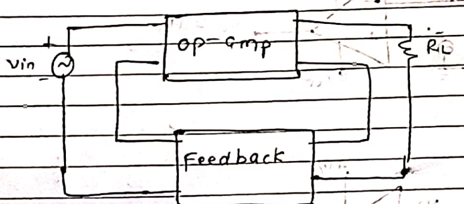




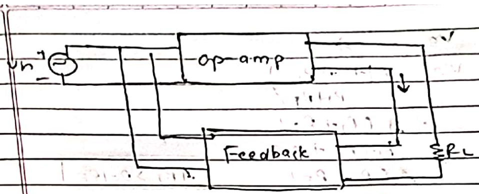
voltage series feedback



vol tage shunt

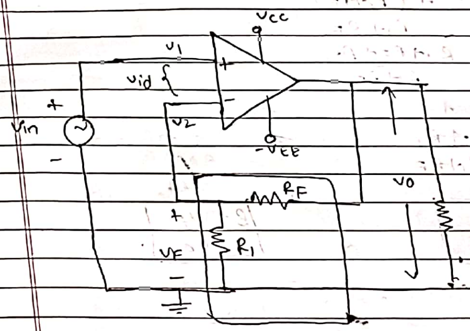


Current series



Current shunt

* Voltage series
(Non inverting amp with Feedback)



$V_o = A(V_1 - V_2)$

$V_1 = V_{in}$

$V_2 = V_f = \frac{R_1}{R_1 + R_f} V_o$

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

$V_o\left(1 + \frac{A R_1}{R_1 + R_F}\right) = A V_{in}$

$$\frac{V_o}{V_{in}} = \frac{A}{\left(1 + \frac{AR_1}{R_1+R_F}\right)}$$

$$= \frac{A(R_1+R_F)}{R_1+R_F+AR_1}$$

$$= \frac{A(R_1+R_F)}{AR_1}$$

$\boxed{AR_1 \gg R_1+R_F}$

$$\boxed{A_f = \frac{V_o}{V_{in}} = 1 + \frac{R_F}{R_1}}$$

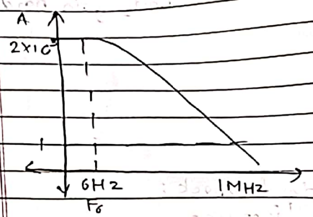
$$A_f = \frac{\frac{A(R_1+R_F)}{R_1+R_F}}{\frac{R_1+R_F+AR_1}{R_1+R_F}}$$

$$= \frac{A}{1+\frac{AR_1}{R_1+R_F}}$$

$$\boxed{A_f = \frac{A}{1+A\beta}}$$

$$\boxed{\beta = \frac{V_f}{V_o}}$$

* Voltage series feedback amplifier: (Non inverting amp)



$$UGB = A_v F_o$$

$$UGB = A_F F_F$$

$$A_v F_o = A_F \cdot F_F$$

$$F_F = \frac{A_v \cdot F_o}{A_F}$$

$$F_F = \frac{AF_o}{A/1+A\beta} = F_o(1+A\beta)$$

$$A_v = 1 + \frac{R_F}{R_1}$$

$$A_F = \frac{A}{1+A\beta}$$

$$R_{if} = R_i(1+A\beta)$$

$$R_{oF} = \frac{R_o}{1+A\beta}$$

* Break Frequency: Frequency at which gain is 3dB down from its value is known as break frequency (F_o).

→ **Unity Gain Bandwidth:** The frequency at which frequency gain = 1 is known as unity gain bandwidth.

$$F_F = F_o(1 + A\beta)$$

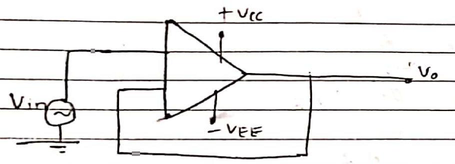
$$V_{OOT} = \pm \frac{V_{sat}}{1 + A\beta}$$

• **Advantages of negative feedback:**

1) Input impedance will increase
2) Output impedance will reduce
3) Bandwidth will increase
4) Affect of noise will be minimum
5) Output offset voltage will reduce
6) Temperature variation effects will be minimum.

* **Applications of Non-inverting amp**

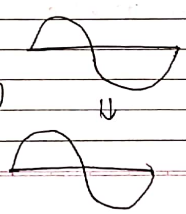
→ **Voltage Follower:**



$A_V = 1 + \frac{R_F}{R_1}$ $\because R_F = 0$ $\therefore A_V = 1$

$\beta = \frac{R_1}{R_1 + R_F}$

$\beta = 1$ $(\because R_F = 0)$



Voltage Follower acts as a buffer.

$$R_{if} = AR_i$$

$$R_{of} = \frac{R_o}{A}$$

$$F_F = AF_o$$

$$V_{OOT} = \pm \frac{V_{sat}}{A}$$

Q. 741C op-Amp having following parameters $R_F = 10k\Omega$ and $R_1 = 1k\Omega$, supply voltage $\pm 15V$. Compute $A_F(A_V)$ R_{if}, R_{of}, F_F, Total output offset voltage with feedback.

→ $A_F = 1 + \frac{R_F}{R_1} = 1 + \frac{10}{1} = 11$

$$R_{if} = R_i(1 + A\beta) = 2\left(1 + 2\times10^5\left(\frac{1}{11}\right)\right)$$

$$= 2\left(1 + \frac{2\times10^5}{11}\right)$$

$$= 3307.78$$

$$R_{of} = \frac{R_o}{1 + A\beta} = \frac{R_o}{\left(1 + \frac{2\times10^5}{11}\right)} = \frac{R_o}{18182.82}$$

$$= \frac{75}{18182.82}$$

$$= 4.12\times10^{-3}$$

$$= 4.12\ m\Omega.$$

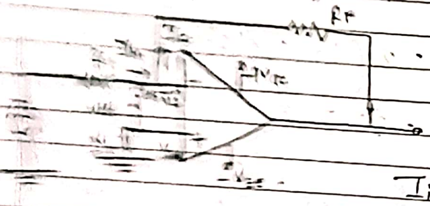
$$= 5\left(\frac{1+2\times10^5}{11}\right)$$

$$= 5\left(\frac{1+2\times10^5}{11}\right) = 90\,mHz.$$

$$V_{out} = \frac{\pm V_{sat}}{1+A\beta}$$

* voltage shunt amp. (Inverting amplifier)

Ideally difference between two ... should be zero means voltage at ... should be equal to voltage at ... terminal. If one terminal is connected ... we can say that the other terminal is ... ground.



$$\infty\ A = \frac{V_o}{V_{id}} = 0$$

$$V_1 = V_2$$

$$I_{in} = I_{B_1} + I_F$$

$$\frac{V_{in} - V_2}{R_1} = \frac{V_2 - V_o}{R_F}$$

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

$$\boxed{\frac{V_o}{V_{in}} = -\frac{R_F}{R_1}}$$

* $$\frac{V_{in} - V_2}{R_1} = \frac{V_2 - V_o}{R_F}$$

$$V_1 - V_2 = \frac{V_o}{A}$$

$$V_2 = \frac{-V_o}{A}$$

$$\frac{V_{in} + V_o/A}{R_1} = \frac{-V_o/A - V_o}{R_F}$$

$$\boxed{\frac{V_o}{V_{in}} = \frac{-A R_F}{R_1 + R_F + A R_1}}$$

$AR_1 >> R_1 + R_F$

Divide Numerator and Denominator with $R_1 + R_F$.

$$\frac{V_o}{V_{in}} = \frac{\frac{-A R_F}{R_1+R_F}}{1 + \frac{A R_1}{R_1+R_F}}$$

$$\boxed{A_f = -\frac{Ak}{1+AB}}$$

B = Feedback gain

k = Multiplying factor

* ① $B = \frac{R_1}{R_1+R_F}$

② $R_{iF} = R_1 + \left(\frac{R_F}{1+A} \parallel R_i\right)$

③ $R_{oF} = \frac{R_o}{1+AB}$

④ $F_f = F_o(1+AB)$

⑤ $V_{OOT} = \frac{\pm V_{sat}}{1+AB}$

* Applications of Inverting Amplifier

① Current to Voltage Converter

$$\Rightarrow \frac{V_o}{V_{in}} = -\frac{R_F}{R_1}$$

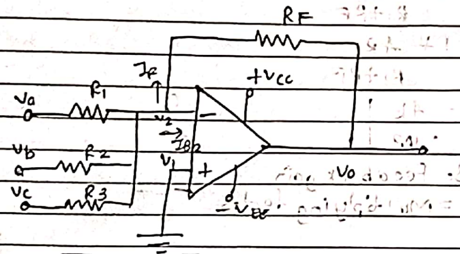
$$V_o = -\frac{R_F}{R_1} V_{in}$$

$$\boxed{V_o = -R_F I_{in}}$$

② Inverter
(Choose R_F and R_1 same).
(For Designing inverter)

* Summing, Scaling and Averaging amp:

① Inverting configuration-



$$I_a + I_b + I_c = I_{B_2} + I_F$$

$$\therefore I_a + I_b + I_c = I_F$$

$$\frac{V_a - V_2}{R_1} + \frac{V_b - V_2}{R_2} + \frac{V_c - V_2}{R_3} = \frac{V_2 - V_o}{R_F}$$

$$\frac{V_a}{R_1} + \frac{V_b}{R_2} + \frac{V_c}{R_3} = \frac{-V_o}{R_F}$$

$$\boxed{V_o = -R_F\left(\frac{V_a}{R_1} + \frac{V_b}{R_2} + \frac{V_c}{R_3}\right)}$$

$$R_1 = R_2 = R_3 = R_F = R$$

$$\boxed{V_o = -(V_a + V_b + V_c)}$$

② Averaging amp

$$R_F = R$$

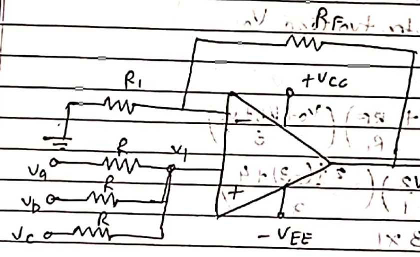
$$R_1 = R_2 = R_3 = 3R$$

③ Scaling amp

$$R_F = R$$

$$R_1 = R_2 = R_3 = \frac{R}{2}$$

* Application of Non-inverting amp:-



$$V_o = \left(1 + \frac{R_F}{R_1}\right) v_1$$

$$V_1 = \left(\frac{R/2}{R/2 + R}\right) V_a + \left(\frac{R/2}{R + R/2}\right) V_b + \left(\frac{R/2}{R + R/2}\right) V_c$$

$$V_o = \left(1+\frac{R_F}{R_1}\right)\left[\frac{R/2}{R/2+R}\right](V_a+V_b+V_c)$$

$$= \left(1+\frac{R_F}{R_1}\right)\left[\frac{R/2}{3R/2}\right](V_a+V_b+V_c)$$

$$V_o = \left(1+\frac{R_F}{R_1}\right)\left(\frac{V_a+V_b+V_c}{3}\right)$$

To work this circuit as summing amplifier, R_F should be twice of R_1, so that gain of circuit would become 3 and it will provide o/p as addition of i/p signals.

* Averaging amplifier: Gain of $\frac{R_F}{R_1}$ value should be set to 1 so that output will be average of all 3 input signals.

eg:- For a given circuit supply voltage $\pm 15V$, $V_a = +2V$, $V_b = -3V$, $V_c = +4V$, $R_1 = 1k\Omega$, $R_F = 2k\Omega$. $R = 1k\Omega$, Find out output voltage V_o.

⇒ Solution,

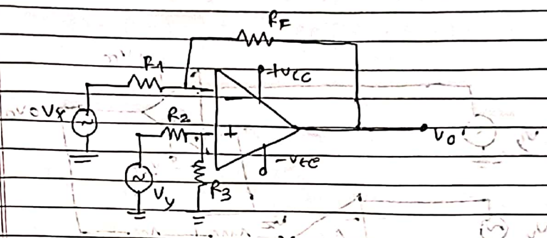
$$V_o = \left(1+\frac{R_F}{R_1}\right)\left(\frac{V_a+V_b+V_c}{3}\right)$$

$$= \left(1+\frac{2}{1}\right)\left(\frac{2+(-3)+4}{3}\right)$$

$$= 3 \times 1$$

$$V_o = 3V$$

* Differential amplifier with one op-amp:



$$V_o = V_{ox} + V_{oy}$$

$$V_{ox} = -\frac{R_F}{R_1}(V_x)$$

$$V_{oy} = \left(1+\frac{R_F}{R_1}\right)V_1$$

$$= \left(1+\frac{R_F}{R_1}\right)\left(\frac{R_3}{R_2+R_3}\right)V_y$$

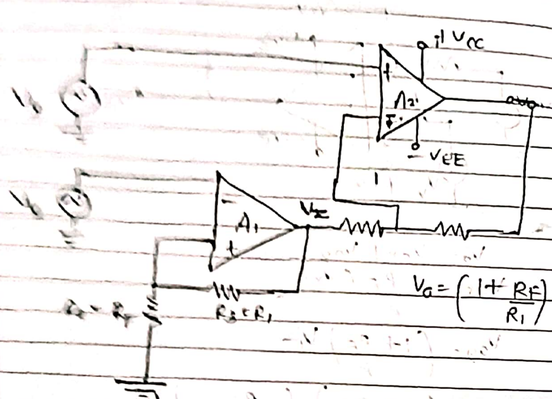
$$= -\frac{R_F}{R_1}V_x + \left(1+\frac{R_F}{R_1}\right)\left(\frac{R_3}{R_3+R_2}\right)V_y$$

$R_1 = R_2$, $R_F = R_3$

$$V_o = -\frac{R_F}{R_1}(V_x - V_y)$$

$$\therefore \boxed{V_o = -\frac{R_F}{R_1}(V_{xy})}$$

... using two op-amp:



$$V_o = \left(1+\frac{R_F}{R_1}\right) V_{xy}$$

⇒ A_1 will work as a non-inverting amp

$$V_z = \left(1+\frac{R_3}{R_2}\right) V_y$$

$$V_o = V_{ox} + V_{oz}$$

$$V_{ox} = \left(1+\frac{R_F}{R_1}\right) V_x$$

$$V_{oz} = -\frac{R_F}{R_1} \cdot V_z$$

$$V_z = \left(1+\frac{R_3}{R_2}\right) V_y$$

$$V_o = \left(1+\frac{R_F}{R_1}\right) V_x + -\frac{R_F}{R_1}\left(1+\frac{R_3}{R_2}\right) V_y$$

$R_3 = R_1$, $R_2 = R_F$

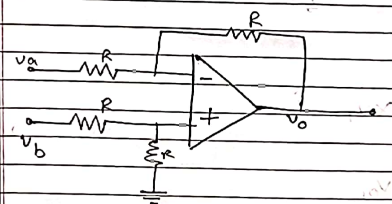
$$= \left(1+\frac{R_F}{R_1}\right) V_x + \left(-\frac{R_F}{R_1}\right)\left(1+\frac{R_1}{R_F}\right) V_y$$

$$= \left(\frac{R_1+R_F}{R_1}\right) V_x - \frac{R_F}{R_1}\left(\frac{R_F+R_1}{R_F}\right) V_y$$

$$= \left(\frac{R_1+R_F}{R_1}\right) V_x - V_y$$

$$= \left(1+R_F/R_1\right) V_{xy}$$

* Differential amp as Subtractor:-

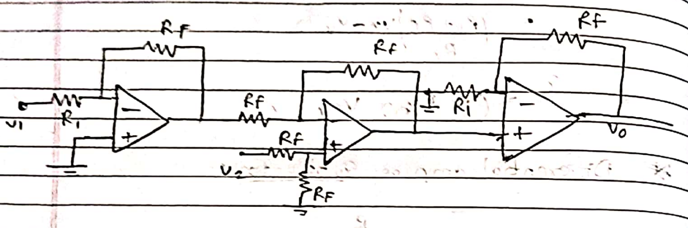


$$V_o = -\frac{R_F}{R_1}(V_a - V_b)$$

$$= -(V_a - V_b)$$

$$\boxed{V_o = V_b - V_a}$$

Ex For given circuit: Define o/p voltage if $R_F = 10\,k\Omega$, $R_1 = 1\,k\Omega$



$$\frac{V_{o_1}}{V_1} = -\frac{R_F}{R_1}$$

$$V_{o_1} = -\frac{R_F}{R_1} \times V_1$$

$$V_{o_2} = V_2 - V_{o_1}$$

$$= V_2 + \frac{R_F}{R_1} \times V_1 = V_2 + 10\,V_1$$

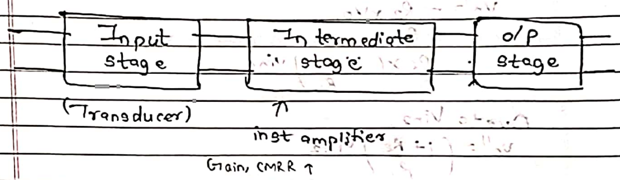
$$V_{o_3} = \left(1 + \frac{R_f}{R_1}\right) V_{o_2}$$

$$= \left(1 + \frac{R_f}{R_1}\right)\left(V_2 + \frac{R_F}{R_1} \times V_1\right)$$

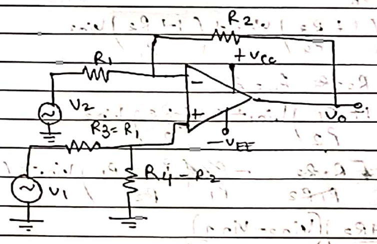
$$= \left(1 + \frac{10}{1}\right)\left(V_2 + 10\,V_1\right)$$

$$\boxed{V_{o_3} = 11\,(V_2 + 10\,V_1)}$$

Instrumentation amplifier :- (IA)

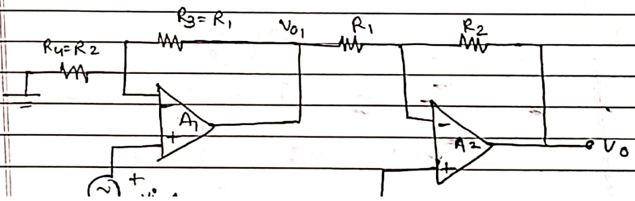


* IA using one op-amp :-



$V_o = V_1 - V_2$

* IA Using 2 op-amp :



$$V_a = \left(1 + \frac{R_3}{R_4}\right) V_{in1}$$

Due to V_{o1},

$$V_o' = -\frac{R_2}{R_1} \times V_{o1}$$

$$= -\frac{R_2}{R_1} \times \left(1 + \frac{R_3}{R_4}\right) v_{in1}$$

Due to V_{in2},

$$v_o'' = \left(1 + \frac{R_2}{R_1}\right) v_{in2}$$

$$V_o = V_o' + V_o''$$

$$= -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4}\right) v_{in1} + \left(1 + \frac{R_2}{R_1}\right) v_{in2}$$

Replace $R_3 = R_1$, $R_4 = R_2$,

$$= -\frac{R_2}{R_1}\left(1 + \frac{R_1}{R_2}\right) V_{in1} + \left(1 + \frac{R_2}{R_1}\right) v_{in2}$$

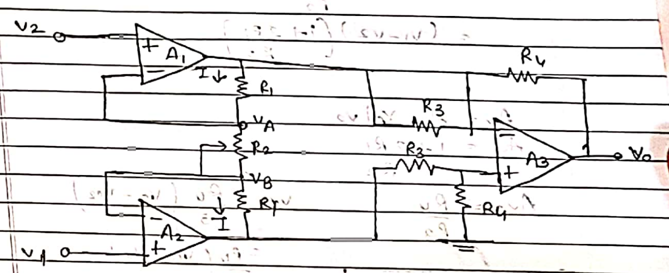
$$= \cancel{-\frac{R_2}{R_1} \times \frac{R_1 + R_2}{R_1 R_2}} \quad -\frac{\cancel{R_2}}{R_1}\left(\frac{R_2 + R_1}{\cancel{R_2}}\right) v_{in1} + \left(\frac{R_1 + R_2}{R_1}\right) v_{in2}$$

$$= \left(\frac{R_1 + R_2}{R_1}\right)\left[V_{in2} - V_{in1}\right]$$

* Advantages of dual Instrumentation op amp

1. High Input Resistance
2. Low Output Resistance
3. CMRR can be maximized by variable resistor

☆ IA using 3A op-amp



$$V_A = V_2$$

$$V_B = V_1$$

$$I = \frac{V_A - V_B}{R_2}$$

$$V_{o1} = V_A + IR_1$$

$$V_{o2} = V_B - IR_1$$

$$V_{o1} = V_A + IR_1$$

$$= V_2 + \left(\frac{V_2 - V_1}{R_2}\right) R_1$$

$$\cancel{V_{o2}} = \frac{(R_1 + R_2) V_2 - R_1 V_1}{R_2}$$

$$V_{o2} = \frac{(R_1 + R_2) V_1 - R_1 V_2}{R_2}$$

$$V_o = V_{o2} - V_{o1}$$

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$$\frac{(R_1+R_2)V_1 - R_1V_2 - [(R_1+R_2)V_2 - R_1V_1]}{R_2}$$

$$= \frac{\cancel{R_1V_1} + R_2V_1 - R_1V_2 - R_1V_2 - R_2V_2 + \cancel{R_1V_1}}{R_2}$$

$$= \frac{\cancel{R_2V_1} \; 2R_1V_1 - 2R_1V_2 + R_2V_1 - R_2V_2}{R_2}$$

$$= \frac{2R_1(V_1 - V_2) + R_2(V_1 - V_2)}{R_2}$$

$$= (V_1 - V_2)\left(1 + \frac{2R_1}{R_2}\right)$$

$$A_v = A_{v_1} \times A_{v_2}$$

$$A_{v_1} = 1 + \frac{2R_1}{R_2}$$

$$A_{v_2} = \frac{R_4}{R_3}$$

$$V_0 = -\frac{R_4}{R_3}(V_{01} - V_{02})$$

$$= \frac{R_4}{R_3}(V_{02} - V_{01})$$

$$\boxed{A_v = \left(1 + \frac{2R_1}{R_2}\right)\frac{R_4}{R_3}}$$

★ Applications of IA:

eg:- 1) Temperature indicators
2) Pressure monitoring and control
3) Temperature controller
4) Light Intensity Meter
5) Electronic weighing scale.