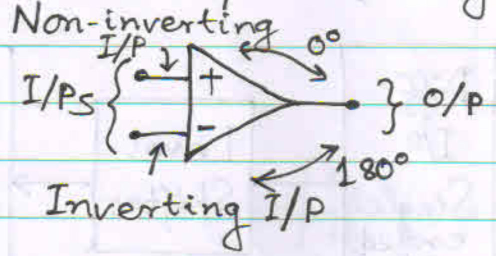
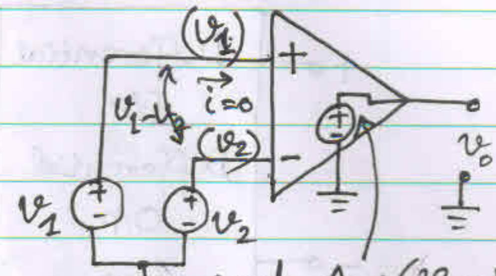
# (Op-Amps)
# Operational Amplifiers

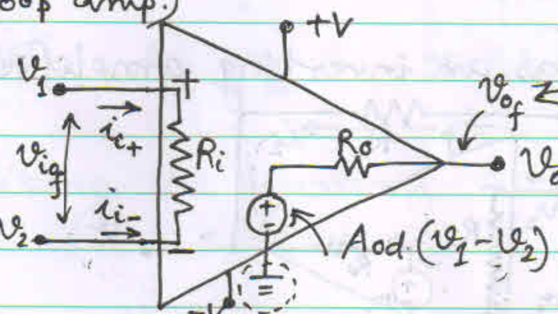
## 1. Ideal op-amp ($\rightarrow$ V-amp): Symbol & operation




fixed $\rightarrow$ $\underbrace{A_{od}}_{\text{Open-loop (OL) differential gain (V)}}(v_1 - v_2)$

## 2. Practical op-amp:
(Open loop amp.)




$A_{cm} \approx 0$

$CMRR = \frac{A_{od}}{A_{cm}}$

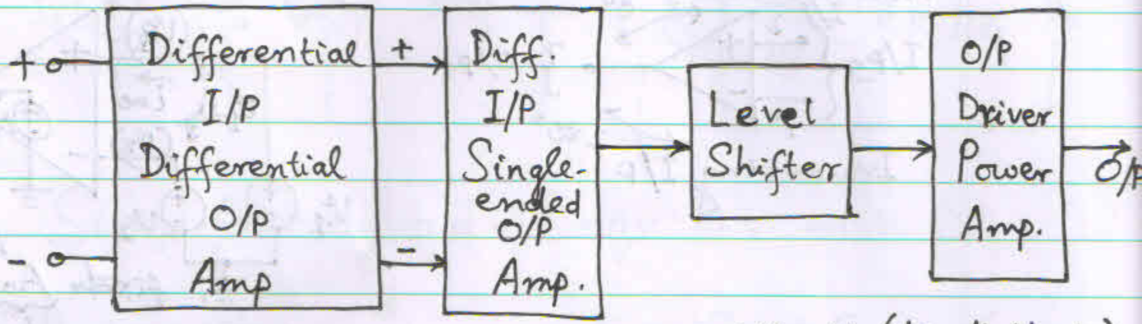
When, $v_1 = v_2 (\neq 0) \Rightarrow v_1$ & $v_2$ are common-mode I/Ps

$\therefore$ $v_o = 0$ for an ideal case
$v_o \neq 0$ for a practical case } Common-mode O/P.

## 3. Op-amp parameters:

| Parameter | Ideal | Practical |
|---|---|---|
| a) I/P resistance ($R_i$) | $\infty$ | Very high (M/G Ω) |
| b) O/P resistance ($R_o$) | 0 | Low or Very Low (Ω) |
| c) OL diff. gain ($A_{od}$) | $\infty$ | Very high (L+M) |
| d) O/P V-swing/range | $\infty$ | $< [+V - (-V)]$ |
| e) O/P current (max.) | $\infty$ | Depends on design |
| Noise handling $\rightarrow$ f) Common Mode Rejection Ratio (CMRR) | $\infty$ | Very high or high |
| g) Power Supply Rejection Ratio (PSRR) | $\infty$ | " " " " |
| h) I/P offset V ($v_{io_f}$) | 0 | Very low (mV) |
| i) O/P offset V ($v_{o_f}$) | 0 | Very low (mV) |
| j) I/P bias I ($i_{i+}$ or $i_{i-}$) | 0 | Very low |
| k) ~~O/P offset I~~ Slew rate & GBW | ~~0~~ $\infty$ | ~~Very low ($R_L$ dep)~~ Very high |

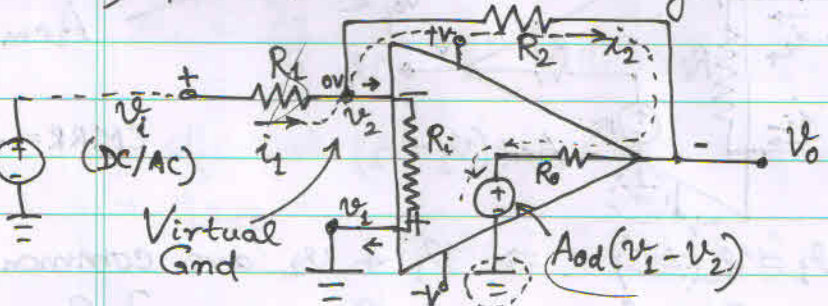
4. Block Diagram (generic)




+V, −V (to all blocks)

BJTs/MOSFETs/FETs(other)

5. a) Op-Amp as an inverting amplifier:




Closed-loop amp. (f/b)

Assume, $R_i \approx \infty$ & $R_o \approx 0$, $R_1$ or $R_2 \ll R_i$

$i_1 \cong i_2$ ($\because i_{R_i} \approx 0 \Rightarrow v_1 = v_2$ for this closed-loop circuit)

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

$$\Rightarrow v_o = -\overbrace{\left(\frac{R_2}{R_1}\right)}^{A_v} \cdot v_i$$

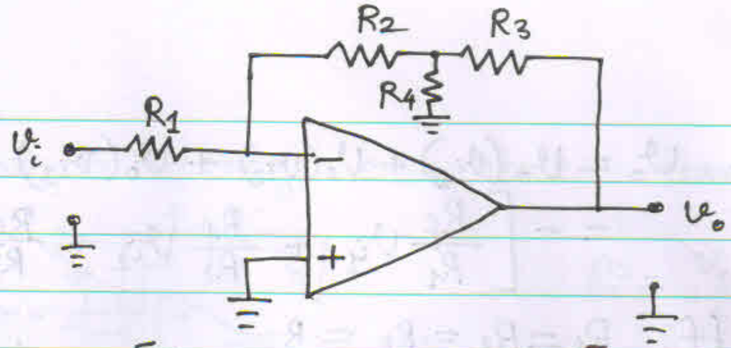
Now, $v_1 = v_2 = 0V$

$\therefore$ We say $v_2$ is at a virtual ground

(I/Ps '+' & '−' are at same potential)

b) If you need a very large gain (e.g. > 1000), increasing $R_2$ results in noise injection in the circuit, since, $V_{n(rms)} = \sqrt{4k \cdot T \cdot R \cdot \Delta f}$

Instead, use a T-network replacement for $R_2$.




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

c) How about the effect of $A_{od}$?
Derivation with a single $R_2$:

$$i_1 = \frac{v_i - v_2}{R_1} \quad \& \quad i_2 = \frac{v_2 - v_o}{R_2}$$

$$\therefore\ v_o = -A_{od} \cdot v_2 \quad \Rightarrow v_2 = -\frac{v_o}{A_{od}}$$

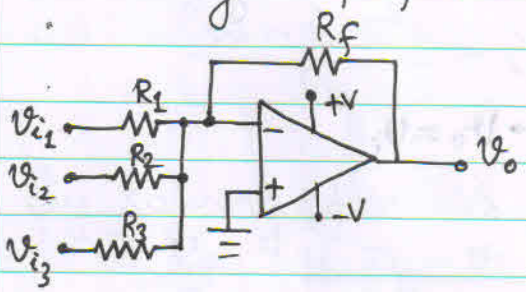
Combining the equations,

$$i_1 = i_2$$

$$\Rightarrow \frac{v_i + \frac{v_o}{A_{od}}}{R_1} = \frac{\frac{-v_o}{A_{od}} - v_o}{R_2}$$

$$\Rightarrow v_o = -\left[\frac{R_2}{R_1} \frac{1}{1 + \frac{1}{A_{od}}\left(1 + \frac{R_2}{R_1}\right)}\right] \cdot v_i$$

6. Summing amplifier: Adder




By using Superposition Theorem based analysis:

$$v_o(v_{i_1}) = -\frac{R_f}{R_1} \cdot v_{i_1}$$

$$v_o(v_{i_2}) = -\frac{R_f}{R_2} \cdot v_{i_2}$$

$$v_o(v_{i_3}) = -\frac{R_f}{R_3} \cdot v_{i_3}$$

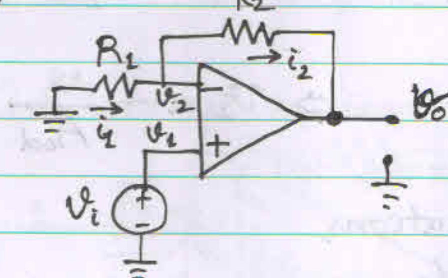
$$\therefore \; v_o = v_o(v_{i_1}) + v_o(v_{i_2}) + v_o(v_{i_3})$$
$$= -\left[ \frac{R_f}{R_1} v_{i_1} + \frac{R_f}{R_2} v_{i_2} + \frac{R_f}{R_3} v_{i_3} \right]$$

If, $R_1 = R_2 = R_3 = R$

$$v_o = -\frac{R_f}{R}\left(v_{i_1} + v_{i_2} + v_{i_2}\right)$$

7. Non-inverting amplifier:

a)




$$i_1 = \frac{-v_2}{R_1} = -\frac{v_i}{R_1}$$

$$i_2 = \frac{v_2 - v_o}{R_2} = \frac{v_i - v_o}{R_2}$$

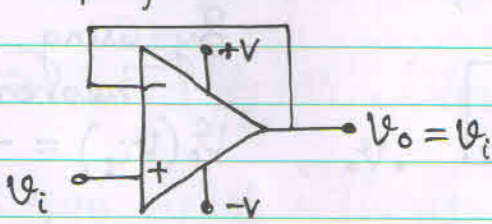
$$\because \; i_1 = i_2$$

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

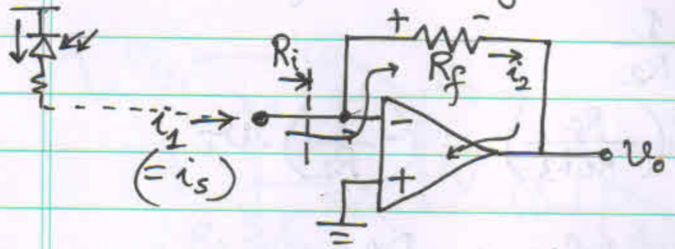
$$\Rightarrow v_o = \left(1 + \frac{R_2}{R_1}\right) v_i$$

b) Voltage follower/buffer/impedance transformer:
In a non-inverting amplifier, if $R_2 = 0$, $\frac{v_o}{v_i} = 1$. However, that will increase power.

A simplified circuit achieving the same is:



8. Current to voltage converter: Trans-impe amp.

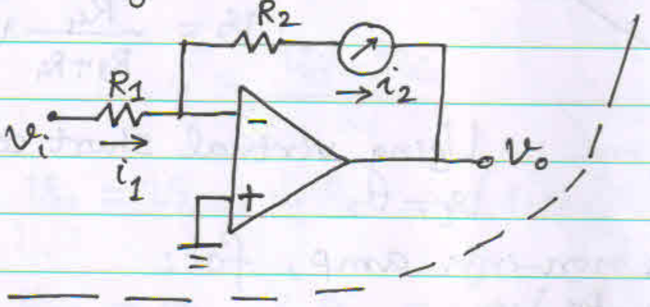


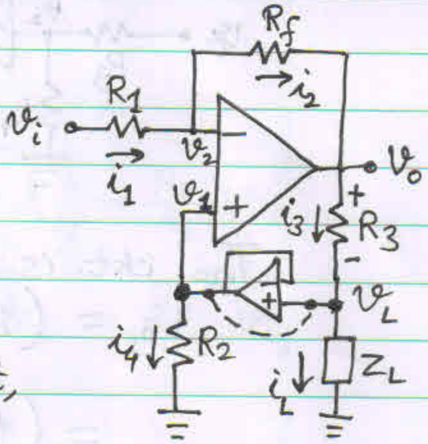
$$R_i = \frac{v_1}{i_1} \cong 0$$

$$i_2 = i_1 = i_S \leftarrow \text{Signal I}$$

$$\therefore\ v_0 = -i_2 . R_f = -i_S . R_f$$

9. Voltage to current converter: Trans-conductance amp.





Using virtual short concept,

$$v_1 = v_2 = Z_L . i_L = v_L$$

Since, $i_1 = i_2$

$$\frac{v_i - i_L Z_L}{R_1} = \frac{i_L . Z_L - v_0}{R_f}$$

Using KCL at the '+' I/P of the op-amp,

$$\frac{v_0 - i_L . Z_L}{R_3} = i_L + \frac{\overbrace{i_L Z_L}^{i_4}}{R_2}$$

(Considering the dotted line as short)

By solving for $(v_0 - i_L Z_L)$, or V across $R_3$

$$\frac{R_f}{R_1} \cdot \frac{i_L Z_L - v_i}{R_3} = i_L + \frac{i_L Z_L}{R_2}$$

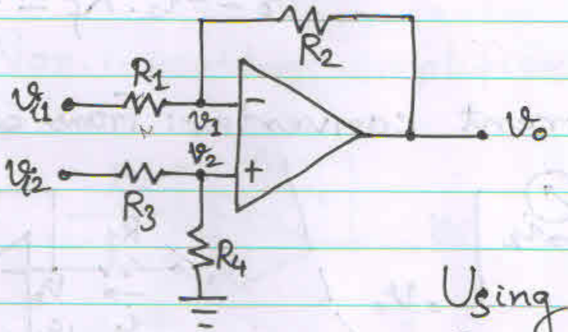
$$\Rightarrow i_L \left( \frac{R_f Z_L}{R_1 R_3} - 1 - \frac{Z_L}{R_2} \right) = v_i \left( \frac{R_f}{R_1 R_3} \right)$$

For making $i_L$ independent of $Z_L$,

$$\frac{R_f}{R_1 R_3} = \frac{1}{R_2}$$

$$\therefore\ i_L = -v_i\left(\frac{R_f}{R_1 R_3}\right) = \left(-\frac{1}{R_2}\right)\cdot v_i$$

10. Difference amplifier: DA




Case 1: $v_{i_1} = (\ )$, $v_{i_2} = 0V$

$$v_{o_1} = -\frac{R_2}{R_1} v_{i_1}$$

Case 2: $v_{i_2} = (\ )$, $v_{i_1} = 0V$

$$v_2 = \frac{R_4}{R_3 + R_4} v_{i_2}$$

Using virtual short concept,

$$v_1 = v_2$$

The ckt. is a non-inv. amp, for:

$$v_{o_2} = \left(1 + \frac{R_2}{R_1}\right) v_2$$

$$= \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) v_{i_2}$$

$$= \left(1 + \frac{R_2}{R_1}\right)\left(\frac{\frac{R_4}{R_3}}{1 + \frac{R_4}{R_3}}\right) v_{i_2}$$

$$v_o = v_{o1} + v_{o2}$$

$$= \left(1 + \frac{R_2}{R_1}\right)\left(\frac{\frac{R_4}{R_3}}{1 + \frac{R_4}{R_3}}\right) v_{i_2} - \frac{R_2}{R_1} v_{i_1}$$

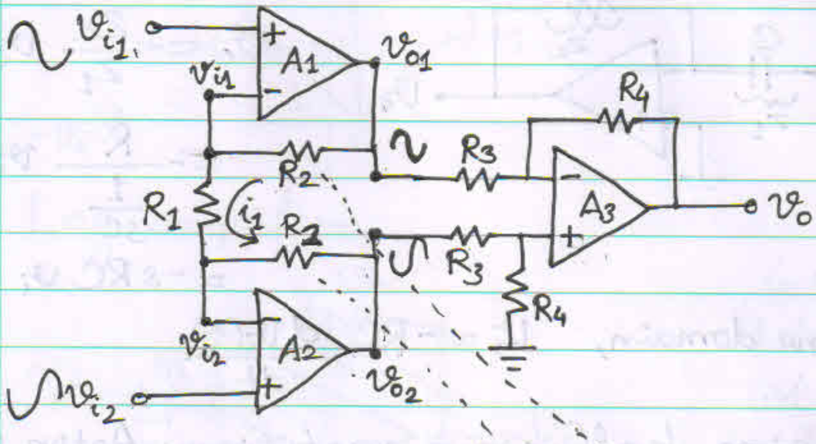
If, $\frac{R_4}{R_3} = \frac{R_2}{R_1}$ (or $R_1 = R_3$ & $R_2 = R_4$)

$$v_o = \frac{R_2}{R_1}\left(v_{i_2} - v_{i_1}\right)$$

Drawbacks: 1) Low I/P $\xrightarrow{}$ $P_i \uparrow$ impedance/resistance.

2) Matching of $\frac{R_2}{R_1}$ & $\frac{R_4}{R_3}$ is critical for a good CMRR.

11. Instrumentation amplifier: IA




$$i_1 = \frac{v_{i1} - v_{i2}}{R_1}$$

$$v_{o1} = v_{i_1} + i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right) v_{i_1} - \frac{R_2}{R_1} v_{i_2}$$

$$v_{o2} = v_{i_2} - i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right) v_{i_2} - \frac{R_2}{R_1} v_{i_1}$$

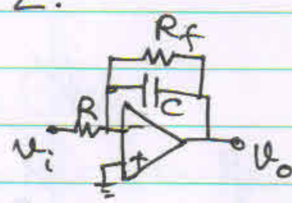
Also,

$$v_o = \frac{R_4}{R_3}\left(v_{o2} - v_{o1}\right)$$

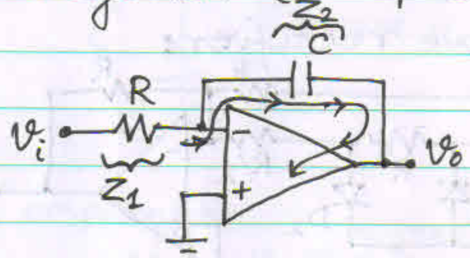
$$= \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)\left(v_{i_2} - v_{i_1}\right)$$

Note: Solves the problem of DA's with high I/P Z.

12. Op-amp as filters (active filters):




a) Integrator (Low pass filter)

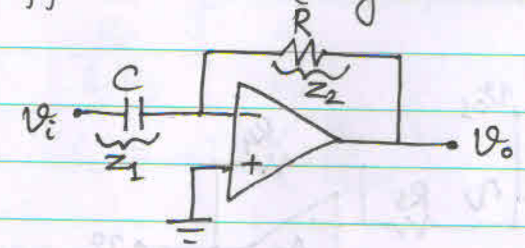



$$v_o = -\frac{Z_2}{Z_1} v_i$$

$$= -\frac{\frac{1}{sC}}{R} v_i = -\frac{1}{s\underbrace{RC}_{\tau}} v_i$$

In time domain, $v_o = \frac{-1}{RC}\int_0^{t_1} v_i(t)\, dt$


## 6. Differentiator (High Pass Filter):

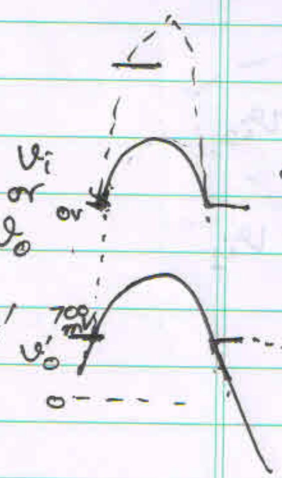


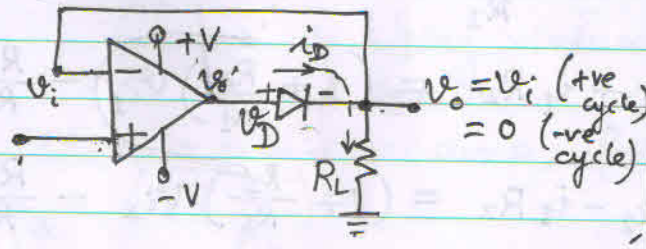

$$v_o = -\frac{Z_2}{Z_1} v_i = -\frac{R}{\frac{1}{sC}} v_i = -sRC\, v_i$$

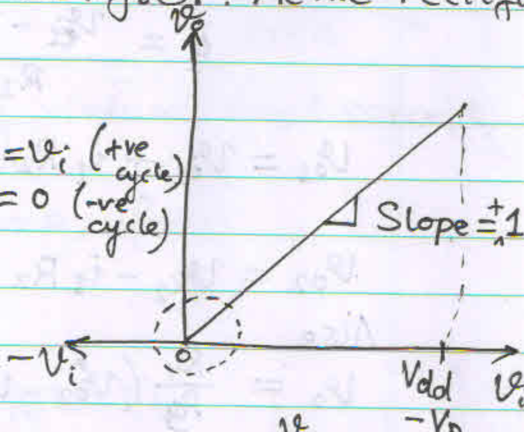
In time domain, $v_o = -RC \dfrac{d v_i(t)}{dt}$

## 13. Precision half-wave rectifier: Active rectifiers

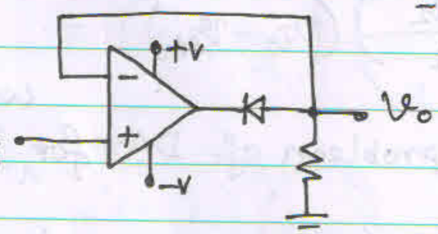
(+ve $V_o$)

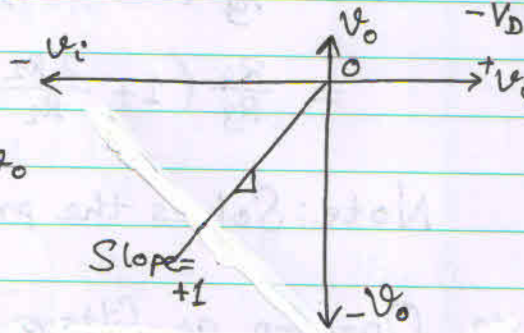


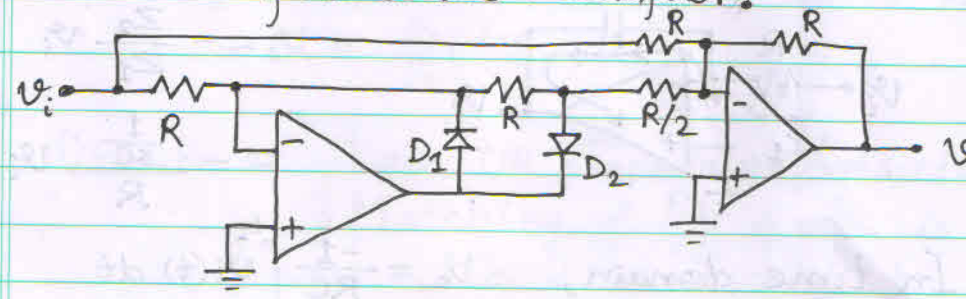




(-ve $V_o$)



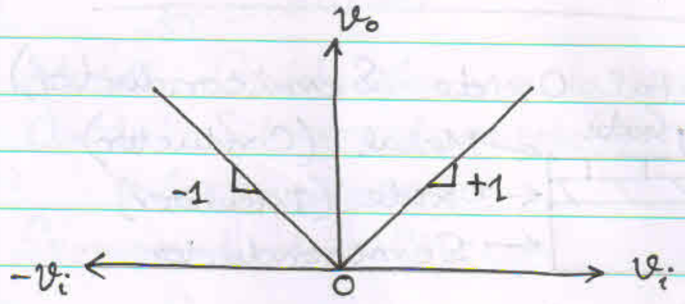




## 14. Precision full-wave rectifier:

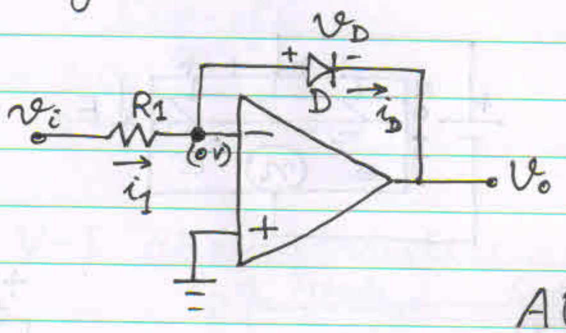


$$= \frac{dV_o}{dt}\Big|_{max}$$

Slew rate $\geqslant 2\pi f V_{max}$




14. Log amplifier:




$i_D = I_S\left(e^{\frac{v_D}{V_T}} - 1\right)$

while D is sufficiently in F.B.

$i_D = I_S . e^{\frac{v_D}{V_T}}$

Also, $i_1 = \frac{v_i}{R_1}$ & $v_o = -v_D$

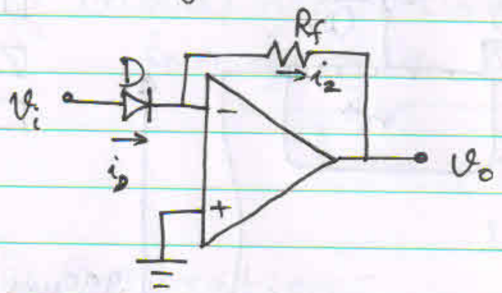
$$\therefore\ i_1 = i_D \cong I_S . e^{\left(\frac{-v_o}{V_T}\right)} = \frac{v_i}{R_1}$$

Taking natural log on both sides,

$$\ln\left(\frac{v_i}{I_S . R_1}\right) = -\frac{v_o}{v_i}$$

$$\Rightarrow v_o = -V_T \ln\left[\frac{v_i}{I_S . R_1}\right]$$

15. Anti-log amplifier:

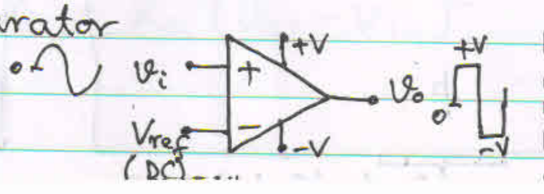



$i_D \cong I_S . e^{\left(\frac{v_i}{V_T}\right)}$

& $v_o = -i_2 . R_f = -i_D . R_f$

$$\Rightarrow v_o = -I_S . R_f . e^{\left(\frac{v_i}{V_T}\right)}$$

16. V Comparator




$v_o = +V - V_{drop}$ (if $v_i > V_{ref}$)

$v_o = -V + V_{drop}$ (if $v_i \leqslant V_{ref}$)