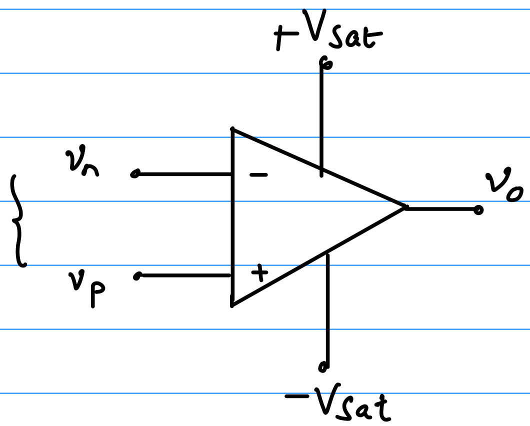
Operational Amplifiers

→ Op-Amps-

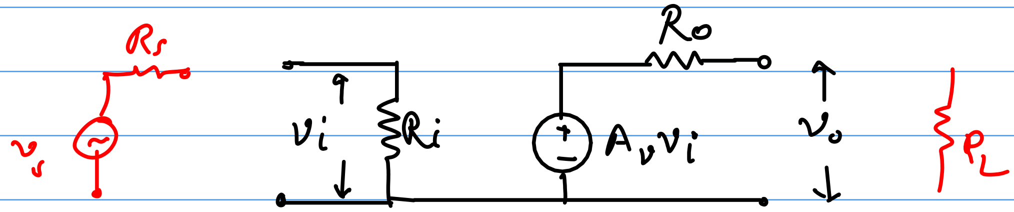
IC 741
max supply = ±15 V

$v_p - v_n = v_i$



* It is a Voltage Amp or a VCVS

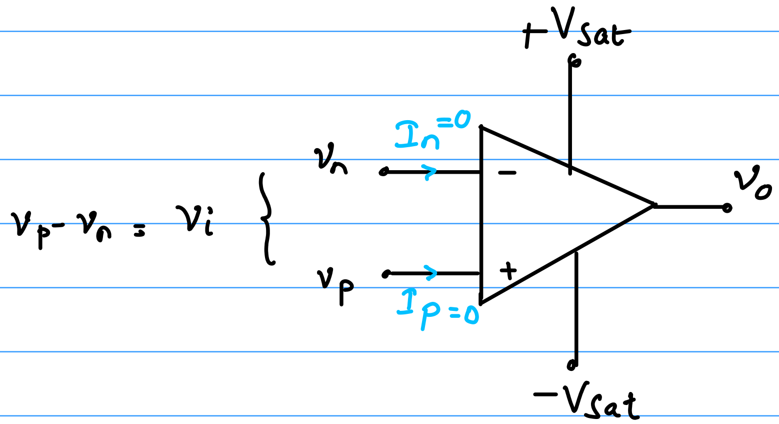
* Equivalent ckt :



*

	Ideal Op-Amp	Practical
Open loop Gain, A_v	∞	10^6
I/p Resistance, R_i	∞	$10^6\ \Omega$
O/p Resistance, R_o	0	$10-100\ \Omega$
Gain BW Product, GBW	∞	10^6 Hz or 1 MHz
Bandwidth, BW	∞	1 MHz (i.e. when gain = 1 or 0 dB

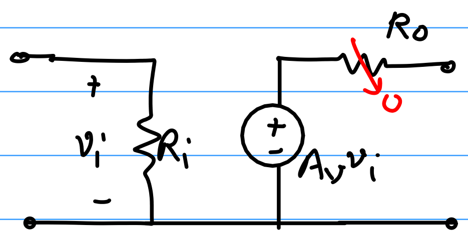
Open loop Operation:



Ideal Op-Amp, $A_v = \infty$

$\boxed{I_n = I_p = 0}$ $\because R_i = \infty$ (whether O.L. or C.L.)

$\boxed{v_o = A_v v_i}$ $(\because R_o = 0)$



$v_o = A_v v_i$ if $R_o = 0$

But $\because$ $A_v = \infty$, $v_o \to \infty$ (Not possible, limited by $\pm V_{sat}$)

So, if $v_i = +ve \longrightarrow v_o = +V_{sat}$ *

if $v_i = -ve \longrightarrow v_o = -V_{sat}$ *

* So, for O.L. operation:

$v_i = +ve \Rightarrow v_p - v_n > 0 \Rightarrow v_p > v_n \rightarrow v_o = +V_{sat}$

$v_i = -ve \Rightarrow v_p - v_n < 0 \Rightarrow v_n > v_p \rightarrow v_o = -V_{sat}$

* In O.L., Op-Amp acts as a comparator.

if $v_p > v_n \longrightarrow v_o = +V_{sat}$ (logic '1')

if $v_p < v_n \longrightarrow v_o = -V_{sat}$ (logic '0')

→ <u>Closed loop Operation:</u> (feedback)

(i) <u>+ve feedback</u>

* o/p connected to +ve i/p terminal (p) directly or through some component or combo of components (like R, L, C, diode, transistors etc.)

* $|A_{CL}| >> |A_{OL}| \; (= A_v)$

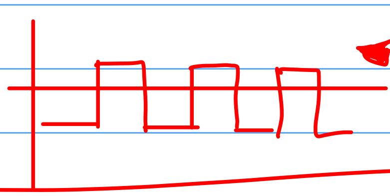
* Since A_v = v. large,

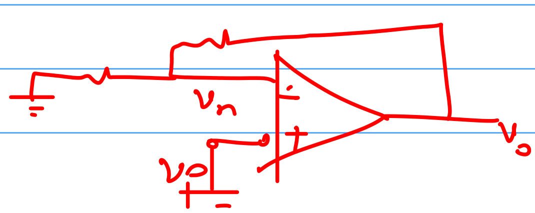
  $A_{CL} \to \infty$ as well

* $v_o = \pm V_{sat}$ depending on whether $v_p > v_n$ or $v_p < v_n$

  (Just like O.L. case)

* Used in Oscillators, Schmidt trigger etc.





(ii) <u>−ve feedback</u>

o/p connected to −ve i/p terminal (n) directly or through some component or combo of components (like R, L, C, diode, transistors etc.)

* $|A_{CL}| << |A_{OL}|$ or $|A_v|$

* e.g. $|A_{CL}|$ could be 10

* $|v_o| \leq |V_{sat}|$

* $|v_o|$ depends on source vol. (Amplifier)

** In −ve f.b., $\boxed{v_i = 0}$ (always, regardless of source vol.)

i.e. $v_p = v_n$ (−ve f.b. only)

VIRTUAL SHORT

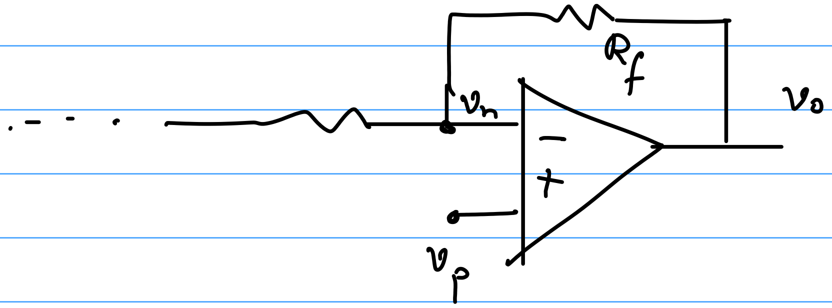
If v_p or $v_n = 0$, both are $0 \Rightarrow$ VIRTUAL GROUND

→ ONLY for −ve f.b.

Not for +ve f.b. or O.L.

* Virtual Short & Virtual Ground :

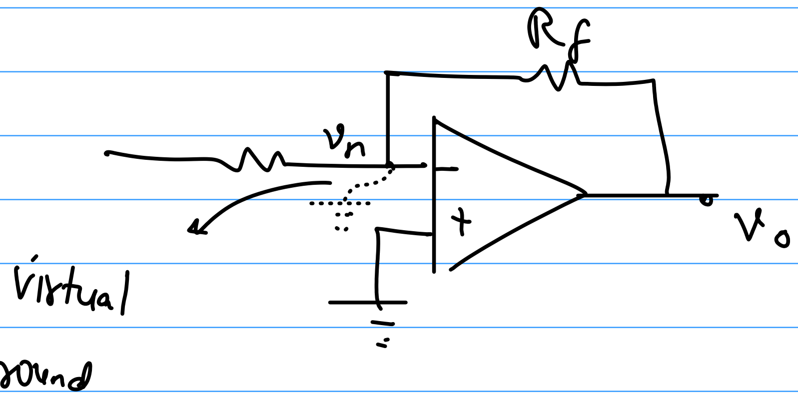
[Happens only if A_v (O.L gain) is very large]



then

$v_p = v_n$

Virtual short

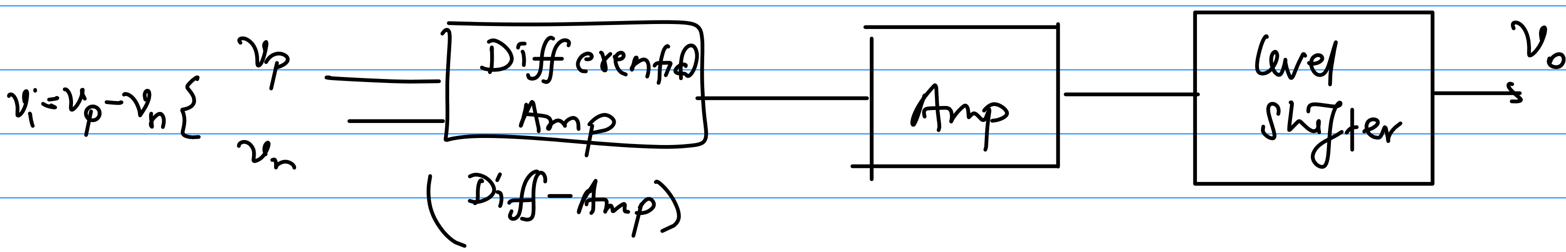


then $v_n = 0$

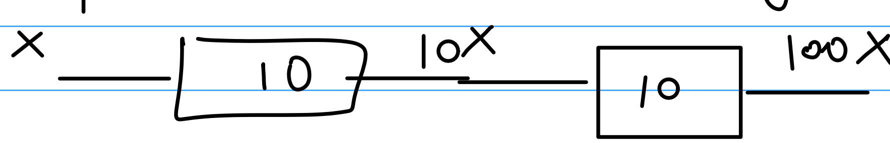
$\because$ $v_p = 0$

Virtual Ground

HW) Read about the internal ckt stages of Op-Amp



* Op amp is a Multistage Amplifier.



Negative feedback :

Modes of Operation :

1) Inverting Amp

* Phase diff b/w O/p & source, $\phi = 180'$

* $v_o \propto -v_s$

2) Non-Inverting Amp

* $\phi = 0'$ or $360'$

* $v_o \propto +v_s$

3) Differential Mode :-

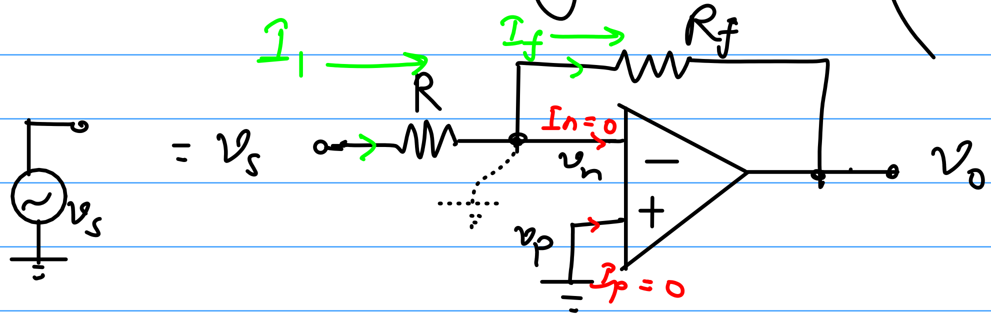
$$\boxed{v_o \propto (v_p - v_n)}$$

if A_v is not very large

$\therefore$ Here virtual short is not applicable so, $v_p \neq v_n$

* Inverting Amp :

(Ideal OpAmps $A_i = \infty$, $R_i = \infty$, $R_0 = 0$)



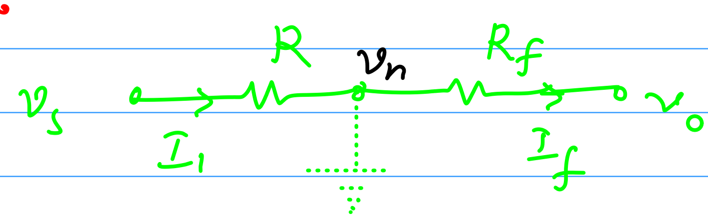
$v_n = 0$

$\because v_p = 0$

(virtual Ground)

$v_0 = ?$

$\Rightarrow$



* KCL $\rightarrow$ $I_1 = I_f + I_n = I_f$ $\quad (\because I_n = 0)$

$\Rightarrow \quad I_1 = I_f$ —— (1)

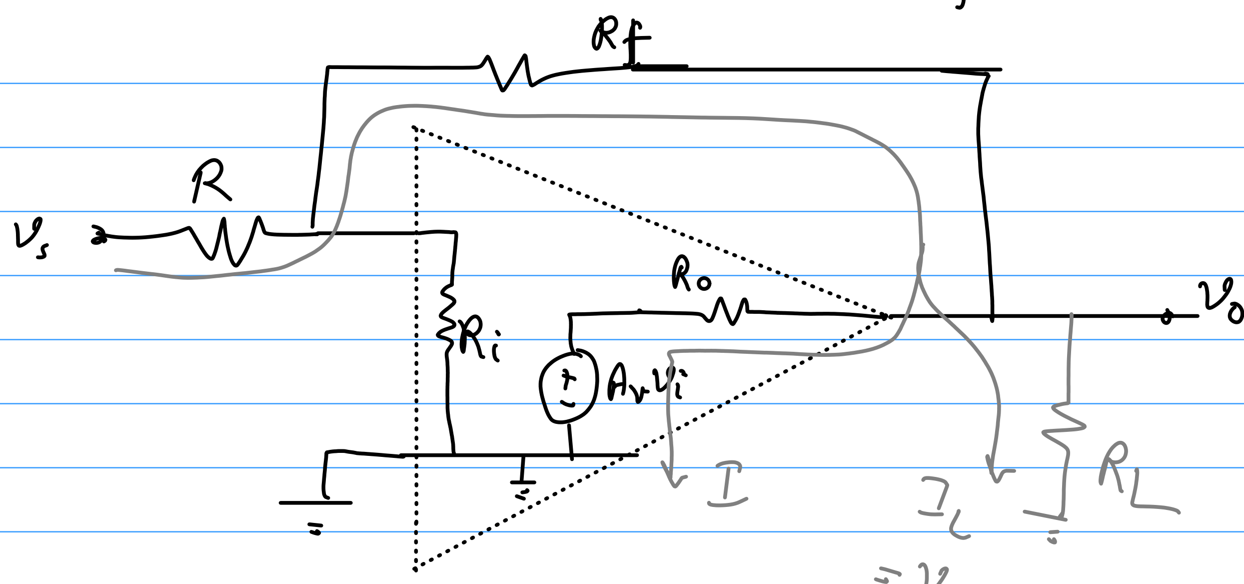
Ohm's law :— $\quad I_1 = \dfrac{v_s - \overset{0}{v_n}}{R}$

$\Rightarrow \quad I_1 = \dfrac{v_s}{R}$ —— (2) $\quad (\because v_n = 0)$

Ohm's law :— $\quad I_f = \dfrac{\overset{0}{v_n} - v_0}{R_f}$

$\Rightarrow \quad I_f = -\dfrac{v_0}{R_f}$ —— (3)

Now from ①, $I_1 = I_f$



$$I_L = \frac{v_o}{R_L}$$

v_o will depend on R_L for Ideal opamp $\because$ $R_o = 0$

So,

$$I_1 = I_f$$

$$\frac{v_s}{R} = -\frac{v_o}{R_f}$$

$$\Rightarrow \boxed{v_o = \left(-\frac{R_f}{R}\right) v_s}$$

(or)

$$\boxed{\frac{v_o}{v_s} = A_{CL} = -\frac{R_f}{R}}$$

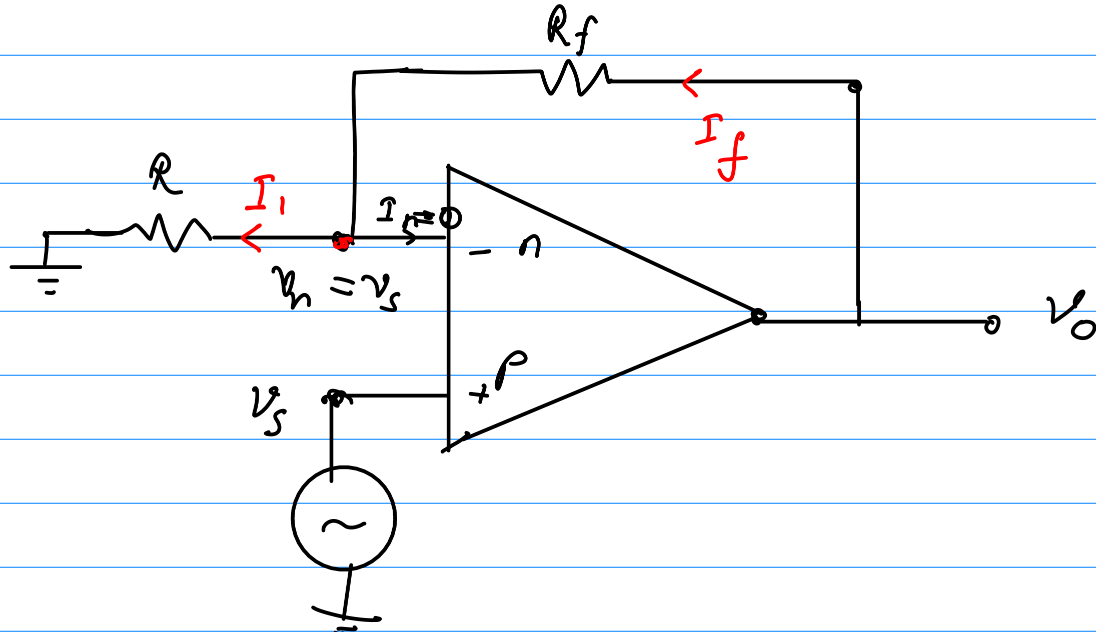
Gain of Inverting Amp. (Always)

$v_o \propto -v_s$

$$\boxed{\phi = 180^\circ}$$

hence <u>inverting</u>

→ Non Inverting Amp :-



<u>Virtual Short</u> → $v_p = v_s$ (by connection)

$v_n = v_p$ (∵ -ve f.b)

So, $v_n = v_s$

KCL at 'n' node ⇒ $I_1 = I_f$

<u>Ohms law</u> : → $I_1 = \dfrac{v_n - 0}{R} = \dfrac{v_s - 0}{R}$

$\Rightarrow I_1 = \dfrac{v_s}{R}$

$I_f = \dfrac{v_o - v_n}{R_f} = \dfrac{v_o - v_s}{R_f}$

$$= \because \quad I_1 = I_f$$

$$\frac{v_s}{R} = \frac{v_o - v_s}{R_f}$$

$$\Rightarrow v_s\left(\frac{1}{R} + \frac{1}{R_f}\right) = \frac{v_o}{R_f}$$

$$\Rightarrow v_o = R_f\left(\frac{1}{R_f} + \frac{1}{R}\right)v_s$$

$$\Rightarrow \boxed{v_o = \left(1 + \frac{R_f}{R}\right)v_s}$$

or

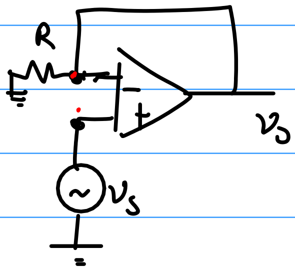
$$\boxed{\frac{v_o}{v_s} = \underset{+ve}{A_{CL}} = \left(1 + \frac{R_f}{R}\right)}$$

** Non inverting Amp gain

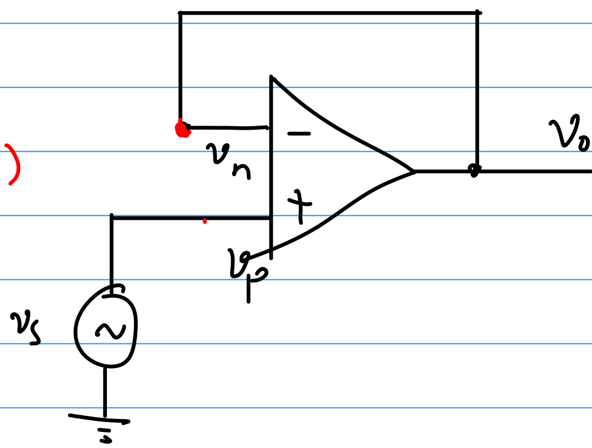
Special case of Non Inv Amp :

$R_f = 0$

$R \neq 0$



(or)



Voltage-Follower

$v_p = v_s$, $v_n = v_s$ ($\because$ -ve f.b virtual short)

so $\boxed{v_o = v_n = v_s}$

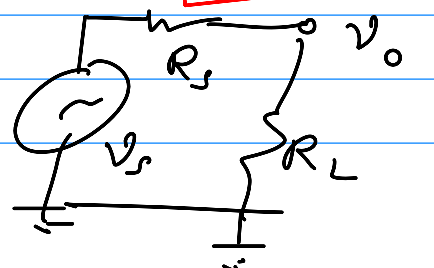
($v_o = v_n$: short ckt)

* $\boxed{v_o = v_s}$ *

Voltage Follower **

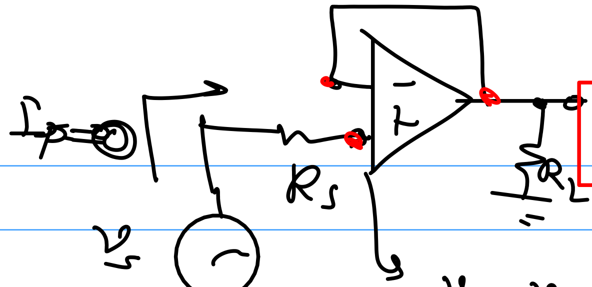
Buffer (or driver) : They are used for impedance matching.

e.g.



$$v_o = \left(\frac{R_L}{R_L + R_s}\right) v_s \neq v_s$$

$< v_s$



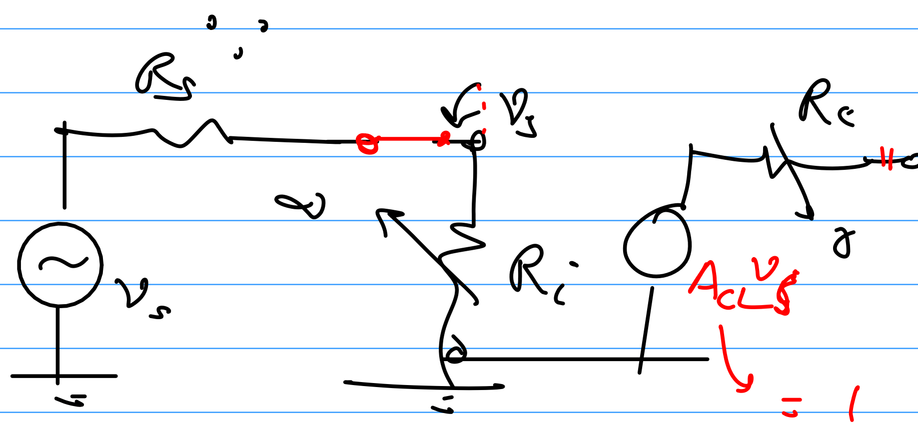
$v_p = v_s$

$$\boxed{v_o = v_s}$$

$$I_L = \frac{v_o}{R_L} = \frac{v_s}{R_L}$$

But $\boxed{v_o = v_s}$

$$\therefore V_{R_s} = 0$$



$A_{CL} v_s$

$= 1$

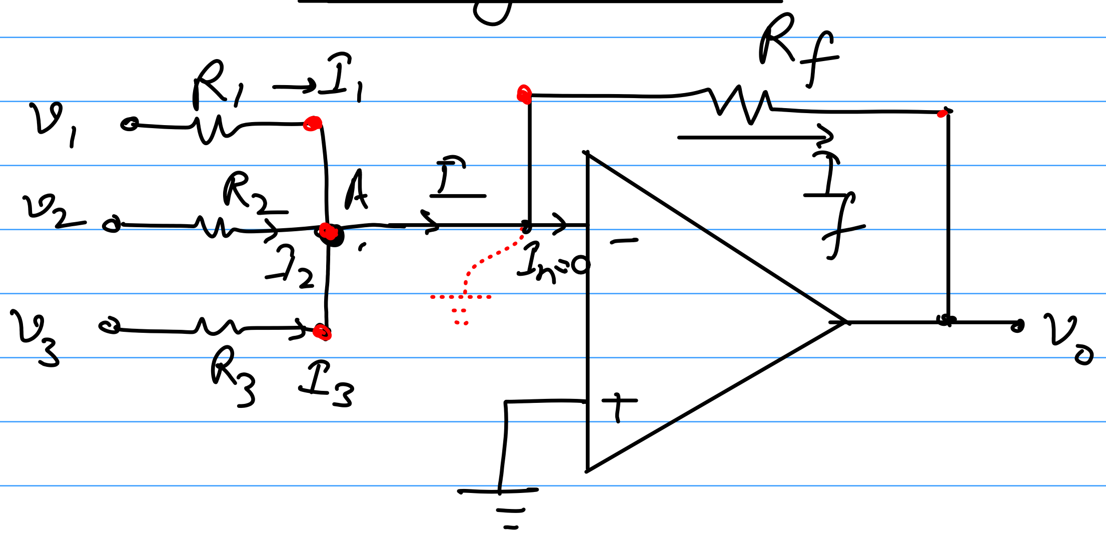
$v_o = v_s$

$$A_{CL} = \left(1 + \frac{R_F \to 0}{R}\right) = 1$$

Op-Amp Ckts :

1) Adder :

(1) Inverting Adder :



$$\boxed{v_A = 0} \quad \because \quad V_A = V_n = V_p = 0 \quad \text{(virtual gnd)}$$

$$I_1 = \frac{V_1 - \cancel{V_A}^{\,0}}{R_1} \Rightarrow I_1 = \frac{v_1}{R_1}$$

||ly $\qquad I_2 = \dfrac{v_2}{R_2}$

& $\qquad I_3 = \dfrac{v_3}{R_3}$

KCL at A :-

$$I_1 + I_2 + I_3 = I = I_f \quad \text{--- (1)}$$

Also,

$$I_f = \frac{v_n - v_0}{R_f} = \frac{0 - v_0}{R_f}$$

$$I_f = -\frac{v_0}{R_f}$$

from (1),

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_0}{R_f}$$

$$\Rightarrow \quad v_0 = -R_f\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]$$

if $R_1 = R_2 = R_3 = R$

$$\Rightarrow \quad v_0 = \left(-\frac{R_f}{R}\right)\underbrace{[v_1 + v_2 + v_3]}_{\text{sum}}$$

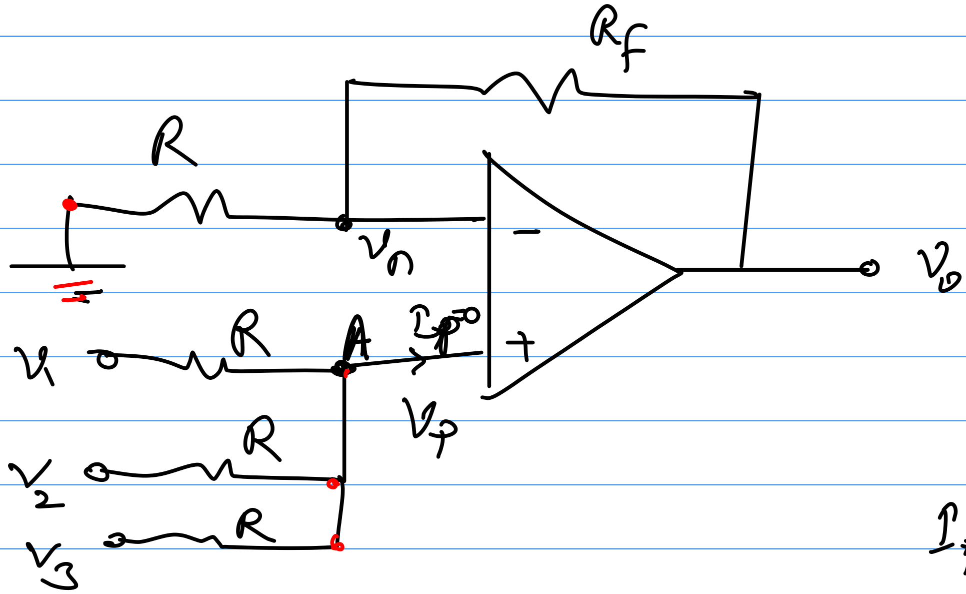
gain of inv. amp

If $R_f = R$

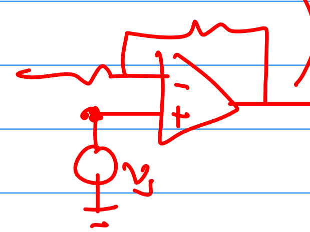
then $\boxed{v_o = -(v_1 + v_2 + v_3)}$

inverting

2) Non Inv Adder:



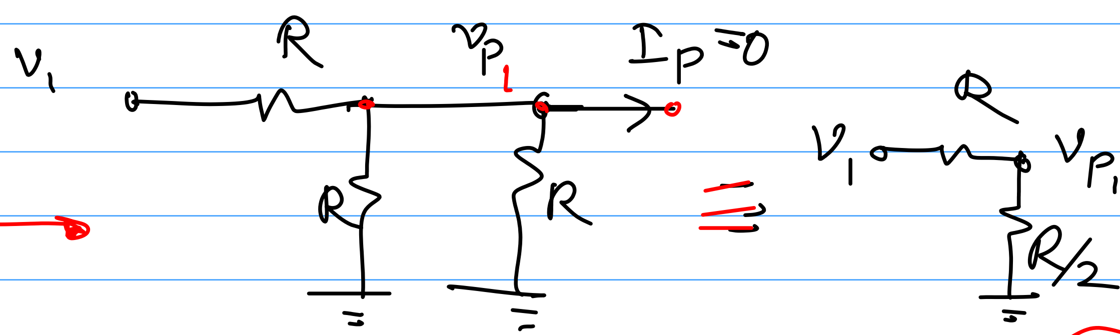
$$v_o = \underbrace{\left(1 + \frac{R_f}{R}\right)}_{\text{gain of Non-Inv-Amp}} v_p$$



$I_p = 0$

Principle of Superposition*:

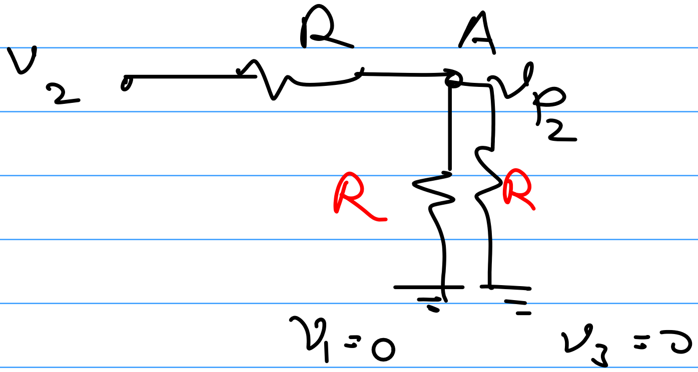
(1)



$v_2 = 0$ $v_3 = 0$

$$v_P = \frac{R/2}{R + R/2} v_1$$

$$\boxed{v_{P_1} = \frac{v_1}{3}}$$



$$\boxed{v_{P_2} = \frac{v_2}{3}}$$

& Similarly, $\boxed{v_{P_3} = \frac{v_3}{3}}$

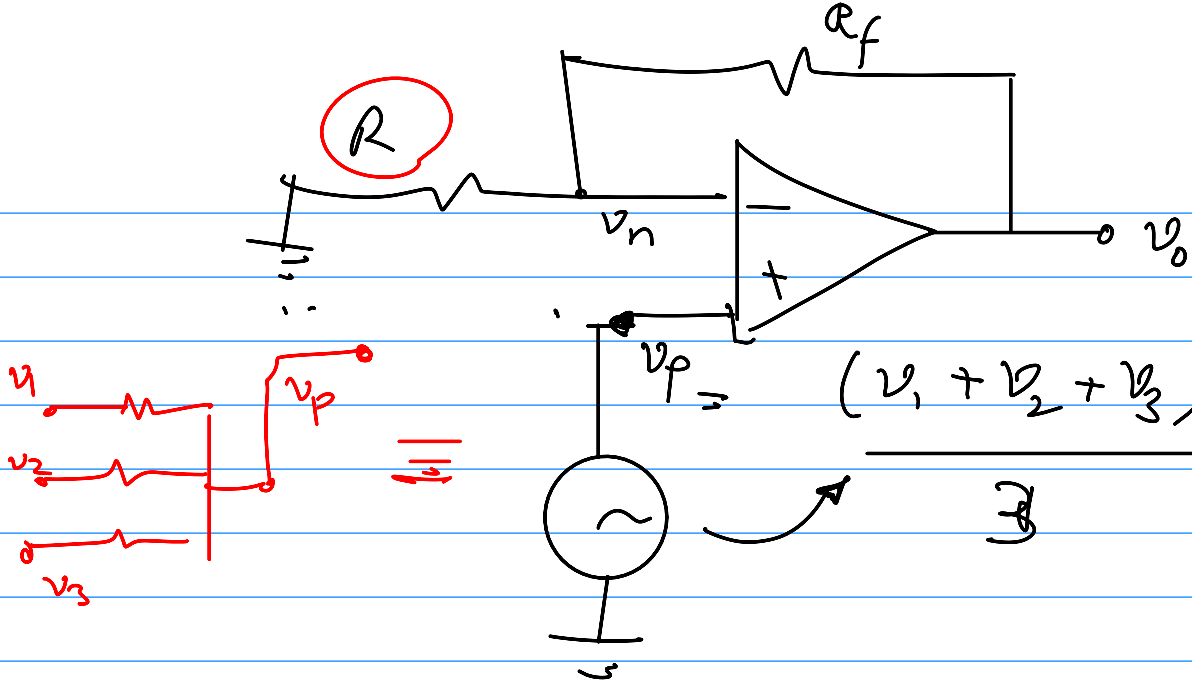
*Superposition :

total effect = Algebraic sum of individual effects

$$v_P = v_{P_1} + v_{P_2} + v_{P_3}$$

$$v_P = \frac{v_1}{3} + \frac{v_2}{3} + \frac{v_3}{3}$$

$$\Rightarrow \boxed{v_P = \frac{(v_1 + v_2 + v_3)}{3}}$$



$$v_p = \frac{(v_1 + v_2 + v_3)}{3} = v_s$$

$$v_o = \left(1 + \frac{R_f}{R}\right) v_s$$

$v_s = v_p$

Non inv. Amp. :-

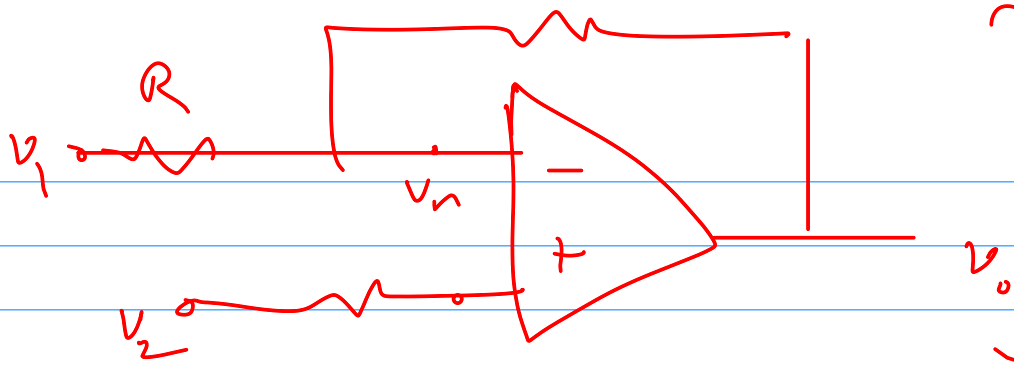
$$v_o = \left(1 + \frac{R_f}{R}\right) v_p$$

$$\Rightarrow \boxed{v_o = \left(1 + \frac{R_f}{R}\right) \left[\frac{v_1 + v_2 + v_3}{3}\right]}$$

if $\left(1 + \frac{R_f}{R}\right) = 3$ (or) $\boxed{\frac{R_f}{R} = 2}$

(or) $\boxed{R_f = 2R}$

then $\boxed{v_o = (v_1 + v_2 + v_3)}$

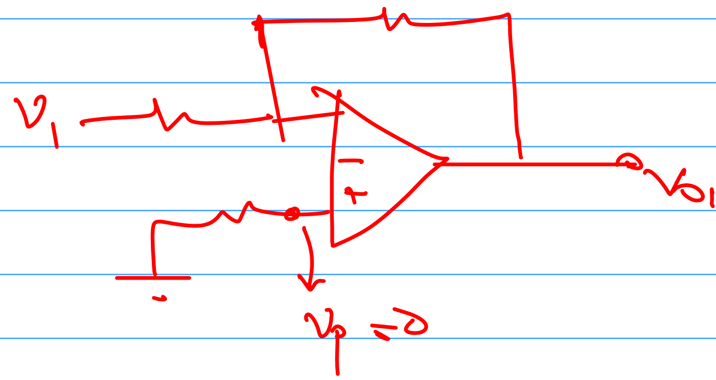


$$V_n = V_2$$

$$\frac{V_1 - V_2}{R} = \frac{V_2 - V_0}{R_F}$$

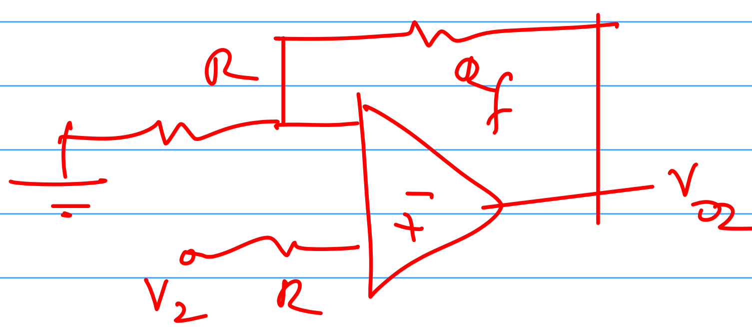
Superposition :–

(i)



$$V_{o1} = -\left(\frac{R_f}{R}\right) V_1$$

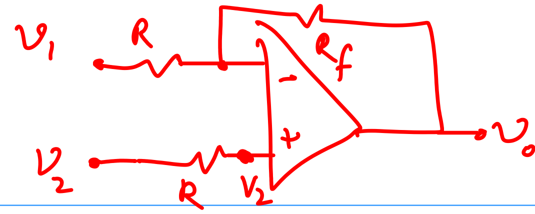
(ii)



$$V_{o2} = \left(1 + \frac{R_f}{R}\right) V_2$$

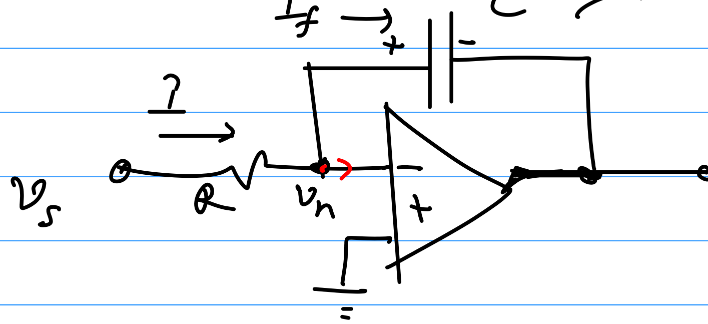
$$V_0 = V_{o1} + V_{o2} \Rightarrow \left(1 + \frac{R_f}{R}\right) V_2 - \left(\frac{R_f}{R}\right) V_1$$

Subtractor ? HW



Integrator :

$v_c = v_n - v_o$



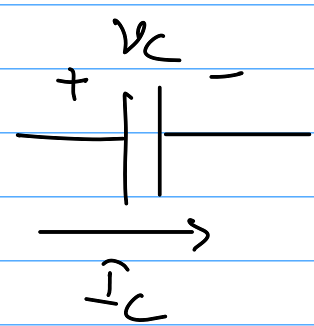
$v_o \propto -\int v_s \, dt$

$v_n = 0 \quad (\because \text{-ve f/b , V.G.})$

$I = \frac{v_s}{R} \quad \because \quad v_n = 0$

I_f = $\underbrace{\text{current through}}$ C

$I_c = C \frac{dV_c}{dt}$ where V_c is vol across cap



So, $$I_f = C\frac{dV_c}{dt} = C\frac{d(V_n - V_0)}{dt}$$

$V_n = 0$

so, $$I_f = -C\frac{dV_0}{dt} = I \quad (\text{by KCL})$$

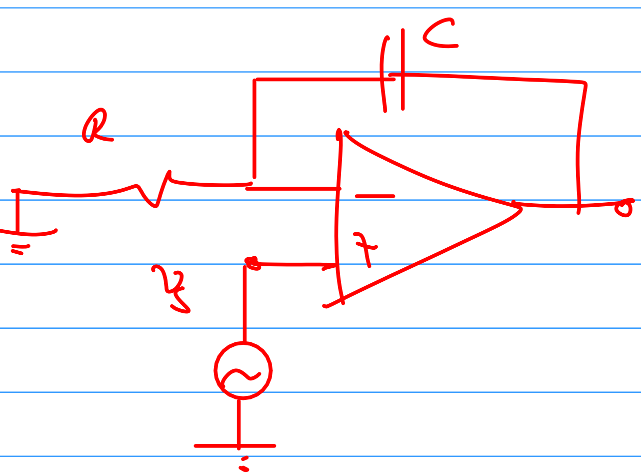
So, $$-C\frac{dV_0}{dt} = \frac{V_s}{R}$$

Integrate both sides

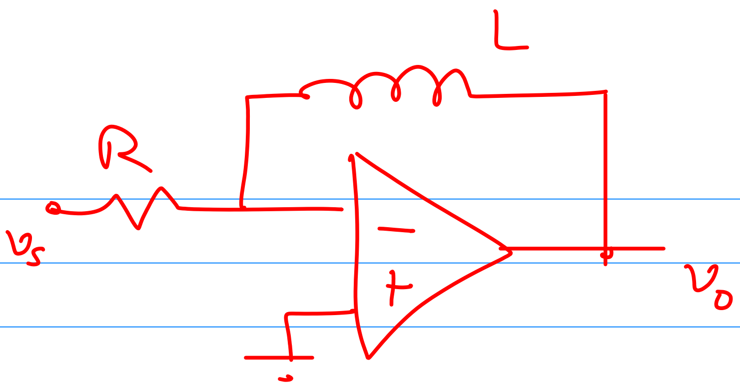
$$\boxed{V_0 = -\frac{1}{RC}\int V_s \, dt}$$

V_0 is integration of V_s with -ve sign

"Inverting" → ∵ V_s connected at -ve terminal



$$V_0 = +\frac{1}{RC}\int V_s \, dt$$

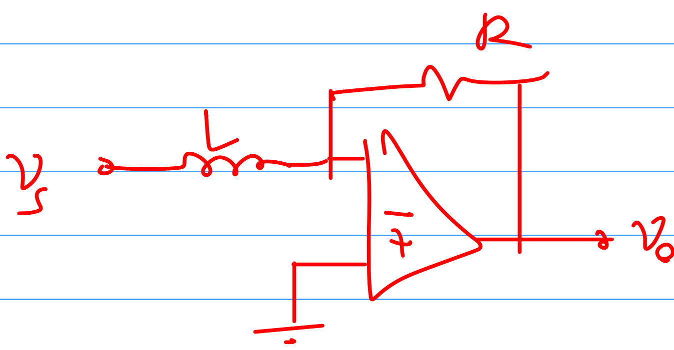


$$v_L = L\frac{dI_L}{dt}$$

$$0 - V_o = L\frac{dI_f}{dt} = L\frac{d}{dt}(I) = L\frac{d}{dt}(v_s/R)$$

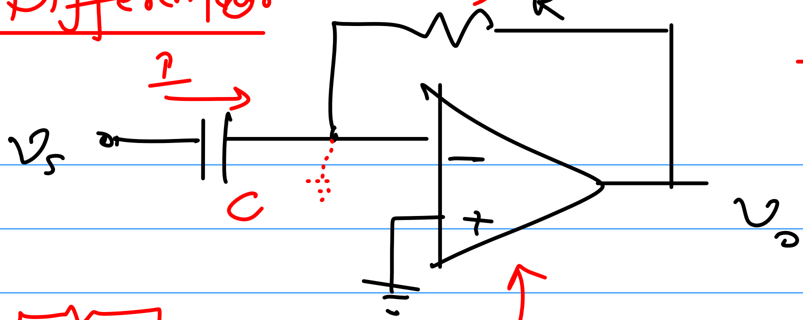
$$v_o = -\frac{L}{R}\frac{dv_s}{dt}$$

(DIFFERENTIATOR)



= Integrator

Differentiator

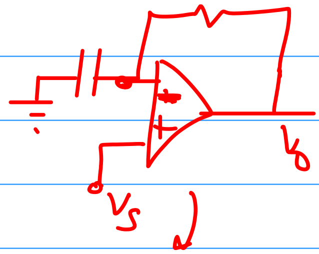


$v_n = 0$ (V.G.)

$$I_f = \frac{0 - v_o}{R} = I = C\frac{d(v_s - 0)}{dt}$$

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

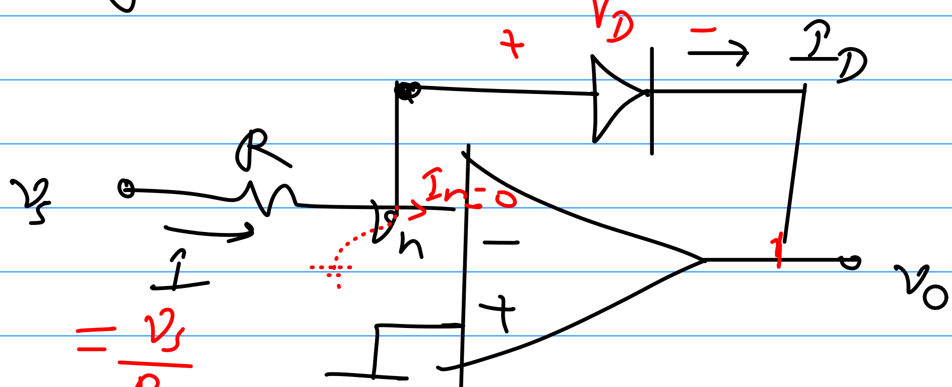
$$\Rightarrow \boxed{v_o = -RC\frac{dv_s}{dt}}$$



$$v_o = RC\frac{dv_s}{dt}$$

$$\boxed{v_o \propto -\frac{dv_s}{dt}}$$

Log - Amplifier :



$$= \frac{v_s}{R}$$

$$\boxed{v_D = v_n - v_o}$$

$v_n = 0$ (V.G.)

$$I = \frac{V_s}{R} \quad ; \quad I_D = I_o\left(e^{\frac{v_D}{\eta v_T}} - 1\right)$$

$$\frac{v_s}{R} = I_0\left[e^{\frac{0 - v_o}{\eta V_T}} - 1\right]$$

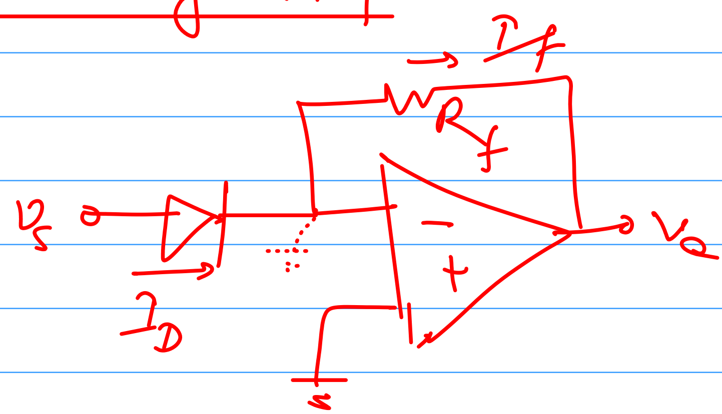
neglect

$$\Rightarrow e^{-v_o/\eta V_T} = \frac{v_s}{I_0 R}$$

$$\boxed{v_o = -\eta V_T \log_e\left(\frac{v_s}{I_0 R}\right)}$$

**

- **Anti-log Amp :-**



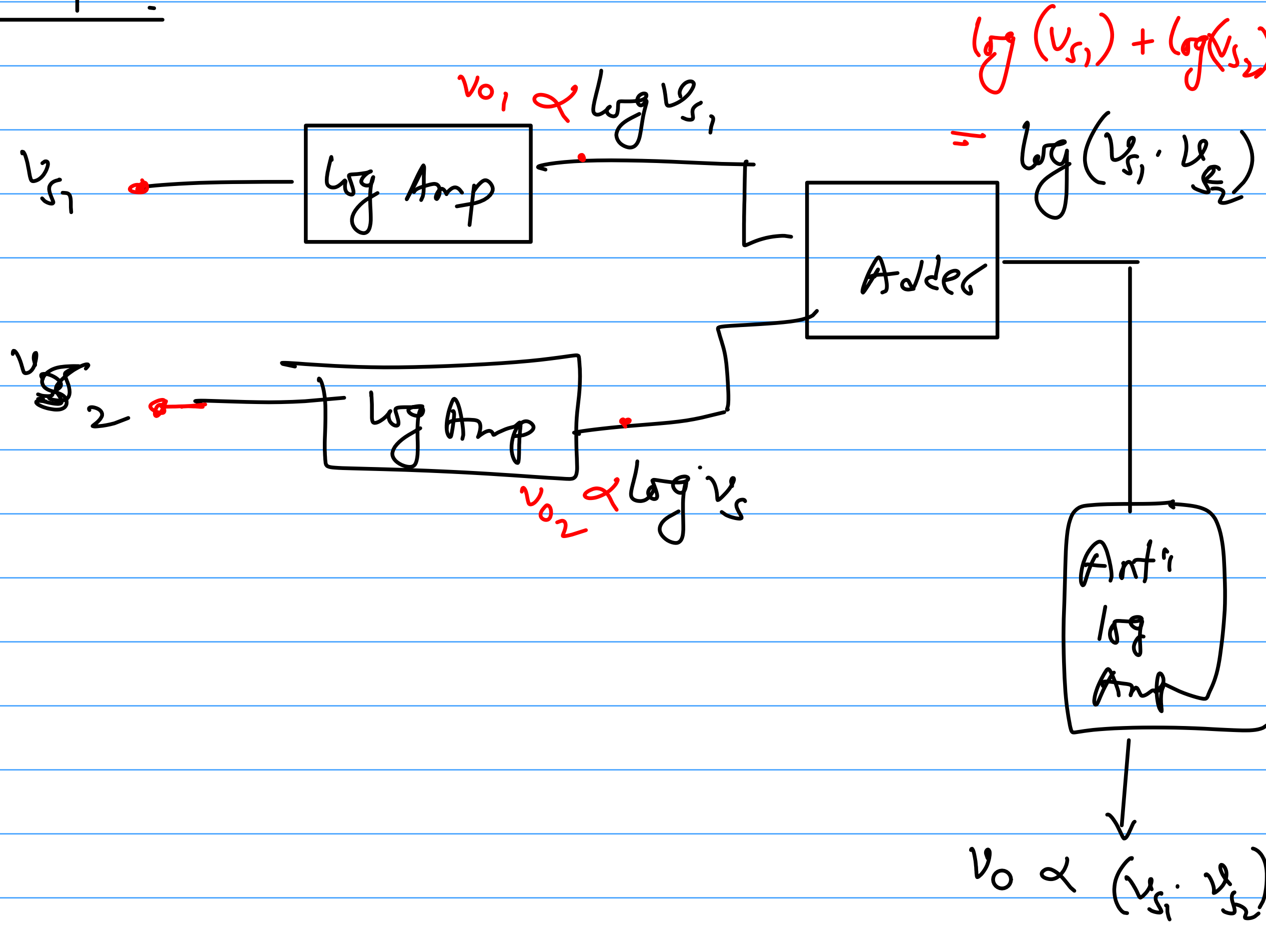
$$I_D = I_0\left(e^{\frac{V_s - 0}{\eta V_T}} - 1\right)$$

$$= I_f = \frac{0 - V_o}{R_f}$$

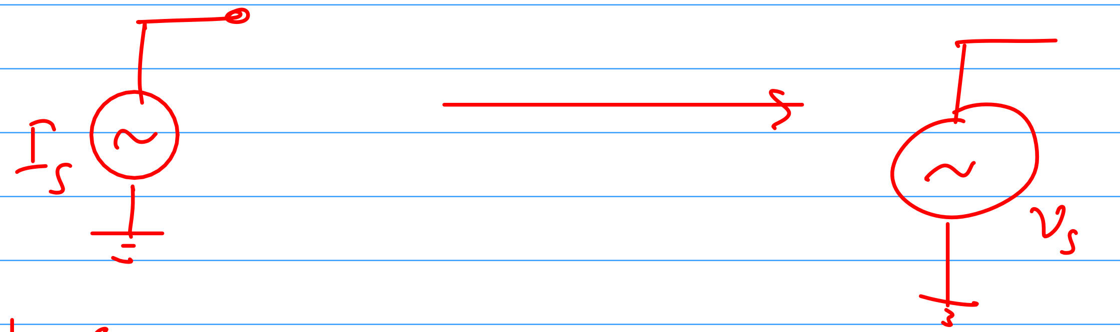
$$\Rightarrow V_o = -R_f I_0 \cdot \exp\left(\frac{V_s}{\eta V_T} - 1\right)$$

$$\boxed{v_o \propto \exp(v_s)}$$

→ Multiplier — $v_o \propto (v_{s_1} \cdot v_{s_2})$



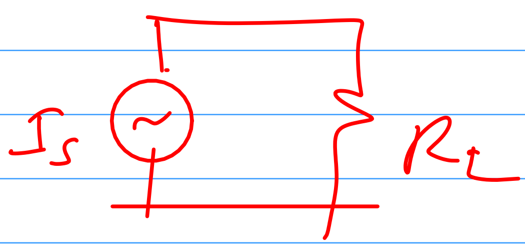
→ Current to voltage converter :-



Current Source

vol. source

Source value should be independent of load

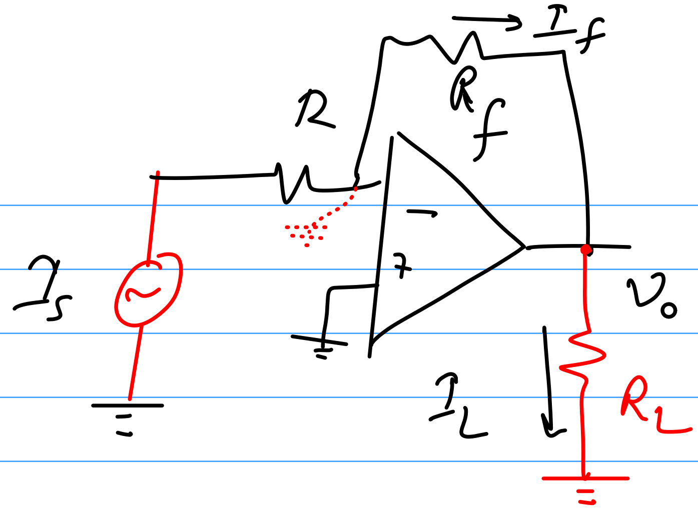


$+$

$V_o = I_L R_L$ — vol depends on load

$-$

Not a vol. source



$$I_s = I_f = \frac{0 - V_o}{R_f}$$

So, $V_o = -R_f I_s$

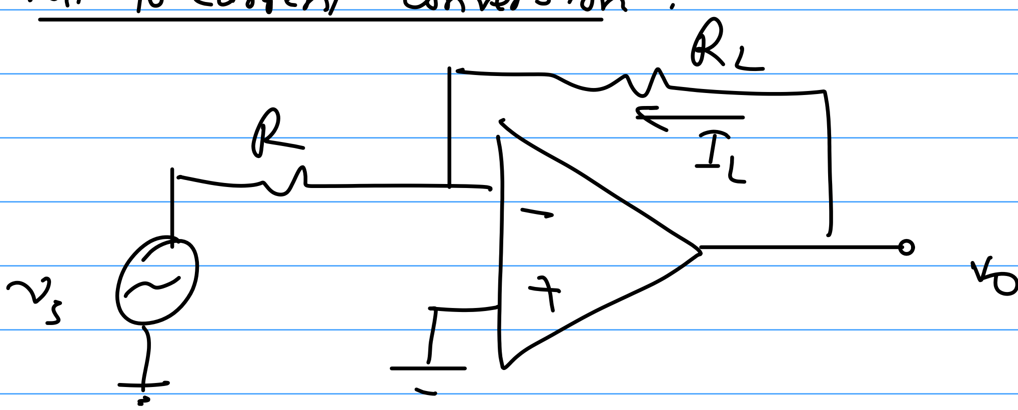
$$I_L = \frac{V_o}{R_L} = \frac{-R_f I_s}{R_L}$$

$V_{Load} = V_o = -R_f I_s$ = Independent of R_L

$V_o \propto I_s$

Conversion

<u>Vol. to current Conversion</u> :



$I_L = ?$

(indep of R_L)