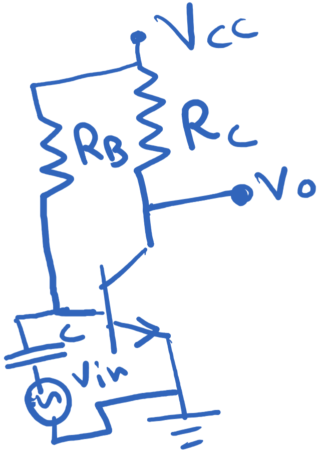
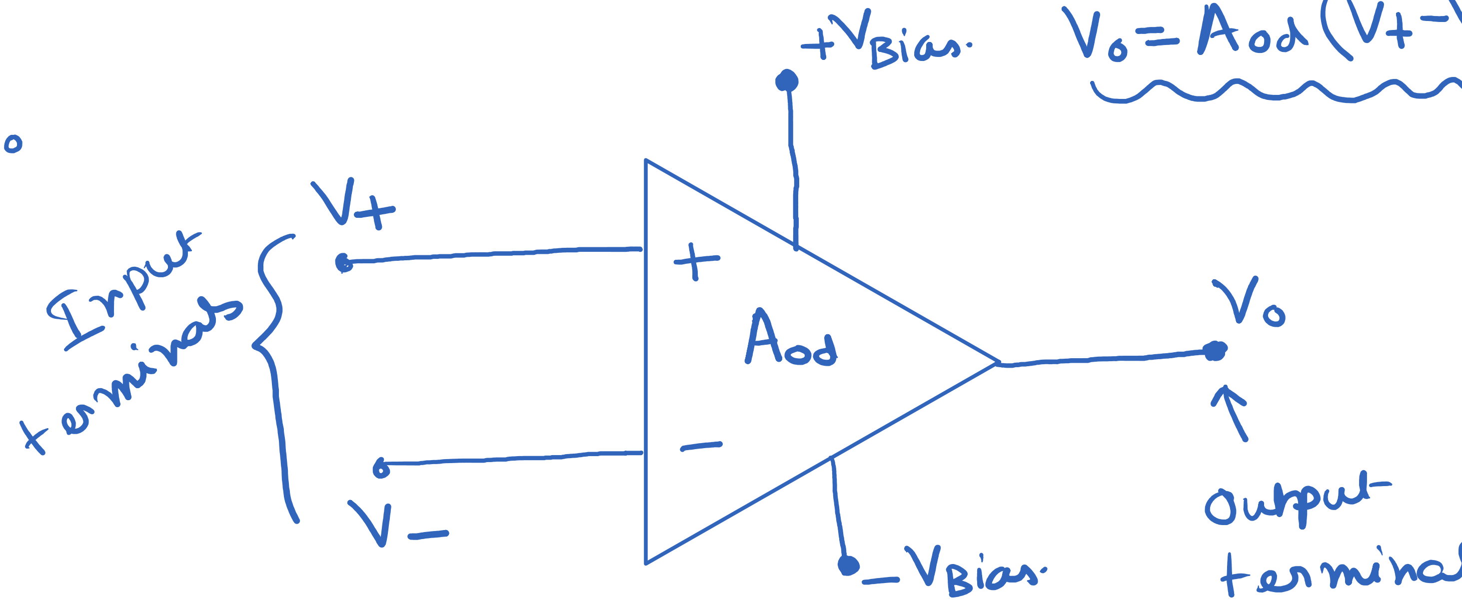
Op-Amp
(Operational Amplifier)

These can be used to carry out mathematical operations such as addition, multiplication, etc.
Op-Amp is not a fundamental block or device. Rather, there are multiple transistors inside the Op-Amp that give rise to it's properties.



$$V_o = A_{od}(V_+ - V_-)$$



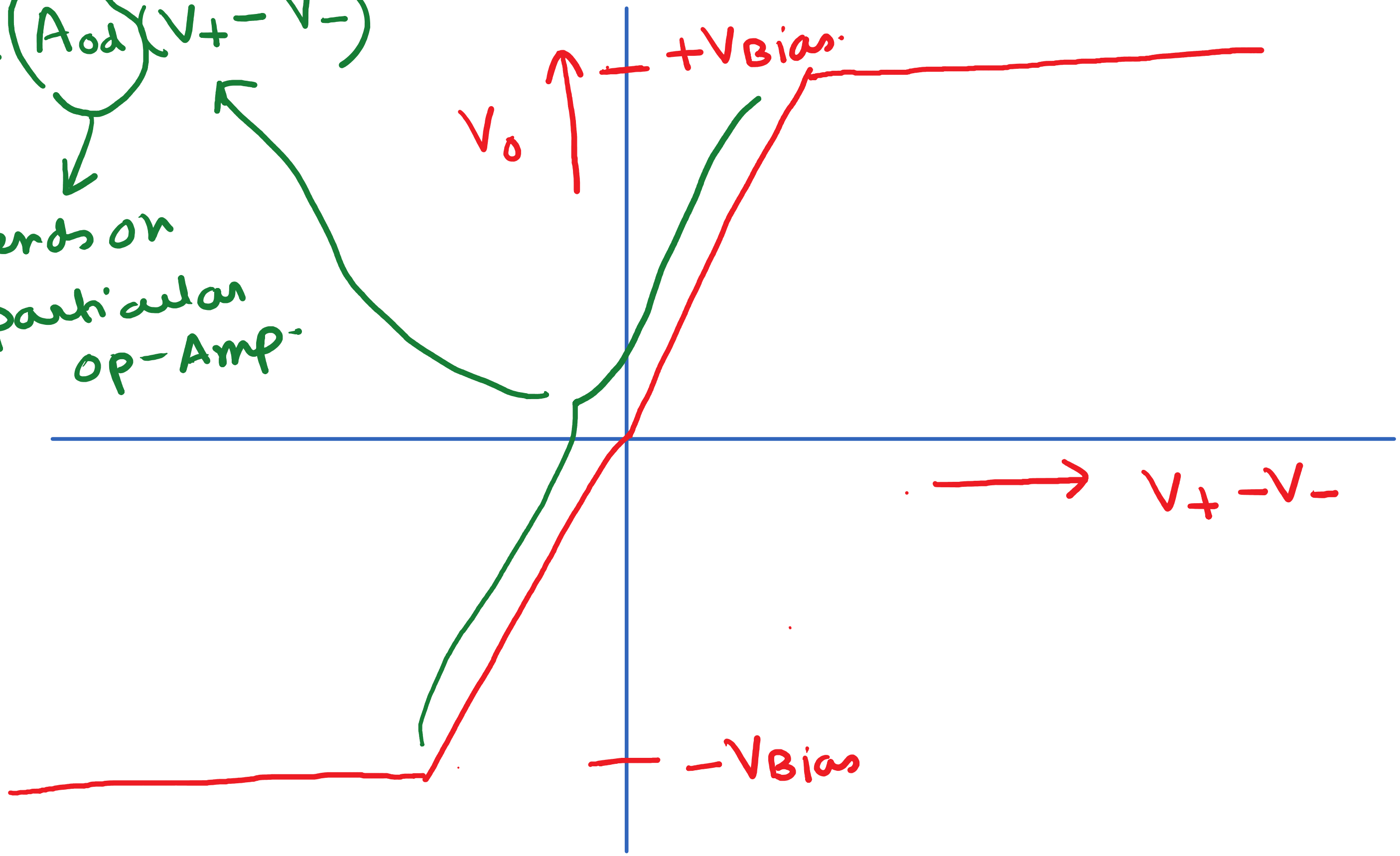
'+' → non-inverting terminal } input
'−' → inverting terminal. } input

A_{od} → open loop gain of the op-Amp. A_{od} is very large and can be taken as ∞ for mathematical derivations.

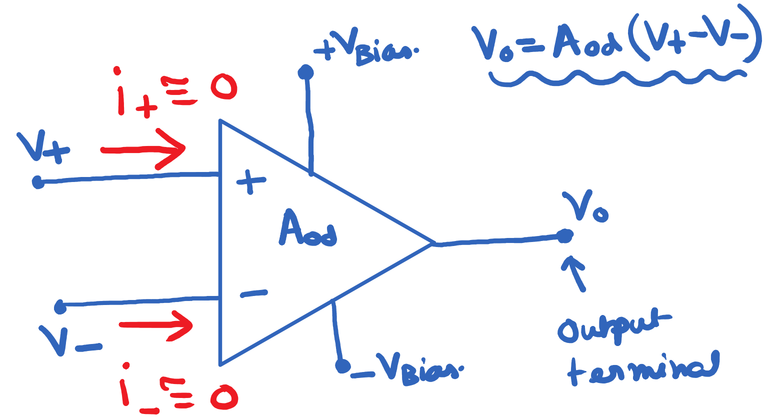
The maximum and minimum voltage across the output of an op-Amp is limited to $+V_{Bias}$ and $-V_{Bias}$ respectively. Generally $+V_{Bias}$ lies in the range of +12V to +15V and $-V_{Bias}$ lies in the range of −15V to −12V.

$V_o = A_{od}(V_+ - V_-)$

depends on the particular op-Amp.



① op-Amp has very large open loop gain. $A_{od} \to \infty$.

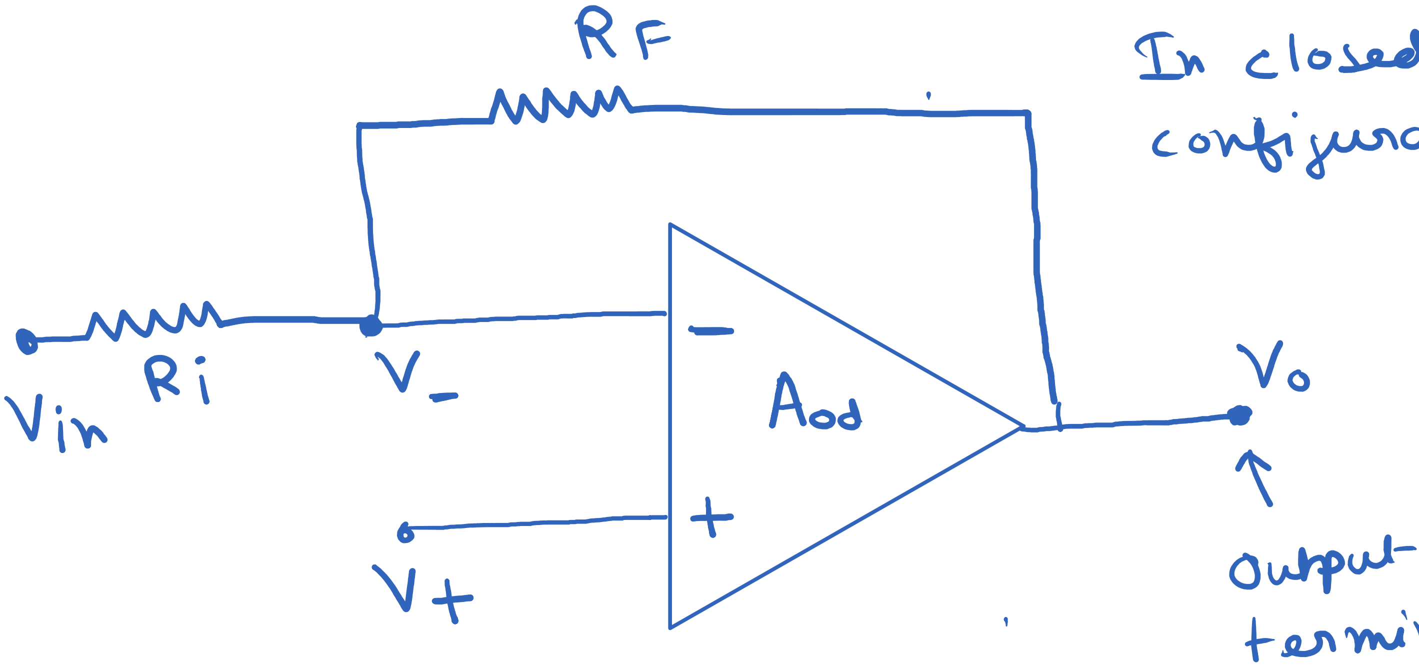


② Almost no current can flow into the op-Amp. So, $i_+ \cong 0$ and $i_- \cong 0$. So, an op-Amp has a very large input impedance.

③ op-Amps have very low (almost zero) output impedance. This means that the output voltage doesnot change with the output current or the output current can change without a change in the output voltage.

4 In closed loop configuration, V_+ and V_- should approximately stay at the same voltage, provided that $-V_{Bias} \leq V_o \leq +V_{Bias}$. This is known as 'Virtual short'

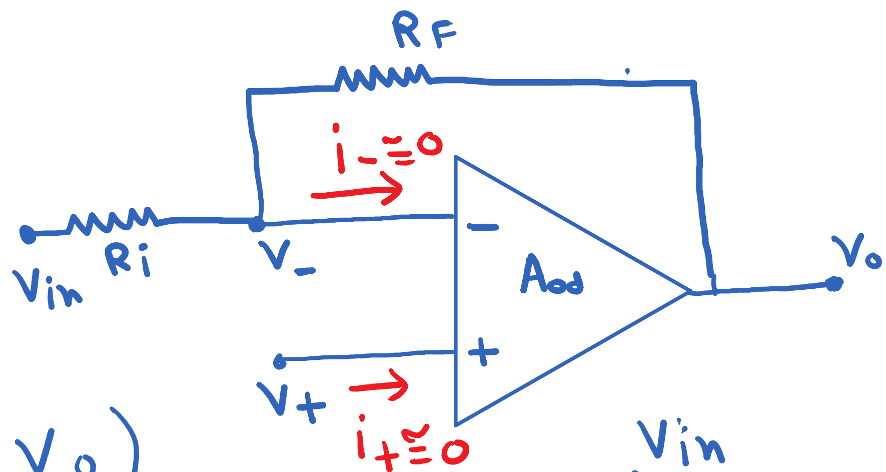
In closed loop configuration, $V_+ \cong V_-$



Closed loop configuration of an op-Amp is the configuration in which the output and at least one of the input terminals is connected by an external impedance.

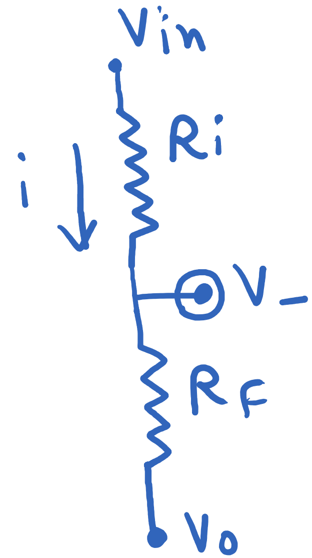
$$V_o = A_{od}(V_+ - V_-) \quad \text{——} \ (1)$$

$$V_- = \frac{R_F}{R_i + R_F} V_i + \frac{R_i}{R_i + R_F} V_o \quad \text{——} \ (2)$$



$$V_o = A_{od}(V_+ - V_-)$$

$$= A_{od}\left(V_+ - \frac{R_F}{R_F + R_i} V_{in} - \frac{R_i}{R_F + R_i} V_o\right)$$



$$\Rightarrow V_o \left\{ 1 + \frac{R_F A_{od}}{R_F + R_i} \right\}$$

$$= A_{od}\left(V_+ - \frac{R_F}{R_F + R_i} V_{in}\right)$$

Dividing both sides by A_{od}, we get.

$$V_o\left\{\frac{1}{A_{od}} + \frac{R_i}{R_i+R_f}\right\} = V_+ - \frac{R_f}{R_i+R_f}V_{in}.$$

Since, $A_{od} \to \infty$, $\frac{1}{A_{od}} \to 0$.

$$\Rightarrow V_o \frac{R_i}{R_i+R_f} = V_+ - \frac{R_f}{R_i+R_f}V_{in}.$$

$$\Rightarrow V_o = \frac{R_i+R_f}{R_i}V_+ - \frac{R_f}{R_i}V_{in} \quad \text{--- } (3)$$

$$V_o = \frac{R_F + R_i}{R_i} V_+ - \frac{R_F}{R_i} V_{in} \quad \text{--- (3)}$$

From (2)

$$V_- = \frac{R_F}{R_i + R_f} V_{in} + \frac{R_i}{R_i + R_F} V_o$$

$$= \frac{R_f}{\cancel{R_i + R_f}} V_{in} + V_+ - \frac{R_F}{\cancel{R_i + R_f}} V_{in}$$

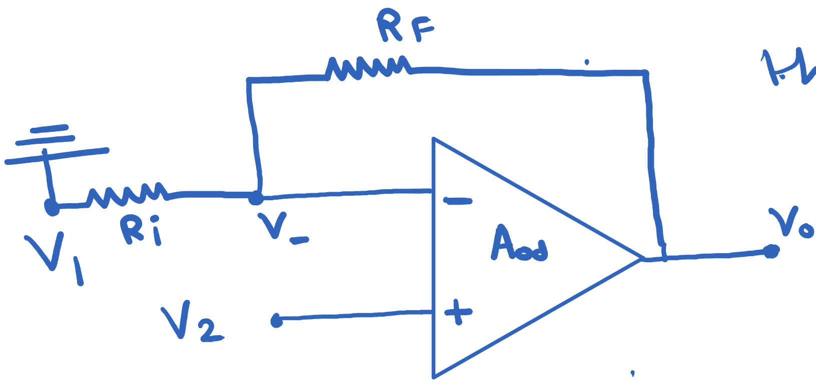
$$= V_+$$

$V_- = V_+$ → This is basically the condition for virtual short.

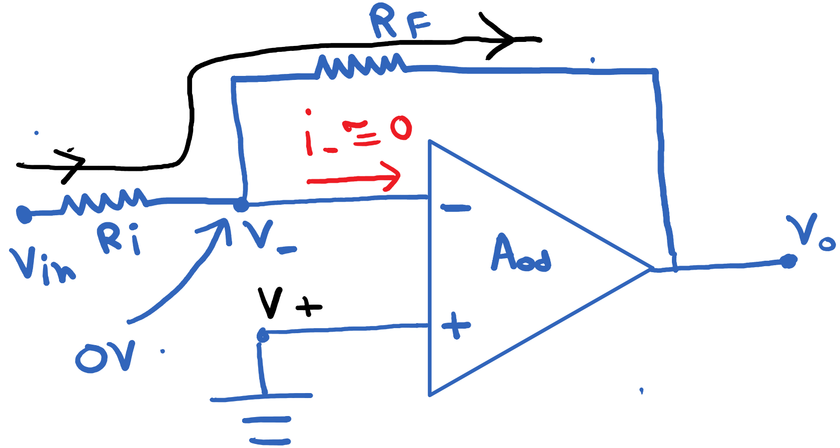
$$V_o = \frac{R_F + R_i}{R_i} V_2 - \frac{R_F}{R_i} V_1$$

Consider $V_2 = 0$. In this case, $V_o = -\frac{R_F}{R_i} V_1$.
This configuration is known as the inverting configuration of op-Amp Amplifier.

Consider $V_1 = 0$. In this case $V_o = \frac{R_F + R_i}{R_i} V_2$
This configuration is known as the non-inverting configuration of op-Amp Amplifier.



Inverting Amplifier:-



$$V_+ = 0$$

$$V_- \simeq V_+ = 0.$$

$$I_{R_i} = \frac{V_{in} - V_-}{R_i} = \frac{V_{in}}{R_i}$$

$$I_{R_F} = I_{R_i} = \frac{V_{in}}{R_i}$$

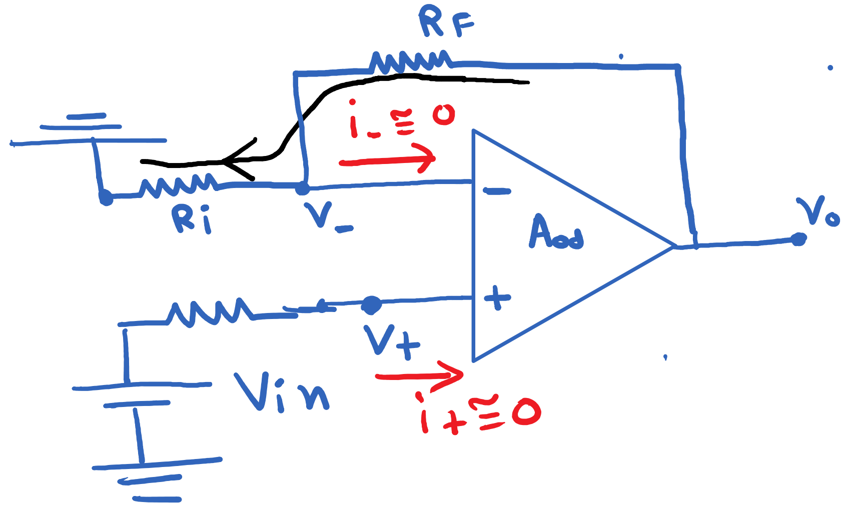
$$V_o = V_- - I_{R_F} \times R_F = 0 - \frac{V_{in}}{R_i} \times R_F$$

$$= -\frac{R_F}{R_i} \times V_{in}$$

$$A_{cl} = V_o / V_{in} = -\frac{R_F}{R_i}$$

Closed loop gain is independent of A_{od}

Non-inverting Amplifier:-



$V_+ = V_{in}$

$V_- \cong V_+ = V_{in}$

$$I_{R_i} = \frac{V_-}{R_i} = \frac{V_{in}}{R_i}$$

$$I_{R_F} = I_{R_i} = \frac{V_{in}}{R_i}$$

$$V_o = V_- + I_{R_F} \times R_F = V_{in} + \frac{V_{in}}{R_i} \times R_F$$

$$= V_{in}\left(1 + \frac{R_F}{R_i}\right)$$

$$= V_{in}\,\frac{R_i + R_F}{R_i}$$

$$A_{cl} = \frac{V_o}{V_{in}} = \frac{R_i + R_F}{R_i}$$

Class - 30

1) Infinite open loop gain (A_{od}).

2) Infinite input impedance.

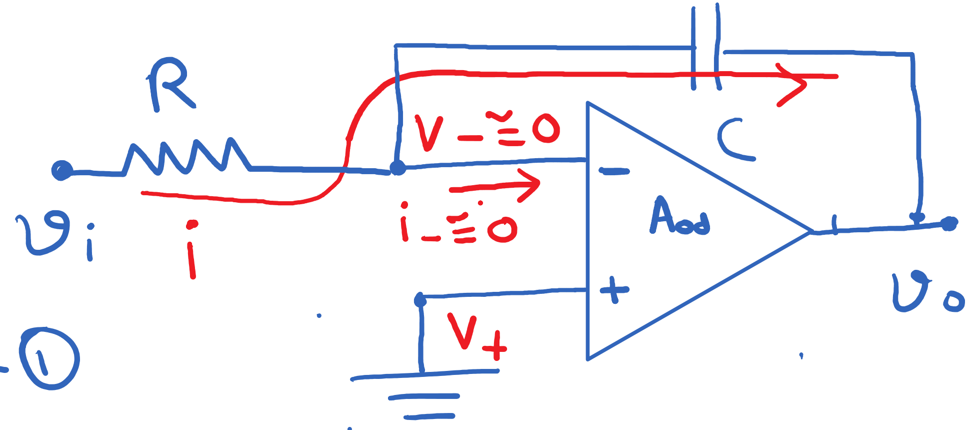
3) Zero output impedance.

4) In closed loop configuration $V_+ \cong V_-$. This is also known as the property of Virtual short.

Integrator:

$V_+ = 0$

$V_- \cong V_+ = 0$



$$i = \frac{v_i - V_-}{R} \cong \frac{v_i}{R} \quad \text{— (1)}$$

$$i = C\frac{d(V_- - v_o)}{dt} \cong -C\frac{dv_o}{dt} \quad \text{— (2)}$$

$$-C\frac{dv_o}{dt} = \frac{v_i}{R} \Rightarrow \frac{dv_o}{dt} = -\frac{v_i}{CR}.$$

$$v_o = -\frac{1}{CR}\int v_i(t)\,dt.$$

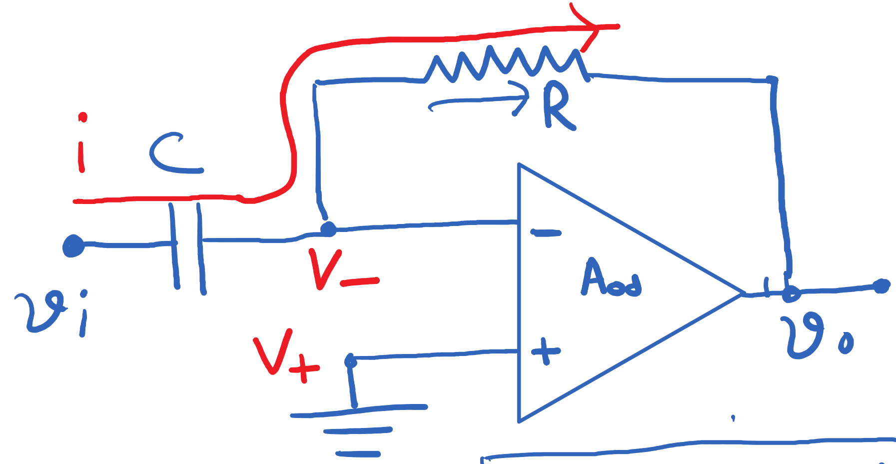
This configuration also acts as a low pass filter

Differentiation:

$$V_- \simeq V_+ = 0$$

$$i = C\frac{d}{dt}(v_i - V_-)$$

$$\simeq C\frac{dv_i}{dt} \quad -(1)$$

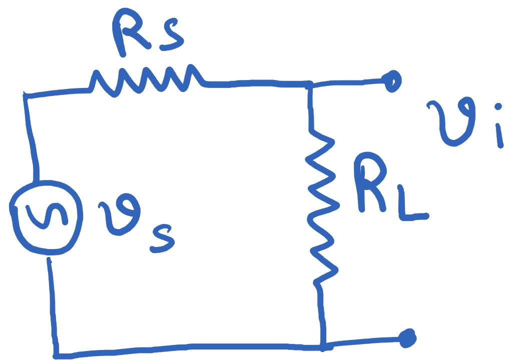


This configuration acts as a high pass filter

$$i = \frac{V_- - v_o}{R} \simeq -\frac{v_o}{R} \quad -(2)$$

$$C\frac{dv_i}{dt} = -\frac{v_o}{R} \Rightarrow v_o = -CR\frac{dv_i}{dt}$$

$$v_i = v_s \times \frac{R_L}{R_s + R_L}$$

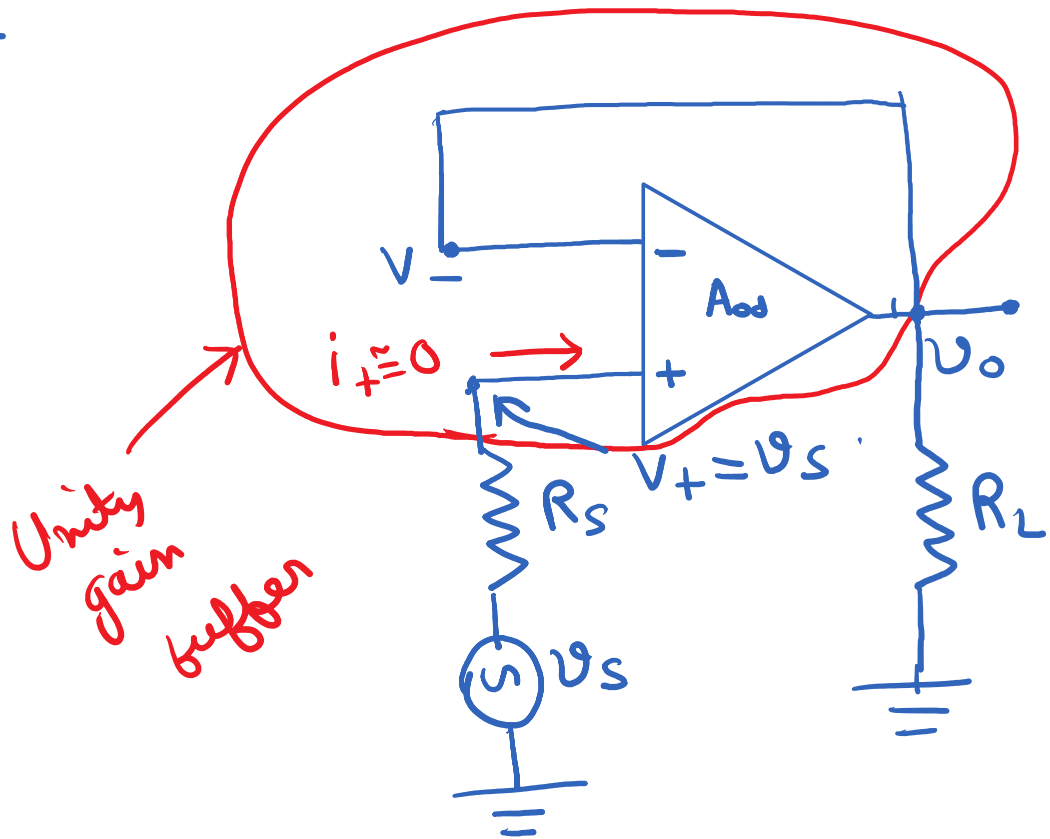


Unity gain buffer:-

$$V_- \simeq V_+ = v_s$$

$$v_o = V_- = v_s$$

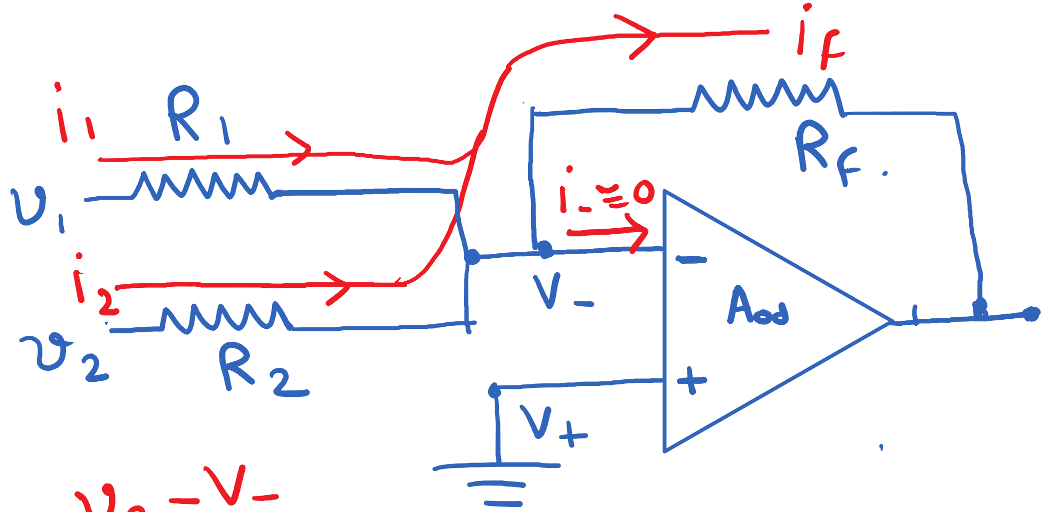
$$v_{R_L} = v_o = v_s$$



Adder:

$V_+ = 0$

$V_- \cong V_+ = 0$



$i_f = i_1 + i_2$

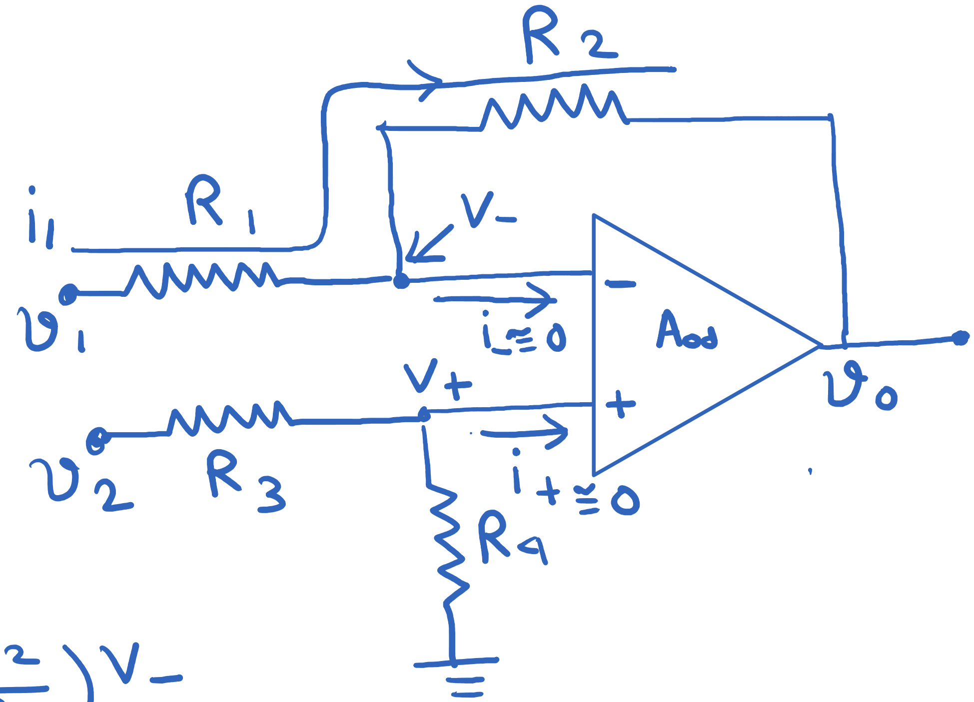
$$\frac{V_- - v_o}{R_F} = \frac{v_1 - V_-}{R_1} + \frac{v_2 - V_-}{R_2}$$

$$\Rightarrow -\frac{v_o}{R_F} = \frac{v_1}{R_1} + \frac{v_2}{R_2}$$

$$\Rightarrow v_o = -\frac{R_F}{R_1} v_1 - \frac{R_F}{R_2} v_2$$

If $R_1 = R_2 = R$, then $v_o = -\frac{R_F}{R}(v_1 + v_2)$

Difference Amplifier :-



$$V_+ = \frac{R_4}{R_3+R_4} v_2$$

$$V_- \cong V_+ = \frac{R_4}{R_3+R_4} v_2 \quad \text{—} \quad (1)$$

$$i_1 = \frac{v_1 - V_-}{R_1} = \frac{V_- - v_0}{R_2}$$

$$\Rightarrow v_0 = \frac{R_2}{R_1} v_1 - \left(1 + \frac{R_2}{R_1}\right) V_-$$

$$= \frac{R_2}{R_1} v_1 - \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3+R_4}\right) v_2$$

$$v_o = \frac{R_2}{R_1} v_1 - \left(1 + \frac{R_2}{R_1}\right) \frac{R_4}{R_3 + R_4} v_2$$

$$= \frac{R_2}{R_1} v_1 - \left(1 + \frac{R_2}{R_1}\right) \frac{R_4/R_3}{1 + \frac{R_4}{R_3}}$$

$$= \frac{R_2}{R_1} v_1 - \frac{R_4}{R_3} \frac{(1 + R_2/R_1)}{(1 + R_4/R_3)} v_2$$

If $\frac{R_2}{R_1} = \frac{R_4}{R_3}$, then $v_o = \frac{R_2}{R_1} v_1 - \frac{R_2}{R_1} v_2$

$$= \frac{R_2}{R_1} (v_1 - v_2)$$

Common-mode rejection ratio (CMRR)

$$v_{cm} = \frac{v_1 + v_2}{2}, \quad v_d = (v_1 - v_2) \implies v_1 = v_{cm} + \frac{v_d}{2}, \quad v_2 = v_{cm} - \frac{v_d}{2}$$

$$A_{cm} = \left.\frac{v_o}{v_{cm}}\right|_{v_1 = v_2 \text{ or } v_d = 0} \xRightarrow{\text{ideal}} 0$$

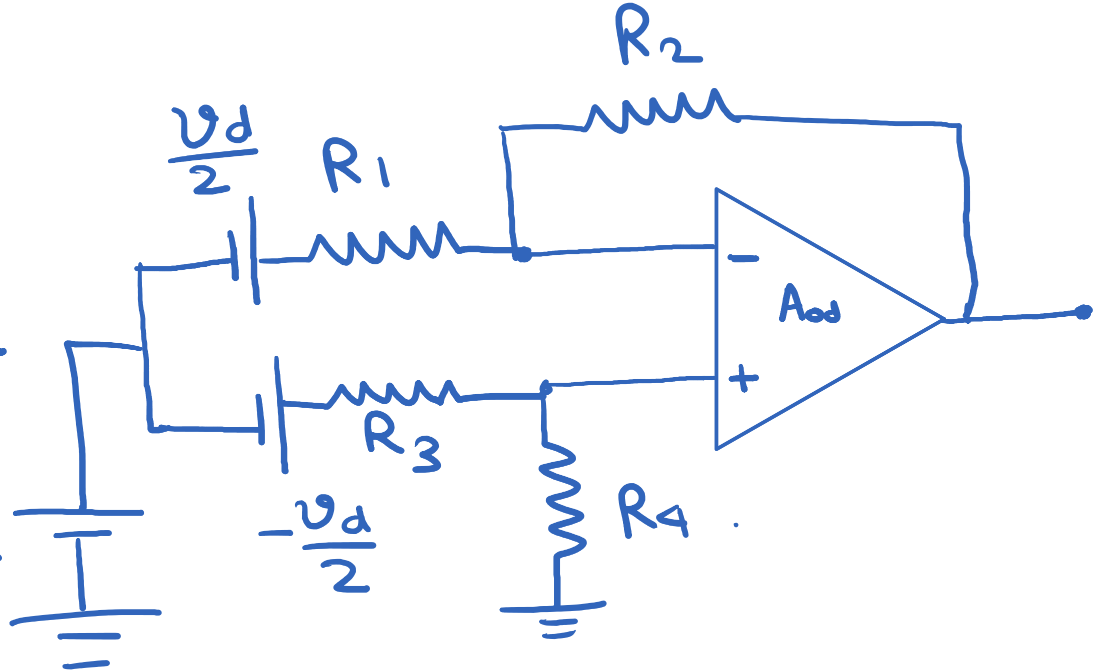
$$A_d = \left.\frac{v_o}{v_d}\right|_{v_{cm} = 0} \xRightarrow{\text{ideal}} \text{Finite value}$$

$$CMRR = \frac{A_d}{A_{cm}} \xRightarrow{\text{ideal}} \infty$$

Higher value of CMRR means better difference amplifier.

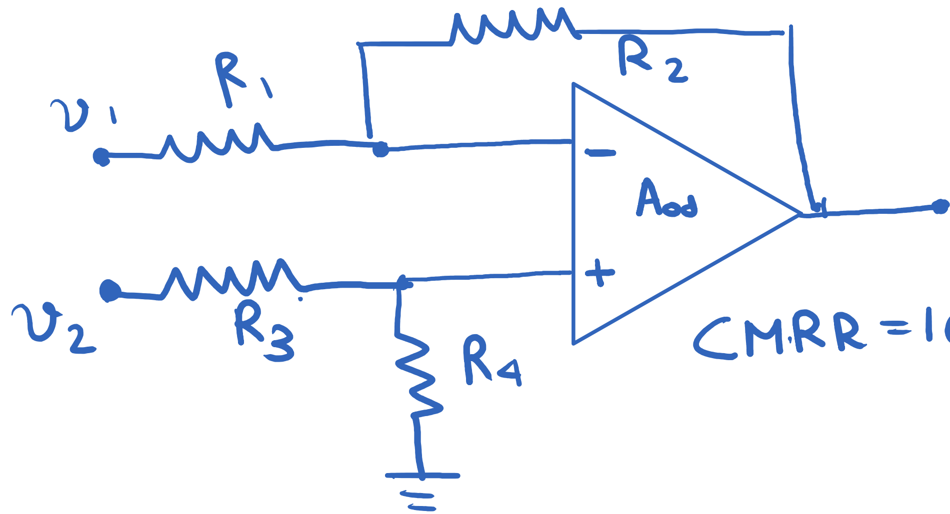
$$v_{cm} = \frac{v_1 + v_2}{2}$$

$$v_d = v_1 - v_2$$



$$\text{CMRR (in dB)} = 20\log_{10}\left|\frac{A_d}{A_{cm}}\right|.$$

Case I	Case II
$v_1 = 200\,\mu V$	$v_1 = 1200\,\mu V$
$v_2 = -200\,\mu V$	$v_2 = 800\,\mu V$
output $= v_{01}$	output $= v_{02}$
$v_1 - v_2 = 400\,\mu V$	$v_1 - v_2 = 400\,\mu V$



CMRR = 100

$$v_o = F_1(v_1) + F_2(v_2)$$

$$= F_1\left(v_{cm} + \frac{v_d}{2}\right) + F_2\left(v_{cm} - \frac{v_d}{2}\right)$$

$$= A_{cm}(v_{cm}) + A_d(v_d)$$

Case I

$v_1 = 200\mu V$

$v_2 = -200\mu V$

$v'_{cm} = \dfrac{v_1 + v_2}{2}$

$= 0\mu V$

$v'_d = v_1 - v_2$

$= 400\mu V$

$v_{01} = A_{cm} v'_{cm} + A_d v'_d$

$= A_{cm} \times 0 + A_d \times 400\mu V.$

Case II

$v_1 = 1200\mu V$

$v_2 = 800\mu V$

$v^2_{cm} = \dfrac{v_1 + v_2}{2}$

$= 1000\mu V$

$v^2_d = v_1 - v_2$

$= 400\mu V$

$v_{02} = A_{cm} \times (1000\mu V) + A_d \times 400\mu V.$

$v_{01} - v_{02}$

$= A_d \times 400\mu V - A_{cm} \times (1000\mu V) - A_d \times 400\mu V$

$= -A_{cm} \times (1000\mu V)$

Percentage difference between the outputs:-

$$\frac{v_{o1} - v_{o2}}{v_{o1}} \times 100\%$$

$$= \frac{-A_{cm} \times (1000\mu V)}{A_d \times 400\mu V} \times 100\%$$

$$= \frac{1000}{400} \times \frac{1}{\frac{A_d}{A_{cm}}} \times 100\% = 2.5 \times \frac{1}{CMRR} \times 100\%$$

$$= 2.5 \times \frac{1}{100} \times 100\% = 2.5\%$$

Class-31

Digital to Analog Converter:-

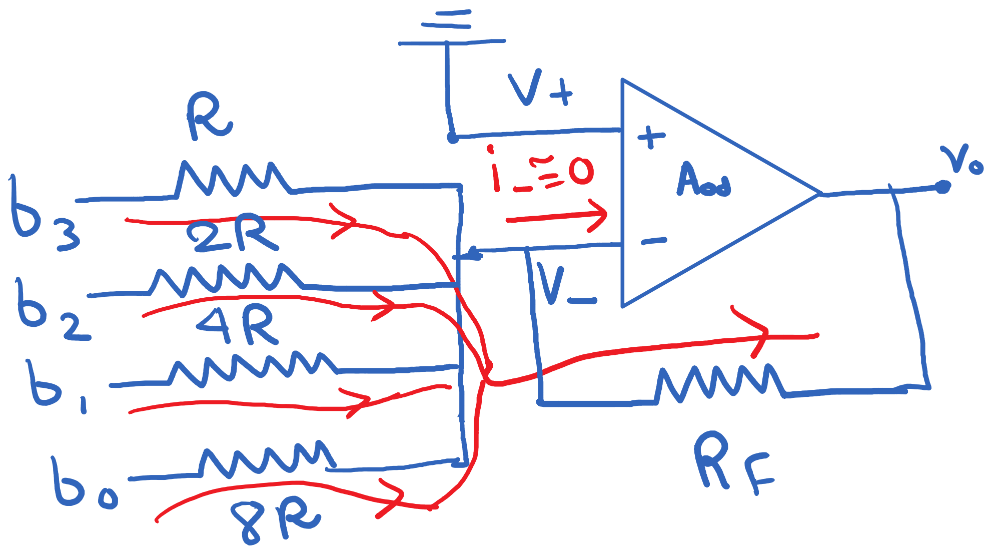
MSB ↖ $b_3 b_2 b_1 b_0$ ↗ LSB $\longrightarrow 2^3 \times b_3 + 2^2 \times b_2 + 2^1 \times b_1 + 2^0 \times b_0$

$$1101 \longrightarrow 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0$$

$$= 8 + 4 + 0 + 1 = 13$$

$$V_+ = 0$$

$$V_- \cong V_+ = 0$$



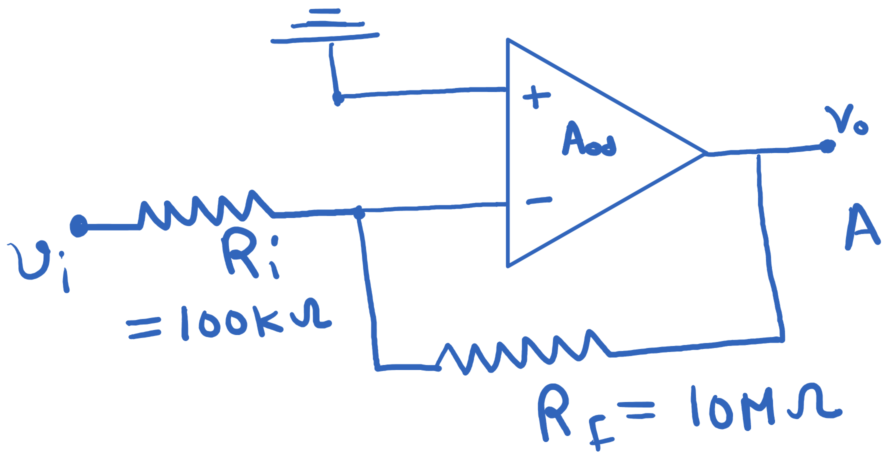
$$\frac{b_3 - V_-}{R} + \frac{b_2 - V_-}{2R} + \frac{b_1 - V_-}{4R} + \frac{b_0 - V_-}{8R} = \frac{V_- - V_o}{R_F}$$

$$\Rightarrow V_o = -\frac{R_F}{R}\left[b_3 + \frac{b_2}{2} + \frac{b_1}{4} + \frac{b_0}{8}\right] \quad (\because V_- \cong 0)$$

$$= -\frac{R_F}{8R}\Big[\underbrace{2^3 b_3 + 2^2 b_2 + 2 b_1 + 2^0 b_0}_{\text{Analog value}}\Big]$$

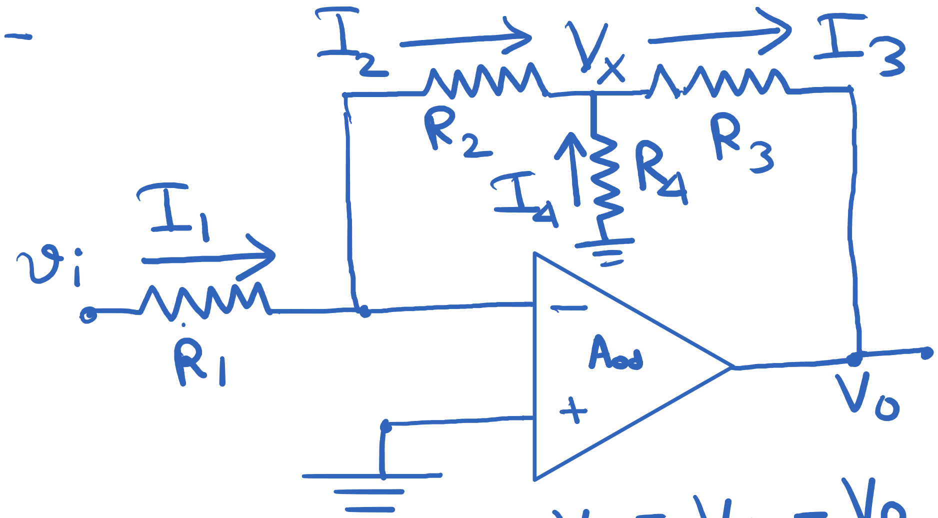
Amplifier with T- network :-

Gain in inverting config :- $-\frac{R_F}{R_i}$



$A_{cl} = 100$

Amplifier with T-network:-



$V_+ = 0$

$V_- \cong V_+ = 0$

$$I_1 = \frac{v_i - V_-}{R_1} = \frac{v_i}{R_1}$$

$$I_2 = \frac{V_- - V_x}{R_2} = -\frac{V_x}{R_2}$$

$$V_o = V_x - V_{R_3}$$

$I_1 = I_2$

$$\Rightarrow \frac{v_i}{R_1} = -\frac{V_x}{R_2} \Rightarrow V_x = -v_i \times \frac{R_2}{R_1}$$

$$I_4 = \frac{0 - V_x}{R_4} = -\left(-v_i \times \frac{R_2}{R_1}\right)\frac{1}{R_4} = v_i \times \frac{R_2}{R_1 R_4}$$

$$I_3 = I_2 + I_4$$

$$= \frac{v_i}{R_1} + \frac{v_i \times R_2}{R_1 R_4}.$$

$$V_o = V_x - V_{R_3}$$

$$= v_i \times \frac{R_2}{R_1} - I_3 R_3$$

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

$$= -v_i \left(\frac{R_2}{R_1} + \frac{R_3}{R_1} + \frac{R_2 R_3}{R_1 R_4} \right)$$

$$= -v_i \times \frac{R_2}{R_1} \underbrace{\left(1 + \frac{R_3}{R_2} + \frac{R_3}{R_4} \right)}_{\text{Gain increases by this factor.}}$$

Class - 32

$$V_+ = v_1 \times \frac{R_4}{R_3+R_4} + v_2 \times \frac{R_3}{R_3+R_4}$$

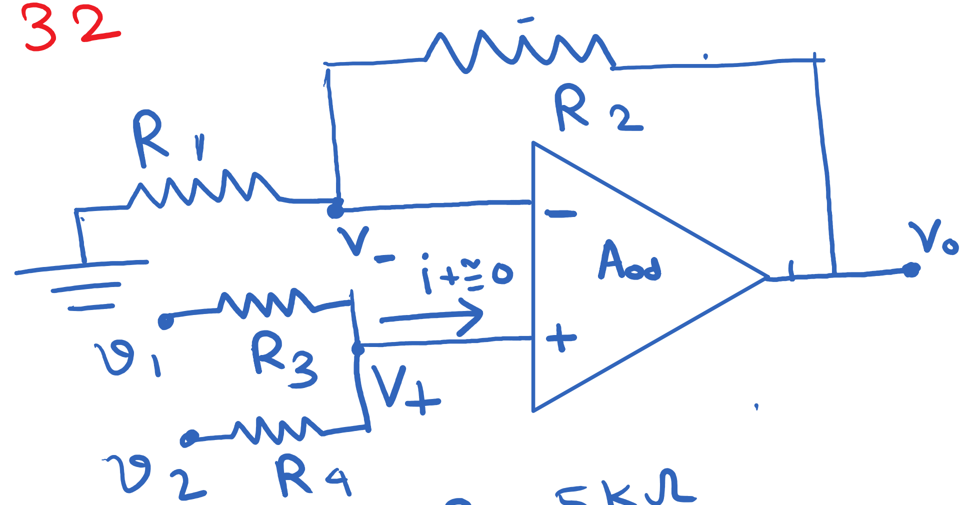
$$V_- \cong V_+ = \frac{v_1 R_4}{R_3+R_4} + \frac{v_2 R_3}{R_3+R_4}$$

$$v_o = \left(1+\frac{R_2}{R_1}\right) V_+$$

$$= \left(1+\frac{R_2}{R_1}\right)\left(\frac{v_1 R_4}{R_3+R_4} + \frac{v_2 R_3}{R_3+R_4}\right)$$

$$A_{v_1} = \left.\frac{v_o}{v_1}\right|_{v_2=0} = \left(1+\frac{R_2}{R_1}\right)\frac{R_4}{R_3+R_4}.$$

$$= \left(1+\frac{70}{75}\right) \times \frac{50}{75} = 10$$



$R_1 = 5k\Omega$

$R_2 = 70k\Omega$

$R_3 = 25k\Omega$

$R_4 = 50k\Omega$

$$A_{v_1} = \left.\frac{v_o}{v_1}\right|_{v_2=0}$$

$$A_{v_2} = \left.\frac{v_o}{v_2}\right|_{v_1=0}$$

$$A_{v_2} = \frac{v_o}{v_2}\bigg|_{v_1=0}$$

$$A_{v_2} = \frac{v_o}{v_2}\bigg|_{v_1=0}$$

$$= \left(1+\frac{R_2}{R}\right)\frac{R_3}{R_3+R_4}$$

$$= \left(1+\frac{70}{5}\right)\times\frac{25}{75} = 5$$

$$A_{v_1} = 10$$

$$A_{v_2} = 5$$

$$V_+ = \frac{v_2 R_4}{R_3+R_4} + \frac{v_3 R_3}{R_3+R_4}.$$

$$V_- \simeq V_+ = \frac{v_2 R_4}{R_3+R_4} + \frac{v_3 R_3}{R_3+R_4}$$

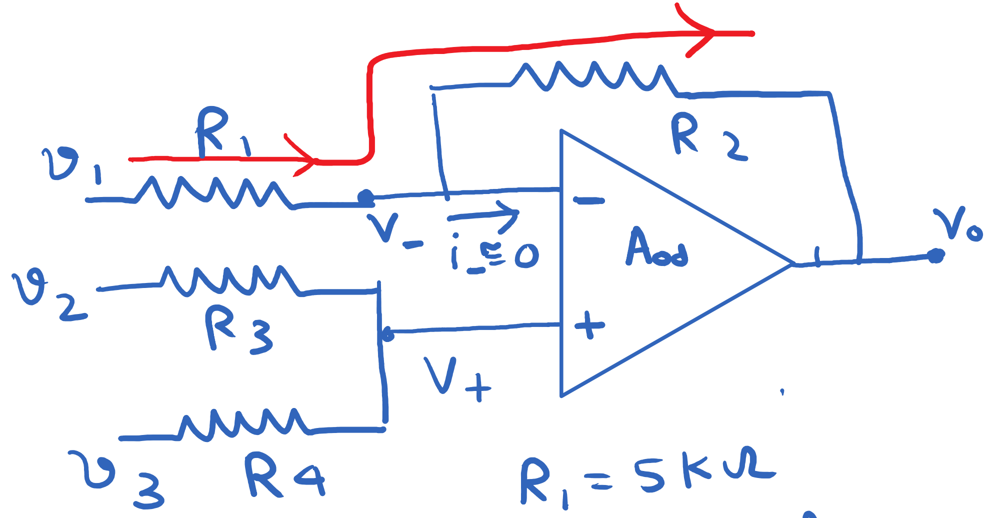
$$\frac{v_1 - V_-}{R_1} = \frac{V_- - v_o}{R_2}$$

$$v_o = V_- + \frac{R_2}{R_1}(V_- - v_1)$$

$$= V_-\left(1+\frac{R_2}{R_1}\right) - \frac{R_2}{R_1} v_1$$

$$= \left(\frac{v_2 R_4}{R_3+R_4} + \frac{v_3 R_3}{R_3+R_4}\right)\left(1+\frac{R_2}{R_1}\right) - \frac{R_2}{R_1} v_1$$

$$= \left(v_2 \frac{50}{75} + v_3 \times \frac{25}{75}\right)\left(1+\frac{70}{5}\right) - \frac{70}{5} v_1$$



$R_1 = 5\,k\Omega$
$R_2 = 70\,k\Omega$
$R_3 = 25\,k\Omega$
$R_4 = 50\,k\Omega$

$$A_{v1} = \frac{v_o}{v_1}\bigg|_{v_2=v_3=0}$$

$$A_{v2} = \frac{v_o}{v_2}\bigg|_{v_1, v_3=0}$$

$$A_{v3} = \frac{v_o}{v_3}\bigg|_{v_1, v_2=0}$$

$$= \left(v_2 \frac{50}{75} + v_3 \times \frac{25}{75}\right)\left(1 + \frac{\quad}{5}\right) \quad \frac{\quad}{5}$$

$$A_{v3} = \frac{v_o}{v_3}\bigg|_{v_1, v_2 = 0}$$

$$= \left(\frac{2}{3}v_2 + \frac{1}{3}v_3\right) \times 15 - 14v_1$$

$$= -14v_1 + 10v_2 + 5v_3$$

$$\left.\begin{aligned} A_{v_1} &= \left.\frac{v_o}{v_1}\right|_{v_2=v_3=0} = -14 \\ A_{v_2} &= \left.\frac{v_o}{v_2}\right|_{v_1=v_3=0} = 10 \\ A_{v_3} &= \left.\frac{v_o}{v_3}\right|_{v_1=v_2=0} = 5 \end{aligned}\right\} \text{Ans}$$

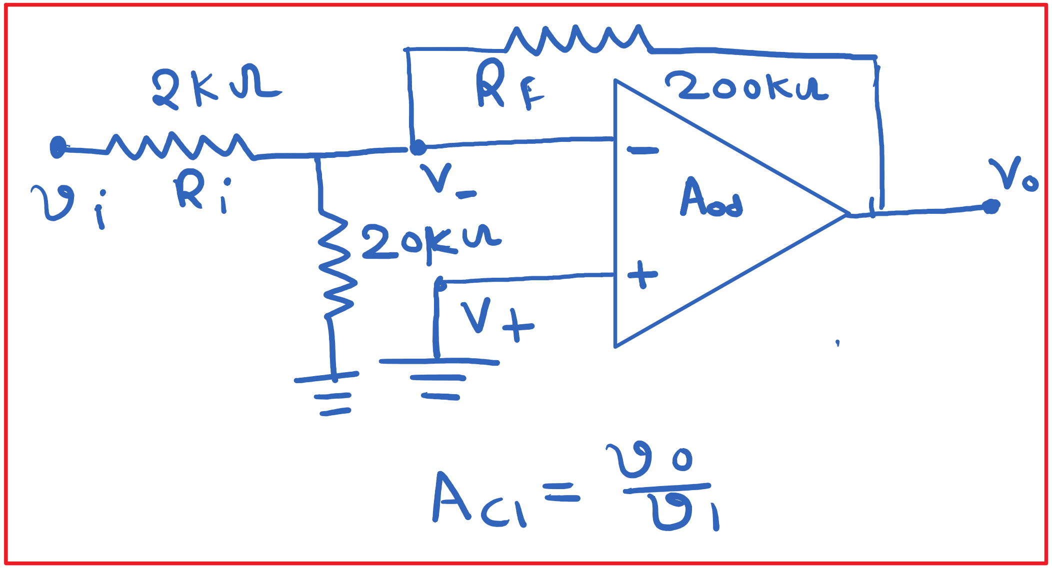
$V_+ = 0$

$V_- \cong V_+ = 0$

$$A_{cl} = -\frac{R_F}{R_i}$$

$$= -\frac{200k\Omega}{2k\Omega}$$

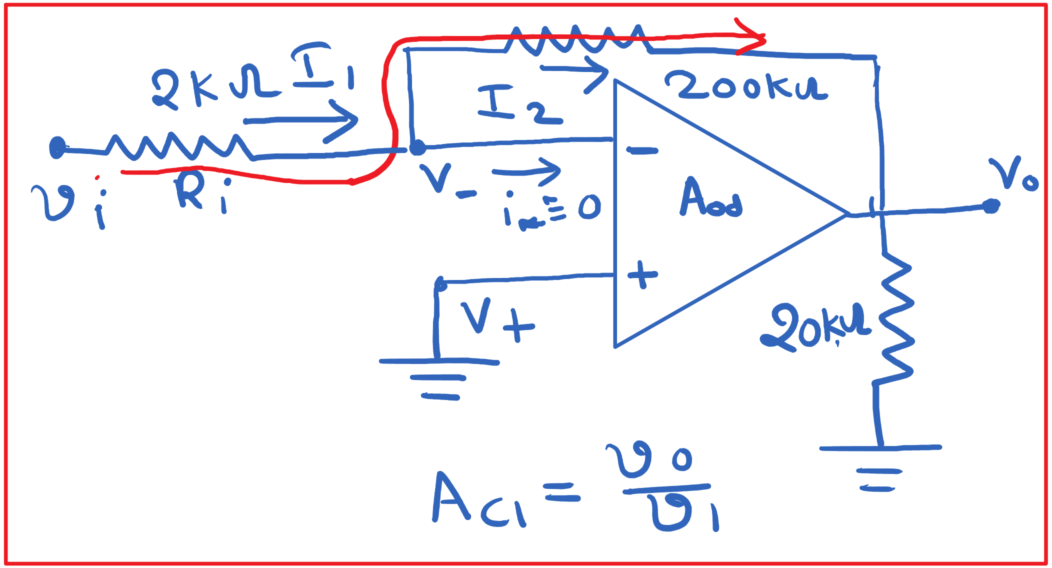
$$= -100$$



$$V_- \simeq V_+ = 0$$

$$I_1 = \frac{v_i - V_-}{R_1} = \frac{v_i}{R_1} = \frac{v_i}{2}$$

$$I_2 = \frac{V_- - v_o}{200} = -\frac{v_o}{200}$$



$$I_1 = I_2$$

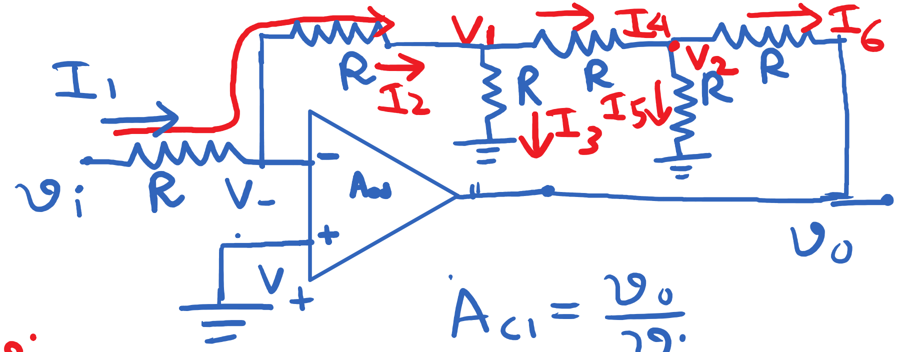
$$\Rightarrow \frac{v_i}{2} = -\frac{v_o}{200}$$

$$\Rightarrow \frac{v_o}{v_i} = -\frac{200}{2} = -100$$

$$A_{c1} = -100.$$

$V_- \cong V_+ = 0$

$I_1 = \dfrac{v_i - V_-}{R} = \dfrac{v_i}{R}$



$A_{c1} = \dfrac{v_o}{v_i}$

$I_2 = I_1 = \dfrac{v_i}{R}$

$V_1 = V_- - I_2 R = -\dfrac{v_i}{R} \times R = -v_i$

$\Rightarrow V_1 = -v_i$

$I_3 = \dfrac{V_1 - 0}{R} = -\dfrac{v_i}{R}$

$I_4 = I_2 - I_3 = \dfrac{2v_i}{R}$

$V_2 = V_1 - I_4 \times R$

$= -v_i - \dfrac{2v_i}{R} \times R$

$= -3v_i$

$I_5 = \dfrac{V_2 - 0}{R} = -\dfrac{3v_i}{R}$

$I_6 = I_4 - I_5$

$= \dfrac{2v_i}{R} - \left(-\dfrac{3v_i}{R}\right)$

$= \dfrac{5v_i}{R}$

$v_o = V_2 - I_6 R = -3v_i - \left(\dfrac{5v_i}{R}\right) R$

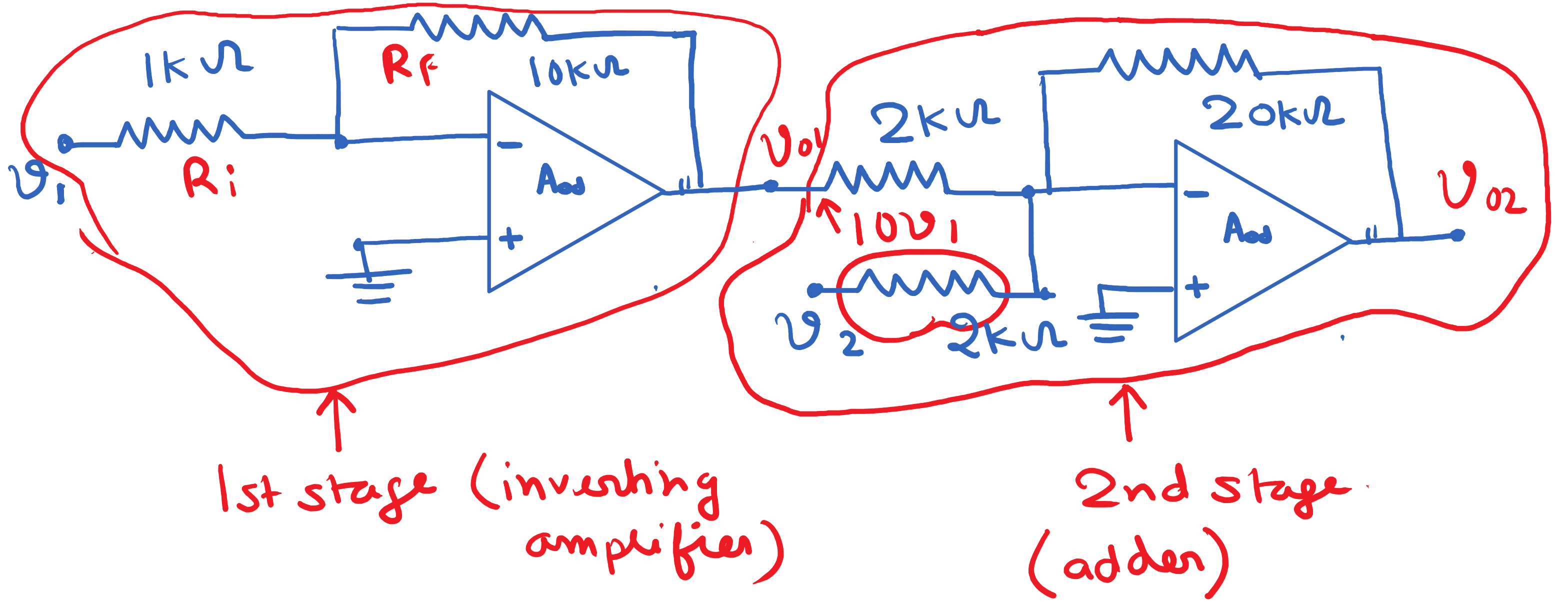
$= -3v_i$

$v_0 = V_2 - I_6 \ldots$

$-\left(\frac{5v_i}{R}\right)R$

$$= -8v_i$$

$$A_{cl} = \frac{v_o}{v_i} = -8$$



For the 1st stage: $A_{cl,1} = -\frac{R_f}{R_i} = -\frac{10}{1}$

$\Rightarrow v_{01} = -10 v_1$

$$v_{02} = -\frac{20}{2} \times v_{01} - \frac{20}{2} \times v_2 = -10 v_{01} - 10 v_2$$

$$= -10 \times (-10 v_1) - 10 v_2$$

$$= 100 v_1 - 10 v_2$$