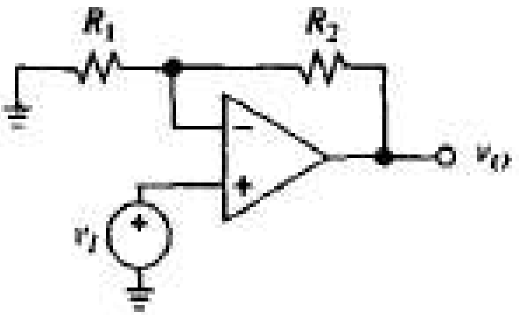
LIC: LECTURE 2

1. Voltage Follower
2. Inverting Amplifier
3. Summing Amplifier
4. Difference Amplifier
5. Integrator using Op-Amp
6. Differentiator using Op-Amp

[1] Franco, Sergio. Design with operational amplifiers and analog integrated circuits. Vol. 1988. New York: McGraw-Hill.

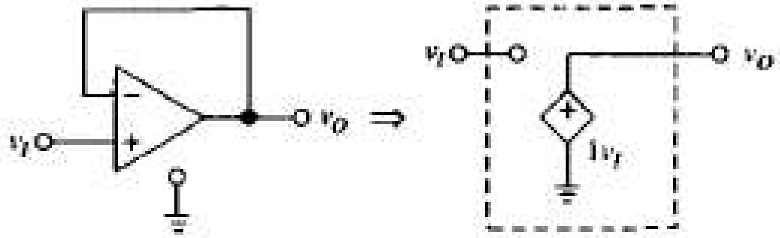
VOLTAGE FOLLOWER USING OP-AMP

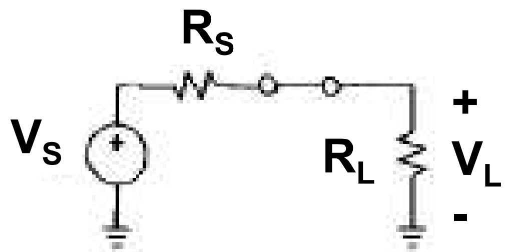


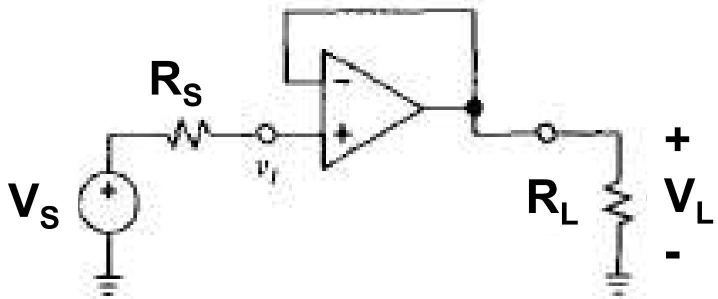
Letting $R_1 = \infty$ and $R_2 = 0$

noninverting amplifier turns it into the *unity-gain* amplifier

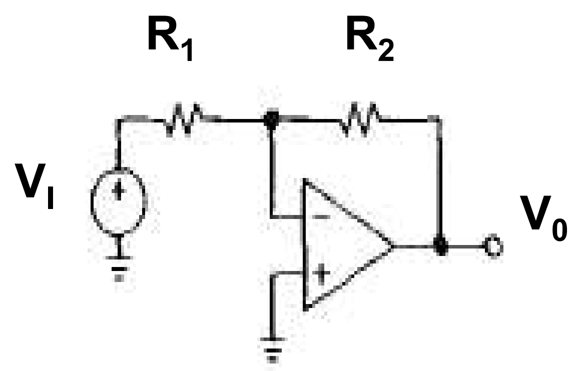
resistance transformer. $R_i = \infty$ $R_o = 0$

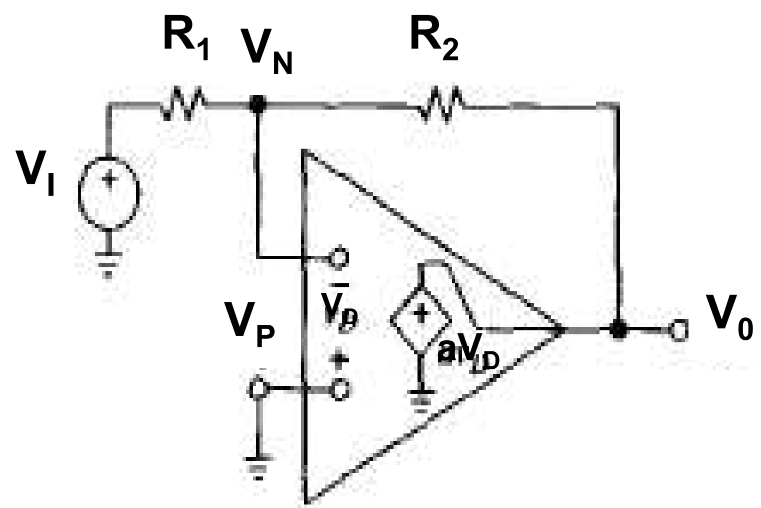






INVERTING AMPLIFIER





$$v_P = 0$$

$$v_N = [R_2/(R_1 + R_2)]v_I + [R_1/(R_1 + R_2)]v_O$$

$$v_N = \frac{1}{1 + R_1/R_2}v_I + \frac{1}{1 + R_2/R_1}v_O$$

$$v_O = a(v_P - v_N) = a\left(-\frac{1}{1 + R_1/R_2}v_I - \frac{1}{1 + R_2/R_1}v_O\right)$$

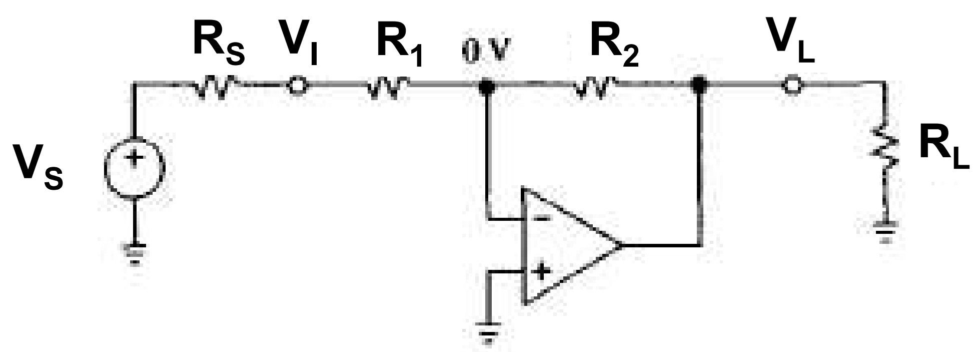
$$A = \frac{v_O}{v_I} = \left(-\frac{R_2}{R_1}\right)\frac{1}{1 + (1 + R_2/R_1)/a}$$

$$A_{\text{ideal}} = \lim_{a\to\infty} A = -\frac{R_2}{R_1}$$

in the limit $a \to \infty$, v_N would be zero exactly,

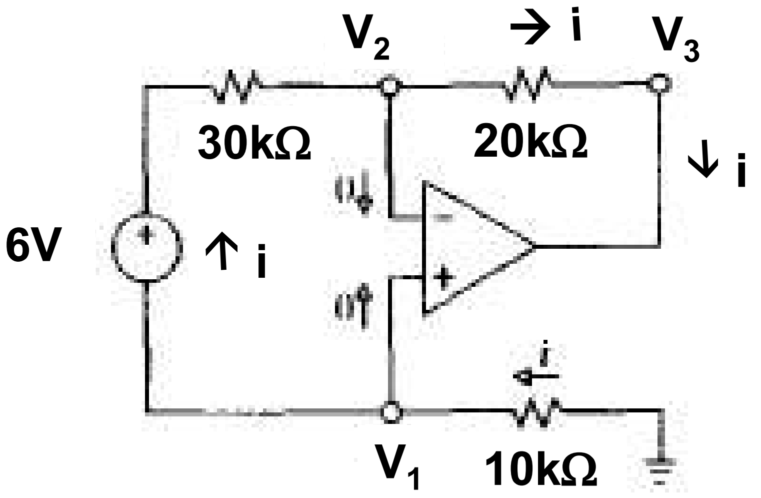
referred to as *virtual ground*

$$R_i = R_1 \qquad R_o = 0$$



$$v_I = \frac{R_1}{R_s + R_1} v_S \qquad v_L/v_I = -R_2/R_1$$

$$\frac{v_L}{v_S} = -\frac{R_2}{R_s + R_1}$$



$V_1 = -i \times 10k$

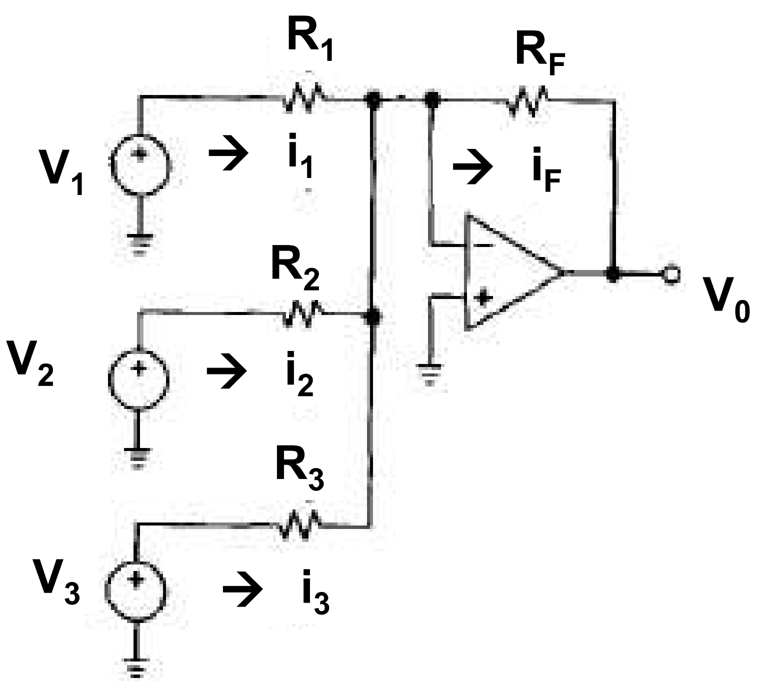
$V_2 = -i \times 30k + 6 - i \times 10k$

$V_2 = V_1 \rightarrow i \times 30k = 6 \rightarrow i = 0.2mA$

$V_1 = -0.2m \times 10k = -2V$

$V_3 = V_2 - i \times 20k = -2 - 4 = -6V$

SUMMING AMPLIFIER



$$i_1 + i_2 + i_3 = i_F$$

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} = -\frac{v_O}{R_F}$$

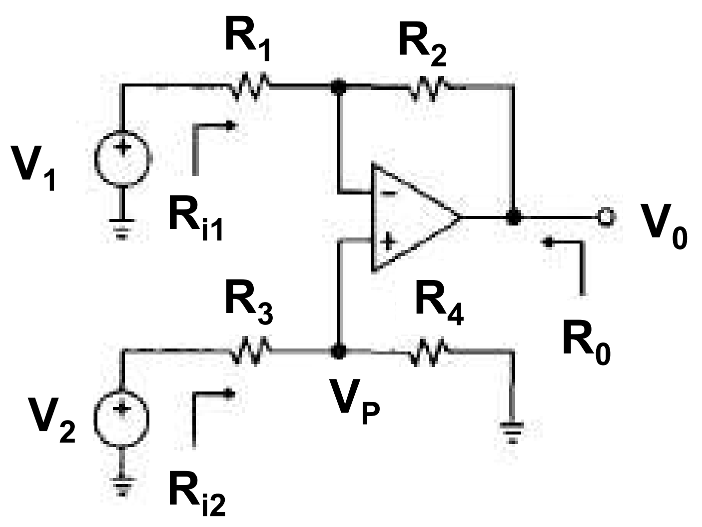
$$v_O = -\left(\frac{R_F}{R_1}v_1 + \frac{R_F}{R_2}v_2 + \frac{R_F}{R_3}v_3\right)$$

Using standard 5% resistances, design a circuit such that $v_O = -2(3v_1 + 4v_2 + 2v_3)$

$\frac{R_F}{R_1} = 6$ $\quad \frac{R_F}{R_2} = 8$ $\quad \frac{R_F}{R_3} = 4$

If $R_F = 20k\Omega$,
$R_1 = 3.33k\Omega$
$R_2 = 2.50k\Omega$
$R_3 = 5.00k\Omega$

DIFFERENCE AMPLIFIER



$v_{O1} = -(R_2/R_1)v_1$ and $R_{i1} = R_1$

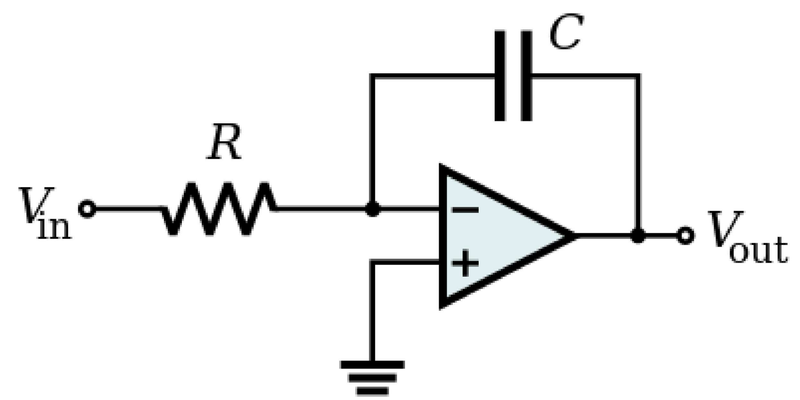
$v_{O2} = (1 + R_2/R_1)v_P = (1 + R_2/R_1) \times [R_4/(R_3 + R_4)]v_2$

$R_{i2} = R_3 + R_4$

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

When $\frac{R_3}{R_4} = \frac{R_1}{R_2}$ $\quad v_O = \frac{R_2}{R_1}(v_2 - v_1)$

INTEGRATOR USING OP-AMP



OP-AMP as INTEGRATOR

- Till now, we have used resistors with op-amp's
- So, now suppose if we use the reactive element like inductor or capacitor along with this.
- Here, as the feedback node will act as a virtual ground.
- KCL at inverting node:

$$I_{in} = I_C$$

$$\frac{V_{in} - 0}{R} = I_C$$

$$\frac{V_{in}}{R} = C_F \frac{dV_C}{dt}$$

$$= C_F \frac{d[0 - V_{out}]}{dt}$$

$$\frac{V_{in}}{R} = -C_F \frac{dV_{out}}{dt}$$

$$\frac{dV_{out}}{dt} = -\frac{1}{RC_F} \cdot V_{in}(t)$$

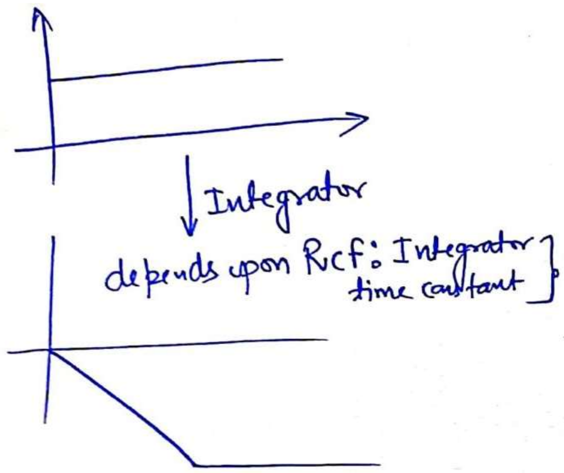
$$\boxed{V_{out}(t) = -\frac{1}{RC_F} \int V_{in}(t)\, dt}$$

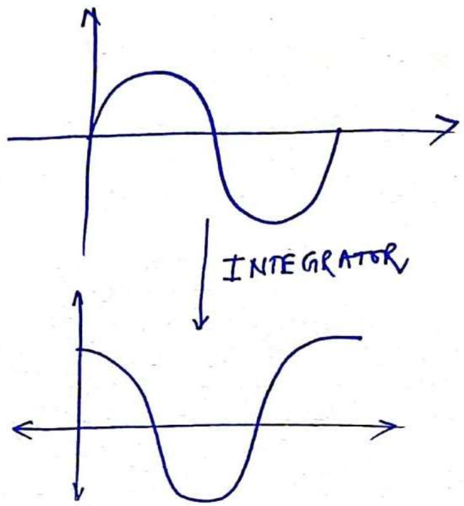
* if initial output voltage is $V_{out}(0^+)$

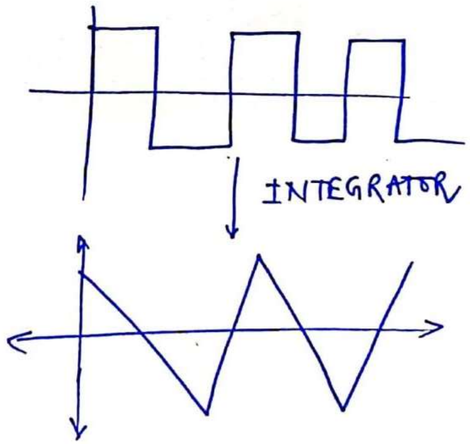
so

$$\boxed{V_{out}(t) = -\frac{1}{RC_F} \int V_{in}(t)\, dt + V_{out}(0^+)}$$

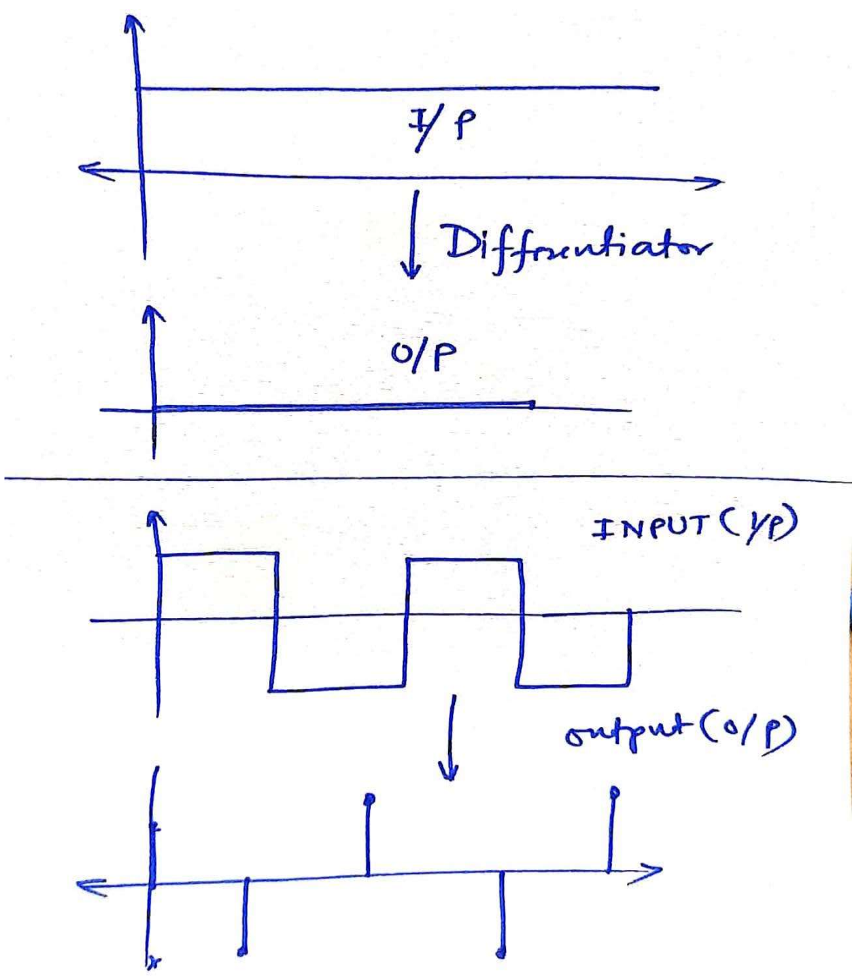
EXAMPLES: INTEGRATOR USING OP-AMP







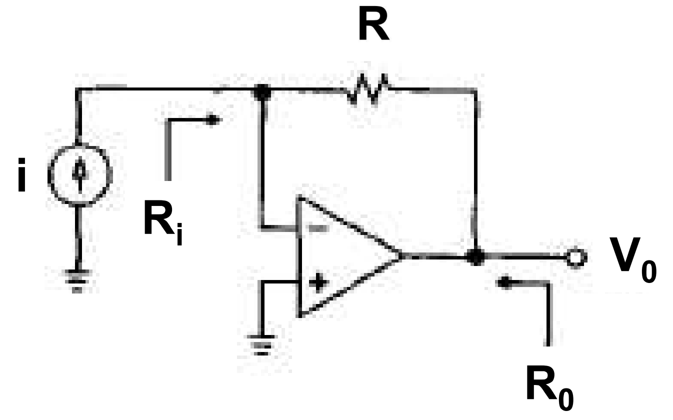
EXAMPLE: DIFFERENTIATOR USING OP-AMP



LIC: LECTURE 4
CIRCUITS WITH RESISTIVE FEEDBACK

1. **Current-Voltage (I-V) Converters**
2. **Voltage-Current (V-I) Converters**
   (i) Floating load V-I Converter
   (ii) Grounded load V-I Converter

Current-Voltage (I-V) Converter



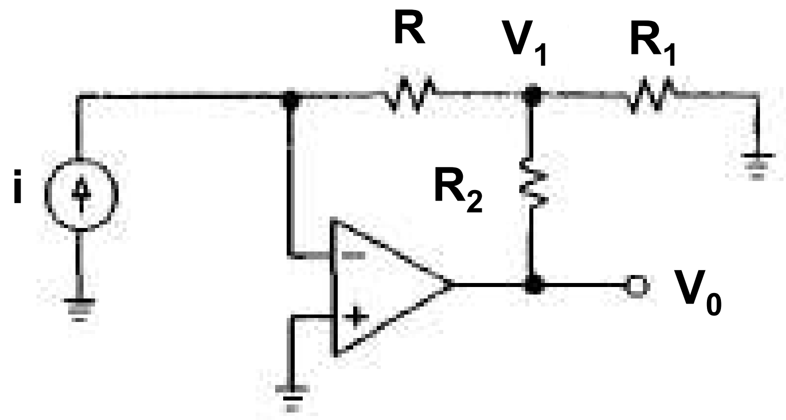
$V_0 = -iR$

$|V_0/i| = R$ is called the sensitivity

For a sensitivity of 1V/mA, we need R = 1kΩ
sensitivity of 1V/μA, we need R = 1MΩ

→ For large sensitivity, we need large resistors

High-Sensitivity *I-V* Converters



$$-v_1/R - v_1/R_1 + (v_O - v_1)/R_2 = 0$$

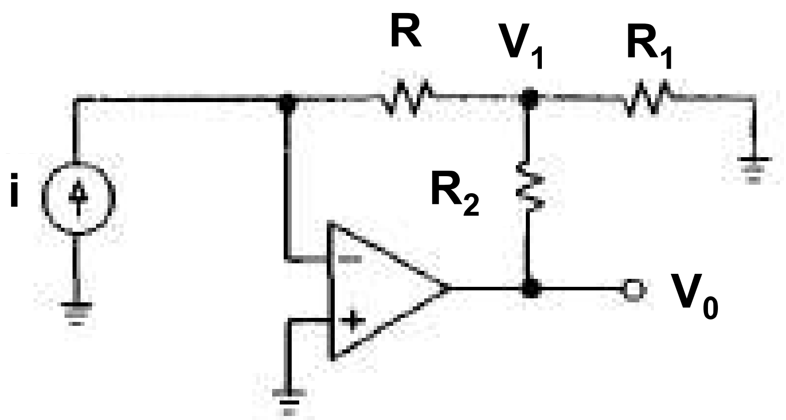
$$v_1 = -Ri$$

$$i + iR/R_1 + v_0R_2 + iR/R_2 = 0$$

$$v_O = -kRi \qquad k = 1 + \frac{R_2}{R_1} + \frac{R_2}{R}$$

increases R by the multiplicative factor k

Example



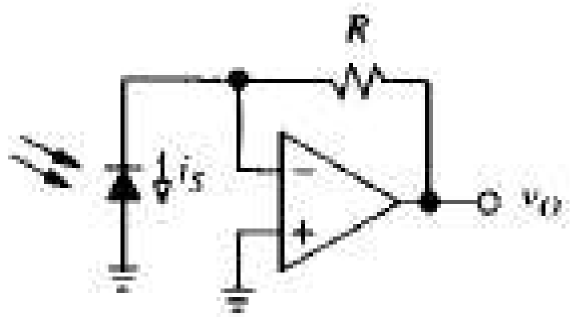
Design the circuit for a sensitivity 0.1V/nA

Sensitivity 0.1V/nA → $kR = 100M\Omega$

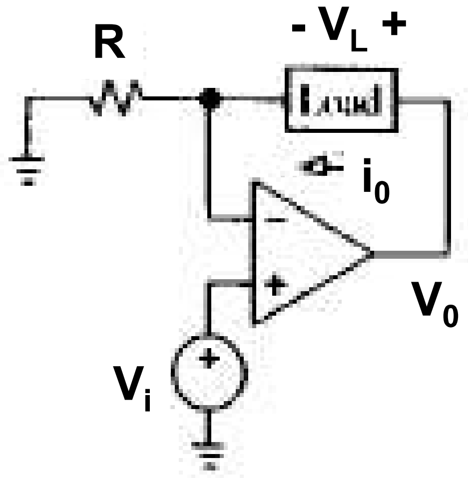
If $R = 1M\Omega$ $$k = 1 + \frac{R_2}{R_1} + \frac{R_2}{R} = 100$$

If $R_1 = 1k\Omega$ we get, $R_2 = 99k\Omega$

Application of I-V converters as photodetectors



Voltage to Current (V-I)Converters
Floating Load

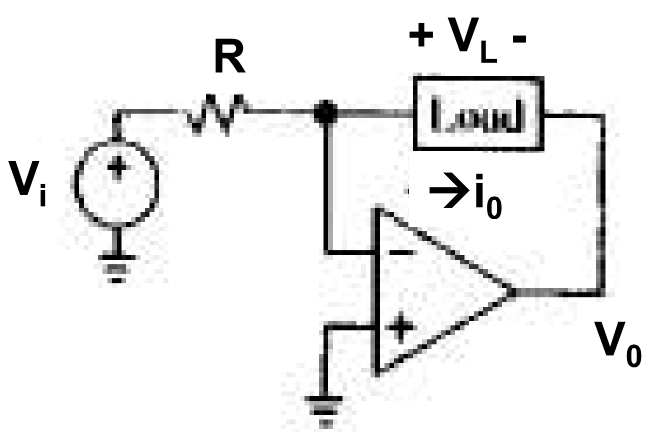


$I_0 = V_i / R$

op amp must swing its output to the value $V_0 = V_i + V_L$

Will do as long as $V_{0L} < V_0 < V_{0H}$

Voltage compliance of the circuit is $(V_{0L} - V_i) < V_L < (V_{0H} - V_i)$



$I_0 = V_i / R$ $V_0 = -V_L$

voltage compliance is now $V_{OL} < v_L < V_{OH}$

Has higher voltage compliance

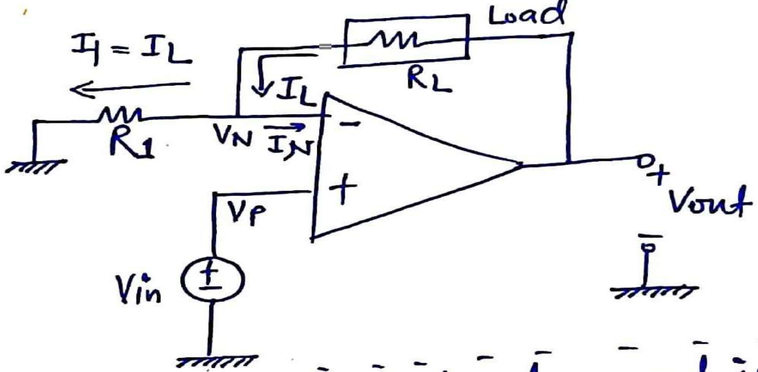
drawback i_O must come from the source

Voltage-Current (V-I) Converters (Floating Load)

FLOATING LOAD V-I CONVERTER: (Active)

GENERAL DISCUSSION:

["floating load: if none of the terminals of a load is connected to ground, it is a floating load."]



* from circuit, $V_P = V_{in}$
* So, by virtual ground concept $\boxed{V_P = V_N = V_{in}}$
* Let current I_L flow through R_1 & current I_L flows through load R_L.
* KCL at node V_N:

$$I_L = I_1 + I_N \quad [I_N = 0;\ \text{I/p impedance of op-amp is very high}]$$

$$\boxed{I_L = I_1}$$

* from circuit:

$$I_1 = \frac{V_N - 0}{R_1} = \frac{V_N}{R_1}$$

$$\boxed{I_1 = \frac{V_{in}}{R_1}} \ *$$

* So, $I_L = \dfrac{V_{in}}{R_1}$ or $\left|\dfrac{I_L}{V_{in}}\right| = \dfrac{1}{R_1}$ ← sensitivity of the circuit

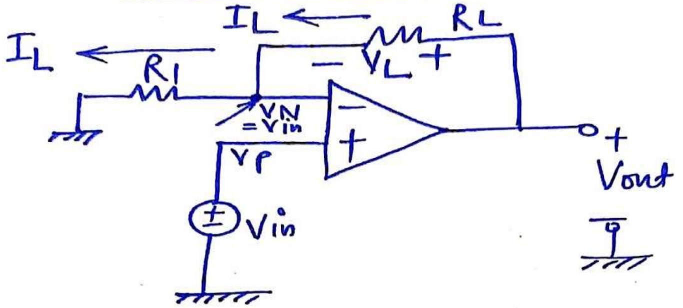
$$\boxed{I_L \propto V_{in}}$$

- i.e. Load current is directly proportional to I/p voltage!
- Also, in the equation $I_L = \frac{V_{in}}{R_1}$, load resistance does not appear.
- This is advantageous as compared to passive V-I converters!
- Here; output → current, Input – voltage; $\text{Gain} = \frac{I}{V}$ = conductance

So, it is named as transconductance Amp. *

Voltage-Current (V-I) Converters (Floating Load)

CIRCUIT-A



- In circuit A, the op-amp outputs, whatever the current I_L, it takes to make the following inverting input voltage V_{in} or ~~to~~ make $R_1 \cdot I_L = V_{in}$

i.e. $\boxed{I_L = \frac{1}{R_1} \cdot V_{in}}$ — (i)

(I_L: output load current; V_{in}: Input Voltage)

- Equ.-(i) holds regardless of the type of load; i.e. it can be linear (resistive transducer) or it can be non-linear (diode).

- So, no matter what the load, the op-amp will force it to carry the current $I_L = \frac{V_{in}}{R_1}$, which depends on the control voltage V_{in} & current setting resistor R_1, but not on the load voltage V_L.

- from circuit A, we can write

$\boxed{V_{out} = V_L + V_{in}}$ where $V_L = I_L R_L$

- So to achieve this, the op-amp must swing it's output to the value

$V_{out} = V_{in} + V_L$

<u>Voltage Compliance</u>: It is the range of permissible value of V_L for which the circuit still works properly, before the onset of opamp-saturation.

Voltage-Current (V-I) Converters (Floating Load)

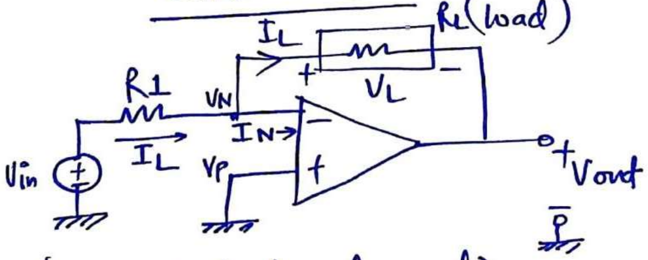
- Opamp's are powered with $+V_{cc}$ & $-V_{EE}$ power supplies; so a maximum output voltage achieved in op-amp will be $+V_{sat}$ & $-V_{sat}$

  So! if $\left.\begin{array}{l} +V_{cc} = 15V \\ -V_{EE} = -15V \end{array}\right\}$ $\begin{array}{l} \pm V_{sat} \approx 0.9V_{cc} \text{ (Approximately)} \\ \pm V_{sat} = \pm 13.5V \end{array}$

- So, Circuit A, $V_{out} = V_{in} + V_L$ is valid as long as $\boxed{-V_{sat} < V_{out} < +V_{sat}}$
- So, voltage compliance of the circuit is

$$\boxed{(-V_{sat} - V_{in}) < V_L < (V_{sat} - V_{in})}$$

CIRCUIT-B*



$\left\{\begin{array}{l} V_P = 0 \text{ (at real ground)} \\ V_N = V_P = 0 \text{ (at virtual ground)} \end{array}\right.$

- Thus it's output terminal must draw the current:

$$I_L = \frac{V_{in} - V_N}{R_1} = \frac{V_{in} - 0}{R_1} = \frac{V_{in}}{R_1}$$

& it must have the voltage swing as $\boxed{V_{out} = -V_L}$ *

- Hence, voltage compliance for circuit B:

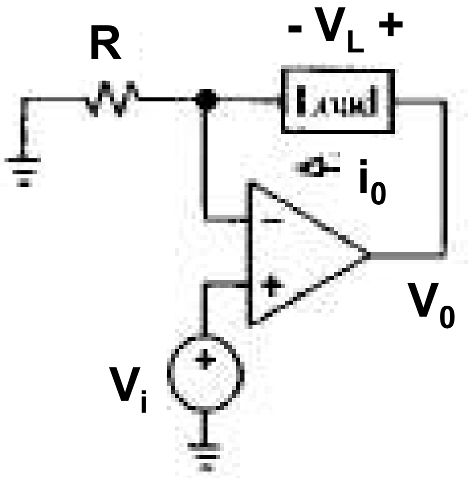
$$\boxed{-V_{sat} < V_L < V_{sat}} *$$

- Drawback of circuit B: I_L must come from the source itself.

OBSERVATIONS: CIRCUIT (A & B)

1) Equation $\frac{V_{in}}{R_1} = I_L$: Holds for both regardless of the polarity of the source.
2) The current arrows of circuit A & B, show current for $V_{in} > 0$; making $V_{in} < 0$ will ~~.....~~ simply make the direction of current reverse.
3) So, two converters are thus said to be bidirectional.

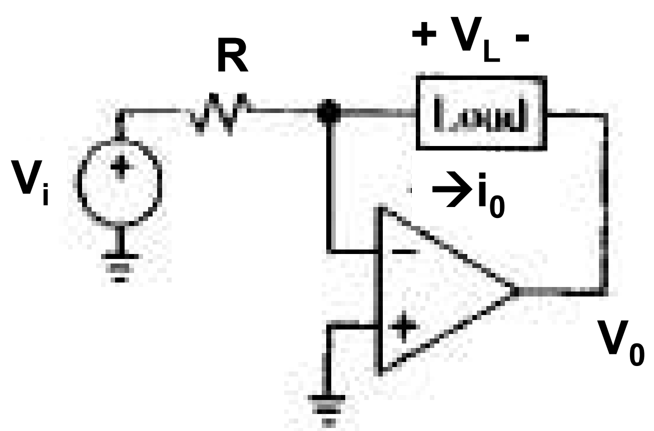
In the circuit, $V_i = 5V$, $R = 10k\Omega$, $\pm V_{sat} = \pm 13V$ and a resistive load R_L
Calculate i_0, voltage compliance and maximum permissible value of R_L



$I_0 = 5/10 = 0.5mA$

Voltage compliance
$(-13 - 5)V < V_L < (13 - 5)V$

$R_L < 8/0.5 = 16k\Omega$

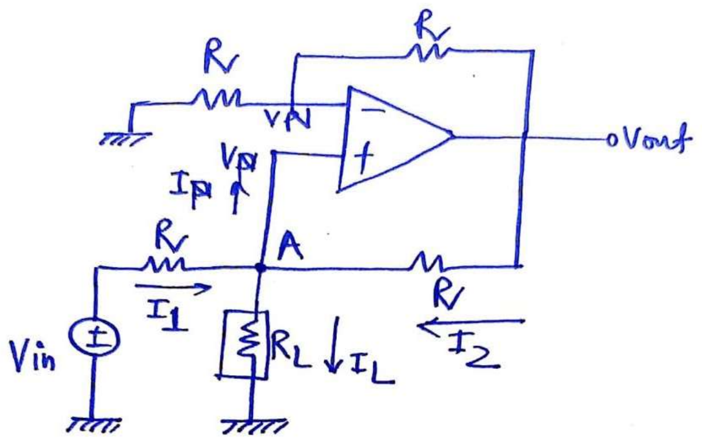


$I_0 = 5/10 = 0.5mA$

Voltage compliance
$-13V < V_L < 13V$

$R_L < 13/0.5 = 26k\Omega$

Voltage-Current (V-I) Converters (Grounded Load)



- Assume that current flowing through R_L is I_L.
- Applying KCL at node A; we get

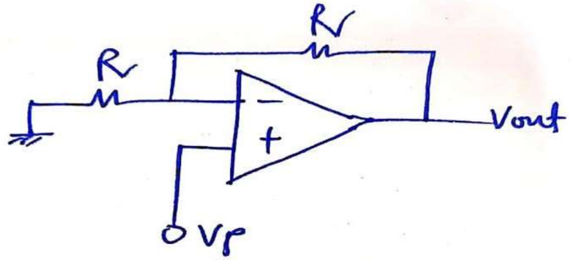
$$I_1 + I_2 = I_L + \cancel{I_P} \quad (I_P = 0)$$

$$I_L = I_1 + I_2$$

$$I_L = \frac{V_{in} - V_P}{R} + \frac{V_{out} - V_P}{R}$$

$$V_{in} + V_{out} - 2V_P = I_L \times R \quad * \text{---} (1)$$

- The circuit is actually looks like a Non-inverting amplifier with Input as V_P as shown below.



So; $V_{out} = \left(1 + \frac{R}{R}\right) V_P$

$$\boxed{V_{out} = 2V_P}$$

- put this value in equ. (1)

$$V_{in} + V_{out} - 2V_P = I_L \times R$$

$$V_{in} + 2V_P - 2V_P = I_L \times R$$

$$V_{in} = I_L \times R$$

$$I_L \times R = V_{in}$$

$$\boxed{I_L = \frac{1}{R} V_{in}} \text{ or } \boxed{I_L \propto V_{in}}$$

$\Rightarrow I_L$ is independent of load resistance R_L

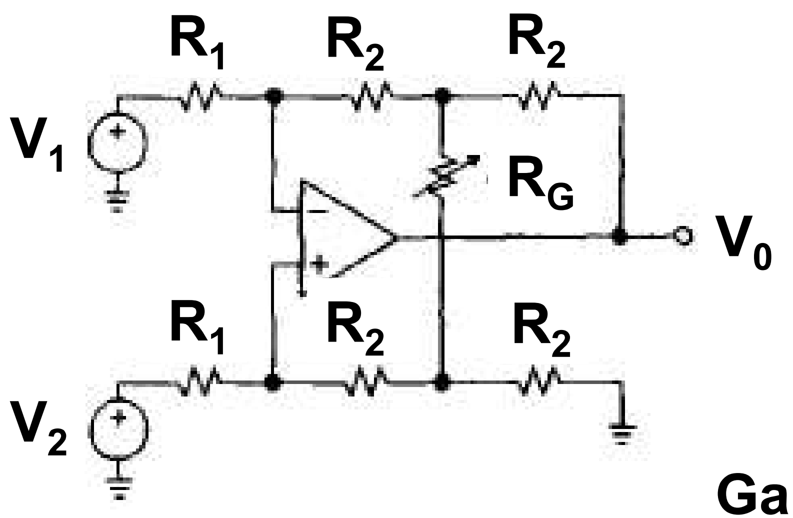
LIC: LECTURE 6
CIRCUITS WITH RESISTIVE FEEDBACK

1. **Difference amplifier with variable gain**
2. **Instrumentation Amplifier (IA)**
   - **(i) Triple Op-Amp IA**
   - **(ii) Dual Op-Amp IA**
   - **(iii) Current-Output IA**
3. **Transducer Bridge Amplifier**

When $\frac{R_4}{R_3} = \frac{R_2}{R_1}$ $\quad v_O = \frac{R_2}{R_1}(v_2 - v_1)$

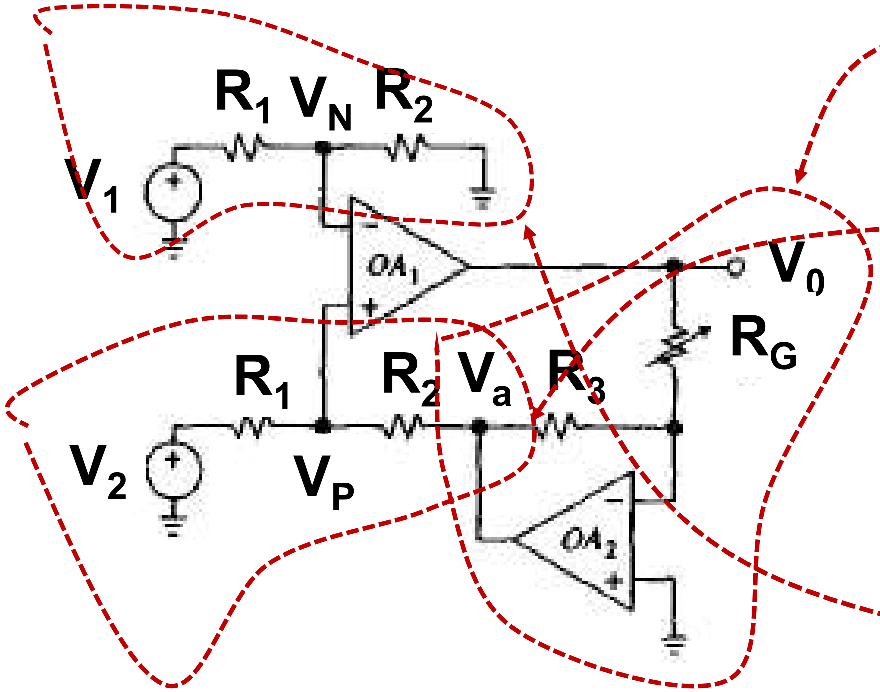
To vary gain we need to vary 2 resistors equally

DIFFERENCE AMPLIFIER WITH VARIABLE GAIN



$$v_O = \frac{2R_2}{R_1}\left(1 + \frac{R_2}{R_G}\right)(v_2 - v_1)$$

Gain varies inversely with R_G



$V_a = (-R_3/R_G)V_0$

$$V_P = V_2 \frac{R_2}{R_1 + R_2} + V_a \frac{R_1}{R_1 + R_2}$$

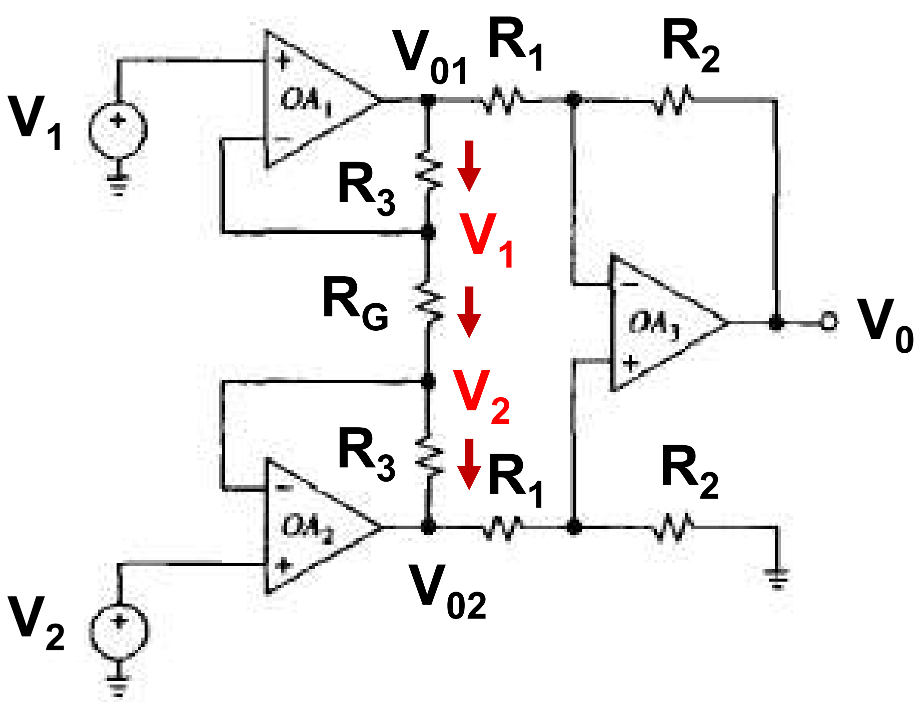
$$V_P = V_2 \frac{R_2}{R_1 + R_2} - V_0 \frac{-R_3}{R_G} \frac{R_1}{R_1 + R_2} \quad \text{----(1)}$$

$$V_N = V_1 \frac{R_2}{R_1 + R_2} \quad \text{----(2)}$$

Equating (1) & (2) $\quad V_0 = \frac{R_2}{R_1} \frac{R_G}{R_3} (V_2 - V_1)$

Gain varies proportionally with R_G

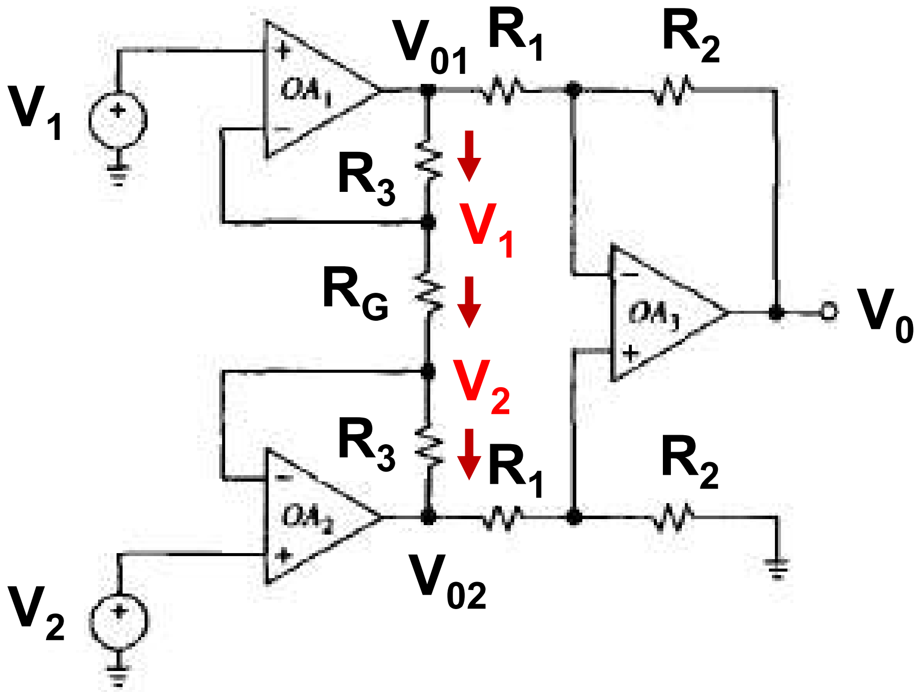
INSTRUMENTATION AMPLIFIER



Triple: OP-AMP INSTRUMENTATION AMPLIFIER

- An instrumentation amplifier (IA) is a difference amplifier meeting the following specifications: **(a) extremely high (ideally infinite) common-mode and differential-mode input impedances;**
- **(b) very low (ideally zero) output impedance; (c) accurate and stable gain, typically in the range of 1 V/V to 10^3 V/V; and**
- **(d) extremely high common-mode rejection ratio.**
- The IA is used to accurately amplify a low-level signal in the presence of a large common-mode component, such as a transducer output in process control and biomedicine.
- For this reason, IAs find widespread application in test and measurement instrumentation—hence the name.

INSTRUMENTATION AMPLIFIER: ANALYSIS

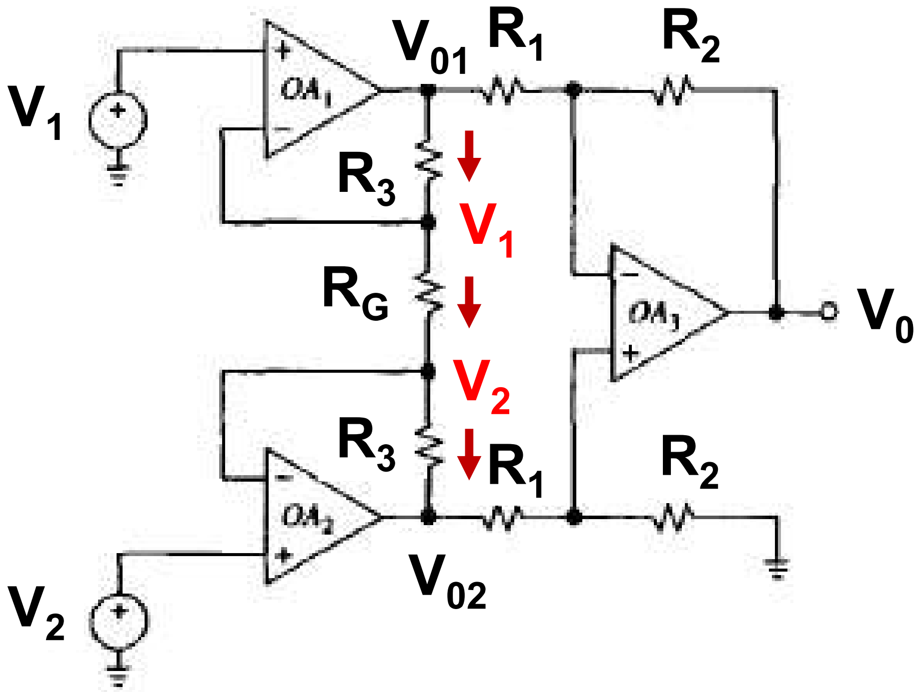


Triple: OP-AMP
INSTRUMENTATION AMPLIFIER

OP-AMP REQUIREMENTS:

1- Op-amp must be provided with $\pm 15V/\pm 12V$ power supply
2- Op-amp must not operate in saturation region
3- Use of negative feedback,
4- Using concept of virtual short
5- To find output expression, we need to first find Vout1 & Vout2
6- Since op-amp is in Linear region, we can use superposition theorem.

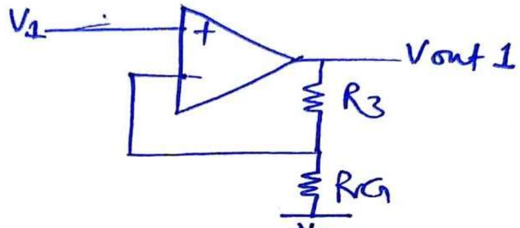
INSTRUMENTATION AMPLIFIER: ANALYSIS



Triple: OP-AMP
INSTRUMENTATION AMPLIFIER

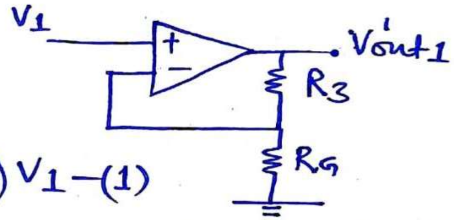
<u>STEP-1</u>: Calculation of V_{out1}:

To find V_{out1}, we can use superposition theorem: So, consider op-amp-1 first*



<u>Case-1</u>: V_1 source active, V_2 source deactivated i.e. $S.C \rightarrow V_2$

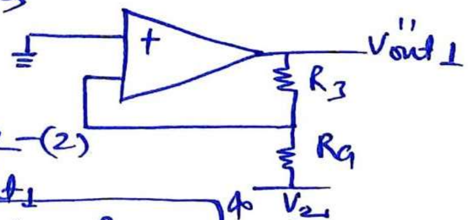
'So, circuit becomes non-inverting amp.'



$$V'_{out1} = \left(1+\frac{R_3}{R_G}\right)V_1 \quad -(1)$$

<u>Case-1</u>: V_2 source active, V_1 source deactivated i.e. $S.C \rightarrow V_1$

'So, circuit becomes inverting amp.'



$$V''_{out1} = -\frac{R_3}{R_G}V_2 \quad -(2)$$

$$V_{out1} = V'_{out1} + V''_{out1}$$

$$\boxed{V_{out1} = \left(1+\frac{R_3}{R_G}\right)V_1 - \frac{R_3}{R_G}\cdot V_2} \quad -(3)$$

INSTRUMENTATION AMPLIFIER: ANALYSIS

STEP-2: Calculation of V_{out2}

* Because of similar section for op-amp 2, we can perform the analysis & find V_{out2}
* So, similarly:

$$\boxed{V_{out2} = \left(1+\frac{R_3}{R_G}\right)V_2 - \frac{R_3}{R_G}\cdot V_1} \quad - (4)$$

STEP-3: Since op-amp-3 is a differential amplifier:

$$V_{out} = \frac{R_2}{R_1}\left[V_{out2} - V_{out1}\right]$$

$$V_{out} = \frac{R_2}{R_1}\left[\left(1+\frac{R_3}{R_G}\right)V_2 - \frac{R_3}{R_G}V_1 - \left(1+\frac{R_3}{R_G}\right)V_1 + \left(\frac{R_3}{R_G}\right)V_2\right]$$

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

$$V_{out} = \frac{R_2}{R_1}\left[(V_2 - V_1) + \frac{2R_3}{R_G}(V_2 - V_1)\right]$$

$$\boxed{V_{out} = \frac{R_2}{R_1}\left[1+\frac{2R_3}{R_G}\right](V_2 - V_1)} \, *$$

- $A_d = \frac{R_2}{R_1}\left[1+\frac{2R_3}{R_G}\right]$

Differential Gain

$$\boxed{V_{out} = A_d(V_2 - V_1)}$$

$$V_{out} \propto (V_2 - V_1) \, *$$

- In differential gain:

$$A_d = \underbrace{\frac{R_2}{R_1}}_{\text{Gain of 2nd stage}} \underbrace{\left[1+\frac{2R_3}{R_G}\right]}_{\text{Gain of 1st stage}}$$

* The gain of the instrumental amplifier can be varied by adjusting variable resistance

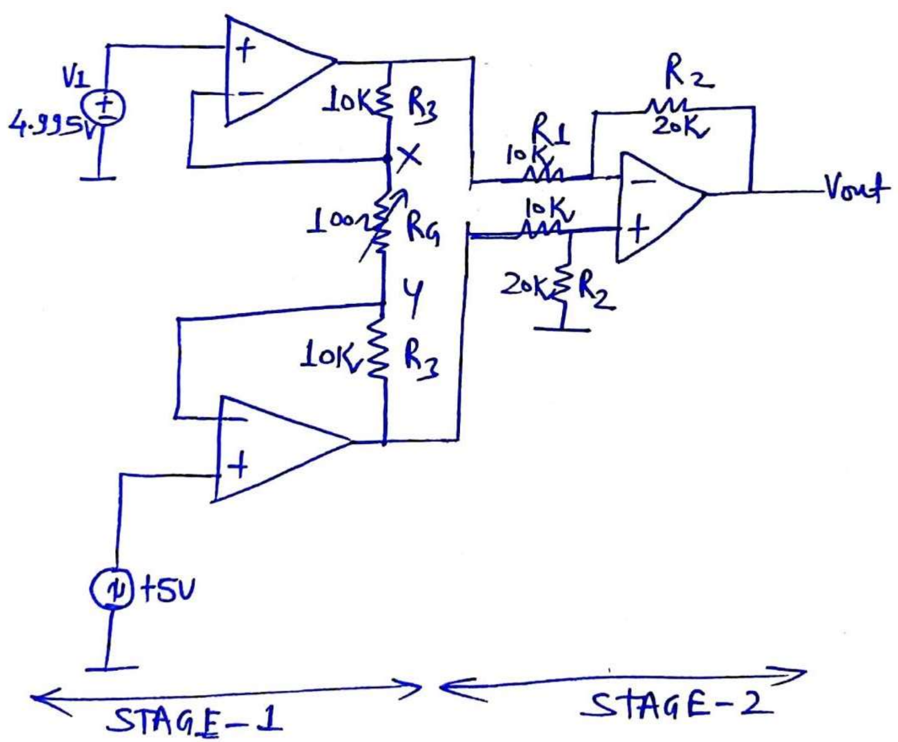
INSTRUMENTATION AMPLIFIER: PROBLEM

Problem: for the given IA, determine the output voltage for the circuit given below.

$R_3 = 10K$, $R_G = 100\Omega$, $R_1 = 10K$

$R_2 = 20K$, $V_1 = 4.995V$

$V_2 = 5V$



Solution: $V_1 = 4.995V$, $V_2 = 5V$

$$V_{out1} = \left(1 + \frac{R_3}{R_G}\right)V_1 - \frac{R_3}{R_G}V_2$$

$$V_{out1} = \left(1 + \frac{10K}{100}\right)V_1 - \left(\frac{10K}{100}\right)V_2$$

$$\boxed{V_{out1} \simeq 4.495V}$$

$$V_{out2} = \left(1 + \frac{R_3}{R_G}\right)V_2 - \frac{R_3}{R_G}V_1$$

$$V_{out_2} = \left(1 + \frac{10K}{100}\right)V_2 - \left(\frac{10K}{100}\right)V_1$$

$$V_{out_2} = (1+100)V_2 - 100V_1$$

$$V_{out_2} = 101V_2 - 100V_1$$

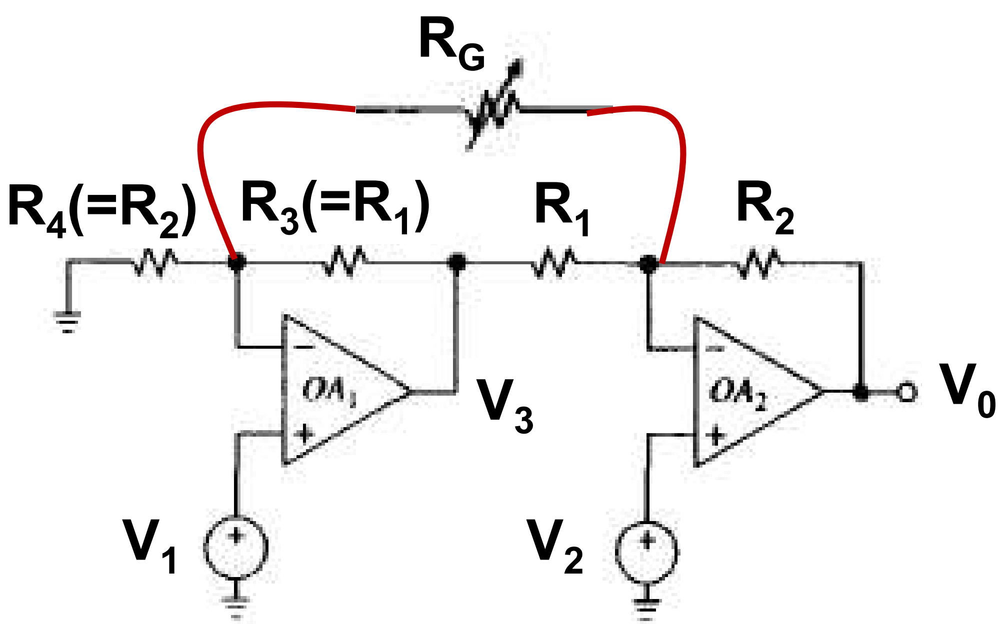
$$\boxed{V_{out2} = 5.5V}$$

So; $V_{out} = \frac{R_2}{R_1}(V_{out2} - V_{out1})$

$$= \frac{20K}{10K}[5.5 - 4.495]$$

$$\boxed{V_{out} = 2.01V}$$ *

DUAL OP-AMP INSTRUMENTATION AMPLIFIER



$$V_3 = \left(1 + \frac{R_3}{R_4}\right) V_1$$

$$V_0 = \left(1 + \frac{R_2}{R_1}\right) V_2 - \frac{R_2}{R_1} V_3$$

$$V_0 = \left(1 + \frac{R_2}{R_1}\right) V_2 - \frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4}\right) V_1$$

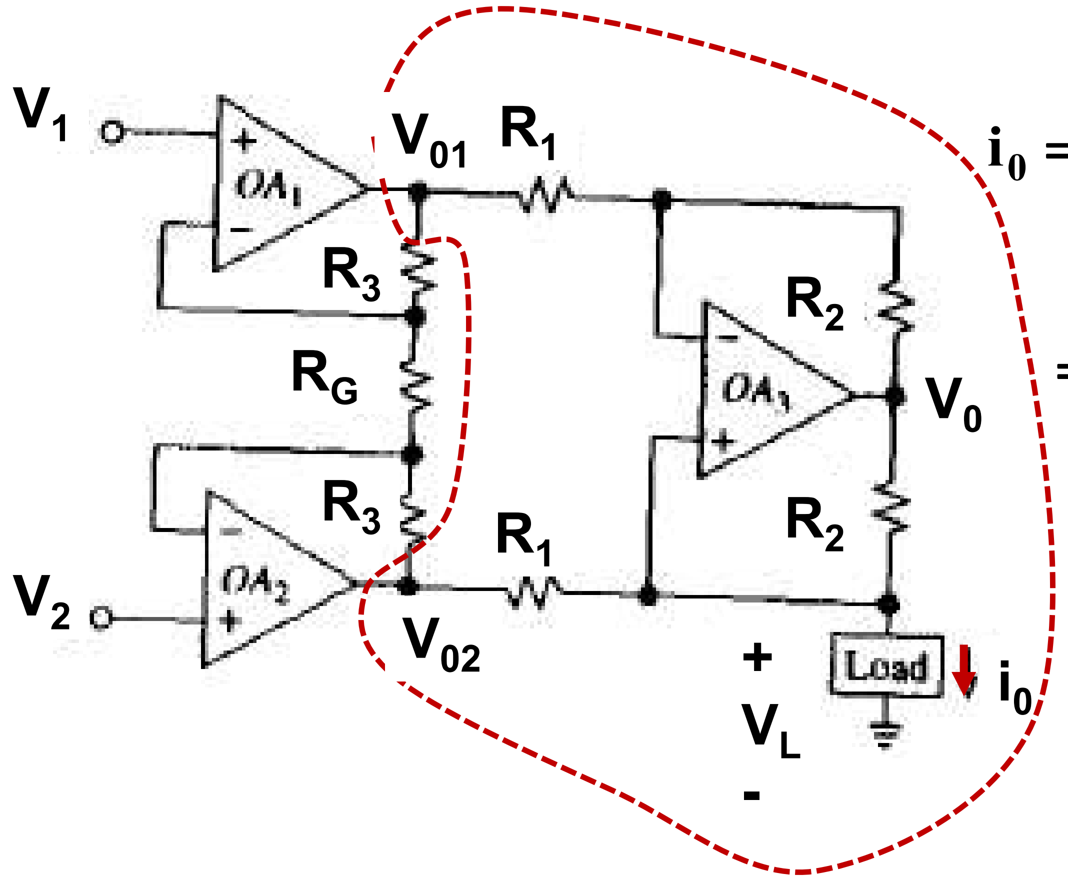
When $\frac{R_4}{R_3} = \frac{R_2}{R_1}$

$$V_0 = \left(1 + \frac{R_2}{R_1}\right)(V_2 - V_1)$$

$$V_0 = \left(1 + \frac{R_2}{R_1} + \frac{2R_2}{R_G}\right)(V_2 - V_1)$$

- When high-quality, costlier op amps are used to achieve superior performance, it is of interest to minimize the number of devices in the circuit.
- A drawback of the dual-op-amp configuration is that it treats the inputs asymmetrically because v1 has to propagate through OA1 before catching up with v2.

CURRENT OUTPUT INSTRUMENTATION AMPLIFIER



$$V_0 = -\frac{R_2}{R_1}V_{01} + \left(1+\frac{R_2}{R_1}\right)V_L$$

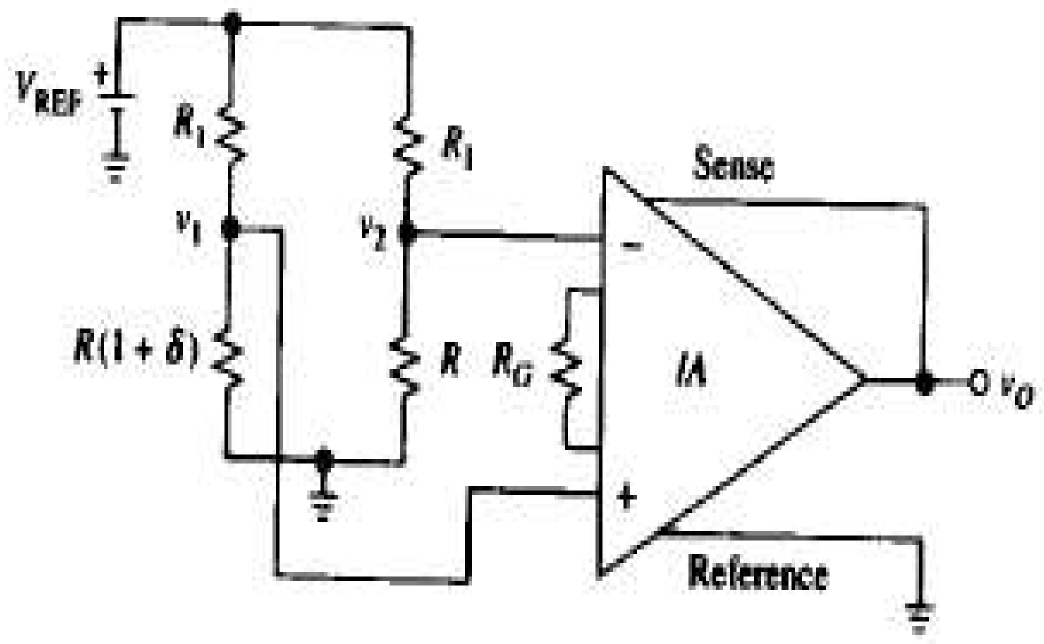
$$i_0 = \frac{V_{02}-V_L}{R_1} + \frac{V_0 - V_L}{R_2} = \frac{V_{02}}{R_1} + \frac{V_0}{R_2} - \left(\frac{1}{R_1}+\frac{1}{R_2}\right)V_L$$

$$= \frac{V_{02}}{R_1} - \frac{R_2}{R_2R_1}V_{01} - \left(\frac{1}{R_1}+\frac{1}{R_2}-\frac{1}{R_2}-\frac{R_2}{R_2R_1}\right)V_L$$

$$i_0 = \frac{1}{R_1}(V_{02}-V_{01})$$

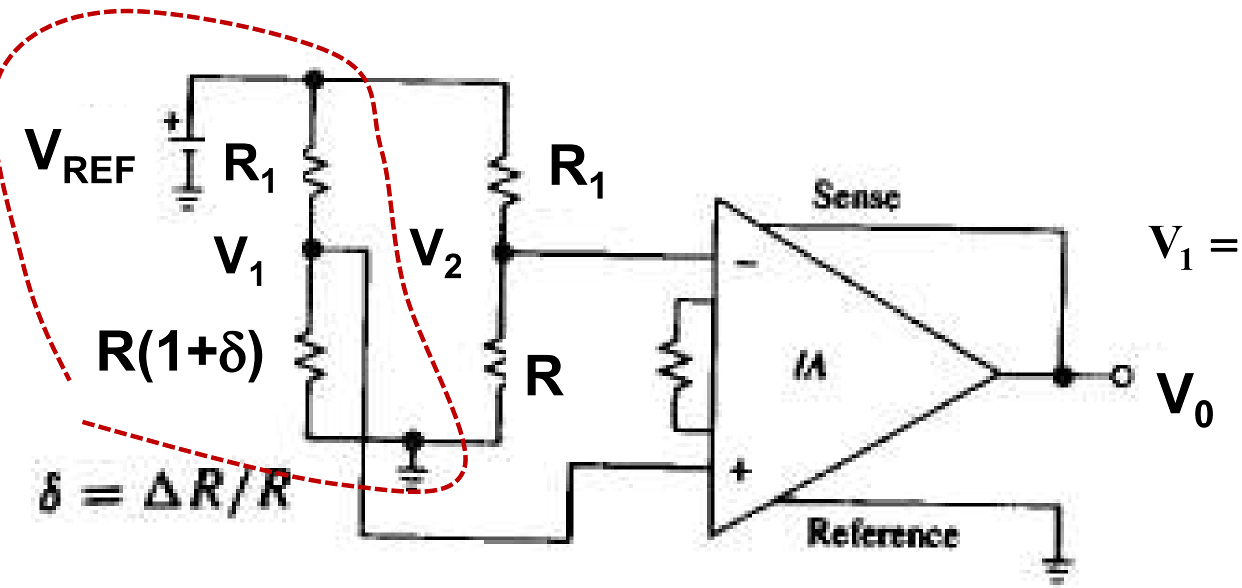
$$i_0 = \frac{1+\frac{2R_3}{R_G}}{R_1}(V_2 - V_1)$$

TRANSDUCER BRIDGE AMPLIFIER



- **Resistive transducers are devices whose resistance varies as a consequence of some environmental condition, such as temperature (thermistors; resistance temperature detectors, or RTDs), light (photoresistors), strain (strain gauges), and pressure (piezoresistive transducers).**
- **By making these devices part of a circuit, it is possible to produce an electric signal that, after suitable conditioning, can be used to monitor as well as control the physical process affecting the transducer.**
- In general it is desirable that the relationship between the final signal and the original physical variable be linear, so that the former can directly be calibrated in the physical units of the latter.
- Transducers play such an important role in measurement and control instrumentation that it is worth studying transducer circuits in some detail

TRANSDUCER BRIDGE AMPLIFIER: ANALYSIS



$\delta = \Delta R / R$

$$V_1 = \frac{R(1+\delta)}{R_1 + R(1+\delta)} V_{REF}$$

$$V_1 = \frac{R}{R_1 + R} V_{REF} + \frac{\delta V_{REF}}{2 + R_1/R + R/R_1 + (1 + R/R_1)\delta}$$

We are interested in 2nd term

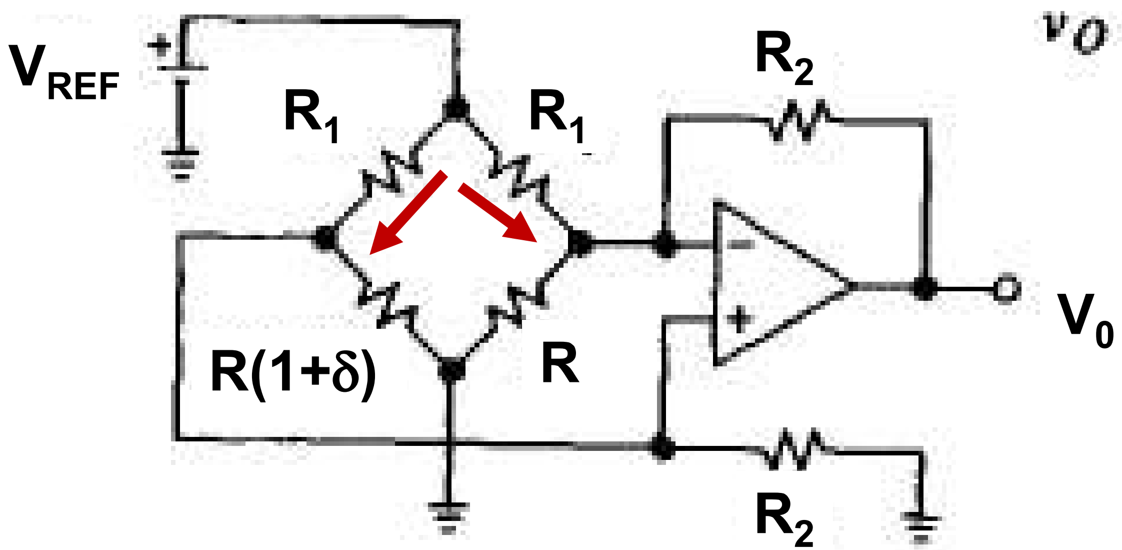
1st term can be eliminated by second voltage divider

$$V_2 = \frac{R}{R_1 + R} V_{REF} \qquad v_O = A(v_1 - v_2)$$

$$v_O = A V_{REF} \frac{\delta}{1 + R_1/R + (1 + R/R_1)(1+\delta)} \qquad \delta \ll 1 \qquad v_O \cong \frac{A V_{REF}}{2 + R_1/R + R/R_1} \delta$$

$$R_1 = R \qquad v_O = \frac{A V_{REF}}{4} \frac{\delta}{1 + \delta/2} \qquad v_O \cong \frac{A V_{REF}}{4} \delta$$

SINGLE OP-AMP TRANSDUCER BRIDGE AMPLIFIER



$$v_O = \frac{R_2}{R} V_{REF} \frac{\delta}{R_1/R + (1 + R_1/R_2)(1+\delta)}$$

For $\delta \ll 1$

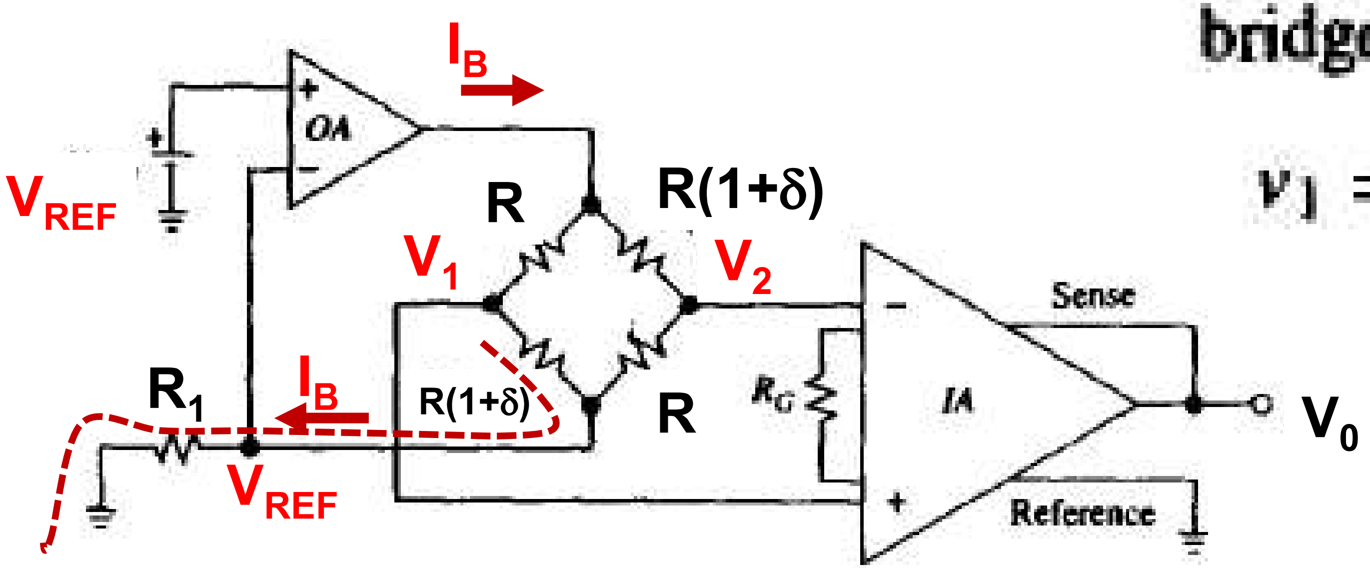
$$v_O \cong \frac{R_2}{R} V_{REF} \frac{\delta}{1 + R_1/R + R_1/R_2}$$

v_O depends linearly on δ

Response is linear as long as δ<<1

Is it possible to eliminate this limitation?

BRIDGE LINERIZATION BY CONSTANT CURENT DRIVE



bridge current $I_B = V_{REF}/R_1$

$$v_1 = V_{REF} + R(1+\delta)I_B/2$$

$$v_2 = V_{REF} + RI_B/2$$

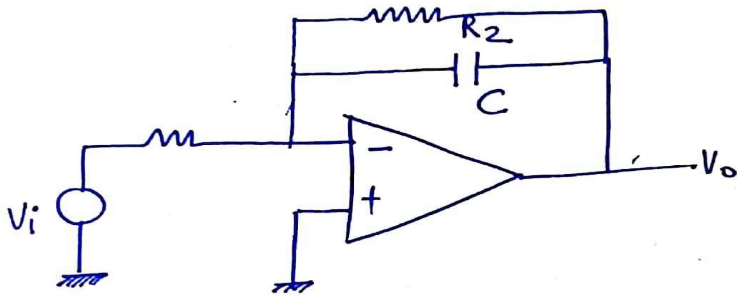
$$v_1 - v_2 = R\delta I_B/2$$

$$v_O = \frac{ARV_{REF}}{2R_1}\delta$$

LIC: LECTURE 8
ACTIVE FILTERS

1. ACTIVE LOW PASS FILTER WITH GAIN
2. ACTIVE HIGH PASS FILTER WITH GAIN
3. ACTIVE BAND PASS FILTER WITH GAIN
4. ACTIVE SECOND ORDER FILTERS: INTRODUCTION

LOW PASS FILTER WITH GAIN



Analysis: Let $Z_2 = R_2 // \frac{1}{SC}$

$$Z_2 = \frac{(R_2 \cdot 1/SC)}{R_2 + 1/SC} = \frac{R_2}{1 + R_2 CS}$$

- Output of the op-amp circuit

$$V_o = -\frac{Z_2}{R_1} \cdot V_i$$

Transfer function:

$$H(s) = \frac{V_o}{V_i} = \frac{-Z_2}{R_1}$$

$$H(s) = -\left[\frac{R_2}{1 + R_2 CS}\right] / R_1$$

$$\boxed{H(s) = \underbrace{-\left(\frac{R_2}{R_1}\right)}_{\text{Passband gain or DC gain} = H_{OLP}} \underbrace{\left[\frac{1}{1 + SRC}\right]}_{\text{Represents filtering action (LPF)}}} \text{ — Transfer function of Active LPF} \quad (1)$$

$$\boxed{H(s) = H_{OLP}\left(\frac{1}{1 + SR_2C}\right)} \quad (2)$$

where $H_{OLP} = \frac{+R_2}{R_1}$

put $s = j\omega$ in equ.(2)

$$H(j\omega) = H_{OLP}\left(\frac{1}{1 + j\omega R_2 C}\right)$$

$$\boxed{H(j\omega) = H_{OLP}\left(\frac{1}{1 + j\omega/\omega_o}\right)}$$

where $\omega_o = 1/R_2 C$

i.e. $\boxed{f_o = \frac{1}{2\pi R_2 C}}$ — cutoff freq. of LPF

$$\boxed{|H(j\omega)| = H_{OLP} \frac{1}{\sqrt{1 + (\omega/\omega_o)^2}}} \quad (3)$$

Magnitude of Transfer function

LOW PASS FILTER WITH GAIN

$$|H(j\omega)| = H_{OLP} \cdot \frac{1}{\sqrt{1+(\omega/\omega_0)^2}} \quad -(3)$$

<u>Case 1:</u> for frequencies $\omega << \omega_0$ [Low frequ. range)

As $\omega << \omega_0$; $\frac{\omega}{\omega_0} << 1$

i.e. $\left(1+\frac{\omega}{\omega_0}\right) \simeq 1$

$\therefore$ $\boxed{|H(j\omega)| = H_{OLP} = \text{Constant}}$

i.e. we have flat response for low frequencies.

<u>Case 2:</u> When $\omega = \omega_0$

$$\boxed{|H(j\omega)| = H_{OLP} \cdot \frac{1}{\sqrt{2}}}$$

ω_0 = cut-off frequency

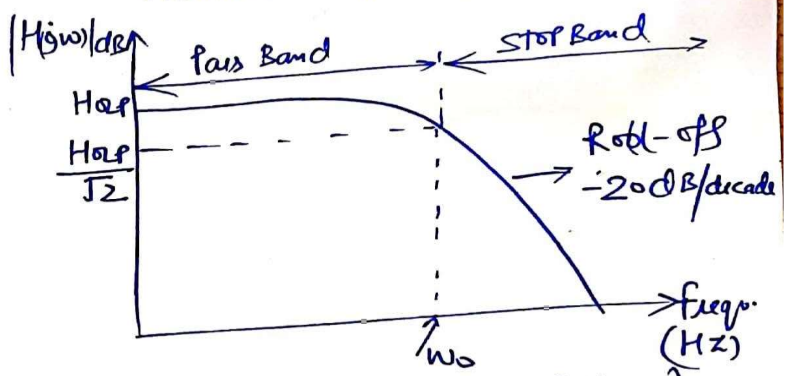
i.e. $|H(j\omega)|_{dB}$ At $\omega = \omega_0$ $\approx$ 3 dB down of max value of H_{OLP}

<u>Case 3:</u> for frequencies $\omega >> \omega_0$

$$\left(1 + \omega/\omega_0\right) \simeq \frac{\omega}{\omega_0}$$

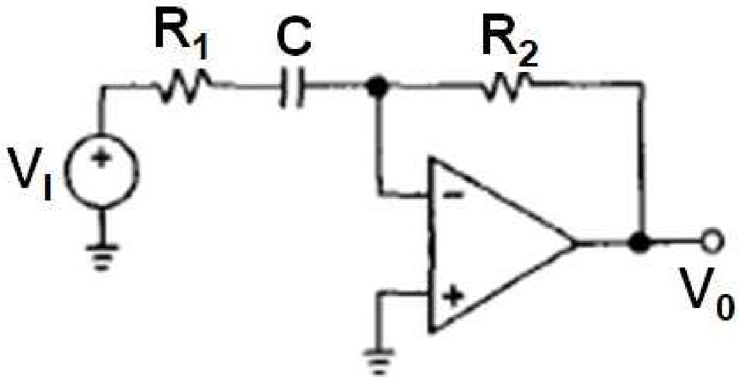
$$|H(j\omega)| = H_{OLP} \cdot \frac{\omega_0}{\omega}$$

- It means that as I/P frequency (ω) increases $\longrightarrow$ $|H(j\omega)|$ decreases



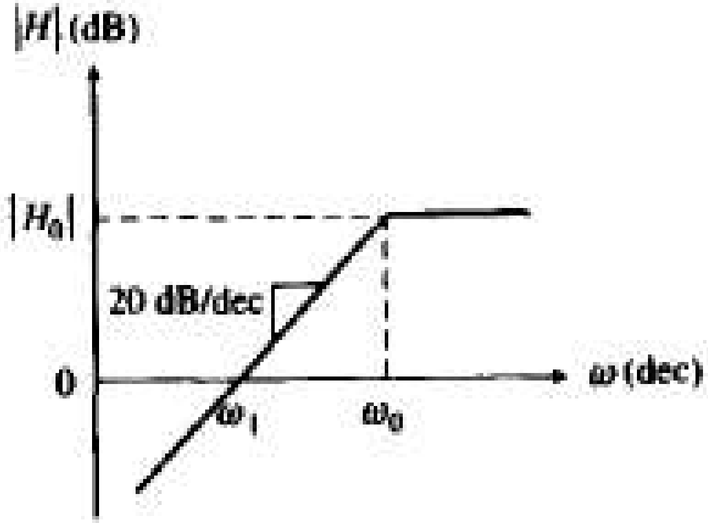
[Response of Low pass filter (magnitude plot)]

HIGH PASS FILTER WITH GAIN



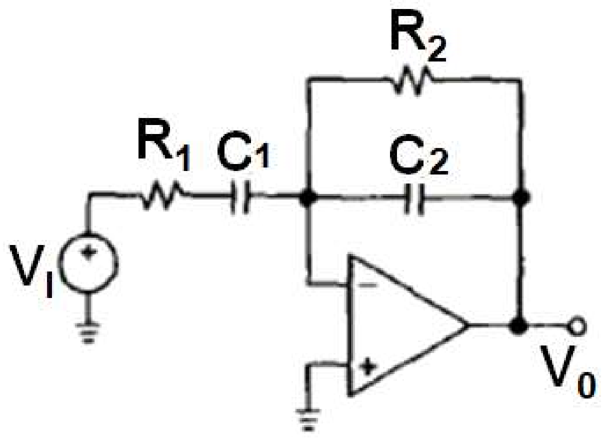
$$\frac{V_0}{V_I} = -\frac{R_2}{R_1 + 1/sC} = -\frac{sCR_2}{1 + sCR_1} = -\frac{R_2}{R_1}\frac{sCR_1}{1 + sCR_1}$$

$$H(j\omega) = H_0 \frac{j\omega/\omega_0}{1 + j\omega/\omega_0} \qquad H_0 = -\frac{R_2}{R_1} \qquad \omega_0 = \frac{1}{R_1 C}$$



H_0 is High frequency gain
ω_0 is 3dB frequency

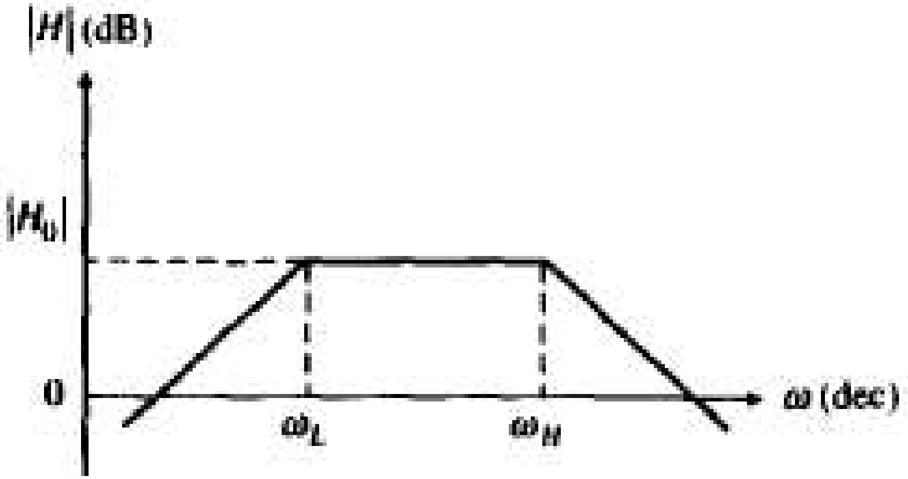
WIDEBAND BAND PASS FILTER WITH GAIN



$$\frac{V_0}{V_I} = -\frac{R_2}{1+sC_2R_2} \Big/ \frac{1+sC_1R_1}{sC_1} = -\frac{R_2}{R_1}\frac{1}{1+sC_2R_2}\frac{sC_1R_1}{1+sCR_1}$$

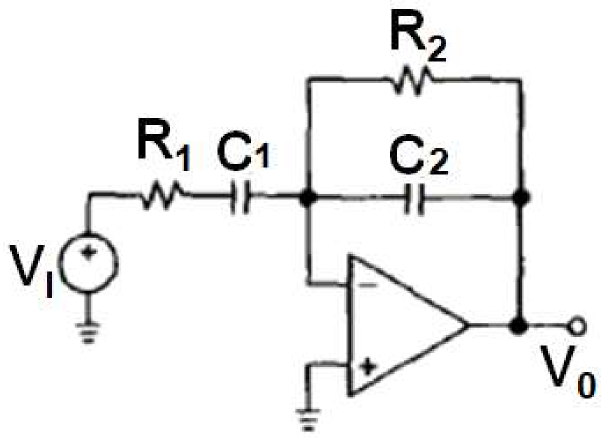
$$H(j\omega) = H_0 \frac{j\omega/\omega_L}{(1+j\omega/\omega_L)(1+j\omega/\omega_H)} \quad H_0 = -\frac{R_2}{R_1} \quad \omega_L = \frac{1}{R_1C_1}$$

$$\omega_H = \frac{1}{R_2C_2}$$



H_0 is mid-frequency gain
ω_L is lower 3dB frequency
ω_H is higher 3dB frequency

Design a BPF for H_0 = 20dB and audio frequency range



H_0 = 20dB → Gain = 10

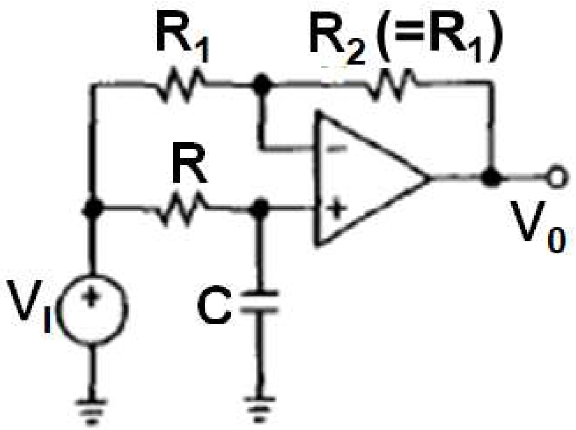
$$\text{gain} = 10 \Rightarrow \frac{R_2}{R_1} = 10$$ If $R_1 = 10k\Omega$, $R_2 = 100k\Omega$

Audio frequency → f_L = 20Hz & f_H = 20kHz

$$\omega_L = \frac{1}{R_1 C_1} = 2\pi 20 \Rightarrow C_1 = 0.7958\mu F$$

$$\omega_H = \frac{1}{R_2 C_2} = 2\pi 20000 \Rightarrow C_2 = 39.78pF$$

Phase Shifters

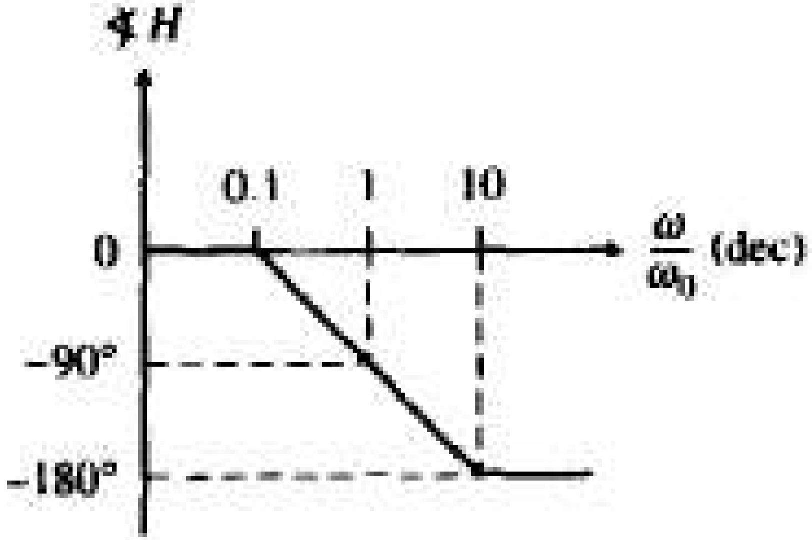


$$H(s) = 2\frac{1}{1+sCR} - 1 = \frac{1-sCR}{1+sCR}$$

$$H(j\omega) = \frac{1 - j\omega/\omega_0}{1 + j\omega/\omega_0} = 1\angle -2\tan^{-1}(\omega/\omega_0)$$

From $|H(j\omega)|$ point, it is a all pass filter

From $\angle H(j\omega)$ point it is a phase shifter



phase = 0° as f→ 0
phase = 90° at f = f_0 = 1/RC
phase = 180° as f→ ∞

LPF $$H(j\omega) = H_0 \frac{1}{1 + j\omega/\omega_0}$$

HPF $$H(j\omega) = H_0 \frac{j\omega/\omega_0}{1 + j\omega/\omega_0}$$

APF $$H(j\omega) = \frac{1 - j\omega/\omega_0}{1 + j\omega/\omega_0}$$

Numerator decides type of filter

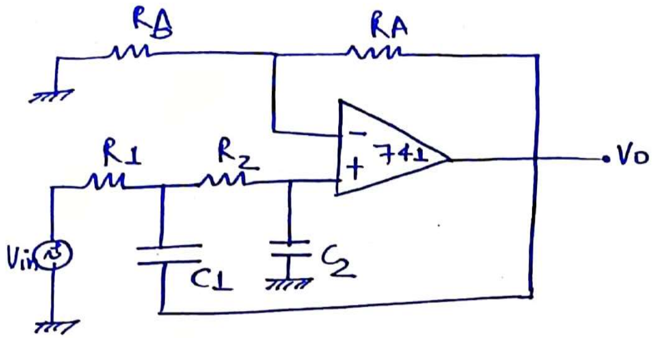
If numerator $N(j\omega)$ =1 → LPF

If numerator $N(j\omega)$ =$j\omega/\omega_0$ → HPF

If numerator $N(j\omega)$ =1-($j\omega/\omega_0$) → APF

H_0 is acting as scaling factor
Moves response up or down

SECOND ORDER KRC FILTER

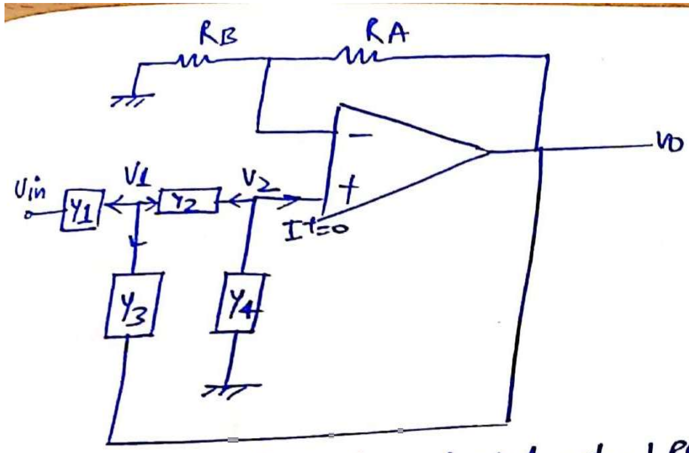


Gain of Non-inverting amplifier

$$\boxed{K = 1 + \frac{R_A}{R_B}} \ *$$

- For frequencies $\boxed{f < f_0}$, i.e. in low frequency region, reactance $\left(X_C = \frac{1}{2\pi f C}\right)$ offered by both capacitors are very high. So both capacitors acts as open circuit.
- So, op-amp allows all the input to reach at the output with gain K below f_0.
- As input frequency increases i.e. in the high frequency region.
- Reactance $X_C = \frac{1}{2\pi f C} \downarrow$ so output of amplifier goes on reducing.
- So, behaves as low pass filter.

SECOND ORDER KRC FILTER



General structure of 2nd-order LPF'

Applying KCL at V_1, we get:

$$(V_1 - V_{in})Y_1 + (V_1 - V_o)Y_3 + (V_1 - V_2)Y_2 = 0$$

$$(Y_1+Y_2+Y_3)V_1 - V_oY_3 - V_2Y_2 = V_{in}Y_1$$

$$V_o = \left[1 + \frac{R_A}{R_B}\right]V_2$$

$$\boxed{V_o = KV_2}$$

$$(Y_1+Y_2+Y_3)V_1 - V_oY_3 - \frac{V_o}{K}Y_2 = V_{in}Y_1$$

$$(Y_1+Y_2+Y_3)V_1 - \left(\frac{Y_2}{K} + Y_3\right)V_o = Y_1 \cdot V_{in} \quad (1)$$

Now KCL at node V_2

$$(V_2 - V_1)Y_2 + V_2Y_4 = 0$$

$+0 \;\; \because I^+ = 0$

$$[Y_2+Y_4]V_2 = V_1Y_2$$

$$(Y_2+Y_4)\frac{V_o}{K} = V_1Y_2$$

$$\boxed{V_1 = \frac{Y_2+Y_4}{KY_2} \cdot V_o} \quad (2)$$

Substitute (2) in (1) we get

$$(Y_1+Y_2+Y_3)\left(\frac{Y_2+Y_4}{KY_2}\right)V_o - \left(\frac{Y_2}{K} + Y_3\right)V_o = Y_1 \cdot V_{in}$$

SECOND ORDER KRC FILTER

$$H(s) = \frac{V_o}{V_{in}}$$

$$\boxed{H(s) = \frac{K Y_1 Y_2}{Y_1 Y_2 + (Y_1 + Y_2 + Y_3) Y_4 + (1-K) Y_2 Y_3}}^{*} \quad -(3)$$

for a LPF:

$$Y_1 = \frac{1}{R_1}, \quad Y_2 = \frac{1}{R_2}, \quad Y_3 = C_1 s, \quad Y_4 = C s_2$$

$$\boxed{H(s) = \frac{K}{1 + R_1 R_2 C_1 C_2 s^2 + [(1-K) R_1 C_1 + R_1 C_2 + R_2 C_2] s}} \quad -(4)$$

Comparing with 2nd order T.F.

$$H(j\omega) = \frac{H_{0LP}}{1 - (\omega/\omega_0)^2 + j(\omega/\omega_0) Q}$$

Comparing, we get: put $s = j\omega$ in eqn.(4)

$$\boxed{H_{0LP} = K = 1 + \frac{R_A}{R_B}}^{*} \qquad \cancel{\frac{1}{\omega_0^2}} \cancel{=} \cancel{\frac{1}{\sqrt{R_1 R_2 C_1 C_2}}}$$

$$\frac{1}{\omega_0^2} = R_1 R_2 C_1 C_2 \qquad \boxed{\omega_0 = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}}^{*}$$

SECOND ORDER KRC FILTER

$$\frac{1}{\omega_0 Q} = (1-K) R_1 C_1 + R_2 C_2 + R_1 C_1$$

$$\& \quad \omega_0 = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

$$Q = \frac{1}{(1-K)\sqrt{\frac{R_1 C_1}{R_2 C_2}} + \sqrt{\frac{R_2 C_2}{R_1 C_1}} + \sqrt{\frac{R_1 C_2}{R_2 C_1}}}$$

Quality factor

If: $R_1 = R_2 = R$, $C_1 = C_2 = C$

$$\boxed{Q = \frac{1}{3-K}}$$

$\alpha \rightarrow$ damping ratio

$\boxed{\alpha = 3-K}$; By choosing the value of K we can get damping ratio