MODULE 4 : OPERATIONAL AMPLIFIER

→ Preview : Basic amplifier concepts & Terminology

→ Operational Amplifier (= Op-amp) is a circuit building block of universal importance.

→ Op-amps are used for long-time

Initial Applications	Later Applications
- Analog computation	- communication
- Instrumentation	- Instrumentation
	- Computing System

→ Early op-amp construction : 10s of $

Discrete components : vaccum tubes ⟶ Transistors + Resistors

→ Mid - 1960 : First IC op-amp produced (μA-709)

- large No of Transistors & Resistors
- single silicon chip.
- Price = High
- characteristics = poor

Dramatically, usage ↑

price ↓

Demand for better quality op-amp ↑

→ Amplifier circuits :

$$\left.\begin{array}{l} v_o(t) \propto v_i(t) \\ v_o(t) = \underline{A}\, v_i(t) \end{array}\right\} \text{Linear Amplifier}$$

→ Magnitude of amplification (= Gain)

→ Also called as proportionality constant

→ shortcomings of amplifier circuits

Input Impedance, Z_i = Low

Gain, A = Moderate

Bandwidth, BW = Limited

"Limitations of Basic Amplifier"

Amplifiers Noise present at the input

→ Environmental Noise

→ Thermal Noise

→ other noise

Solution : Operational Amplifiers

Op-amp is popular for its

- versatility
- characteristics ≃ Ideal
- Easy to design circuits
- Performance levels : Theoritically predicted

→ Integrated circuit (IC) version of op-amp components :

- Transistors (Large Numbers = 10)
- Resistors
- Capacitor (usually one)

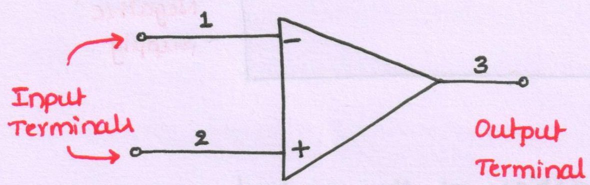
In this chapter,

- Op-amp is treated as a circuit building block
- Op-amp is studied with
  - Terminal characteristics
  - Applications

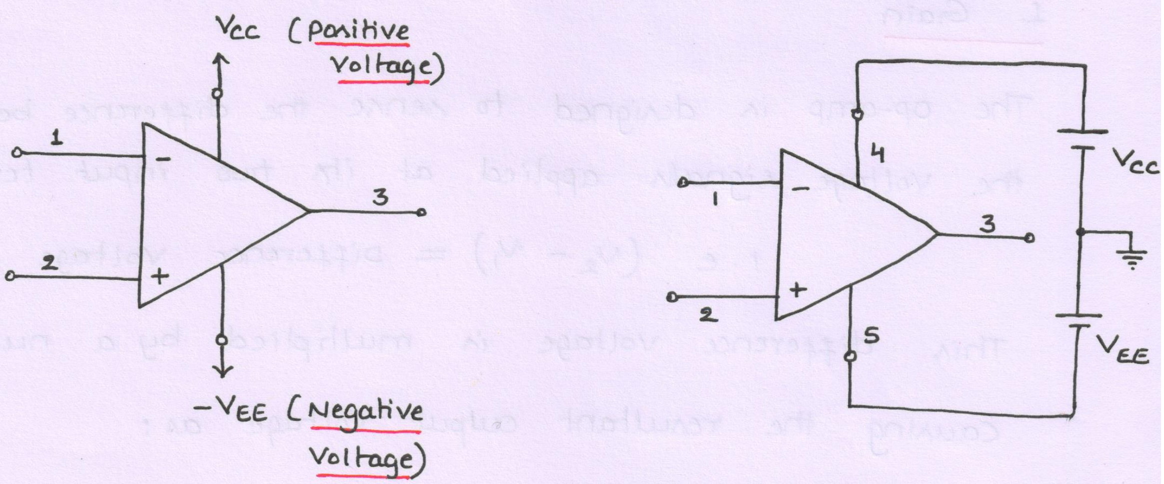
5.1 The Ideal op-amp

5.1.1 The Op-amp Terminals

- Op-amp : Three Terminals (From signal point of view)
- IC op-amps require Two DC power supplies

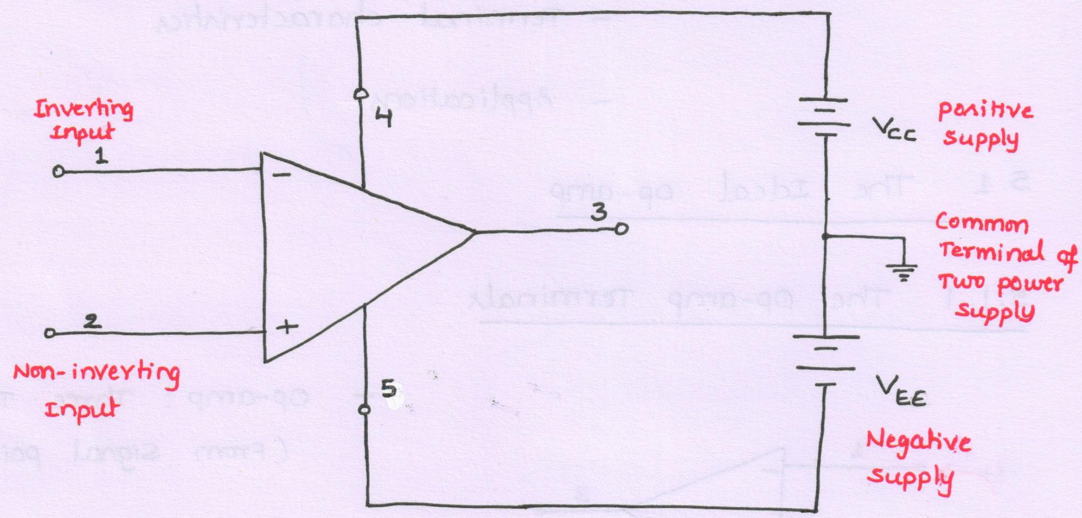


(a) Op-amp circuit symbol



(b) Op-amp with DC power supplies

- op-amp have terminals for
  - Frequency compensation
  - offset Nulling



5.1.2 Function and characteristics of the Ideal op-amp

Op-amp circuit function

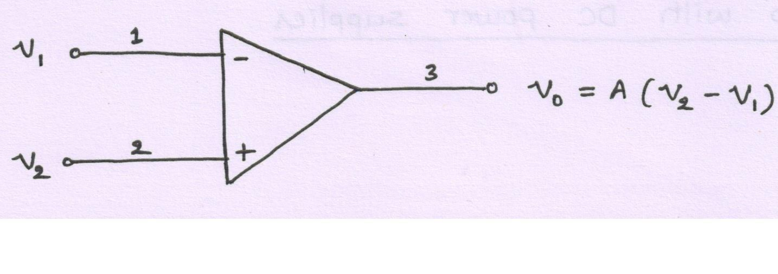
1. Gain

The op-amp is designed to sense the difference between the voltage signals applied at its two input terminals.

i.e $(v_2 - v_1)$ = Difference Voltage

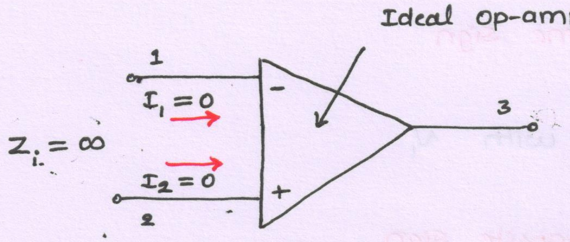
This difference voltage is multiplied by a number, A causing the resultant output voltage as:

$$v_o = A(v_2 - v_1)$$



Note: All terminal voltages are measured w.r.t ground.

2. Input current and Input Impedance



- op-amp is not supposed to draw any input current
- Signal current into terminal-1, is zero $\boxed{I_1 = 0}$
- Signal current into terminal-2, is zero $\boxed{I_2 = 0}$

$$\Rightarrow \boxed{Z_i = \infty}$$

3. Output Impedance

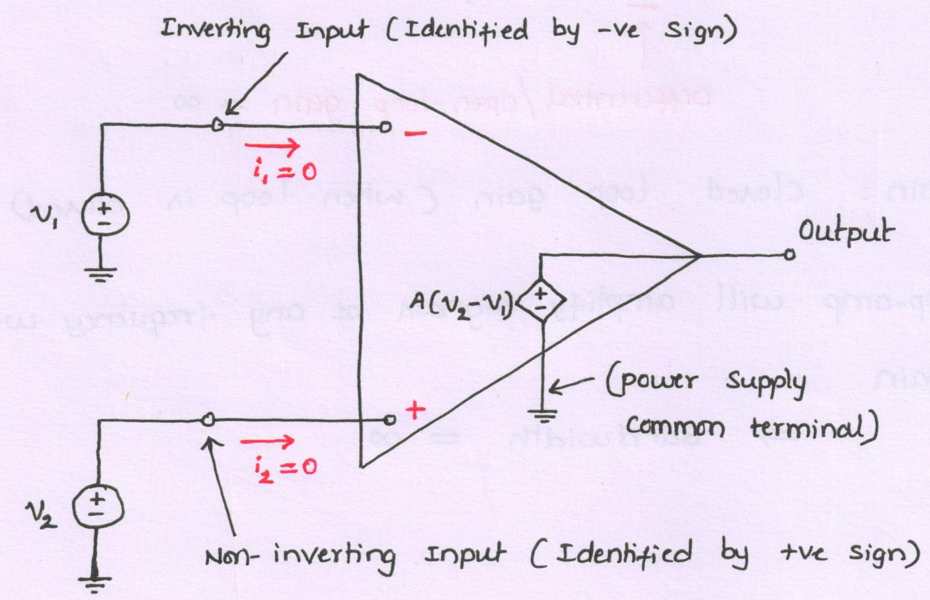
Output terminal = output terminal of an ideal voltage source.

i.e $\boxed{v_0 = A\,(v_2 - v_1)}$

$\Rightarrow$ output Impedance of an ideal op-amp = zero

$$\boxed{Z_0 = 0}$$

Equivalent circuit Model



(c) Equivalent circuit of the Ideal - Op-amp

→ Output is in phase with v_2

$$\left.\begin{aligned} v_o &= +ve \\ v_2 &= +ve \end{aligned}\right\} \text{Same sign}$$

→ Output is in out-of-phase with v_1

$$\left.\begin{aligned} v_o &= +ve \\ v_1 &= -ve \end{aligned}\right\} \text{Opposite sign}$$

→ Op-amp responds only to the difference signal

i.e $\boxed{v_2 - v_1}$

ignores any common signal to both inputs

<u>Example</u>: if $v_1 = v_2 = 1V$, then

$v_o = 0$ (Ideally)

The property is referred as Common Mode Rejection

$$\left.\begin{aligned} &\text{Common mode gain} = 0 \\ &\text{Common mode rejection} = \infty \end{aligned}\right\} \text{Ideal op-amp}$$

→ op-amp is a differential input, single ended output amplifier

since, $v_o = \underline{A}\,(v_2 - v_1)$

↑

Differential/open-loop gain $= \infty$

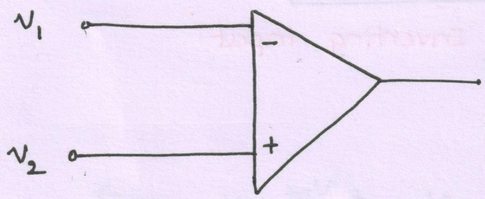
→ Another gain: closed loop gain (when loop is closed)

→ Ideal op-amp will amplify signals of any frequency with equal gain

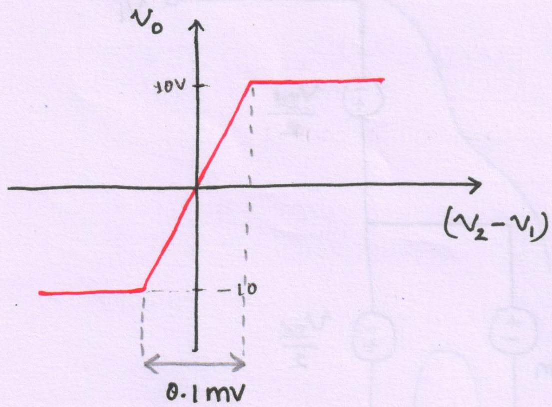
$\Rightarrow$ Bandwidth $= \infty$

Summarizing characteristics of an Ideal-Op-amp

1. $Z_i = \infty, \; i_1 = 0, \; i_2 = 0$
2. $Z_o = 0$
3. $A_{CM} = 0 \Rightarrow$ Common Mode Rejection $= \infty$
4. $A_{OL} = \infty$
5. $BW = \infty$



$V_o = A(V_2 - V_1)$



Max/Min output $= 10V = V_o$

$A = 10^5$

$$(V_2 - V_1) = \frac{V_o}{A} = \frac{10}{10^5} = 0.1 \text{ mv}$$

$(V_2 - V_1) < 0.1$ mv for linear operation

5.1.3 Differential and Common Mode Signals

→ Differential input signal : $V_{Id} = V_2 - V_1$ —— (a)

→ Common mode input signal : $V_{Icm} = \frac{1}{2}(V_1 + V_2)$

$2V_{Icm} = V_2 + V_1$ —— (b)

Adding (a) and (b)

$$\begin{aligned} V_2 - \cancel{V_1} &= V_{Id} \\ V_2 + \cancel{V_1} &= 2V_{Icm} \\ \hline 2V_2 &= V_{Id} + 2V_{Icm} \end{aligned}$$

$$\boxed{v_2 = v_{Icm} + \frac{v_{Id}}{2}} \quad \text{—— (c)}$$

Non-inverting input

subtracting (a) and (b)

$$v_2 + v_1 = 2 v_{Icm}$$
$$v_2 - v_1 = v_{Id}$$

$$2v_1 = 2v_{Icm} - v_{Id}$$

$$\boxed{v_1 = v_{Icm} - \frac{v_{Id}}{2}} \quad \text{—— (d)}$$

Inverting input

Representing pictorially :

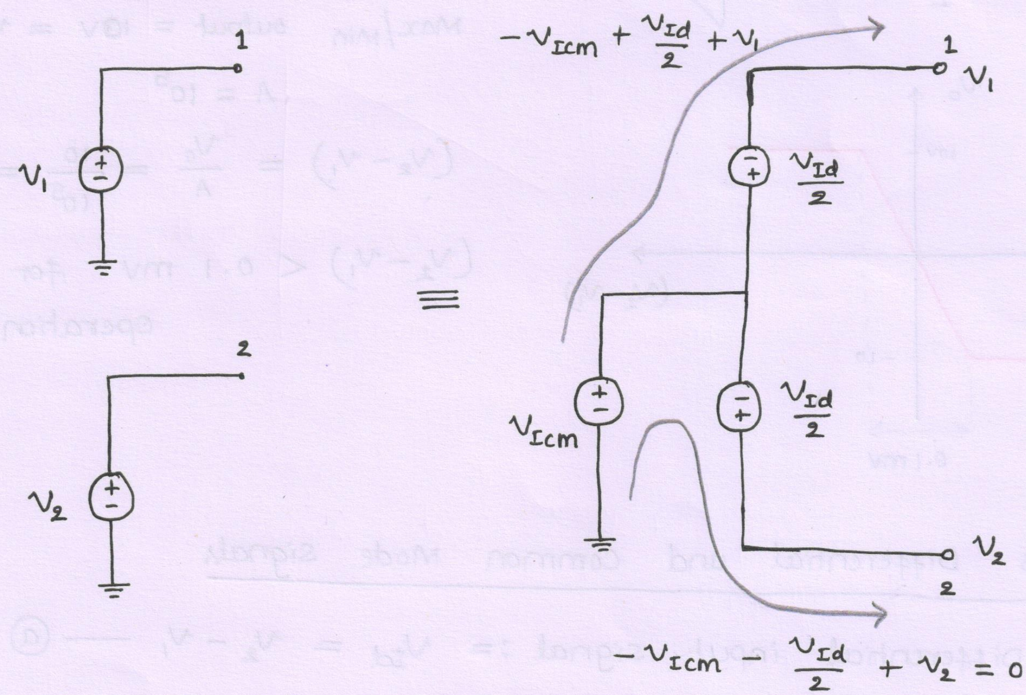


Fig. (d) Representing v_1 & v_2 in terms of v_{Icm} and v_{Id}

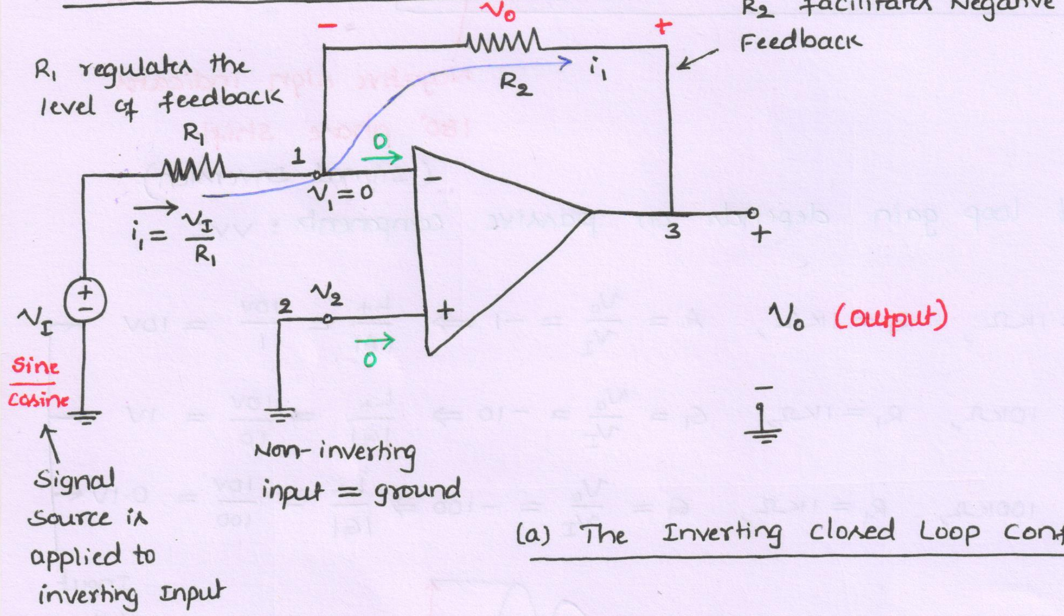
5.2 The Inverting Configuration

The two basic closed loop op-amp configurations are :

1. Inverting configuration
2. Non-inverting configuration

} Employ op-amp & Resistors

5.2.1 The Inverting Configuration : The closed loop gain



(a) The Inverting closed Loop Configuration

$$v_0 = \underline{A}\,(v_2 - v_1) \longrightarrow \text{For Ideal op-amp}$$

Very large, Ideally $= \infty$

$$\frac{v_0}{A} = v_2 - v_1 \cong 0 \Rightarrow v_1 = v_2$$

$A = \infty$

Voltage at inverting input $= v_1 = v_2 = 0$

Virtual ground   ground

As $A \longrightarrow \infty$, $v_1 \cong v_2$

(Do not physically short, terminals 1 and 2)

$v_1 = v_2 = 0 \Rightarrow$ Virtual short circuit between the two input terminals

Virtual short circuit : The voltage that exist at v_2 appears at v_1

$$v_o = -i_1 R_2 = -\frac{v_I}{R_1} \times R_2$$

$$i_1 = \frac{v_I}{R_1}$$

$$\boxed{\text{The closed loop gain} = G = \frac{v_o}{v_I} = -\frac{R_2}{R_1}}$$

$\Rightarrow$ Ratio between R_2 & R_1 resistances

Negative sign indicates 180° phase shift (signal Inversion)

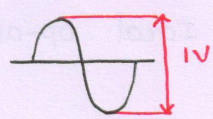
closed loop gain depends on passive components : VVI

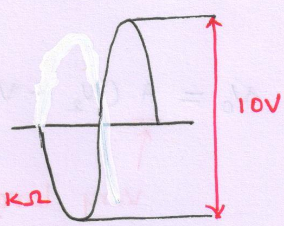
if $R_2 = 1K\Omega$, $R_1 = 1K\Omega$, $G = \frac{v_o}{v_I} = -1 \Rightarrow \frac{L+}{|G|} = \frac{10V}{1} = 10V$

if $R_2 = 10K\Omega$, $R_1 = 1K\Omega$, $G = \frac{v_o}{v_I} = -10 \Rightarrow \frac{L+}{|G|} = \frac{10V}{10} = 1V$

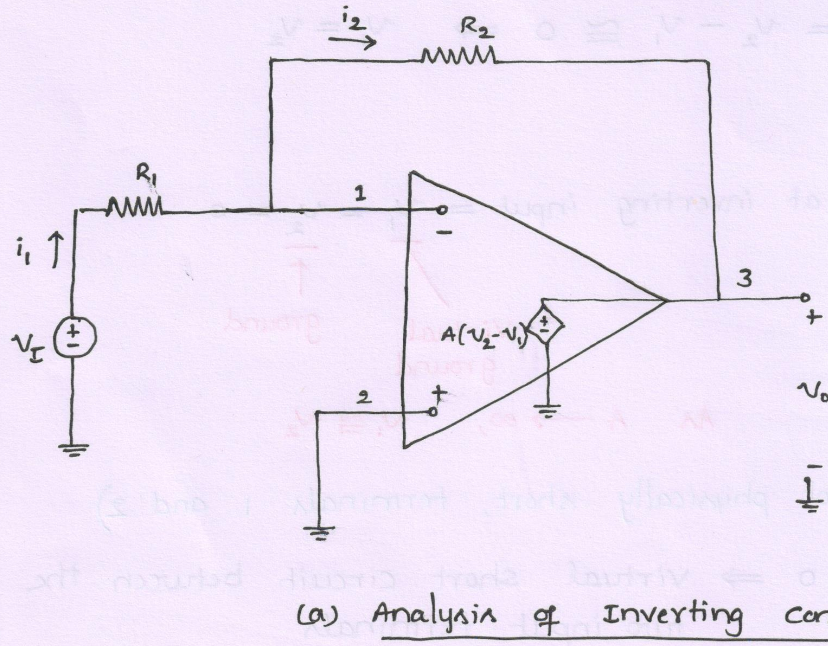
if $R_2 = 100K\Omega$, $R_1 = 1K\Omega$, $G = \frac{v_o}{v_I} = -100 \Rightarrow \frac{L+}{|G|} = \frac{10V}{100} = 0.1V$

Input voltages required

$v_i =$ 

$v_o =$ 

$R_2 = 10K\Omega$, $R_1 = 1K\Omega$



Assumption: Ideal op-amp

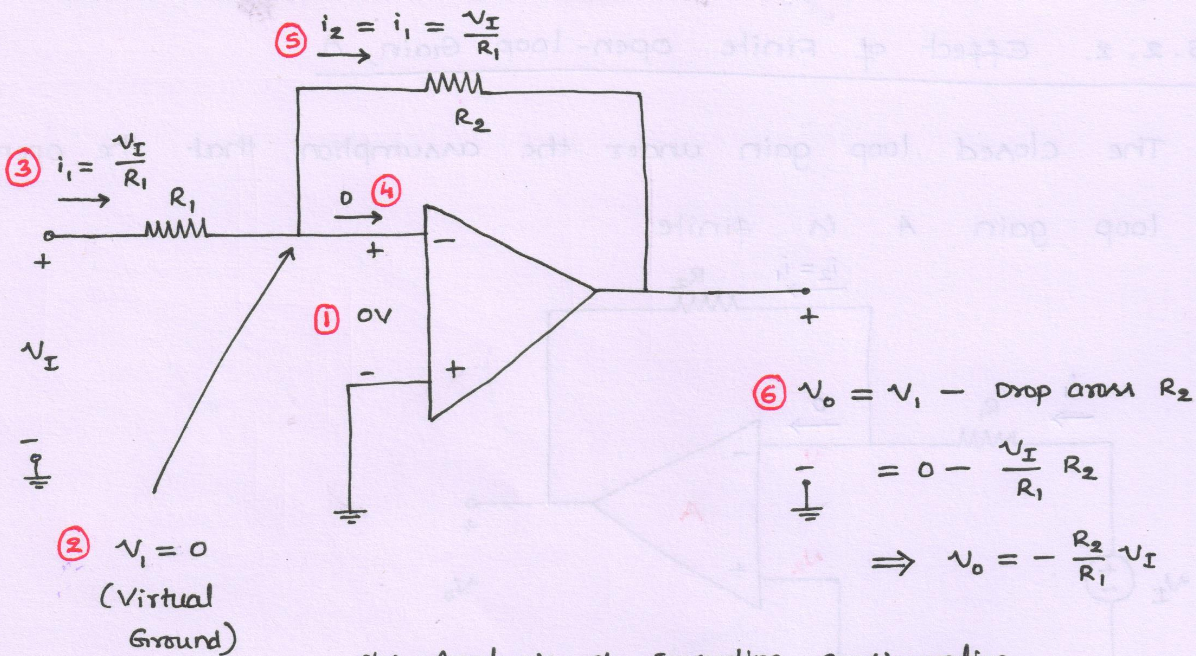
$A \rightarrow$ very large, Ideally $= \infty$

Open loop gain

$$G = \frac{v_o}{v_I}$$

closed loop gain

(a) Analysis of Inverting configuration



(b) Analysis of Inverting Configuration

<u>Note:</u> circled numbers indicate the order of the analysis steps

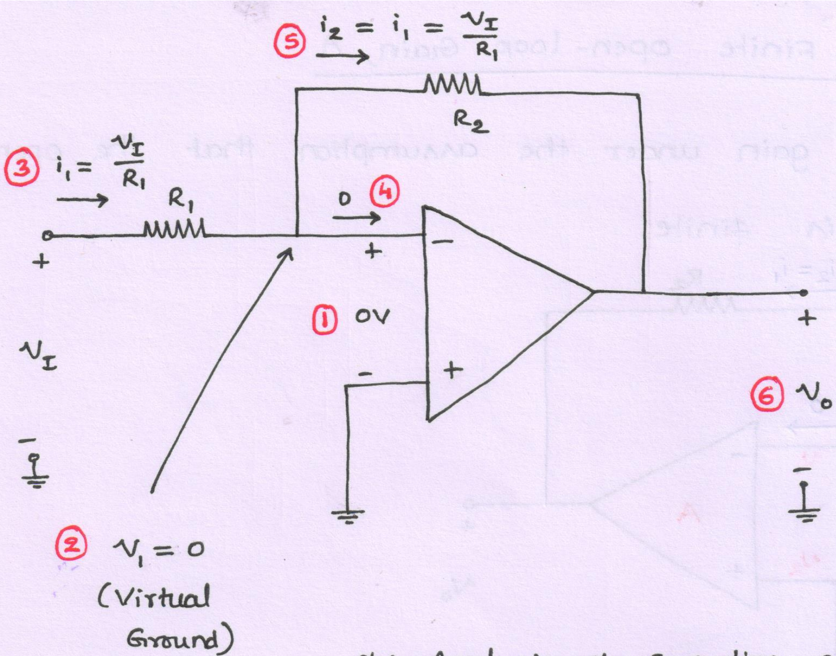
& <u>observations</u>

1. closed loop gain : $G = \frac{v_o}{v_I} = -\frac{R_2}{R_1}$

   - G depends on external passive components, R_1 and R_2
   - Negative sign in the G eqn. indicates 180° phase shift w.r.t input.

     $\Rightarrow$ Inverting Configuration
   - G is independent of the op-amp gain, A
   - $G < A$, due to negative feedback

     stable & predictable



6 $v_o = v_1 -$ Drop across R_2

$$= 0 - \frac{v_I}{R_1} R_2$$

$$\Rightarrow v_o = -\frac{R_2}{R_1} v_I$$

(b) Analysis of Inverting Configuration

__Note:__ circled numbers indicate the order of the analysis steps

& Observations

1. Closed loop gain : $G = \frac{v_O}{v_I} = -\frac{R_2}{R_1}$

   - G depends on external passive components, R_1 and R_2

   - Negative sign in the G eqn. indicates 180° phase shift w.r.t input.

     $\Rightarrow$ Inverting Configuration

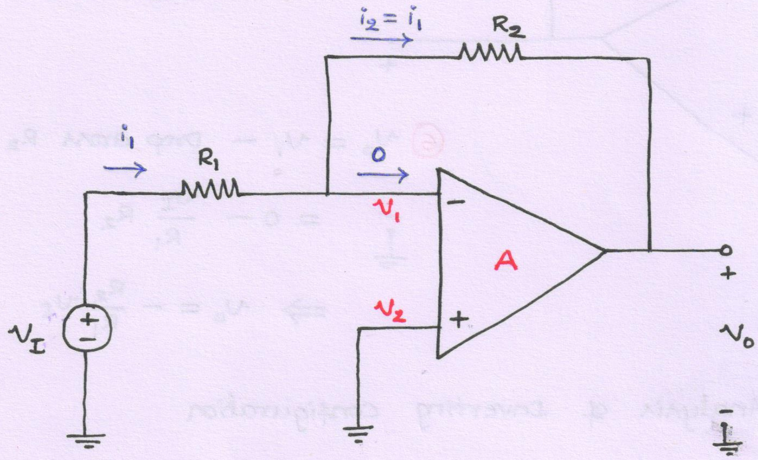
   - G is independent of the op-amp gain, A

   - $G < A$, due to negative feedback

     stable & predictable

5.2.2. Effect of Finite open-loop Gain, A

The closed loop gain under the assumption that the open loop gain A is finite.



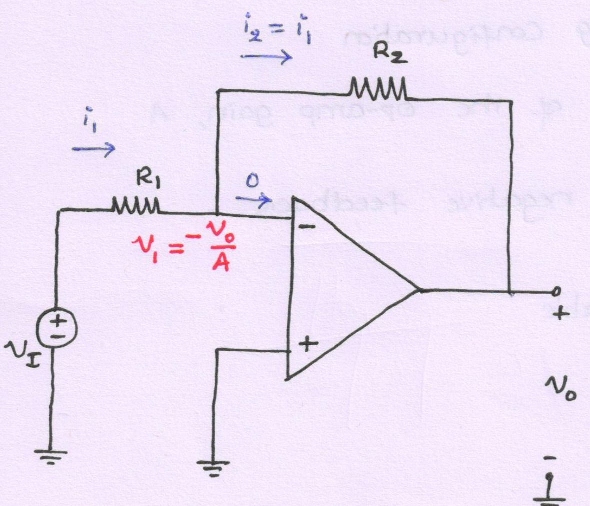
(a) Analysis of the inverting configuration with A = finite

Recall, $G = -\dfrac{R_2}{R_1}$ for $A = \infty$

$$v_o = A(\underbrace{v_2}_{0\text{V (ground)}} - v_1)$$

$$v_o = A(0 - v_1)$$

$$\Longrightarrow v_1 = -\frac{v_o}{A} = \text{Voltage at inverting input}$$



The current i_1 through R_1 is given by

$$i_1 = \frac{v_I - v_1}{R_1} \qquad v_1 = -\frac{v_o}{A}$$

Therefore, $$i_1 = \frac{v_I + \frac{v_o}{A}}{R_1}$$

since $R_i = \infty$, current through R_2, $i_2 = i_1$

The output voltage, v_0 is given by

$$v_0 = v_1 - \text{Drop across } R_2$$

$$v_0 = v_1 - \underbrace{i_2}_{= i_1} R_2$$

$$v_0 = \underbrace{v_1}_{= -\frac{v_0}{A}} - \underbrace{i_1}_{= \frac{\left(v_I + \frac{v_0}{A}\right)}{R_1}} R_2$$

Therefore, $$v_0 = -\frac{v_0}{A} - \frac{v_I + \frac{v_0}{A}}{R_1} R_2$$

$$v_0 = -\frac{v_0}{A} - v_I \frac{R_2}{R_1} - \frac{v_0}{A} \frac{R_2}{R_1}$$

$$v_0 + \frac{v_0}{A} + \frac{v_0}{A} \frac{R_2}{R_1} = -v_I \frac{R_2}{R_1}$$

$$v_0 \left[1 + \frac{1}{A}\left(1 + \frac{R_2}{R_1}\right)\right] = -v_I \frac{R_2}{R_1}$$

$$\frac{v_0}{v_I} = \frac{-R_2/R_1}{1 + \frac{\left(1 + \frac{R_2}{R_1}\right)}{A}}$$

Therefore, closed loop gain

$$\boxed{G = \frac{v_0}{v_I} = \frac{-\frac{R_2}{R_1}}{1 + \frac{\left(1 + \frac{R_2}{R_1}\right)}{A}}} \quad \text{Non-ideal gain} \qquad (1)$$

Observations :

1. If $A \rightarrow \infty$, then $G = -\frac{R_2}{R_1}$ (Ideal value)

   Also, as $A \rightarrow \infty$, $v_1 = -\frac{v_0}{\underbrace{A}_{= \infty}} \longrightarrow 0$ (Virtual ground assumption)

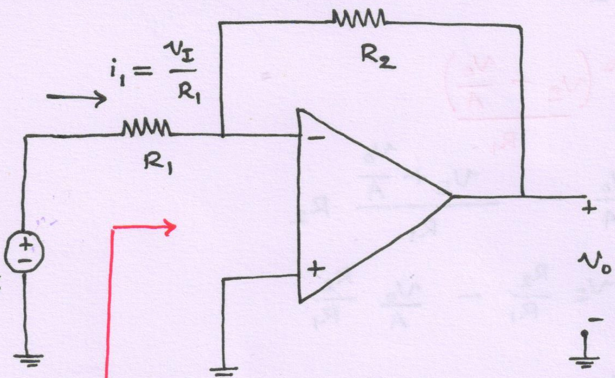
2. To minimize dependance G on A, we should make

$$\boxed{1 + \frac{R_2}{R_1} << A}$$ in eqn. (1)

Alternatively, $\dfrac{\left(1+\dfrac{R_2}{R_1}\right)}{A} << 1$, Therefore, $G \cong -\dfrac{R_2}{R_1}$

Typically, $A = 10^5$

5.2.3 Input and Output Resistances



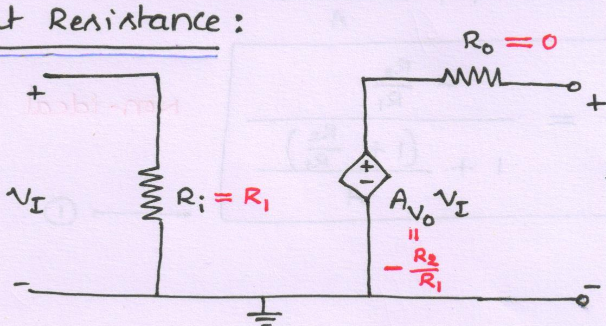
R_i (Input Resistance of closed-loop inverting amplifier)

$$R_i \equiv \frac{v_I}{i_1} = \frac{v_I}{v_I/R_1}$$

$$\Rightarrow \boxed{R_i = R_1}$$

Voltage Amplifier Model of Inverting Configuration

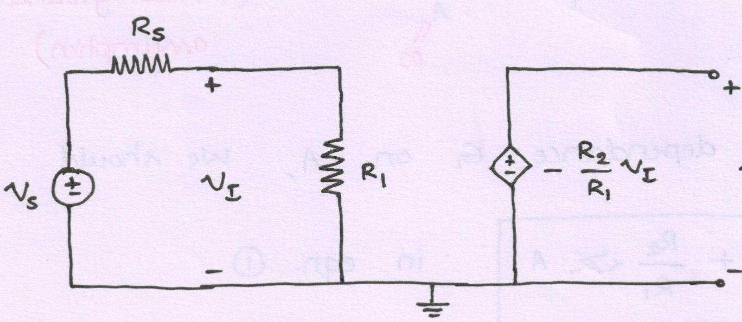
⊛ Input Resistance:



$$v_o = -\frac{R_2}{R_1} v_I$$

$R_i = \infty$ (perfect Voltage Amplifier)

(a) Voltage Amplifier Model : Inverting Configuration



$$v_I = v_s \frac{R_1}{R_1 + R_s}$$

$$v_I = v_s \frac{1}{1 + \frac{R_s}{R_1}}$$

$$v_I = v_s \frac{1}{1 + \frac{R_s}{R_1}}$$

⇒ Amplifier input resistance forms a voltage divider with source resistance, R_s that feeds the amplifier

⇒ For $v_I = v_s$, R_1 = High

To avoid the loss of signal strength, voltage amplifiers are required to have high input resistance

→ For Inverting configuration,

$$\boxed{R_i = R_1}$$

To avoid loss of signal strength of voltage amplifier

$$\boxed{R_i = R_1 = \text{Large}} \quad \text{—— (1)}$$

Ideally, $R_i = \infty$

However,

closed-loop gain, $G = -\frac{R_2}{R_1}$

To obtain larger closed loop gain, G

$$\boxed{R_2 = \text{Large}, \quad \text{and} \quad R_1 = \text{small}} \quad \text{—— (2)}$$

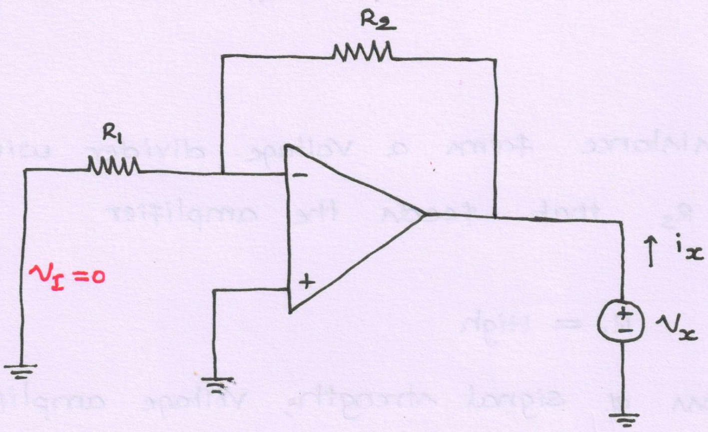
Further, to avoid the loss of signal strength

↑ R_1, R_2 becomes impractically large ($> M\Omega$)

⇒ Inverting configuration suffer's from a low input resistance.

⊛ Output Resistance :

The inverting configuration to determine output resistance is shown in Fig. (b)



$$V_o = -\frac{R_2}{R_1} V_I$$

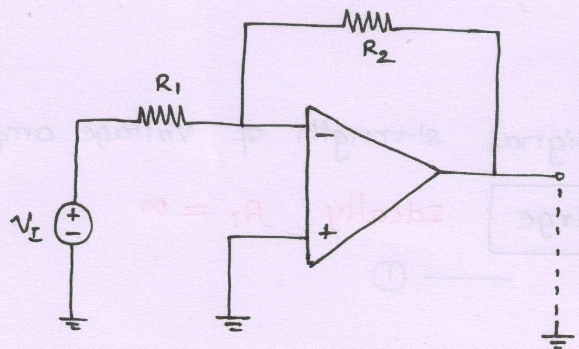
$V_I = 0$ (Input = short circuit)

$$\boxed{V_o = 0}$$

$$i_x \to \infty$$

$$\Rightarrow \boxed{R_o = 0}$$

(b) Inverting configuration circuit to Determine R_o



Example 5.2

Assuming op-amp to be ideal, derive an expression for the closed loop gain, $\frac{v_O}{v_I}$ of the circuit shown below. Use this circuit to design an inverting amplifier with a gain of 100 and an input resistance of $1\,M\Omega$. Assume that for practical reasons it is required not to use resistors greater than $1\,M\Omega$. Compare your design with that based on the inverting configuration.

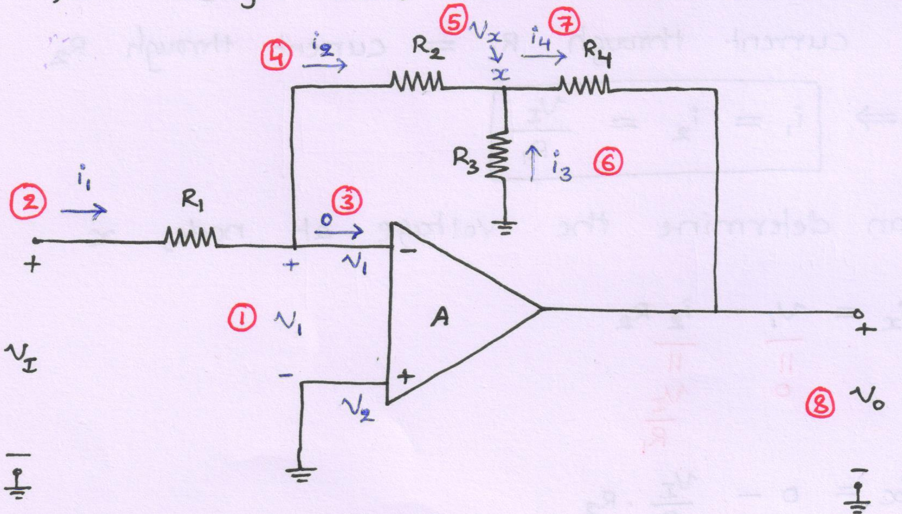


Fig. (a)

Note: circled numbers, indicate the sequence of steps in the analysis

Solution

→ Op-amp is assumed to be ideal

$$\Rightarrow A = \infty$$

We know that $v_o = A\,(v_2 - v_1)$, $v_2 = 0$ (ground)

$$v_o = A\,(0 - v_1)$$

$$v_1 = -\frac{v_o}{A} = 0 \qquad (A = \infty)$$

Therefore, voltage at inverting input, $\boxed{v_1 = 0}$

→ Knowing v_1, we can determine the current i_1 as follows:

$$i_1 = \frac{v_I - \underbrace{v_1}_{=0}}{R_1}$$

$$i_1 = \frac{v_I - 0}{R_1}$$

$$\boxed{i_1 = \frac{v_I}{R_1}}$$

→ For an op-amp, $R_i = \infty$

⇒ zero current flows into the inverting input

Therefore, current through R_1 = current through R_2

$$\Rightarrow \boxed{i_1 = i_2 = \frac{v_I}{R_1}}$$

→ Now, we can determine the voltage at node x

$$v_x = \underbrace{v_1}_{=0} - \underbrace{i_2}_{=\frac{v_I}{R_1}} R_2$$

$$v_x = 0 - \frac{v_I}{R_1} \cdot R_2$$

Therefore, $$\boxed{v_x = -\frac{R_2}{R_1} v_I}$$

→ This in turn enables us to find i_3

$$i_3 = \frac{0 - \underbrace{v_x}_{= -\frac{R_2}{R_1} v_I}}{R_3}$$

$$i_3 = -\frac{v_x}{R_3} = -\frac{1}{R_3}\left(-\frac{R_2}{R_1} v_I\right)$$

$$\boxed{i_3 = \frac{R_2}{R_1 R_3} v_I}$$

→ Applying KCL at node x yields i_4:

$$i_4 = \underbrace{i_2}_{=\frac{v_I}{R_1}} + \underbrace{i_3}_{=\frac{R_2}{R_1 R_3} v_I}$$

$$i_4 = \frac{v_I}{R_1} + \frac{R_2}{R_1 R_3} v_I$$

→ Finally, we can determine v_o as follows:

$$v_o = \underbrace{v_x}_{= -\frac{R_2}{R_1} v_I} - \underbrace{i_4}_{= \frac{v_I}{R_1} + \frac{R_2}{R_1 R_3} v_I} \cdot R_4$$

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

$$v_o = -v_I \left[\frac{R_2}{R_1} + \frac{R_4}{R_1} + \frac{R_2 R_4}{R_1 R_3} \right]$$

$$\frac{v_o}{v_I} = -\left[\frac{R_2}{R_1} + \frac{R_4}{R_1} + \frac{R_2 R_4}{R_1 R_3} \right]$$

$$\frac{v_o}{v_I} = -\frac{R_2}{R_1} \left[1 + \frac{R_4}{R_2} + \frac{R_4}{R_3} \right]$$

$$\boxed{\frac{v_o}{v_I} = -\frac{R_2}{R_1} \left[1 + \frac{R_4}{R_2} + \frac{R_4}{R_3} \right]}$$

→ R_1 = Input resistance = $1M\Omega$ (required)

if we choose $R_2 = R_3 = R_4 = 1M\Omega$, then $\frac{v_o}{v_I} \neq -100$

let $R_2 = 1M\Omega$, and R_3 and R_4 are selected so that $\frac{v_o}{v_I} = -100$

i.e $$\underbrace{\left(\frac{v_o}{v_I}\right)}_{=-100} = -\frac{\overset{1M\Omega}{R_2}}{\underbrace{R_1}_{=1M\Omega}} \left[1 + \frac{R_4}{\underbrace{R_2}_{=1M\Omega}} + \frac{R_4}{R_3} \right]$$

$$-100 = -\frac{\cancel{1M\Omega}}{\cancel{1M\Omega}} \left[1 + \frac{R_4}{1M\Omega} + \frac{R_4}{R_3} \right]$$

$$-100 = -1 \left[1 + \frac{\overset{=1M\Omega}{R_4}}{1M\Omega} + \frac{\overset{=1M\Omega}{R_4}}{R_3} \right]$$

if we choose, $R_4 = 1M\Omega$, then 2^{nd} factor = 1

Therefore, to have a total gain of 100, R_3 required is

$$-100 = -1\left[1 + 1 + \frac{1M\Omega}{R_3}\right]$$

$$98 = \frac{1M\Omega}{R_3}$$

$$\Rightarrow R_3 = \frac{1M\Omega}{98} = 10.2\ K\Omega$$

$$\boxed{R_3 = 10.2\ K\Omega}$$

Comparison : considering basic inverting configuration

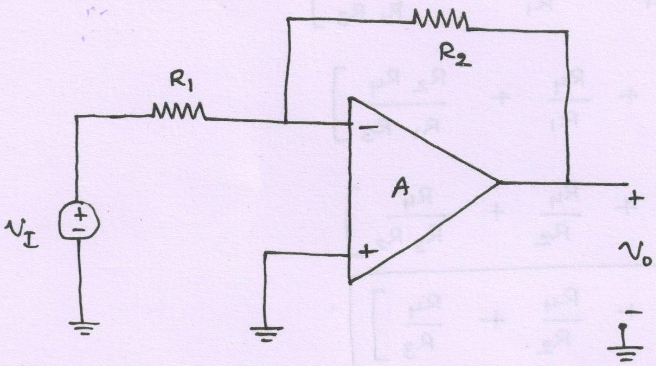


Fig. (b)

w. k. t $\underline{G} = -\frac{R_2}{R_1}$

↑

closed loop gain

$R_1 = 1M\Omega$ (required)

Therefore, to have a gain of −100, R_2 required is calculated as follows

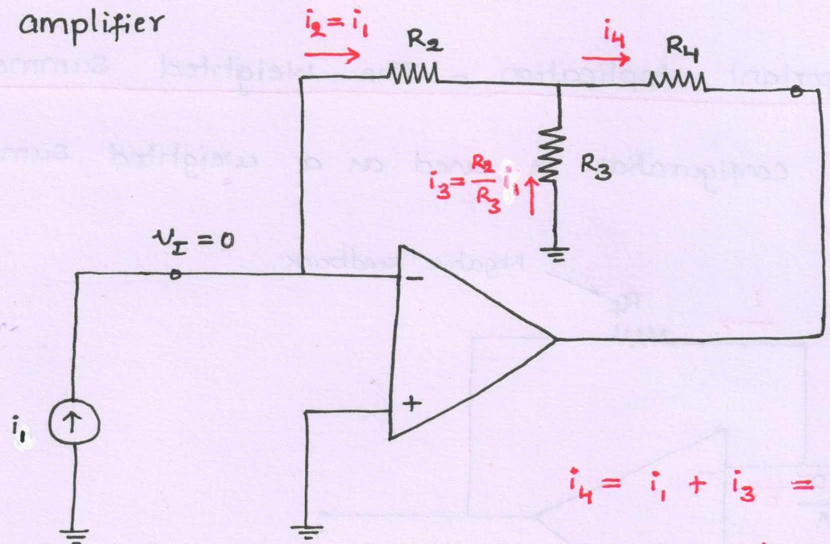
$$-100 = -\frac{R_2}{1M\Omega}$$

$$\Rightarrow \boxed{R_2 = 100\ M\Omega}$$ (very large value)

Conclusion : The circuit shown in Fig. (a) is able to realize a large voltage gain without using large resistors in the feedback path.

4) Current Amplifier

A circuit shown in Fig. (a) is modified as a current amplifier



$i_4 = i_1 + i_3 = i_1 + \frac{R_2}{R_1} i_1$

$i_4 = i_1 \left(1 + \frac{R_2}{R_1}\right)$

Fig. (c)

→ R_2 and R_3 are in effect parallel

→ By making R_3 lower than R_2 by a factor, K

i.e $R_3 = \dfrac{R_2}{K}$, where $K > 1$

→ R_3 is forced to carry a current K-times that in R_2

→ $i_2 = i_1$

$i_3 = K i_1$

$i_4 = \underbrace{(K+1)}_{\text{current multiplication}} i_1$, since $i_4 = \underset{\substack{\parallel \\ i_1}}{i_2} + i_3$

⇒ The current multiplication enables a large voltage drop across R_4

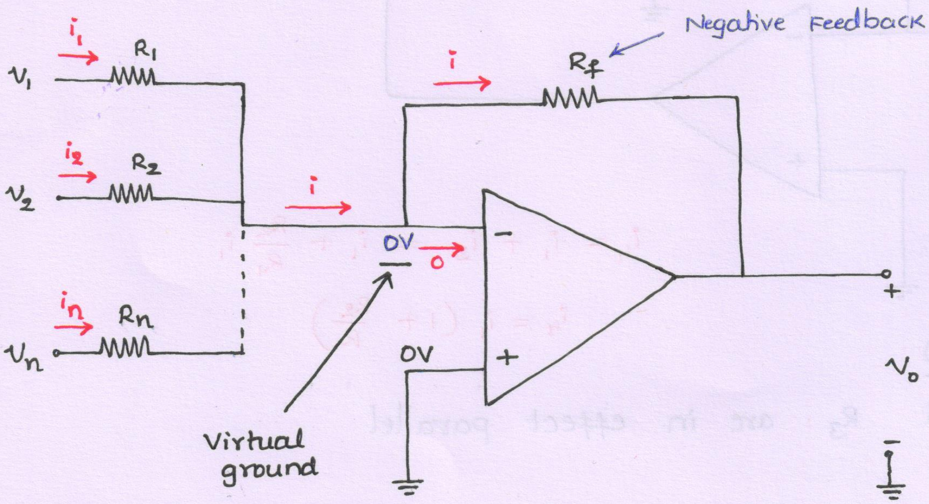
$\Rightarrow V_o$ = large, without using large value for R_4

Also, i_4 is independent of the value of R_4

Therefore, Fig. (C) can be used as a current amplifier.

5.2.4 An Important Application – The weighted summer

→ An inverting configuration is used as a weighted summer



(a) A weighted summer

→ A weighted summer circuit is shown in Fig. (a)

→ R_f : Resistor in negative feedback path

$V_1, V_2, \ldots\ldots\ldots V_n$: Input signals applied to inverting input

$R_1, R_2, \ldots\ldots\ldots R_n$: Resistors of corresponding input signals

→ The ideal op-amp will have a virtual ground appearing at its negative input terminal

Therefore, the currents $i_1, i_2, \ldots\ldots i_n$ are given by

$$i_1 = \frac{V_1}{R_1}, \quad i_2 = \frac{V_2}{R_2}, \ldots\ldots\ldots i_n = \frac{V_n}{R_n}$$

All these currents sum together to produce the current i ; i.e

$$i = i_1 + i_2 + \cdots\cdots + i_n$$

→ This i is forced to flow through R_f, since no current flows into the input terminals of an ideal op-amp.

→ The output voltage, V_o can be determined by ohm's law,

$$V_o = \underbrace{V_1}_{\substack{= \\ 0V \\ \text{(Virtual Ground)}}} - \underbrace{\text{Drop across } R_f}_{\substack{= \\ i R_f}}$$

$$V_o = 0 - i R_f = -i R_f$$

$$i = (i_1 + i_2 + \cdots\cdots i_n)$$

$$V_o = -(\underbrace{i_1}_{= \frac{V_1}{R_1}} + \underbrace{i_2}_{= \frac{V_2}{R_2}} + \cdots\cdots + \underbrace{i_n}_{= \frac{V_n}{R_n}}) R_f$$

$$V_o = -\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots\cdots + \frac{V_n}{R_n}\right) R_f$$

$$\boxed{V_o = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \cdots\cdots + \frac{R_f}{R_n} V_n\right)} \quad \text{— (1)}$$

Weights

⇒ The output voltage is weighted sum of the input signals $V_1, V_2, \cdots\cdots V_n$

The circuit is referred to as "weighted summer"

→ The summing coefficients may be independently adjusted by adjusting the corresponding "feed-in" resistor (R_1 to R_n)

Disadvantage:

→ All summing co-efficients are of the same sign (see eqn. (1))

→ The need may arise for summing signals with opposite signs

9 Weighted Summer : summing signals with opposite sign

The weighted summer for summing signals with opposite signs can be implemented using two op-amps shown in Fig. (a)

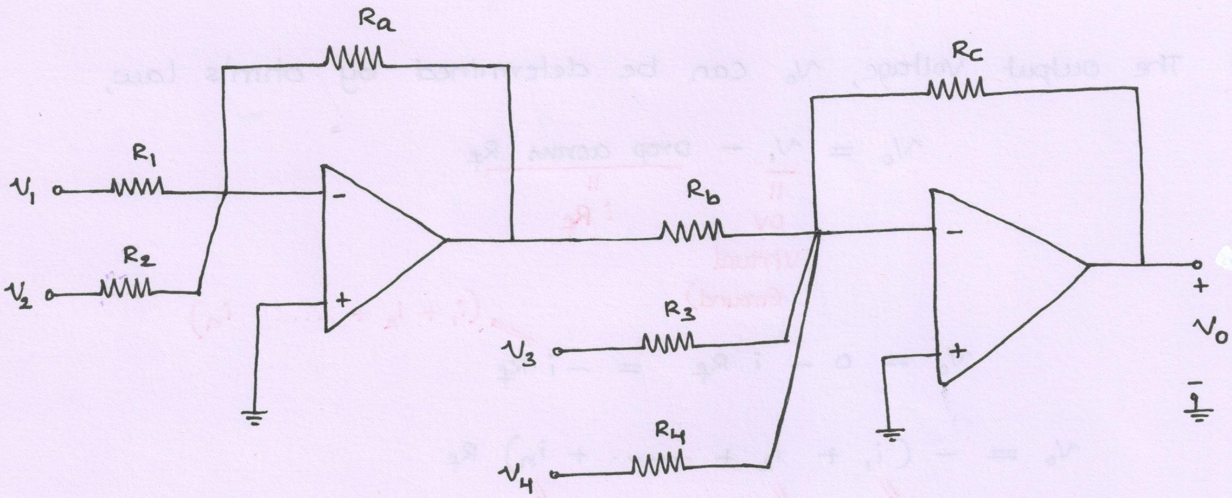


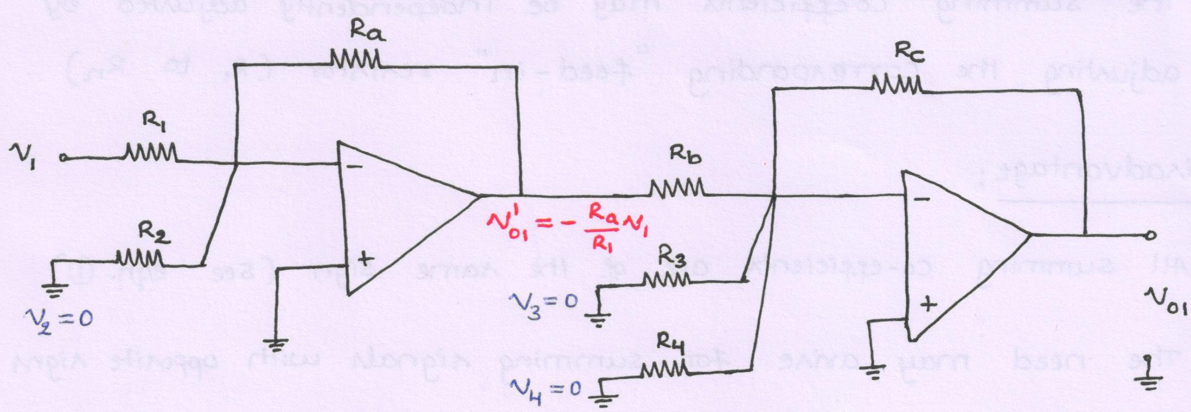
Fig. (a) : Weighted summer Implementation for summing coefficients of both signs

→ Assume op-amps are ideal

→ Apply superposition principle to obtain the expression for output voltage, V_o

$$V_o = A V_1 + B V_2 + C V_3 + D V_4 \quad : \text{Linear circuit}$$

→ Considering V_1 alone and assuming $V_2 = V_3 = V_4 = 0$



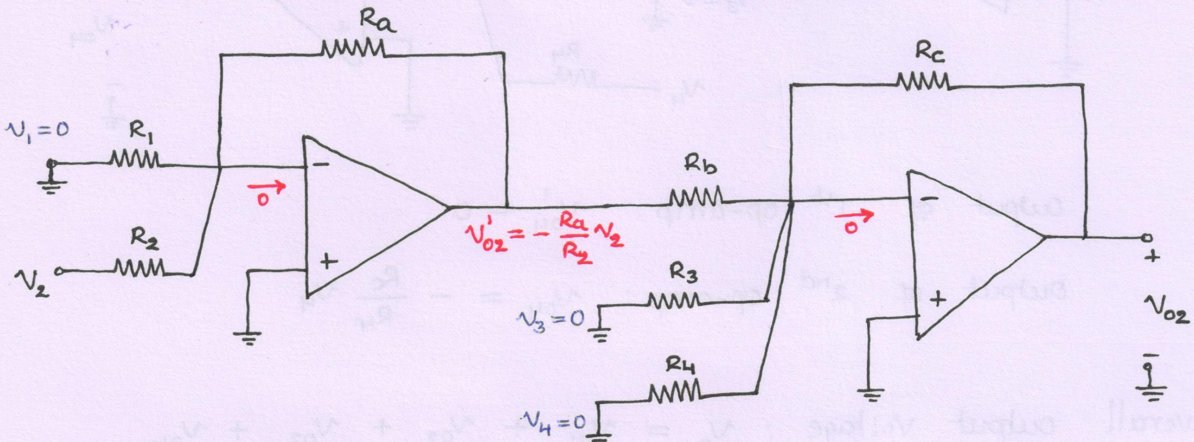
Output of 1^{st} op-amp : $v_{01}' = -\dfrac{R_a}{R_1} v_1$ (Inverting configuration)

Output of 2^{nd} op-amp : $v_{01} = -\dfrac{R_c}{R_b} v_{01}'$

$$= -\frac{R_c}{R_b}\left(-\frac{R_a}{R_1} v_1\right)$$

$$\boxed{v_{01} = +\frac{R_a R_c}{R_b R_1} v_1}$$

→ considering v_2 alone and assuming $v_1 = v_3 = v_4 = 0$



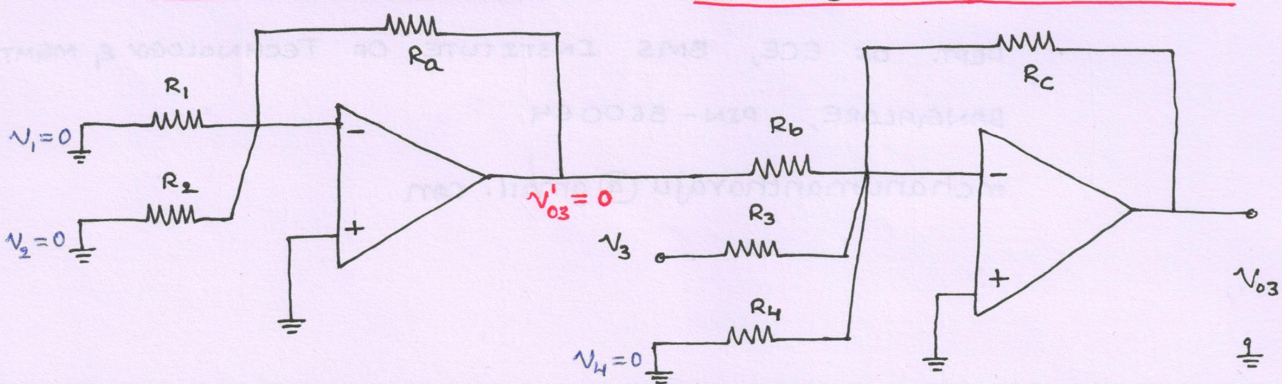
Output of 1^{st} op-amp : $v_{02}' = -\dfrac{R_a}{R_2} v_2$

Output of 2^{nd} op-amp : $v_{02} = -\dfrac{R_c}{R_b} v_{02}'$

$$= -\frac{R_c}{R_b}\left(-\frac{R_a}{R_2} v_2\right)$$

$$\boxed{v_{02} = +\frac{R_a R_c}{R_b R_2} v_2}$$

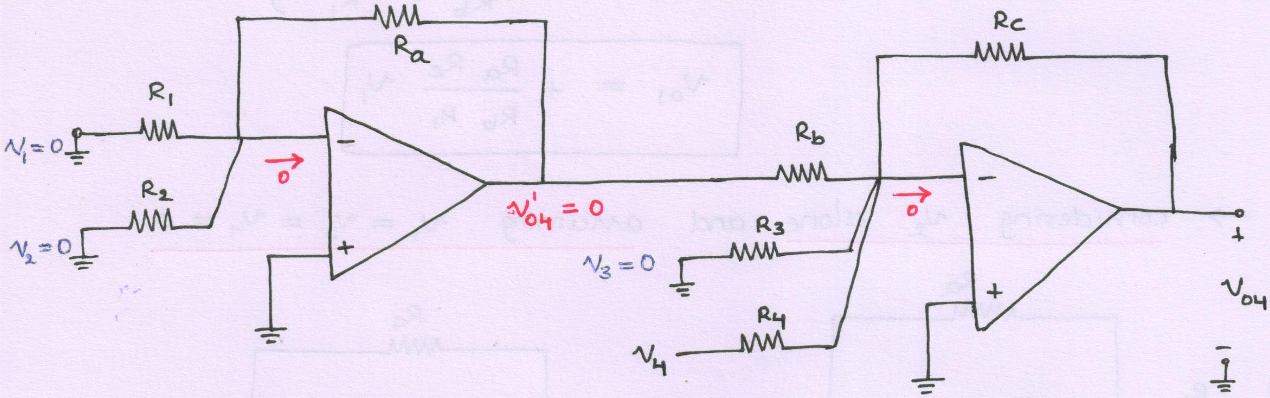
→ considering v_3 alone and assuming $v_1 = v_2 = v_4 = 0$



Output of 1^{st} op-amp : $v'_{03} = 0$

Output of 2^{nd} op-amp : $v_{03} = -\frac{R_c}{R_3} v_3$

→ considering v_4 alone and assuming $v_1 = v_2 = v_3 = 0$



Output of 1^{st} op-amp : $v'_{04} = 0$

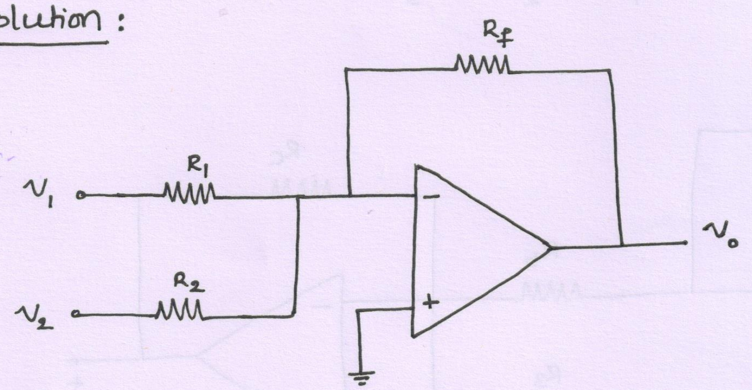
Output of 2^{nd} op-amp : $v_{04} = -\frac{R_c}{R_4} v_4$

Overall output voltage : $v_0 = v_{01} + v_{02} + v_{03} + v_{04}$

$$\boxed{v_0 = v_1\left(\frac{R_a}{R_1}\right)\left(\frac{R_c}{R_b}\right) + v_2\left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right) - v_3\left(\frac{R_c}{R_3}\right) - v_4\left(\frac{R_c}{R_4}\right)}$$

Exercise D5.7 : Design an inverting amplifier to form the weighted sum v_o of two inputs v_1 and v_2. It is required that $v_o = -(v_1 + 5v_2)$. Choose values for R_1, R_2, and R_f so that for a maximum output voltage of 10V the current in the feedback resistor will not exceed 1mA.

Solution :



For the circuit shown, applying superposition principle

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

Since it is required that $v_o = -(v_1 + 5v_2)$, we want to have

$$\frac{R_f}{R_1} = 1 \quad \text{and} \quad \frac{R_f}{R_2} = 5$$

It is also desired that for a maximum output voltage of 10V, the current in the feedback resistor does not exceed 1 mA.

Therefore, $\frac{10\,V}{R_f} \leq 1\,mA$

$$\Rightarrow R_f \geq \frac{10\,V}{1\,mA}$$

$$\boxed{R_f \geq 10\,k\Omega}$$

let us choose R_f to be $10K\Omega$, then $\boxed{R_1 = R_f = 10K\Omega}$

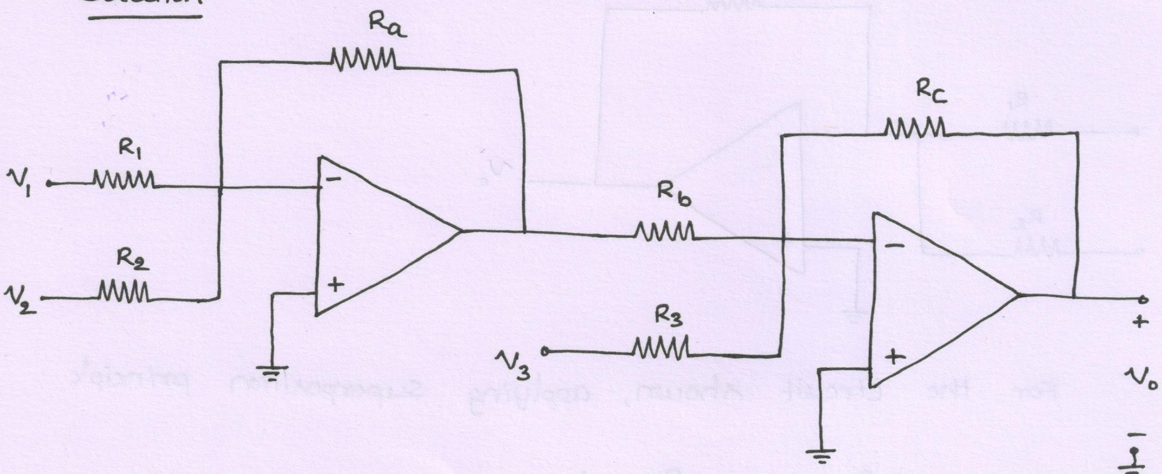
$$R_2 = \frac{R_f}{5} = \frac{10K\Omega}{5} = 2K\Omega$$

$$\boxed{R_2 = 2K\Omega}$$

Exercise D5.8 : Design a weighted summer that provides

$$v_o = 2v_1 + v_2 - 4v_3$$

Solution



(a) Weighted summer : coefficients of both signs

Applying superposition principle, we get

$$\boxed{v_o = \left(\frac{R_a}{R_1}\right)\left(\frac{R_c}{R_b}\right)v_1 + \left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right)v_2 - \frac{R_c}{R_3}v_3}$$

We want to design the circuit such that : $v_o = 2v_1 + v_2 - 4v_3$

Thus, we need to have : $\left(\frac{R_a}{R_1}\right)\left(\frac{R_c}{R_b}\right) = 2$, $\left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right) = 1$, & $\frac{R_c}{R_3} = 4$

We have three equations & we have to find six unknowns

let us choose : $R_a = R_b = R_c = 10K\Omega$

then we have, $R_3 = \frac{R_c}{4} = \frac{10}{4} = 2.5K\Omega$

$$\left(\frac{R_a}{R_1}\right)\left(\frac{R_c}{R_b}\right) = 2 \Rightarrow \frac{10}{R_1} \times \frac{10}{10} = 2 \Rightarrow R_1 = 5K\Omega$$

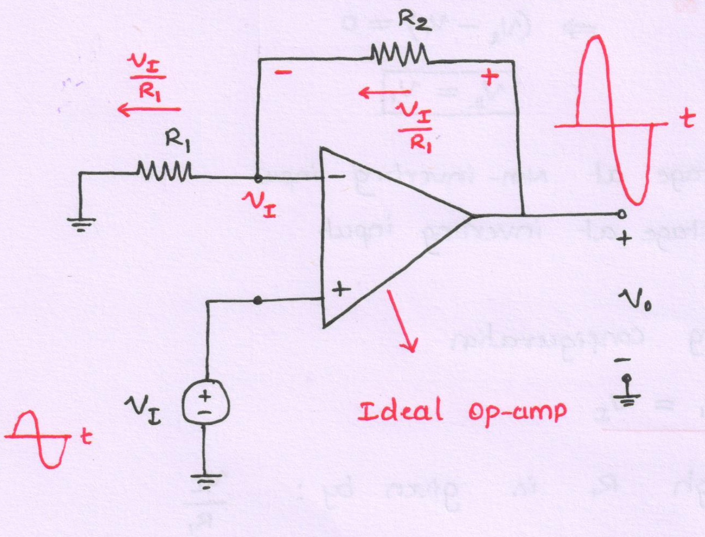
$$\left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right) = 1 \Rightarrow \frac{10}{R_2} \times \frac{10}{10} = 1 \Rightarrow R_2 = 10K\Omega$$

5.3 The Non-Inverting Configuration

→ Second closed loop configuration

→ The input signal, v_I is applied directly to the positive input terminal of the op-amp, while one terminal of R_1 is connected to ground.

5.3.1 The closed-Loop Gain

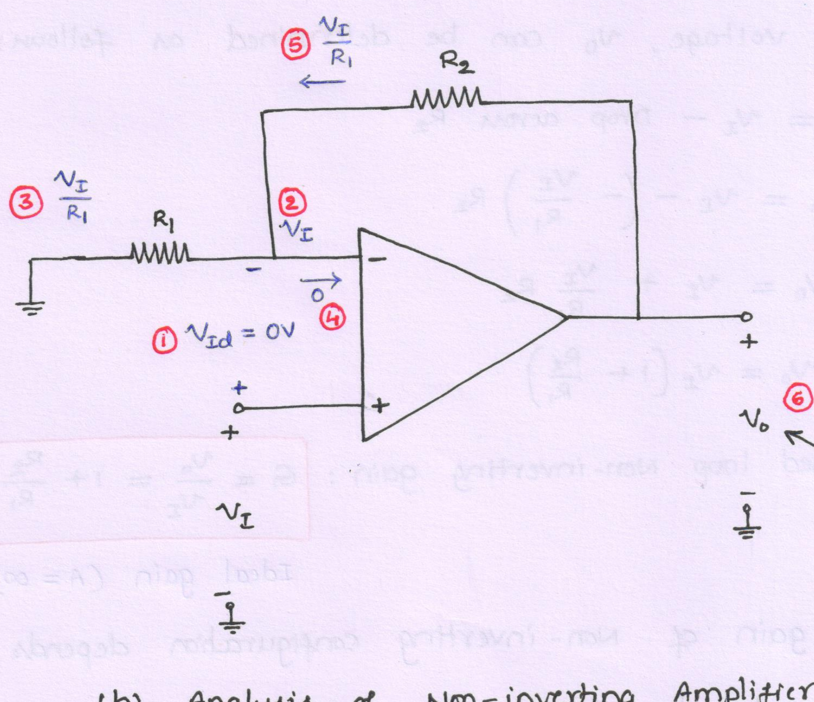


→ External components R_1 & R_2 form a closed loop

→ Output is fed back to the inverting input terminal.

→ Input signal is applied to the non-inverting input terminal

(a) The Non-inverting Configuration



$$v_o = v_I + \frac{v_I}{R_1} R_2$$

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

(b) Analysis of Non-inverting Amplifier circuit

④ To Determine closed loop gain : G

Assumption: - op-amp is ideal with $A = \infty$

- virtual short circuit exists between its two input terminals

$$v_0 = A\,(\underbrace{v_2 - v_1}_{v_{Id}})$$

$$\frac{v_0}{\underset{\infty}{A}} = (v_2 - v_1)$$

$$\Rightarrow (v_2 - v_1) = 0$$

$$\boxed{v_2 = v_1}$$

v_2 = voltage at Non-inverting input

v_1 = voltage at inverting input

→ For the Non-inverting configuration

$$v_2 = v_1 = v_I$$

→ The current through R_1 is given by : $\frac{v_I}{R_1}$

This current will flow through R_2

→ The output voltage, v_0 can be determined as follows:

$$v_0 = v_I - \text{Drop across } R_2$$

$$v_0 = v_I - \left(-\frac{v_I}{R_1}\right) R_2$$

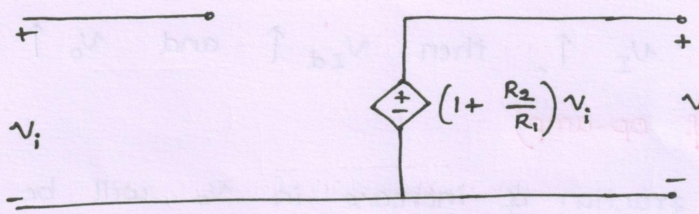
$$v_0 = v_I + \frac{v_I}{R_1} R_2$$

$$v_0 = v_I\left(1 + \frac{R_2}{R_1}\right)$$

⟹ closed loop Non-inverting gain : $\boxed{G = \frac{v_0}{v_I} = 1 + \frac{R_2}{R_1}}$

Ideal gain $(A = \infty)$

→ closed loop gain of Non-inverting configuration depends entirely on external passive components (Independent of A)



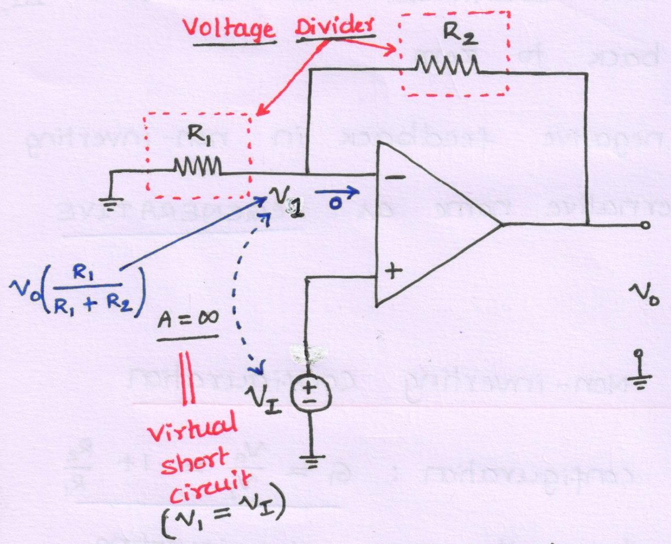
(c) Equivalent circuit model for the non-inverting configuration

→ Input impedance : $R_i = \infty$

→ output impedance : $R_o = 0$

→ Voltage gain : $A_{v_o} = 1 + \frac{R_2}{R_1}$

→ Degenerative Feedback : An insight into the operation of Non-inverting Configuration



→ R_1 and R_2 acts as a voltage divider feeding a fraction of output voltage, v_o back to the inverting input of the op-amp (Since current into the op-amp inverting input = zero)

i.e $v_1 = v_o\left(\frac{R_1}{R_1+R_2}\right)$ ——(1)

→ Since $A = \infty$ (ideal op-amp)

⇒ There is a virtual short circuit between the two input terminals of the op-amp

Therefore, the virtual short circuit forces the voltage at the inverting input to be equal to the voltage applied at positive input.

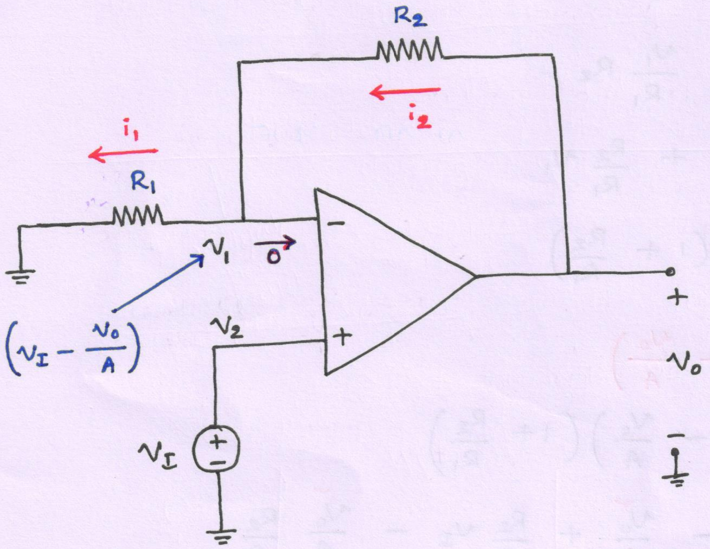
Thus, $v_o\left(\frac{R_1}{R_1+R_2}\right) = v_I$ ⇒ yields gain G ——(2)

where $G = \frac{v_o}{v_I} = \left(1 + \frac{R_2}{R_1}\right)$ (Derived earlier)

5.3.3 Effect of Finite Open-Loop Gain

The effect of finite open-loop gain of the op-amp non-inverting configuration is derived as follows :

Assumption : op-amp is ideal, except for open loop gain, A (i.e $A \neq \infty$)



→ Voltage at inverting input : v_1

$$v_o = A(\underbrace{v_2}_{= v_I} - v_1)$$

$$v_o = A(v_I - v_1)$$

$$v_o = A v_I - A v_1$$

$$A v_1 = A v_I - v_o$$

$$\boxed{v_1 = v_I - \frac{v_o}{A}}$$

→ $i_1 = \dfrac{v_1 - 0}{R_1} = \dfrac{v_1}{R_1}$

$$\boxed{i_1 = \frac{v_1}{R_1}}$$

→ $i_2 = \dfrac{v_o - v_1}{R_2}$

→ The op-amp has its input impedance, $R_i = \infty$, Therefore current draw by the op-amp is zero

$$\Rightarrow \quad \underset{\frac{v_1}{R_1}}{\underset{\parallel}{i_1}} = \underset{\frac{v_o - v_1}{R_2}}{\underset{\parallel}{i_2}}$$

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

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

$$v_o = v_1 + \frac{R_2}{R_1} v_1$$

$$v_o = \underset{\left(v_I - \frac{v_o}{A}\right)}{\underset{\parallel}{\underline{v_1}}} \left(1 + \frac{R_2}{R_1}\right)$$

$$v_o = \left(v_I - \frac{v_o}{A}\right)\left(1 + \frac{R_2}{R_1}\right)$$

$$v_o = v_I - \frac{v_o}{A} + \frac{R_2}{R_1} v_I - \frac{v_o}{A}\frac{R_2}{R_1}$$

$$v_o \left[1 + \frac{1}{A} + \frac{1}{A}\frac{R_2}{R_1}\right] = v_I \left[1 + \frac{R_2}{R_1}\right]$$

$$v_o \left[1 + \frac{1}{A}\left(1 + \frac{R_2}{R_1}\right)\right] = v_I \left[1 + \frac{R_2}{R_1}\right]$$

$$\boxed{G = \frac{v_o}{v_I} = \frac{\left(1 + \frac{R_2}{R_1}\right)}{\left[1 + \frac{\left(1 + \frac{R_2}{R_1}\right)}{A}\right]}} \quad \text{Non-ideal gain } (A \neq \infty) \qquad (1)$$

Observations :

→ The denominator of eqn. (1) is similar to that of finite loop gain eqn. of inverting configuration.

⇒ Feedback loop of inverting configuration
|| Equal
Feedback loop of Non-inverting configuration

→ The numerator of eqn. 1 is : $1 + \frac{R_2}{R_1}$

whereas numerator of finite loop gain equation of inverting configuration is : $-\frac{R_2}{R_1}$

→ For $A = \infty$, in eqn. 1,

$$G = \frac{v_o}{v_I} = \left(1 + \frac{R_2}{R_1}\right)$$: Ideal Non-inverting gain

→ For $A >> 1 + \frac{R_2}{R_1}$

or $1 >> \frac{\left(1 + \frac{R_2}{R_1}\right)}{A}$

then $\boxed{G = \frac{v_o}{v_I} = \left(1 + \frac{R_2}{R_1}\right)}$: Ideal Non-inverting gain

comparison of Ideal Vs Non-ideal gain of Non-inv. Amplifier

let $\frac{R_2}{R_1} = 9$

→ if $A = \infty$, Ideal closed loop gain, $G = \frac{v_o}{v_I} = 1 + \frac{R_2}{R_1}$

$$G = 1 + 9 = 10$$

$$\boxed{G = 10}$$

→ if $A = 10^5$, Non-ideal closed loop gain, $G = \frac{v_o}{v_I} =$

$$G = \frac{\left(1 + \frac{R_2}{R_1}\right)}{\left[1 + \frac{1 + \frac{R_2}{R_1}}{A}\right]} = \frac{1 + 9}{\left[1 + \frac{1+9}{10^5}\right]}$$

$$G = \frac{10}{1 + 10 \times 10^{-5}} = 9.999$$

Error is 1-part in 10,000 which is 0.01 %

5.3.4 The Voltage Follower

→ R_i = High for non-inverting configuration

→ This property enables us to use non-inverting configuration as a buffer amplifier

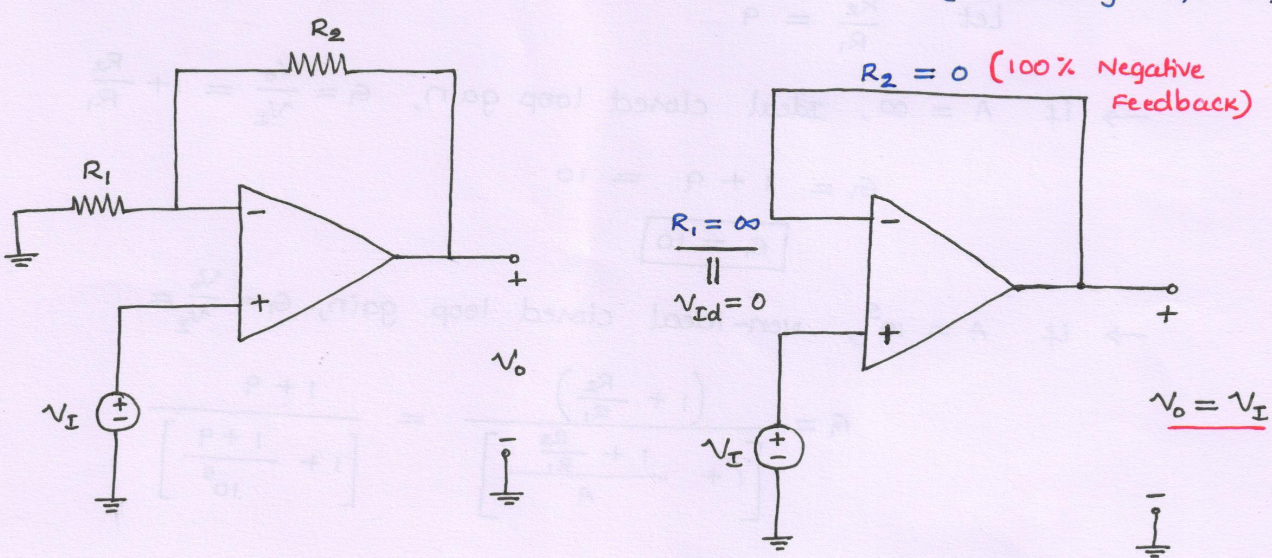
||

connects a source with a high-impedance to a low-impedance load

→ Buffer amplifier : Do not provide gain but It is a impedance transformer

→ For non-inverting configuration :

setting, $R_2 = 0$ (short circuit)
$R_1 = \infty$ (open circuit)
} unity-gain Amplifier
||
Voltage follower (commonly referred)



(a) Non-inverting configuration (b) Voltage follower

→ For the unity-gain buffer or follower amplifier, the output follows the input.

→ For the non-inverting configuration, the ideal closed loop gain is:

$$G = \frac{V_o}{V_I} = \left(1 + \frac{R_2}{R_1}\right) \quad \text{—— (1)}$$

if we make, $R_2 = 0$ and $R_1 = \infty$ then eqn. (1) changes to:

$$G = \frac{V_o}{V_I} = \left(1 + \frac{0}{\infty}\right)$$

$$\Rightarrow \quad G = \frac{V_o}{V_I} = \underline{1}$$

unity gain

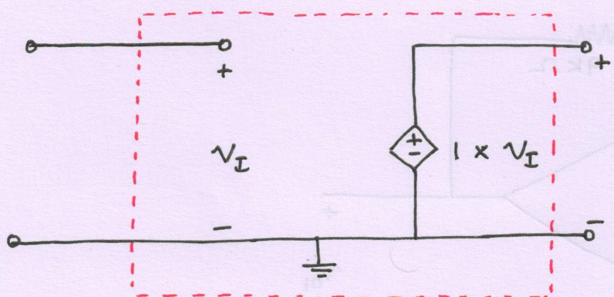
$$\boxed{V_o = V_I}$$

→ In ideal case, the voltage follower as:

$$V_o = V_I$$

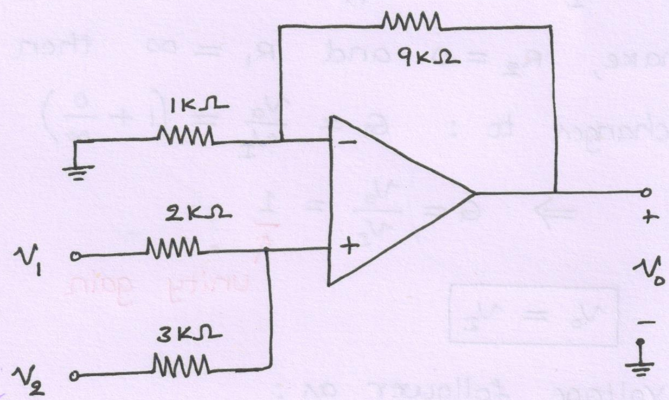
$$R_{in} = \infty$$

$$R_{out} = 0$$



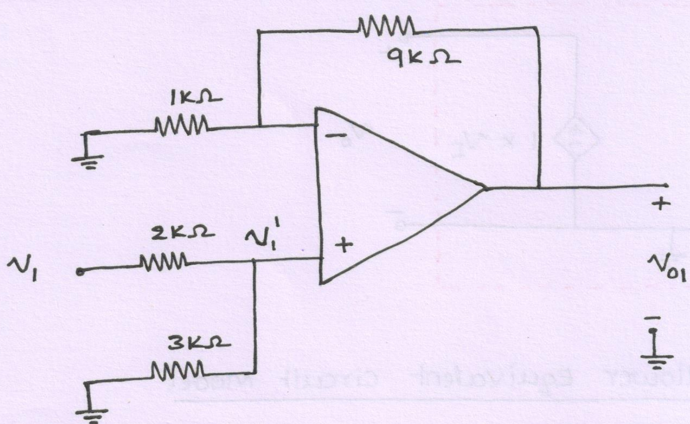
<u>Voltage Follower Equivalent Circuit Model</u>

Exercise 5.9: Using the superposition principle, find the output voltage for the circuit shown.



Solution: Using the principle of superposition, we find the output voltage as follows:

↳ contribution of V_1 to V_o, set $V_2 = 0$



$$V_1' = V_1 \frac{3}{3+2} = 0.6\,V_1$$

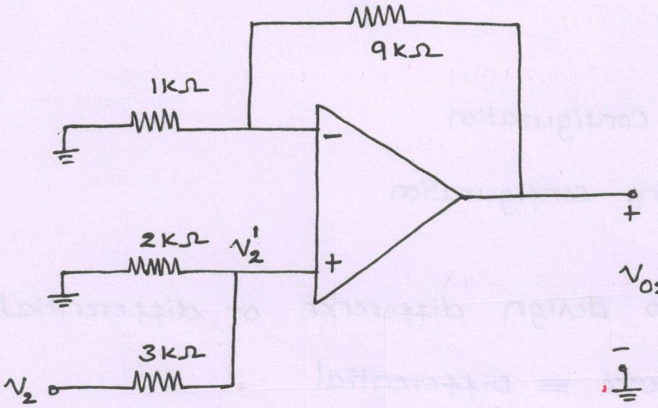
Thus $V_{01} = \left(1 + \frac{9K}{1K}\right) \times 0.6\,V_1$

$$V_{01} = 10 \times 0.6\,V_1 = 6V_1 \Rightarrow \boxed{V_{01} = 6V_1}$$

↳ contribution of V_2 to V_o, set $V_1 = 0$

$$V_2' = \frac{2}{2+3} V_2 = 0.4\,V_2$$

Thus, $V_{02} = \left(1 + \frac{9K}{1K}\right) V_2' = 10 \times 0.4\,V_2 \Rightarrow \boxed{V_{02} = 4V_2}$



Thus, overall output voltage, $V_o = V_{o1} + V_{o2}$

$$\boxed{V_o = 6V_1 + 4V_2}$$

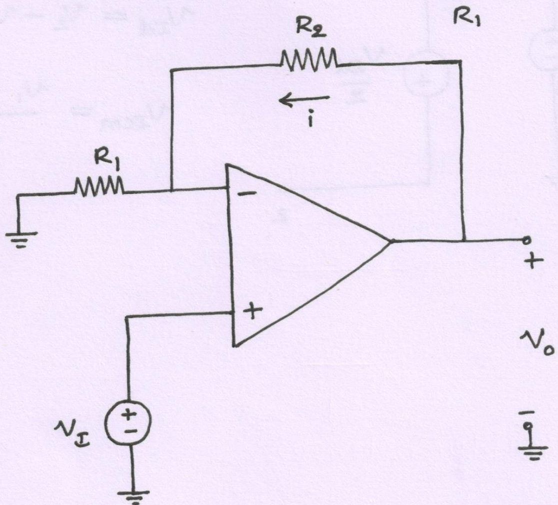
__Exercise D5.11__ : Design a non-inverting amplifier with a gain of 2. At the maximum output voltage of 10V, the current in the voltage divider is to be 10 µA.

__Solution__ : $G = 2$

We know that, $G = 1 + \frac{R_2}{R_1}$ for non-inverting configur^n

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

$$\frac{R_2}{R_1} = 1 \Rightarrow \boxed{R_2 = R_1}$$



if $V_o = 10V$, then it is desired that $i = 10\,\mu A$

Thus, $i = \frac{10V}{R_1 + R_2} = 10\,\mu A$

$$\Rightarrow R_1 + R_2 = \frac{10V}{10\,\mu A}$$

$$R_1 + R_2 = 1M\Omega$$

since $R_1 = R_2$

$$\Rightarrow \boxed{R_1 = 0.5\,M\Omega} \text{ and } \boxed{R_2 = 0.5\,M\Omega}$$

5.4 Difference Amplifiers

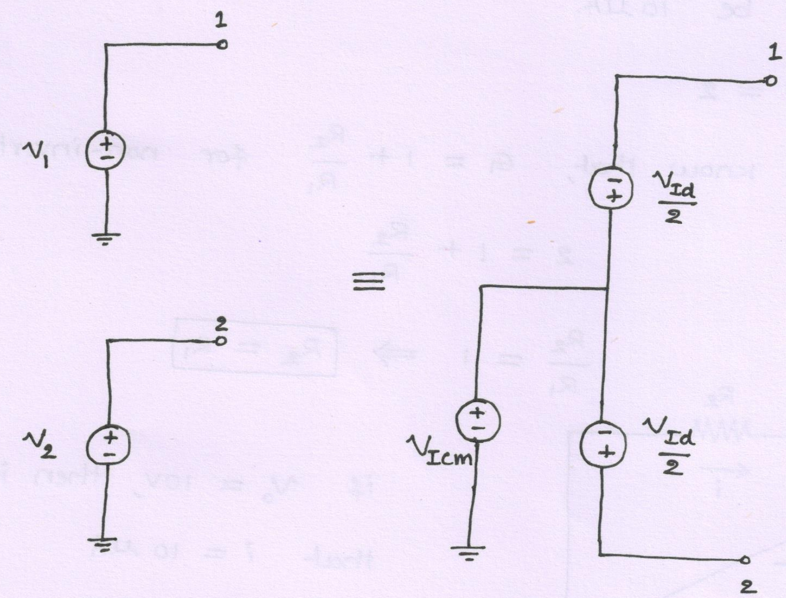
Preview: Inverting configuration

Non-inverting configuration

→ Op-amps are used to design difference or differential amplifier   Difference ≡ Differential

→ A differential amplifier is one that responds to the difference between the two input signals applied at its input and ideally rejects signals that are common to the two inputs.

→ Recall

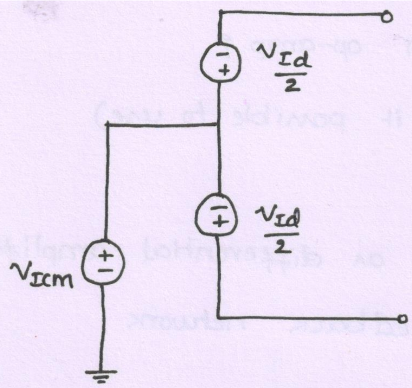


$$v_1 = v_{Icm} - \frac{v_{Id}}{2}$$

$$v_2 = v_{Icm} + \frac{v_{Id}}{2}$$

$$v_{Id} = v_2 - v_1$$

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



$v_{I1} = v_{Icm} - \frac{v_{Id}}{2}$

$v_{Id} = v_{I2} - v_{I1}$

$v_{Icm} = \frac{v_{I1} + v_{I2}}{2}$

$v_{I2} = v_{Icm} + \frac{v_{Id}}{2}$

(b) Representation of the input signals in terms of their differential and common mode components

Difference amplifier :

Amplifies ⟶ Differential input signal (v_{Id})

Rejects ⟶ Common mode input signal (v_{Icm})

$$v_o = A_d \, v_{Id} + A_{cm} \, v_{Icm}$$

A_d: Differential gain

A_{cm}: common mode gain (Ideally, zero)

Efficiency of Differential amplifier is measured by

① Degree of rejection of v_{Icm}

② preference to v_{Id}

This is usually quantified by a measure known as:

Common Mode Rejection Ratio (CMRR)

$$CMRR = 20 \log \frac{|A_d|}{|A_{cm}|}$$

by default op-amp : Differential Amplifier

Why not just use an op-amp?

Because: $A \rightarrow \infty$ (Makes it possible to use)

But

It is possible to use op-amp as differential amplifier by

① Appropriate feedback network

② Finite closed loop gain, G

predictable & stable

5.4.1 A single Op-amp Difference Amplifier

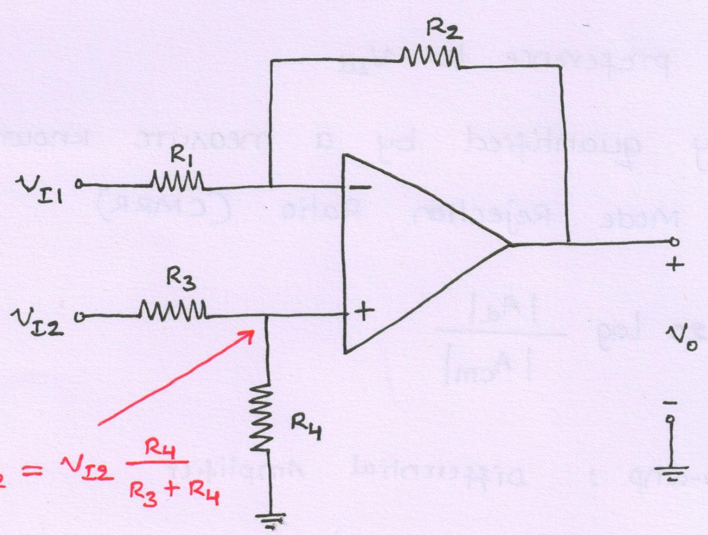
Non-inverting configuration $\longrightarrow \left(\frac{V_o}{V_I}\right) = 1 + \frac{R_2}{R_1} \longrightarrow$ positive

Inverting configuration $\longrightarrow \left(\frac{V_o}{V_I}\right) = -\frac{R_2}{R_1} \longrightarrow$ Negative

combining two configurations

$\downarrow$

step in right direction to get the difference between two input signals

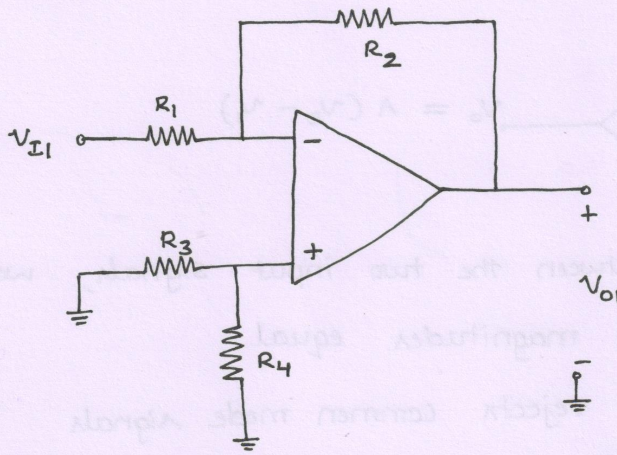


$$V_2 = V_{I2} \frac{R_4}{R_3 + R_4}$$

(a) A Difference Amplifier

Applying superposition principle :

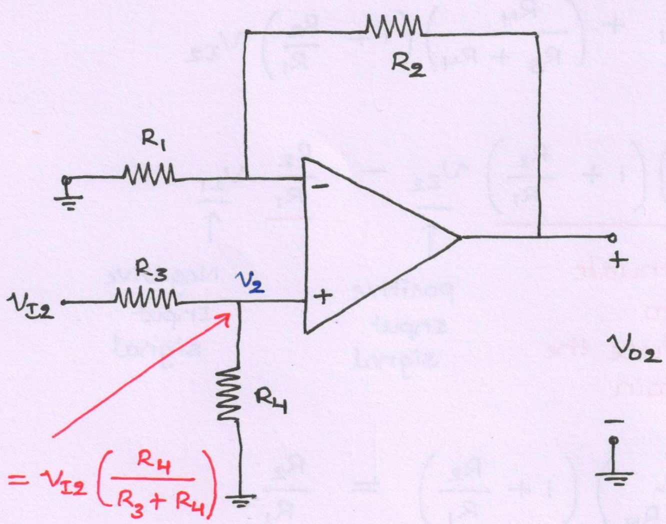
↳ **Contribution of V_{I1} to output, V_o** : Assume $V_{I2} = 0$



The equivalent circuit is an "Inverting configuration"

Therefore, $\boxed{V_{O1} = -\frac{R_2}{R_1} V_{I1}}$

↳ **Contribution of V_{I2} to output, V_o** : Assume $V_{I1} = 0$



$V_2 = V_{I2}\left(\frac{R_4}{R_3 + R_4}\right)$

The equivalent circuit is an "Non-inverting configuration"

Therefore,

$$V_{O2} = \underbrace{V_2}_{= V_{I2}\left(\frac{R_4}{R_3+R_4}\right)}\left(1 + \frac{R_2}{R_1}\right)$$

$$\boxed{V_{O2} = V_{I2}\left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right)}$$

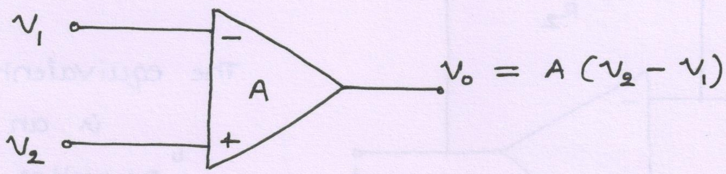
↳ Overall output voltage, V_o of the difference amplifier is the sum of V_{O1} and V_{O2}

Thus we have, $V_o = V_{O1} + V_{O2}$

$$\boxed{V_o = -\frac{R_2}{R_1} V_{I1} + V_{I2}\left(\frac{R_4}{R_4 + R_3}\right)\left(1 + \frac{R_2}{R_1}\right)} \quad \text{— ①}$$

- The output voltage of op-amp in open-loop mode is

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



- To get the difference between the two input signals, we have to make the two gain magnitudes equal

$\Rightarrow$ This rejects common mode signals

Consider output voltage, V_o of difference amplifier

$$V_o = -\frac{R_2}{R_1} V_{I1} + \left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right) V_{I2}$$

or

$$V_o = \underbrace{\left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right)}_{\text{Attenuate to reduce the gain}} \underset{\substack{\uparrow \\ \text{positive Input signal}}}{V_{I2}} - \frac{R_2}{R_1} \underset{\substack{\uparrow \\ \text{Negative Input signal}}}{V_{I1}}$$

Therefore,

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

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

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

$$1 + \frac{R_2}{R_1} = \frac{R_2}{R_1} + \underbrace{\frac{R_2 R_3}{R_1 R_4}}_{= 1}$$

(For LHS = RHS)

$$1 + \frac{R_2}{R_1} = \frac{R_2}{R_1}\,\frac{R_3}{R_4} + \frac{R_2}{R_1}$$

$$\boxed{R_3 = R_1 \quad \text{and} \quad R_2 = R_4}$$ condition to work as a difference amplifier

$\Rightarrow$ LHS = RHS

Therefore, eqn. ① changes to

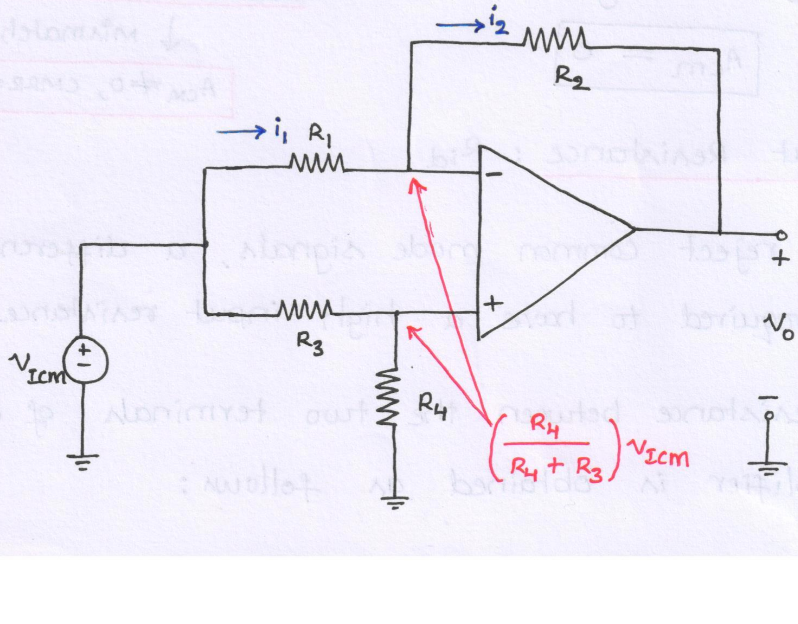
$$v_o = \underbrace{\left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right)}_{\substack{\text{Applying matching}\\ \text{condition for the}\\ \text{1st term}\\ \| \\ \frac{R_2}{R_1}}} v_{I2} - \frac{R_2}{R_1} v_{I1}$$

$$v_o = \frac{R_2}{R_1} v_{I2} - \frac{R_2}{R_1} v_{I1}$$

$$\boxed{v_o = \frac{R_2}{R_1}\left(v_{I2} - v_{I1}\right)}$$

$$\boxed{\text{Differential Gain : } A_d = \frac{v_o}{v_{I2} - v_{I1}} = \frac{R_2}{R_1}}$$

$\Rightarrow$ Common Mode Gain : A_{cm}



$$i_1 = \frac{\left[v_{Icm} - \frac{R_4}{R_4+R_3} v_{Icm} \right]}{R_1}$$

$$i_1 = \frac{v_{Icm}}{R_1} \left[\frac{\cancel{R_4} + R_3 - \cancel{R_4}}{R_4 + R_3} \right]$$

$$\boxed{i_1 = v_{Icm} \frac{R_3}{R_4 + R_3} \frac{1}{R_1}}$$

The output voltage, v_o is given by

$$v_o = \frac{R_4}{R_4 + R_3} v_{Icm} - \underbrace{i_2 R_2}_{\text{Drop across } R_2}$$

substituting $i_2 = i_1$, since op-amp do not draw current

$$v_o = \frac{R_4}{R_4 + R_3} v_{Icm} - v_{Icm} \frac{R_3}{R_4 + R_3} \frac{1}{R_1} R_2$$

$$v_o = \frac{R_4}{R_4 + R_3} v_{Icm} - \frac{R_2}{R_1} \frac{R_3}{R_4 + R_3} v_{Icm}$$

$$v_o = \frac{R_4}{R_4 + R_3} v_{Icm} \left[1 - \frac{R_2}{R_1} \frac{R_3}{R_4} \right]$$

$$\boxed{\text{Common Mode Gain } (A_{cm}) = \frac{v_o}{v_{Icm}} = \left(\frac{R_4}{R_4 + R_3} \right) \left[1 - \frac{R_2}{R_1} \frac{R_3}{R_4} \right]}$$

if we apply matching condition : $R_1 = R_3$ & $R_2 = R_4$

$\downarrow$ Mismatch

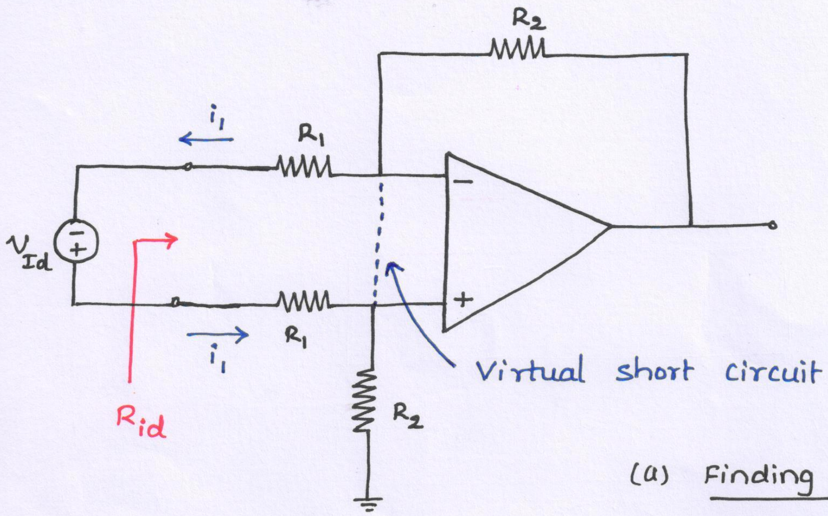
$\boxed{A_{cm} \neq 0, \ CMRR \neq \infty}$

then $\boxed{A_{cm} = 0}$

4) Differential Input Resistance : R_{id}

→ In addition to reject common mode signals, a difference amplifier is required to have a high input resistance.

→ The input resistance between the two terminals of a difference amplifier is obtained as follows :



$R_3 = R_1$, $R_4 = R_2$ } Assumption

(a) Finding the input resistance of the difference amplifier

Now $R_{id} \equiv \dfrac{V_{Id}}{i_1}$

The two input terminals of the op-amp track each other in potential. Therefore, we may write loop equation as

$$- V_{Id} + i_1 R_1 + \underline{0} + i_1 R_1 = 0$$

↑ Virtual short circuit

$$V_{Id} = 2 i_1 R_1$$

$$\boxed{R_{id} = \frac{V_{Id}}{i_1} = 2R_1}$$

→ If differential amplifier is required to have large differential gain, then R_1 = small

i.e $\underline{A_d} = \dfrac{R_2}{R_1}$; for large A_d, $\underline{R_1 = \text{small}}$

Not easy to vary (Drawback)

⇒ R_{id} = Input resistance = $2R_1$ (small)

⇒ Drawback of the differential amplifier