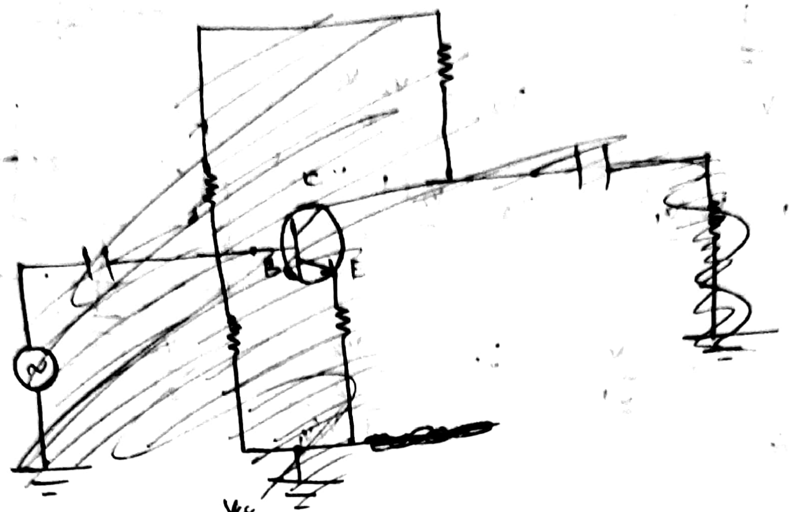
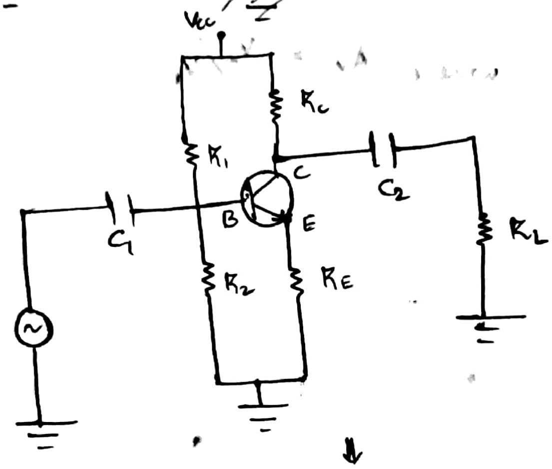
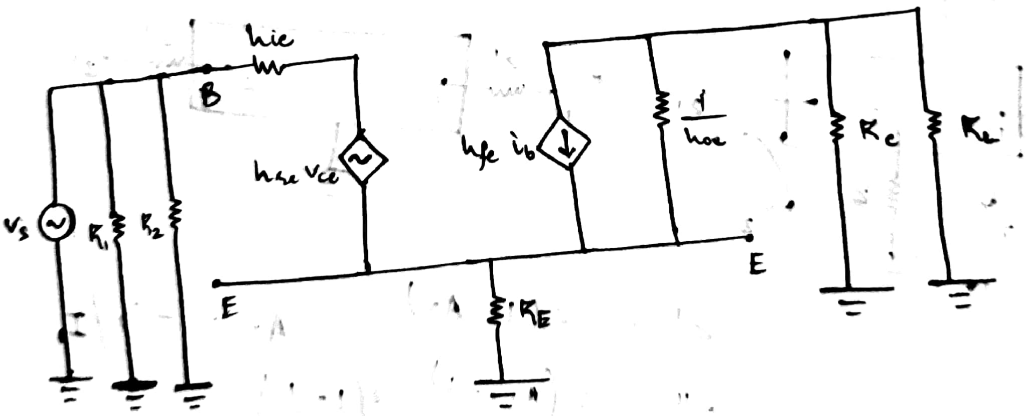
Feedback ⇒ A part of output voltage / current feeded back to input.





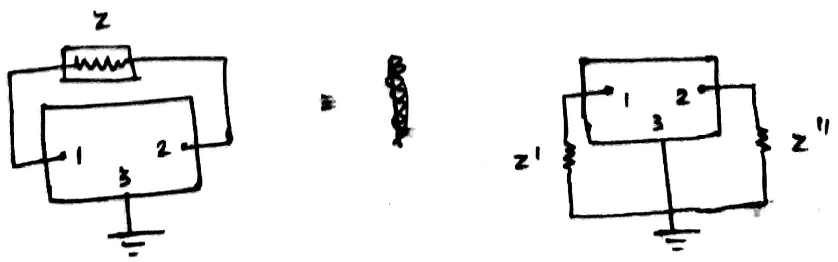
⇓



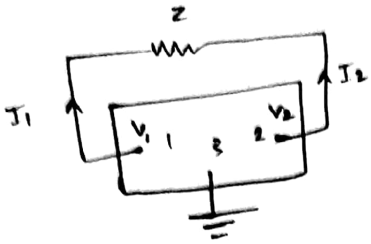
$i_e = i_b + i_c$

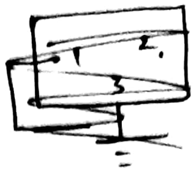
Miller's Theorem

Impedance ⇒ z, z', z''



z' & z'' $\Rightarrow$





$$I_1 = \frac{V_1 - V_2}{z}$$

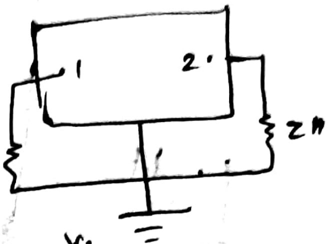
$$I_1 = \frac{V_1(1 - V_2/V_1)}{Z}$$

$$I_1 = \frac{V_1}{\frac{Z}{1 - V_2/V_1}} = \frac{V_1}{z'}$$

$$I_2 = \frac{V_2 - V_1}{z}$$

$$I_2 = \frac{V_2(1 - V_1/V_2)}{z}$$

$$I_2 = \frac{V_2}{\frac{z}{1 - V_1/V_2}} = \frac{V_2}{z''}$$

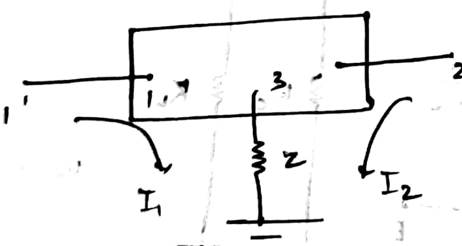


$$z' = \frac{Z}{1 - A_v} \quad \text{where } A_v = V_2/V_1$$

$$z'' = \frac{z}{1 - 1/A_v}$$

$$= \frac{zA_v}{A_v - 1}$$

Miller's Theorem Sequel

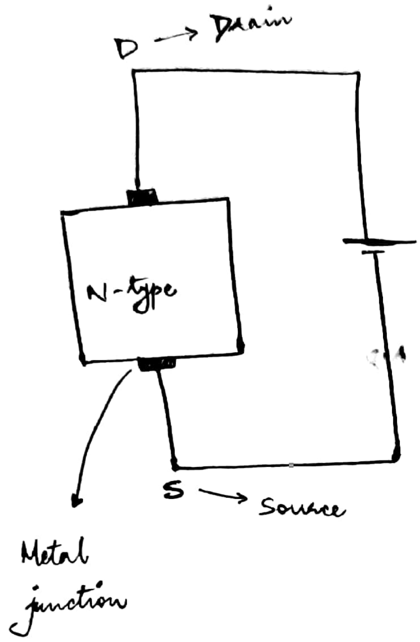


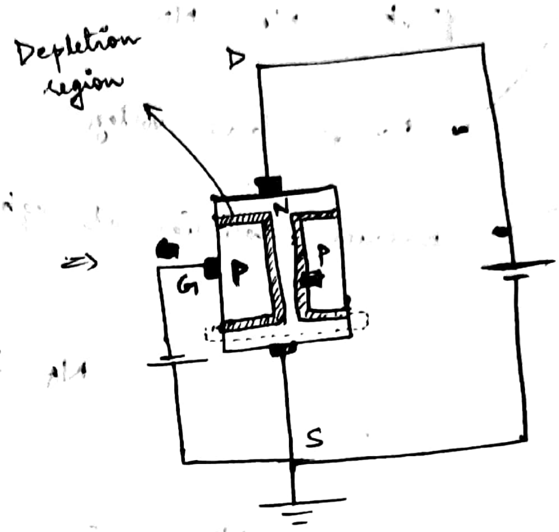
$\equiv$

$$z' = z(1 - A_I) \qquad A_I = -I_2/I_1$$

$$z'' = \frac{z(A_I - 1)}{A_I} = z\left(1 - \frac{1}{A_I}\right)$$

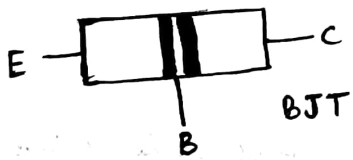
Field - Effect Transistor (FET)



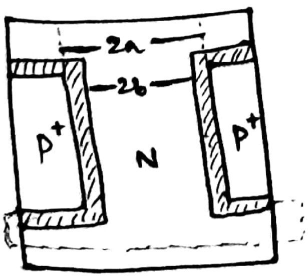


FET

$$V_B = \frac{q}{2\epsilon_0 k} \frac{N_A N_D}{N_A + N_D} W^2$$



BJT	FET
Current controlled device	Field Controlled device
Much slower	Very fast device
Difficult to construct	Easy to construct
High power device	Low power device



Effective channel width = 2b

Metallurgical channel width = 2a

Width of depletion range in one side = a − b

$$V_B + |V_R| = \frac{q}{2\epsilon_0 k}\,\frac{N_A N_D}{N_A + N_D}\,w^2 , \; V_j$$

Reverse bias voltage

Barrier potential at eqbm.

$$N_A >> N_D$$

$$V_j = \frac{q}{2\epsilon_0 k}\,\frac{N_D}{1 + \frac{N_D}{N_A}}\,w^2$$

$$V_B + |V_R| = V_j = \frac{q}{2\epsilon_0 k} N_D\, w^2$$

$$(a-b) = W = \left[\frac{2\epsilon_0 k}{q N_D}\left(V_B + |V_R|\right)\right]^{1/2}$$

Pinch-off voltage (V_P) is the reverse bias gate voltage at which channel closes (completely covered with depletion region)

$$a = \left[\frac{2\epsilon_0 k}{q N_D}\left(V_B + |V_P|\right)\right]^{1/2}$$

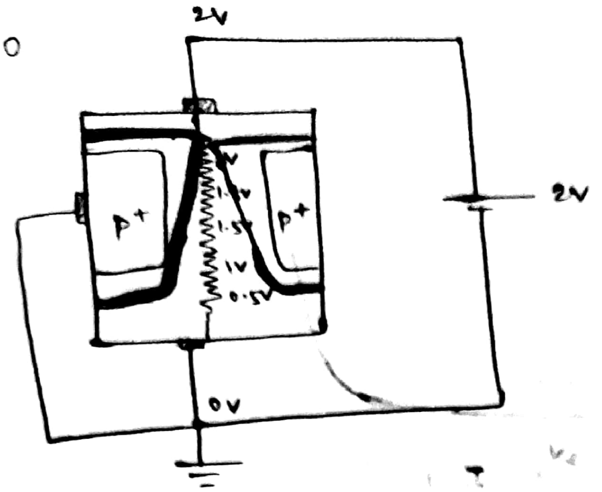
$$a^2 = \frac{2\epsilon_0 k}{q N_D}\left(V_B + |V_P|\right)$$

$$\cancel{V_B + |V_P|} = \cancel{\frac{q N_D a^2}{2\epsilon_0 k}}$$

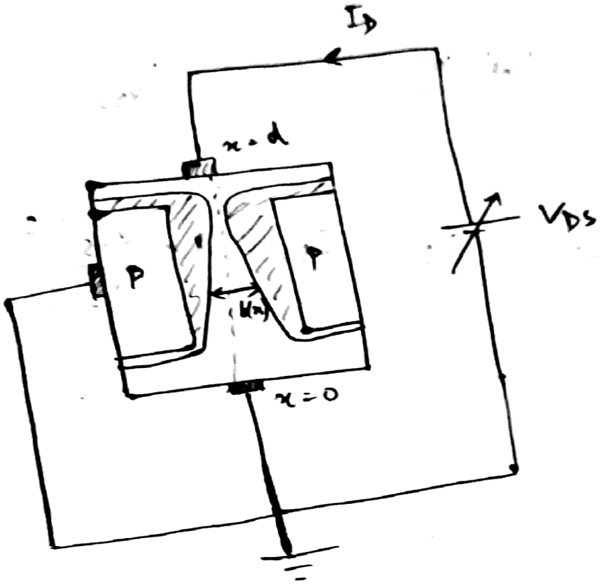
$$V_B + |V_P| = \frac{q N_D a^2}{2\epsilon_0 k}$$

Case - I

$V_{GS} = 0$



The channel acts as a resistor (voltage drops across it)

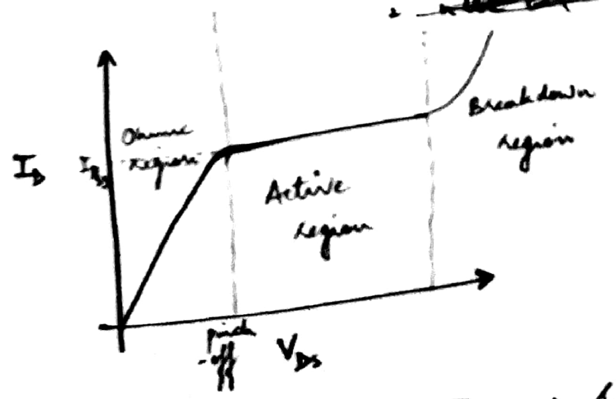


b as a function of x. (b(x))

Let width of FET be w.

$$\sigma = n\mu_e e + p\mu_h e \approx n\mu_e e$$

$$I_D = J_D \times A$$
$$= J_D \times (w \cdot 2b(x))$$
$$= (\sigma E) \times (w \cdot 2b(x))$$
$$I_D = (n\mu e)\left(\frac{V_{DS}}{d}\right)(2w \cdot b(x)) = n\mu e\, E \cdot (2w\, b(x))$$



$\mu \propto \frac{1}{E^{1/2}}$ (Moderate voltage)

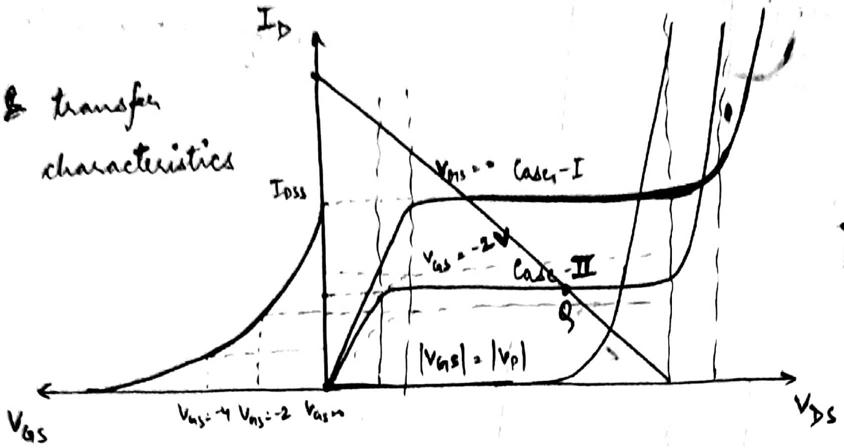
$\mu \propto \frac{1}{E}$ (Higher voltage)

$I_{DSS} \Rightarrow$ Saturation Drain current

Case - II

$V_{GS} < 0$

& transfer characteristics

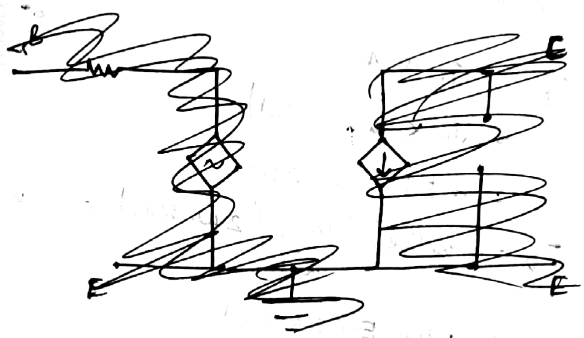


~~$I_D = I_{DSS}$~~

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

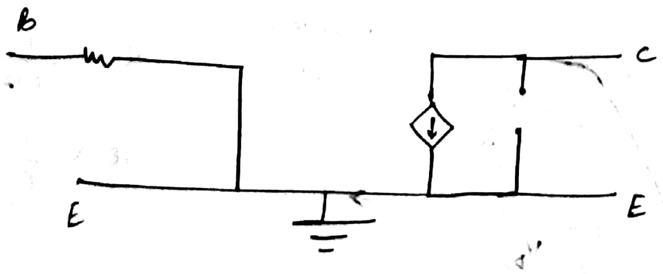
Approximate h-parameter model

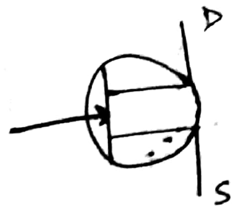
If $h_{oe} R_L \leq 0.1$

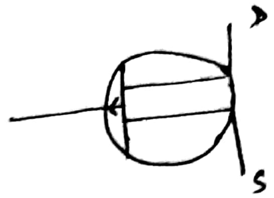


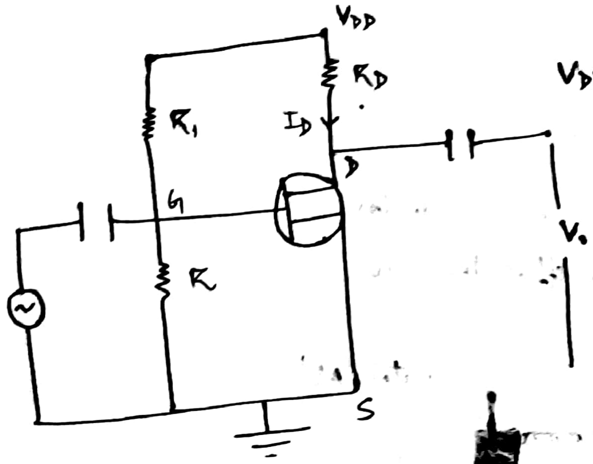
$\frac{1}{h_{oe}}$ will be open circuited & $h_{re} V_{ce}$ can be neglected

Small signal analysis will be like this ⇒









$$V_{DD} = I_D R_D + V_{DS}$$

$$v_{GS} = V_{GS} + v_s$$

$$i_D = I_D + i_d$$

$$v_{DS} = V_{DS} + v_{ds}$$

$$i_D = f(v_{DS}, v_{GS})$$

$$i_D = I_D + \left(\frac{\partial i_D}{\partial v_{DS}}\right)_{\text{at Q-point}} \Delta v_{DS} + \left(\frac{\partial i_D}{\partial v_{GS}}\right)_{\text{at Q-point}} \Delta v_{GS}$$

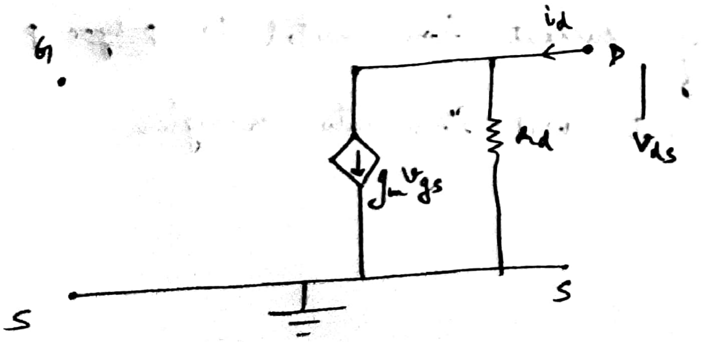
$(v_{DS} - \Delta v_{DS} = v$ [redacted] $DS)$ [redacted]

$$i_D - I_D = \left(\frac{\partial i_D}{\partial v_{DS}}\right) \Delta v_{DS} + \left(\frac{\partial i_D}{\partial v_{GS}}\right) \Delta v_{GS}$$

$$i_d = \left(\frac{1}{r_d}\right) v_{ds} + (g_m)\, v_{gs}$$

$r_d \rightarrow$ drain resistance

$g_m \rightarrow$ transfer conductance



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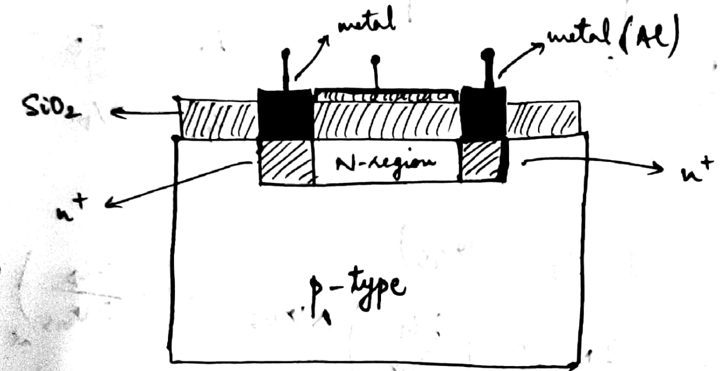
Voltage amplification factor : $\mu = -\left(\frac{\partial v_{DS}}{\partial v_{GS}}\right)_{I_D} = -\left(\frac{v_{ds}}{v_{gs}}\right)_{i_{d=0}}$

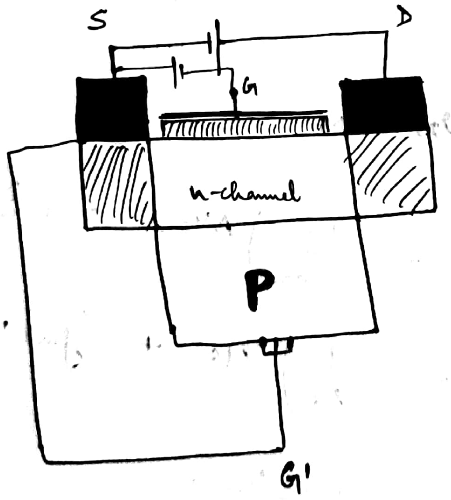
$$\mu = r_d \cdot g_m$$

MOSFET :

Metal-oxide semiconductor field-effect transistor

Input impedance < 100 MΩ



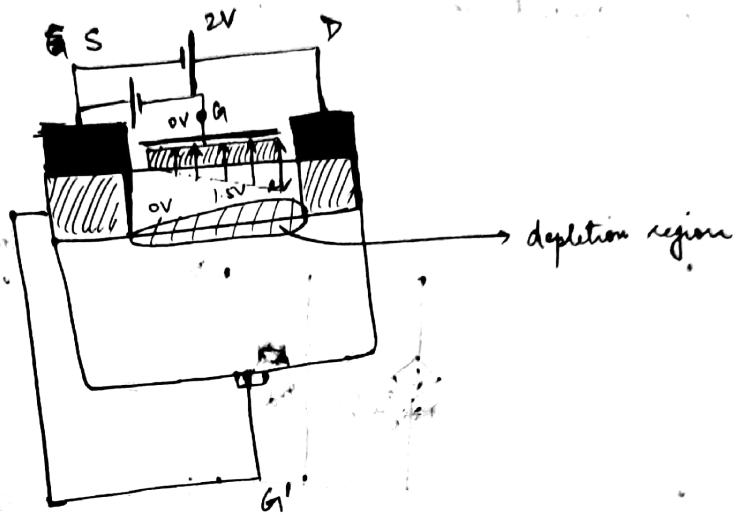


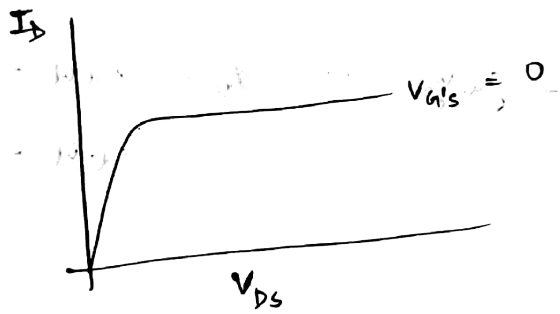
n^+ will create a depletion region & will resist any leakage of current from metal to ~~p-type~~ p

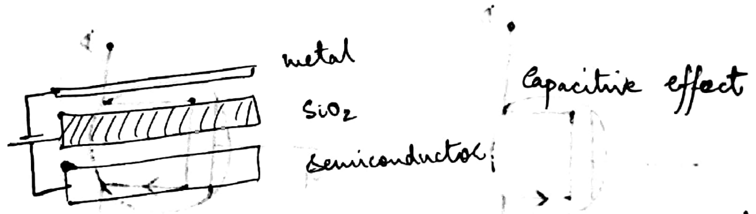
all current will flow into n-region

~~&~~ n^+ will ensure the ohmic junction b/w metal - n^+ - n.

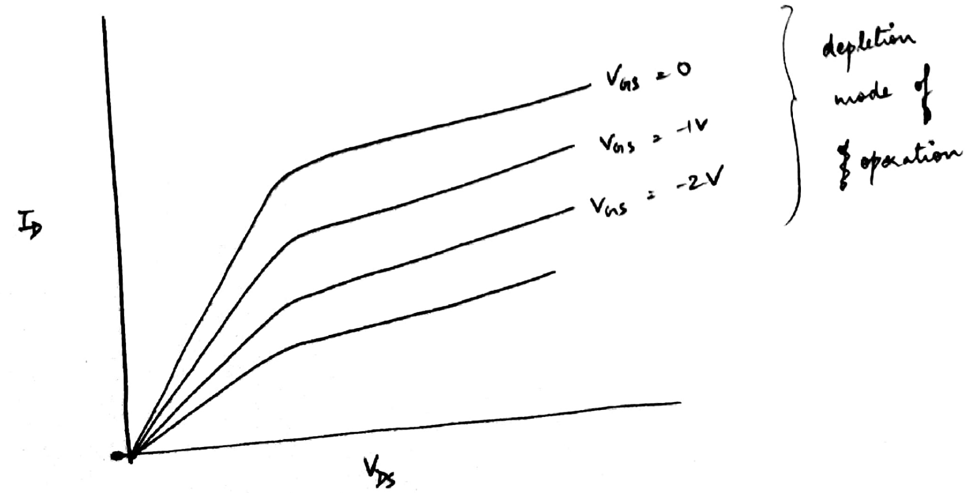
If n^+ was not there, then there would have been a non-ohmic ~~reg~~ region b/w metal & n-channel.



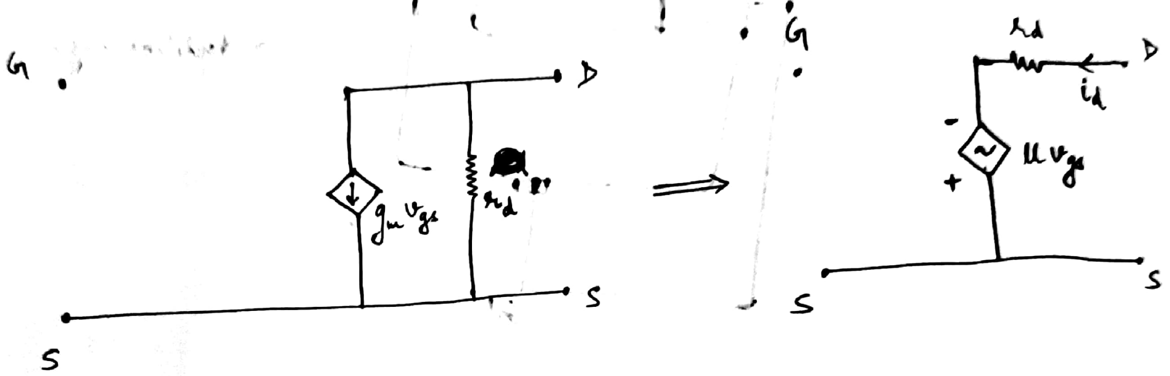




Input impedance ~~a~~ is high in MOSFET due to the capacitive effect

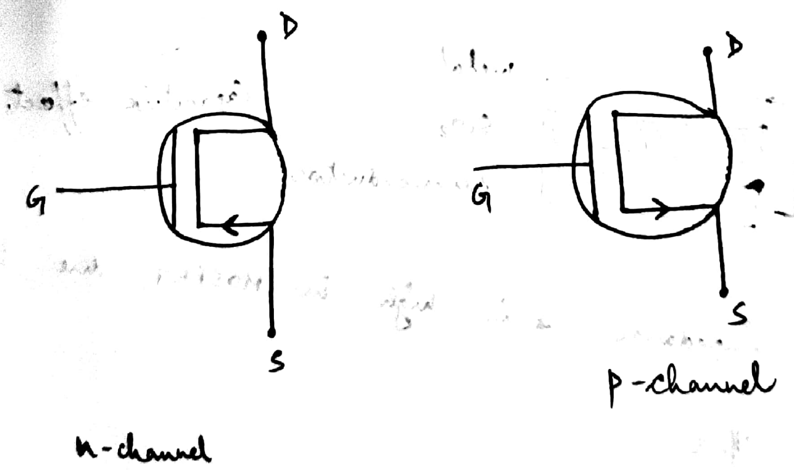


In enhancement mode of operation, the n-channel was not created previously but is created automatically & it is difficult to control it.



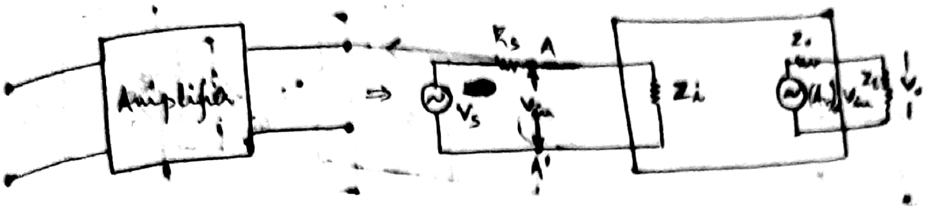
$$i_d = \frac{v_{ds}}{r_d} + g_m v_{gs} \Rightarrow v_{ds} = r_d i_d - r_d g_m v_{gs}$$
$$= r_d \cdot i_d - \mu v_{gs}$$

MOSFET ⇒



Feedback Amplifiers

1) Voltage Amplifier



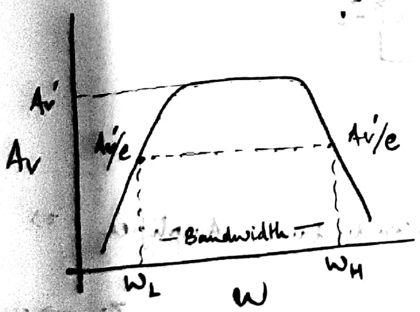
$$V_{in} = \frac{V_s}{R_s + Z_i} Z_i = \frac{V_s}{1 + \frac{R_s}{Z_i}}$$

$(A_v)_o \Rightarrow$ Intrinsic voltage amplification factor of amplifier when R_L is open

if $Z_i \gg R_s$
$V_{in} \approx V_s$
$\therefore$ we need high input impedance

Issues with practical amplifiers $\Rightarrow$

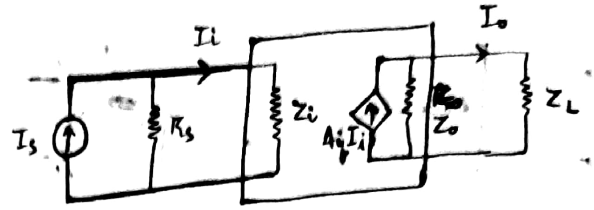
1) Input impedance is moderate
2) Stability of gain
★ 3) Gain-Bandwidth product is not satisfactory



Bandwidth $= \omega_H - \omega_L$

Ideal voltage amplifier $\Rightarrow$ $Z_i \to \infty$
$Z_o \to 0$

2) Current Amplifier



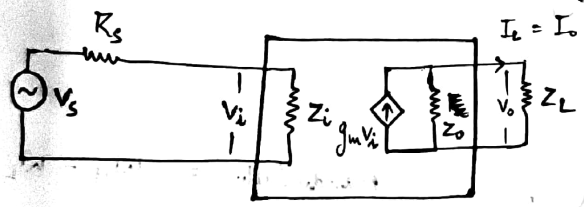
$$I_o = A_I I_s$$

Ideal Current Amplifier

$\Rightarrow Z_i \to 0$

$Z_o \to \infty$

3) Transconductance Amplifier

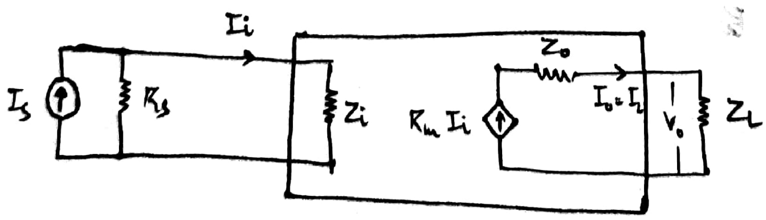


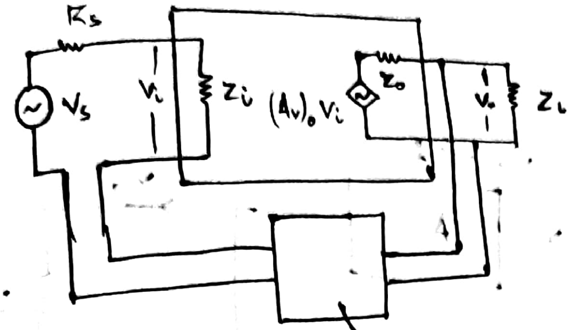
Ideal transconductance Amplifier $\Rightarrow$

$Z_i \to \infty$

$Z_o \to \infty$

4) Transresistance Amplifier





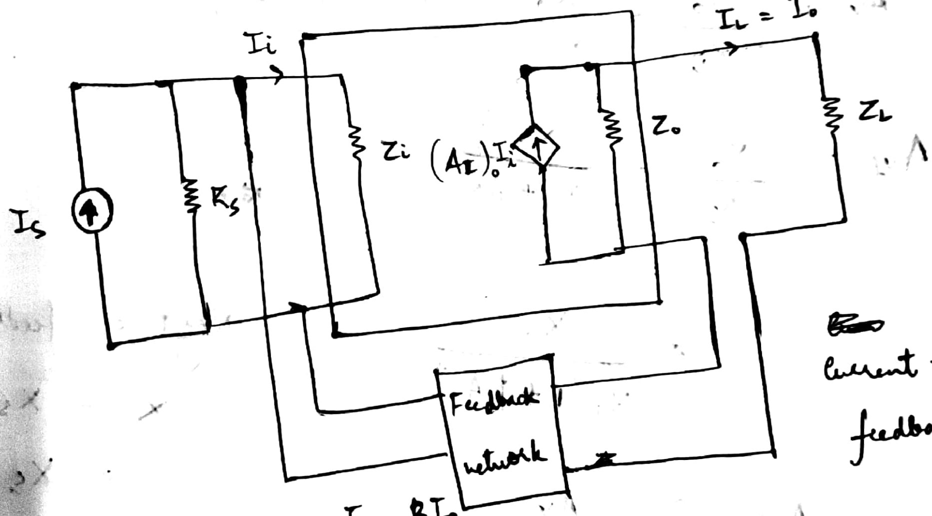
$V_i = V_s - \beta V_o$

Voltage-Series feedback

Feedback network

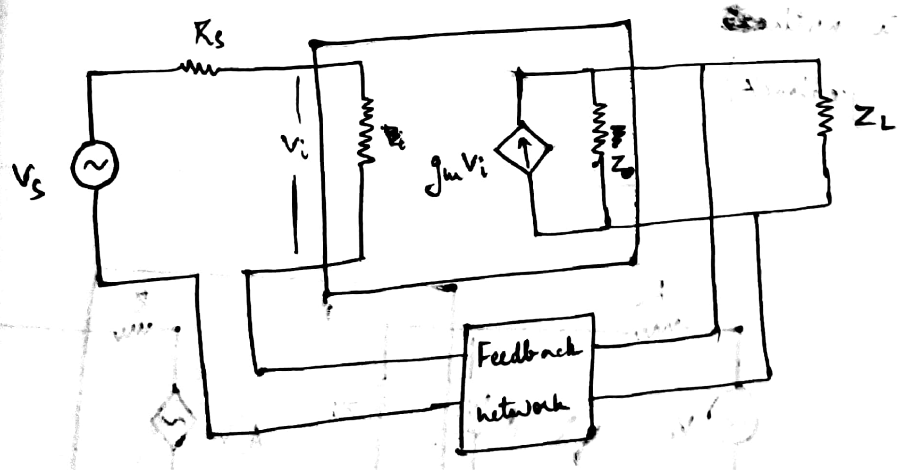
$V_f = \beta V_o$

feedback voltage



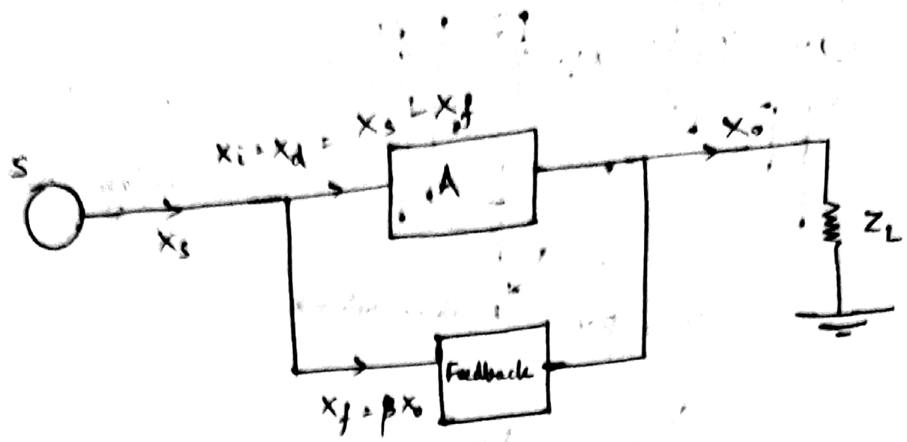
Current-shunt feedback

$I_f = \beta I_o$



Current-series feedback

$V_f = \beta I_o$



$$A_v = \frac{x_o}{x_i} = \frac{x_o}{x_s} \quad \text{(gain without feedback)}$$

$$A_{vf} = \frac{x_o}{x_s} = \frac{x_o}{x_i + \beta x_o}$$

$$= \frac{x_o}{x_i(1 + \beta A_v)}$$

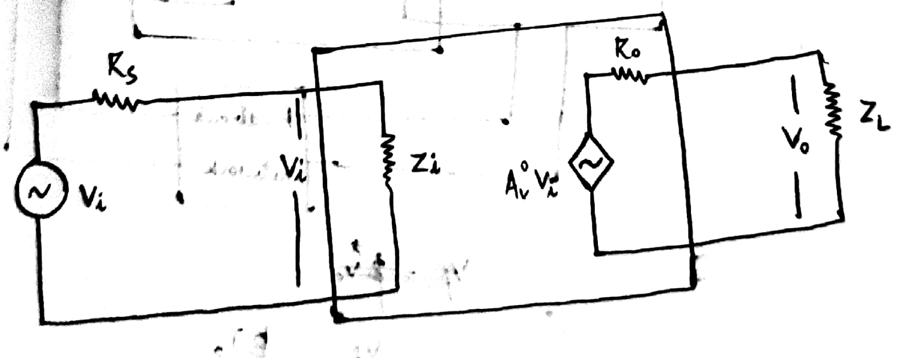
$$A_{vf} = \frac{A_v}{1 + \beta A_v}$$

(gain with feedback)

Negative feedback

$x_i = x_s - x_f$

$= x_s - \beta x_o$



Input impedance (seen from source) $\Rightarrow Z_i' = R_s + Z_i$

Output impedance $= R_o$ (without considering Z_L as part of transistor)

$R_o' = R_o \| Z_L$ (with " " " " " ")

$$A_v = \frac{V_o}{V_s}$$

$$V_o = \frac{A_v^{\circ} V_i}{R_o + Z_L} \times Z_L$$

$$V_i = \frac{V_s}{R_s + Z_i} \times Z_i$$

$$V_o = \frac{A_v^{\circ}}{R_o + Z_L} Z_L \frac{V_s}{R_s + Z_i} Z_i$$

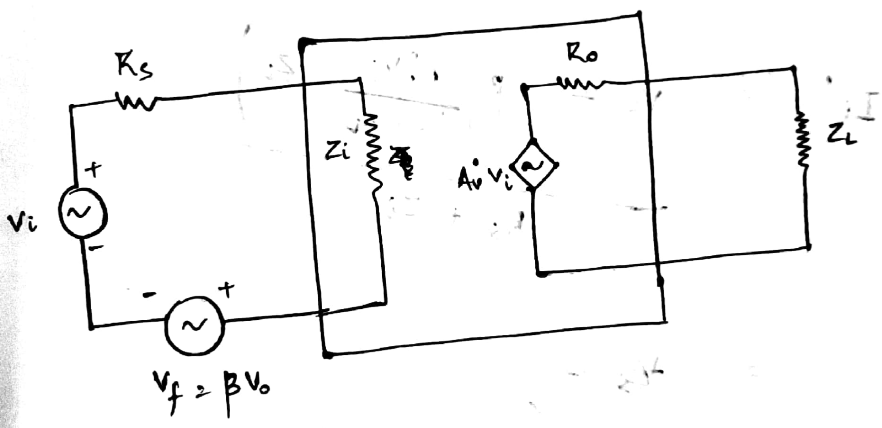
$$= \left[A_v^{\circ} \frac{Z_i}{R_s + Z_i} \right] \cdot \frac{Z_L V_s}{R_o + Z_L} = A_v \cdot \frac{Z_L}{R_o + Z_L} \cdot V_s$$

$$A_V = A_v \frac{Z_L}{R_o + Z_L}$$

Input impedance $Z_i' = R_s + Z_i$

Output impedance $= R_o$

gain $A_v = A_v \dfrac{Z_L}{R_o + Z_L}$



$$A_{vf} = \frac{V_o}{V_s}$$

$$V_o = \frac{A_v^{\circ} V_i}{R_o + Z_L} Z_L$$

$$V_i = \frac{V_s - \beta V_o}{R_s + Z_i} \cdot Z_i$$

$$V_o = \frac{A_v^{\circ}}{R_o + Z_L} \cdot Z_L \frac{V_s - \beta V_o}{R_s + Z_i} Z_i$$

$$V_o = \left[A_v^{\circ} \frac{Z_i}{R_s + Z_i} \right] \cdot \frac{Z_L}{R_o + Z_L} (V_s - \beta V_o)$$

$$V_o = \underbrace{A_v \cdot \frac{Z_L}{R_o + Z_L}}_{A_v} (V_s - \beta V_o)$$

$\cancel{A_{vf}} \rightarrow \quad V_o = A_v (V_s - \beta V_o)$

$$V_o (1 + \beta A_v) = A_v V_s$$

$$A_{vf} = \frac{A_v}{1 + \beta A_v} = \frac{V_o}{V_s} = \frac{A_v}{D} \qquad D = 1 + \beta A_v$$

$$Z_{if}' = \frac{V_s}{I_i'}$$ (Input impedance seen by source when feedback is on)

$$I_i' = \frac{V_s - \beta V_o}{R_s + Z_i}$$

$$\cancel{I_i' = \frac{V_s - \beta\left(\frac{A_v V_i}{R_o + Z_L} Z_L\right)}{R_s + Z_i}}$$

$$= \cancel{V_s}$$

$$I_i' = \frac{V_s - \beta\left(\frac{V_s A_v}{1 + \beta A_v}\right)}{R_s + Z_i}$$

$$I_i' = \frac{V_s}{(R_s + Z_i)(1 + \beta A_v)}$$

$$Z_{if}' = (R_s + Z_i)\underbrace{(1 + \beta A_v)}_{D} = Z_i' \cdot D$$

$$D = 1 + \beta A_v$$

Output impedance = $R_{of} = \dfrac{V_o}{I_o}$

$$I_o = \frac{V_o - A_v^{\circ} V_{in}''}{R_o} = \frac{V_o - A_v^{\circ}\left(\dfrac{-\beta V_o}{R_s + Z_i}\right) \times Z_i}{R_o}$$

$$V_{in}'' = \frac{V_f}{R_s + Z_i} \times Z_i \qquad I_o = \frac{V_o}{R_o}\left(1 + \frac{\beta A_v^{\circ} Z_i}{R_s + Z_i}\right)$$

$$= \frac{-\beta V_o}{R_s + Z_i} \times Z_i$$

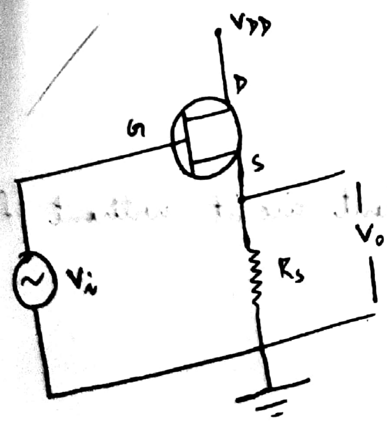
$$R_{of} = \frac{V_o}{I_o} = \frac{R_o}{1 + \dfrac{\beta A_v^{\circ} Z_i}{R_s + Z_i}} = \frac{R_o}{1 + \beta A_v}$$

where

$$A_v = \frac{A_v^{\circ} Z_i}{R_s + Z_i}$$

$$R_{of}' = R_{of} \parallel Z_L$$

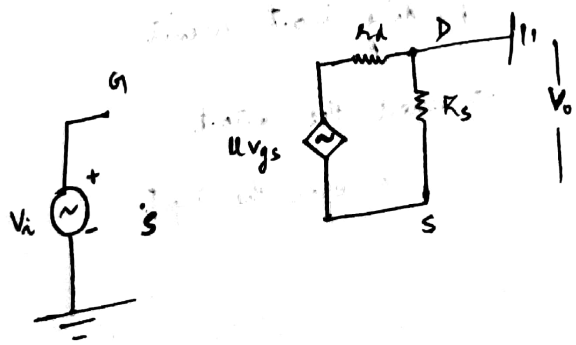
$$= \frac{R_o'}{1 + \beta A_v} = \frac{R_o'}{D}$$



$$V_{GS} = V_G - V_S$$

$$V_{in} = V_{GS} = V_i - V_s$$

$$= V_i - V_o \qquad (\beta = 1)$$



$$A_{vf} = \frac{i_d R_s}{V_i}$$

$$i_d = \frac{\mu v_{gs}}{r_d + R_s}$$

$$= \frac{\mu (v_g - v_s)}{r_d + R_s}$$

$$= \frac{\mu (v_i - v_o)}{r_d + R_s}$$

$$i_d = \frac{\mu (v_i - i_d R_s)}{r_d + R_s}$$

$$i_d r_d + i_d R_s = \mu v_i - \mu i_d R_s$$

$$i_d = \frac{\mu v_i}{r_d + (\mu+1) R_s}$$

$$\frac{i_d}{V_i} = \frac{\mu}{r_d + (\mu+1) R_s}$$

$$A_{vf} = \frac{\mu R_s}{r_d + (\mu+1) R_s}$$

Aliter

$$A_{vf} = \frac{A_v}{1 + \beta A_v} \qquad \beta = 1$$

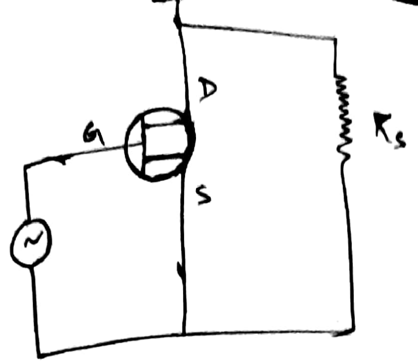
$$= \frac{A_v}{1 + A_v}$$

Rules for finding equivalent circuit without feedback

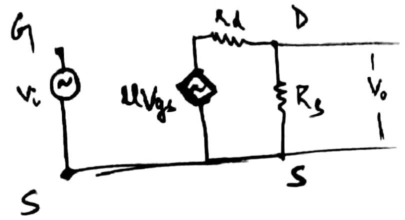
Finding input circuit

v ⇒ short the output

& open the input



Equivalent circuit without feedback



$$A_v = \frac{V_o}{V_i}$$

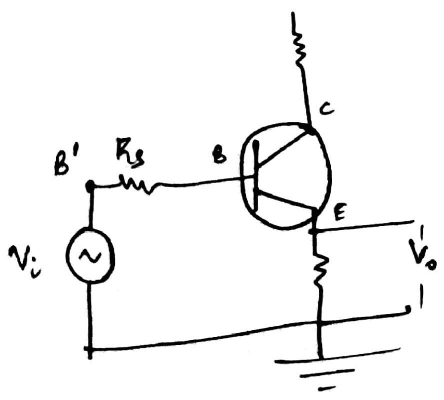
$$= \frac{i_d R_s}{V_i}$$

$$= \frac{\frac{\mu V_{gs}}{r_d + R_s} R_s}{V_i} \qquad V_{gs} = V_i$$

$$A_v = \frac{\mu R_s}{r_d + R_s}$$

$$A_{vf} = \frac{A_v}{1 + A_v}$$

$$= \frac{\frac{\mu R_s}{r_d + R_s}}{1 + \frac{\mu R_s}{r_d + R_s}} = \frac{\mu R_s}{r_d + (\mu + 1) R_s}$$



$$V_i = i_b R_s + V_{be} + V_o$$

$$V_i = V_{b'e} + V_o$$

$$V_{in} = V_{b'e} = V_i - V_o$$

Current Feedback

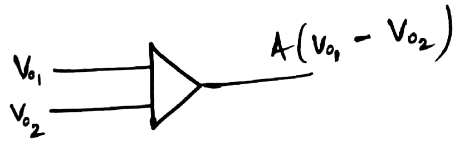
$$I_f = \beta I_o$$

$$A_{If} = \frac{A_I}{1 + \beta A_I}$$

$$R_{if} = \frac{R_i}{1 + \beta A_i}$$

Operational Amplifier (OP-AMP)

1) Differential Amplifier



2) Direct coupled amplifier

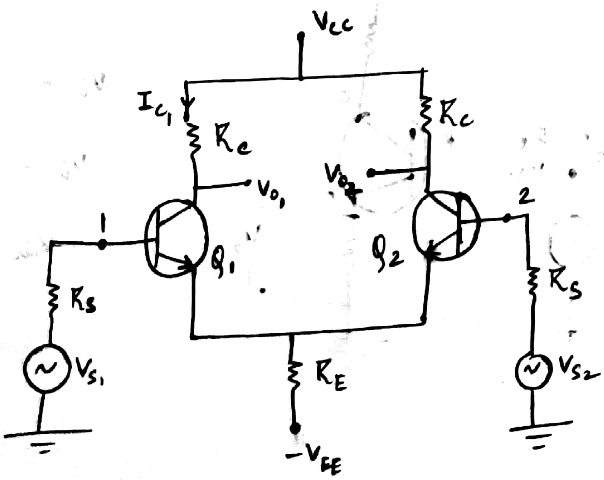
3) Infinite input impedance ($> 100\ M\Omega$)

4) Infinite gain (practically > 1000)

5) Infinite bandwidth (ideally)

6) Zero output impedance

Differential Amplifier



$V_{o1} = V_{cc} - I_{c1} R_c$

$v_{o1} = V_{cc} - i_{c1} R_A$

$V_{o2} = V_{cc} - I_{c2} R_c$

$v_{o2} = V_{cc} - i_{c2} R_c$

$v_{o1} = A_1 v_{s1}$

$A_1 \rightarrow$ Gain of amplifier when input is given to base of Q_1

$v_{o1} = A_1 \times v_{s1}'$

$v_{s1}' \Rightarrow$ Effect of v_{s2} when there is no v_{s1}

$v_{o1} = \left(A_1 \dfrac{v_{s1}'}{v_{s2}}\right) v_{s2}$

$v_{o1} = A_1' v_{s2}$

$A_1' \Rightarrow$ Gain of Q_1 w.r.t input at Q_2

By principle of superposition

$$v_{o1} = A_1 v_{s1} + A_1' v_{s2}$$

1 $\Rightarrow$ Inverting
2 $\Rightarrow$ Non-Inverting
} when V_{o1} is considered as output

Differential voltage $V_d = V_{s1} - V_{s2}$

Common voltage $V_c = \frac{1}{2}(V_{s1} + V_{s2})$

$$V_{s1} = \frac{1}{2}(V_d + 2V_c)$$

$$V_{s2} = \frac{1}{2}(2V_c - V_d)$$

$$V_{o1} = \frac{1}{2} A_1 (V_d + 2V_c) + \frac{1}{2} A_1' (2V_c - V_d)$$

$$= V_d\left(\frac{A_1 - A_1'}{2}\right) + V_c(A_1 + A_1')$$

$V_{o_1} = A_d V_d + V_c A_c$

$A_d = \frac{A_1 - A_1'}{2}$

$A_d >> A_c$

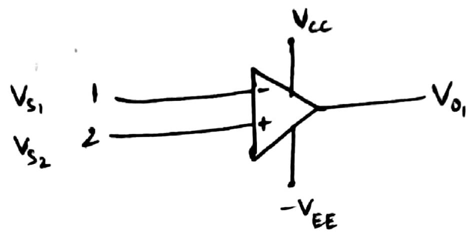
$A_c = A_1 + A_1'$

$V_{o_1} = A_d V_d$

CMRR $\rightarrow$ Common Mode Rejection Ratio (ρ)

$$\rho = \frac{|A_d|}{|A_c|}$$

$\rho \uparrow \Rightarrow$ Better Amplifier



~~Vs~~ Case - I

When $V_{s_1} = V_{s_2} = V_s$

$V_d = 0$

$V_c = \frac{1}{2}(V_{s_1} + V_{s_2}) = V_s$

$V_{o_1} = A_c V_c$

$A_d = 0$

$\frac{V_{o_1}}{V_s} = A_c$

Case - II

When $V_{s_1} = -V_{s_2} = V_s$

$A_c = 0$

$V_c = 0$

$V_d = 2V_{s_1} = 2V_s$

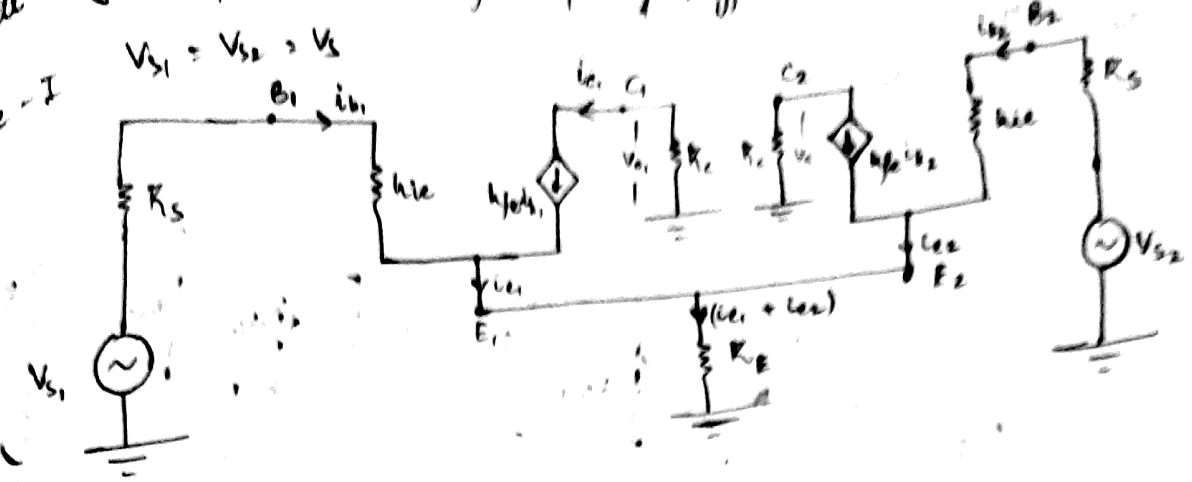
$V_{o_1} = A_d V_d$

$\frac{V_{o_1}}{V_s} = 2A_d$

$A_d = \frac{V_{o_1}}{2V_s}$

Small Signal Equivalent Model for ~~[illegible]~~ Differential Amplifier

Case - I $V_{s1} = V_{s2} = V_s$



$$v_{o1} = -i_{c1} R_c = -h_{fe} i_{b1} R_c$$

$$= \cancel{h_{fe} R_c}\, i_{b1}$$

KCL $\Rightarrow$ $i_{e1} + i_{e2} = (i_{b1} + h_{fe} i_{b1}) + (i_{b2} + h_{fe} i_{b2})$

$\because$ All resistances are same in KVL, $i_{b1} = i_{b2}$

$$i_{e1} + i_{e2} = 2(1 + h_{fe}) i_b$$

KVL $\Rightarrow$ $$v_s = (R_s + h_{ie}) i_b + R_E [2(1 + h_{fe}) i_b]$$

$$= i_b [R_s + h_{ie} + 2(1 + h_{fe}) R_E]$$

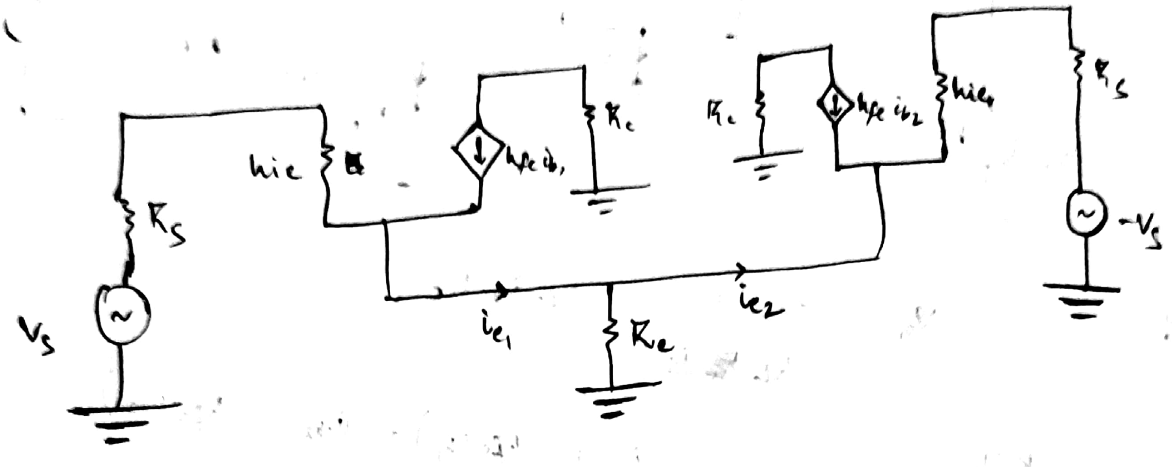
$$v_{o1} = -h_{fe} R_c \frac{v_s}{(R_s + h_{ie}) + 2(1 + h_{fe}) R_E}$$

$$A_c = \frac{v_{o1}}{v_s}$$

$$= \frac{-h_{fe} R_c}{(R_s + h_{ie}) + 2(1 + h_{fe}) R_E}$$

Case - II

$$V_{s_1} = -V_{s_2} = V_s$$



$$|i_{e_1}| = |i_{e_2}|$$

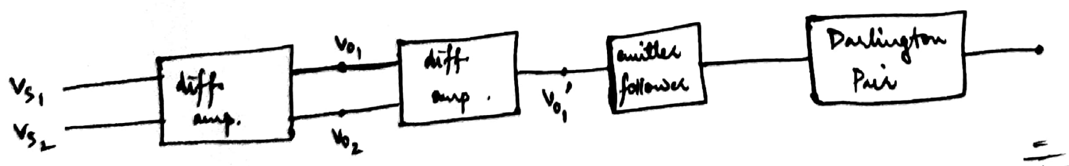
$$i_{e_1} + i_{e_2} = 0$$

$$v_{o_1} = -i_{c_1} R_c$$
$$= -h_{fe} i_{b_1} R_c$$

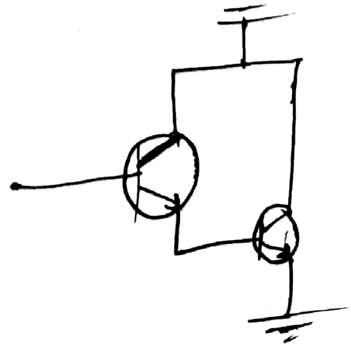
$$v_{o_1} = \frac{-h_{fe} R_c v_s}{R_s + h_{ie}}$$

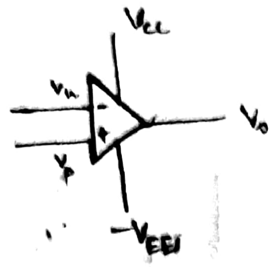
$$A_d = \frac{v_{o_1}}{2 v_s} = \frac{-h_{fe} R_c}{2(R_s + h_{ie})}$$

OP - AMP



Darlington pair ⇒





Need of diff. amp. with $A_c << A_d$

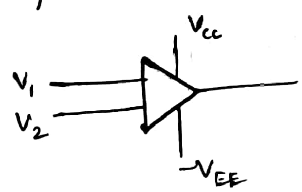
$$v_o = A_d\left[\text{signal} + \text{noise} - \text{noise}\right] + A_c\left[\frac{\text{signal} + \text{noise} + \text{noise}}{2}\right]$$

$$v_o = A_d \cdot \text{signal} + A_c\left(\frac{\text{signal}}{2} + \text{noise}\right)$$

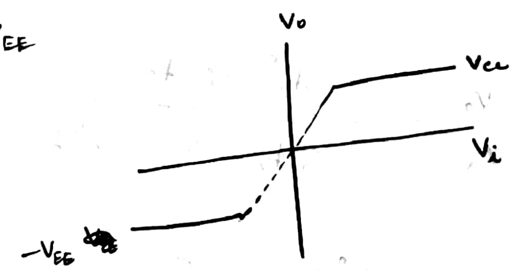
$$A_c << A_d$$

$$v_o = A_d \cdot \text{signal}$$

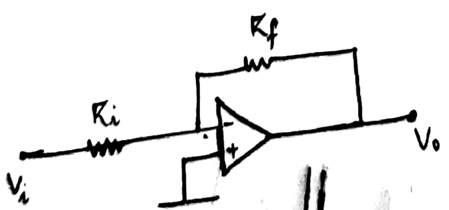
Open loop OP-AMP



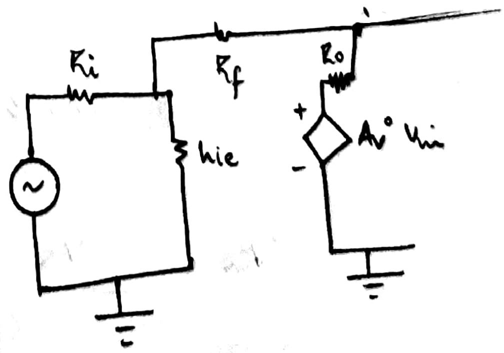
$$V_o = A_v^o (V_1 - V_2)$$

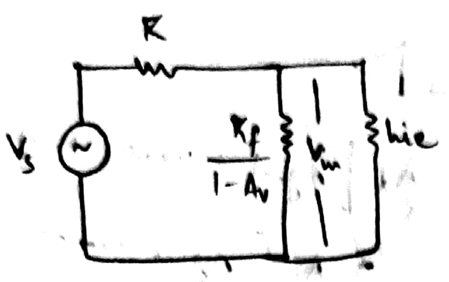


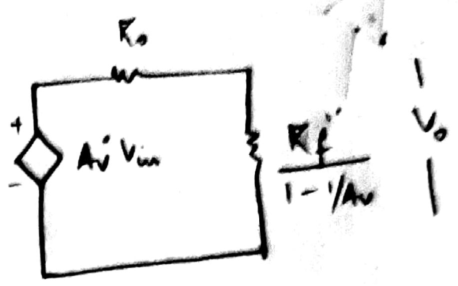
Inverting Amp



Inverting Amp







$$A_v = \frac{V_o}{V_{in}} \qquad \cancel{R_f}\; A_{vf} = \frac{V_o}{V_s}$$

$$V_o = \frac{A_v^{\circ} V_{in}}{R_o + \frac{R_f}{1-\frac{1}{A_v}}} \cdot \frac{R_f}{1 - 1/A_v}$$

$$= \frac{A_v^{\circ} V_{in} (1 - 1/A_v)}{R_o - \frac{R_o}{A_v} + R_f} \cdot \frac{R_f}{1 - 1/A_v}$$

$$A_v = \frac{V_o}{V_{in}} = \frac{A_v^{\circ} R_f A_v}{R_o A_v - R_o + A_v R_f}$$

$$A_v = \frac{A_v^{\circ} R_f + R_o}{R_o + R_f}$$

$$R_o \to 0$$

$$A_v \approx A_v^{\circ}$$

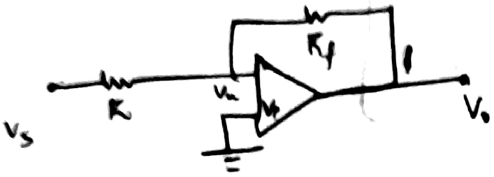
$$V_{in} = \frac{V_s}{R_1 + \left(\frac{R_f}{1-A_v} \parallel z_i\right)} \left(\frac{R_f}{1-A_v} \parallel z_i\right)$$

$$A_{vf} = \frac{-Y}{Y_f - \frac{1}{A_v}(Y + Y_f + Y_i)} \qquad Y = 1/R$$

$$Y_i = \frac{1}{Z_i} \qquad Y_f = \frac{1}{R_f}$$

$$A_{vf} = \frac{-Y}{Y_f} \quad (\text{As } A_v \to \infty)$$

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



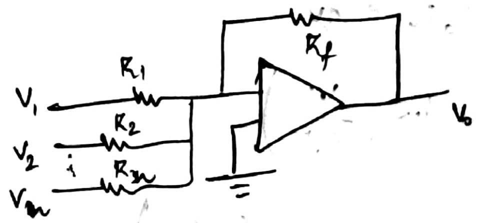
$V_n \approx V_p$ I

If V_p is grounded, V_n will also be grounded

$$\frac{V_s - 0}{R} = \frac{0 - V_o}{R_f}$$

$$A_v = \frac{V_o}{V_s} = \frac{-R_f}{R}$$

Adder circuit



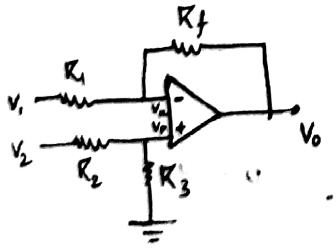
$$\frac{V_1 - 0}{R_1} + \frac{V_2 - 0}{R_2} + \cdots \frac{V_n}{R_n} = \frac{0 - V_o}{R_f}$$

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

$$R_1 = R_2 \cdots = R_n = R$$

$$V_o = \frac{-R_f}{R}(V_1 + V_2 \cdots + V_n)$$

Subtractor circuit



$$V_n = V_p = \frac{V_2}{R_2 + R_3} \times R_3$$

$$\frac{V_1 - V_n}{R_1} = \frac{V_n - V_o}{R_f}$$

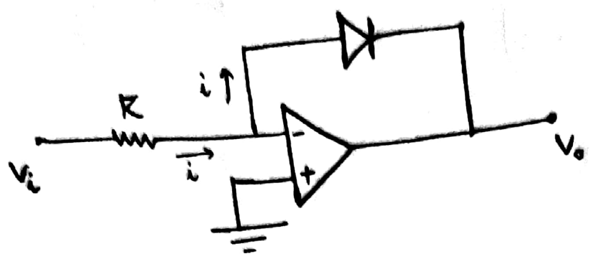
$$\Rightarrow V_1 - \frac{V_2}{\left(1 + \frac{R_2}{R_3}\right)}(R_1 + R_f) = -V_o R_1$$

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

$$V_1 - V_2 = -V_o \frac{R_1}{R_f}$$

$$V_o = \frac{-R_f}{R_1}(V_1 - V_2)$$

Log Amplifier



$$\frac{V_i - 0}{R} = I_0 \left[e^{\frac{q(0 - V_0)}{\eta k_B T}} - 1 \right]$$

$$= I_0 \, e^{\frac{-qV_0}{\eta k_B T}} - I_0$$

$$\approx I_0 \, e^{\frac{-qV_0}{\eta k_B T}} \qquad V_T = \frac{k_B T}{q}$$

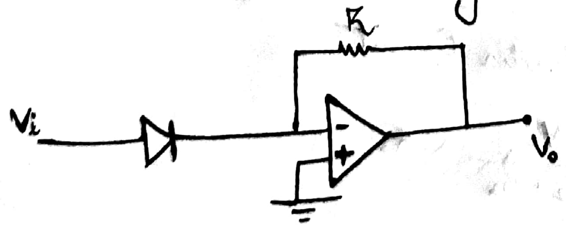
$$\frac{V_i}{R} \approx I_0 \, e^{\frac{-V_0}{\eta V_T}}$$

$$V_i = I_0 R \, e^{\frac{-V_0}{\eta V_T}}$$

$$\frac{-V_0}{\eta V_T} = \ln\left(\frac{V_i}{I_0 R}\right)$$

$$V_0 = -\eta V_T \ln\left(\frac{V_i}{I_0 R}\right)$$

Anti-Log Amplifier

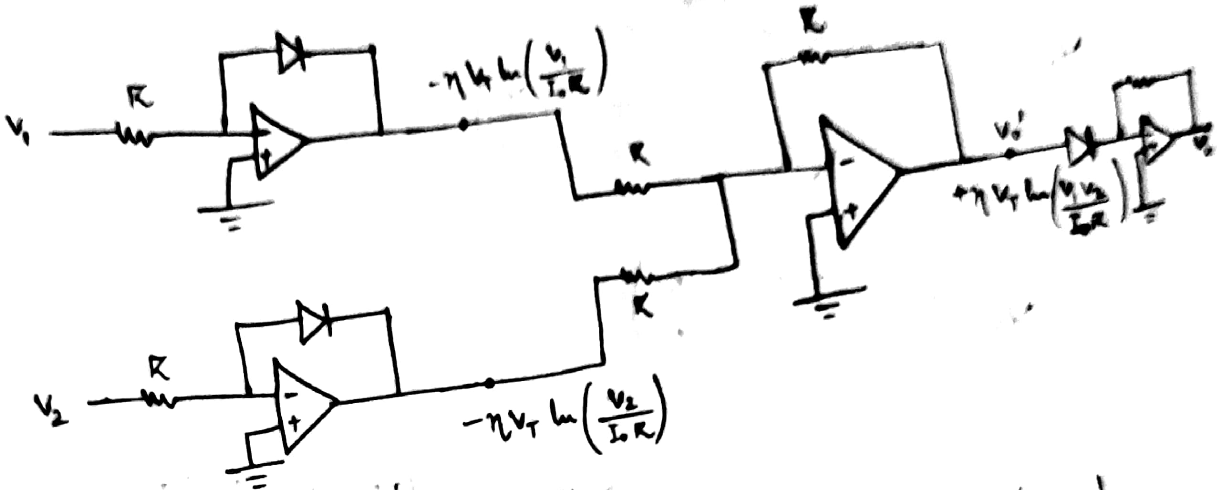


$$I_0 \left[e^{\frac{q(V_i - 0)}{\eta k_B T}} - 1 \right] = \frac{0 - V_0}{R}$$

$$I_0 \, e^{\frac{V_i}{\eta V_T}} = \frac{-V_0}{R}$$

$$V_o = -I_o R\, e^{\frac{V_i}{\eta V_T}}$$

Multiplier circuit



$$V_o' = +\eta V_T \ln\left(\frac{V_1}{I_o R}\right) + \eta V_T \ln\left(\frac{V_2}{I_o R}\right)$$

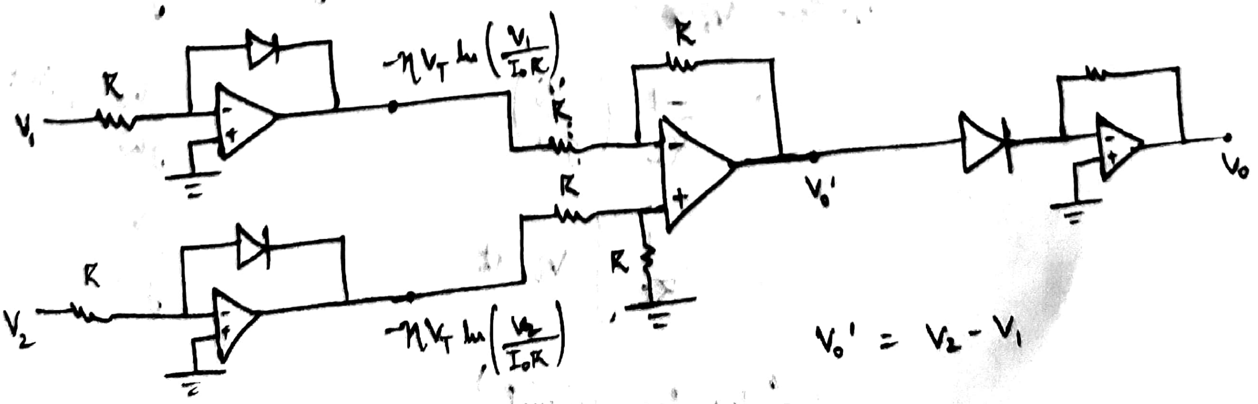
$$= +\eta V_T \ln\left(\frac{V_1 V_2}{(I_o R)^2}\right)$$

$$V_o = -I_o R\, e^{\frac{\eta V_T}{\eta V_T} \ln\left(\frac{V_1 V_2}{(I_o R)^2}\right)}$$

$$= \frac{-I_o R}{\cancel{\;}} \cdot \frac{V_1 V_2}{(I_o R)^2}$$

$$V_o = \frac{-V_1 V_2}{(I_o R)^2}$$

Divider circuit



$$V_o' = V_2 - V_1$$

$$V_o' = -\eta V_T \ln \frac{V_2}{I_o R} + \eta V_T \ln\left(\frac{V_1}{I_o R}\right)$$

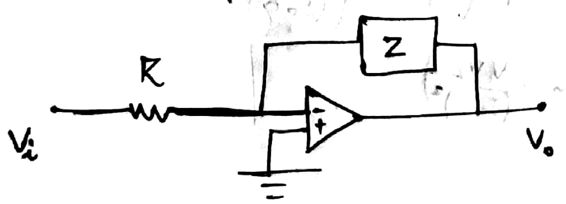
$$= +\eta V_T \ln\left(\frac{V_1}{V_2}\right)$$

$$V_o = -I_o R\, e^{\frac{V_o'}{\eta V_T}}$$

$$= -I_o R\, e^{\frac{\eta V_T}{\eta V_T} \ln\left(\frac{V_1}{V_2}\right)}$$

$$V_o = -I_o R \left(\frac{V_1}{V_2}\right)$$

Differentiator / Integrator Circuit



$$\frac{V_i - 0}{R} = \frac{0 - V_o}{Z}$$

$$V_o = \frac{-Z}{R} V_i$$

If $Z = C$

$$V_o = \frac{-1}{(j\omega c)R} V_i$$

$$V_i = V_o e^{j\omega t}$$

$$\int V_i \, dt = \int V_o e^{j\omega t} dt$$

$\cancel{V_i = V_o e^{j\omega t}}$

$$= \frac{-1}{Rc}\left(\frac{V_i}{j\omega}\right)$$

$$= \frac{V_o}{j\omega} e^{j\omega t}$$

$$= \frac{-1}{Rc}\int V_i \, dt$$

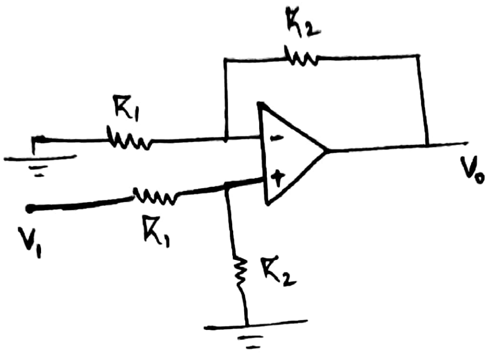
$$= \frac{V_i}{j\omega}$$

(Integrator circuit)

If $z = L$

$$V_o = -\frac{L}{R}\frac{dV_i}{dt}$$ (Differentiator Circuit)

Non-Inverting OP-AMP



$$V_n = V_p = \frac{V_1}{R_1 + R_2} R_2$$

$$\frac{0 - V_n}{R_1} = \frac{V_n - V_o}{R_2}$$

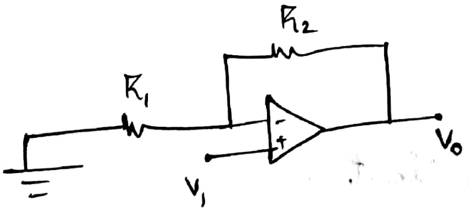
$$-R_2 V_n = R_1 V_n - R_1 V_o$$

$$R_1 V_o = (R_1 + R_2) V_n$$

$$R_1 V_o = (R_1 + R_2) \frac{V_1}{R_1 + R_2} R_2$$

$$V_o = \frac{R_2}{R_1} V_1$$

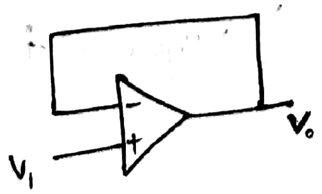
$$V_o = \left(1 + \frac{R_2}{R_1}\right) V_n$$



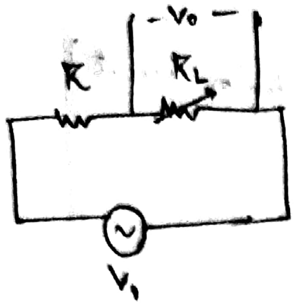
$$V_o = \left(1 + \frac{R_2}{R_1}\right) V_1$$

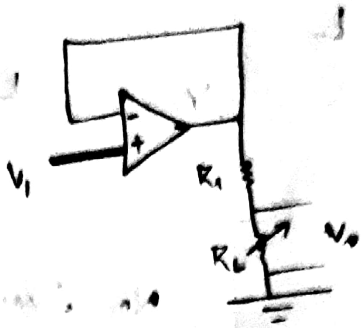
$$A_v = 1 + \frac{R_2}{R_1}$$

Unit Gain Amplifier



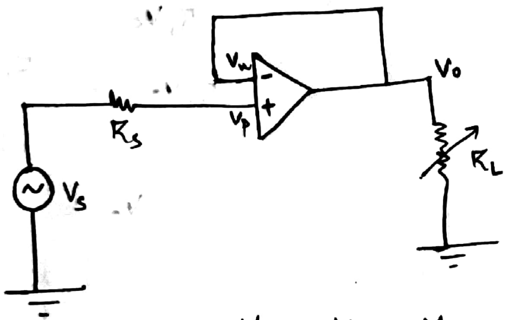
$$V_o = V_1$$

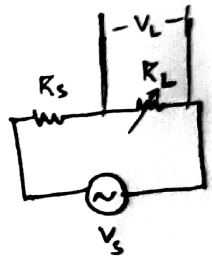




$$V_L = \frac{V_1}{R_1 + R_L} R_L$$

$$= \frac{V_1}{1 + R/R_L}$$





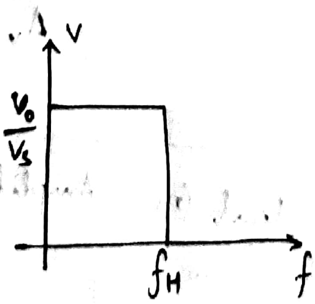
$$V_L = \frac{V_s}{R_s + R_L} R_L$$

$$V_o = V_n = V_p$$

Filter circuit

Low pass filter

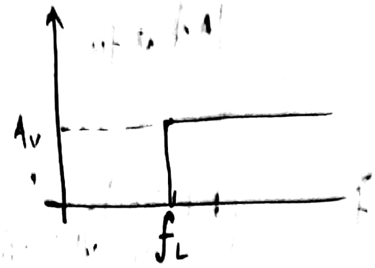
$A_V = \frac{V_o}{V_s}$



Ideal

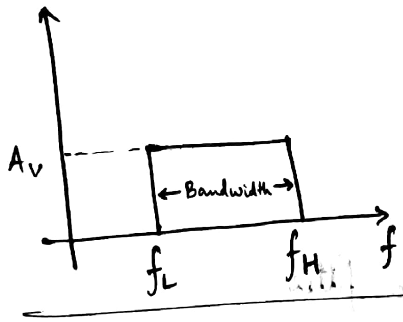
$f_H \rightarrow$ Higher cutoff frequency

High pass filter

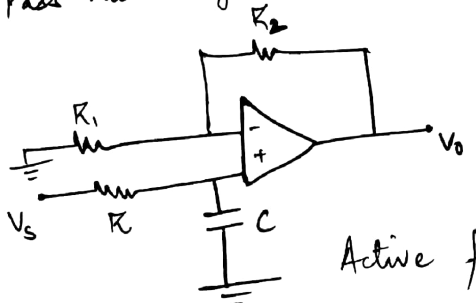


$\rightarrow$ lower cutoff frequency

Band pass filter



Low Pass Filter Design



Active filter

$$V_n = V_p = \frac{V_s}{R+Z} Z$$

$$= \frac{V_s}{R + \frac{1}{j\omega C}} \times \frac{1}{j\omega C}$$

$$= \frac{V_s}{1 + j\omega CR}$$

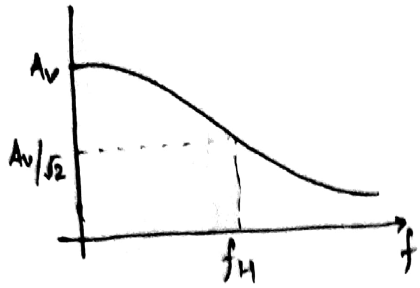
$$V_o = \left(1 + \frac{R_2}{R_1}\right) V_p$$

$$= \left(1 + \frac{R_2}{R_1}\right) \frac{V_s}{1 + j\omega CR}$$

$$|V_o| = \left(1 + \frac{R_2}{R_1}\right) \frac{|V_s|}{\sqrt{1 + \omega^2 C^2 R^2}}$$

$$|A_v| = \frac{|V_o|}{|V_s|} = \left(1 + \frac{R_2}{R_1}\right) \frac{1}{\sqrt{1 + \omega^2 C^2 R^2}}$$

$$|A_v|_{max} = 1 + \frac{R_2}{R_1}$$

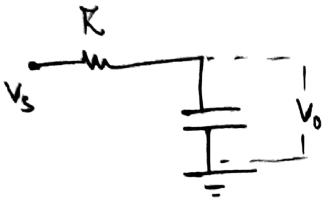


$|A_v|$ at f_H = $\frac{1}{\sqrt{2}} |A_v|_{max}$.

$$\left(1 + \frac{R_2}{R_1}\right) \frac{1}{\sqrt{1 + \omega_H^2 C^2 R^2}} = \frac{1}{\sqrt{2}} \left(1 + \frac{R_2}{R_1}\right)$$

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

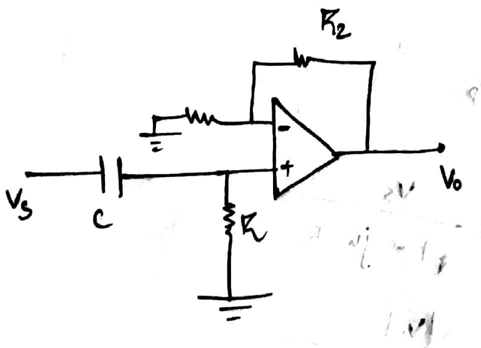
$$f_H = \frac{1}{2\pi RC}$$



Passive filter

$$V_o = V_p = \frac{V_s}{1 + j\omega CR}$$

High Pass Filter Design



$$V_o = \left(1 + \frac{R_2}{R_1}\right) V_p$$

$$= \left(1 + \frac{R_2}{R_1}\right) \frac{V_s}{R + \frac{1}{j\omega C}} R$$

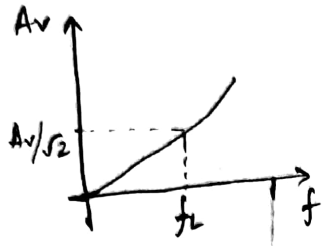
$$V_o = \left(1 + \frac{R_2}{R_1}\right) \frac{V_s R}{\left(R + \frac{1}{j\omega C}\right)}$$

$$|A_v| = \frac{|V_o|}{|V_s|} = \left(1 + \frac{R_2}{R_1}\right) \frac{R}{\sqrt{R^2 + \frac{1}{\omega^2 C^2}}}$$

$\omega \to \infty \Rightarrow |A_v|_{max}$

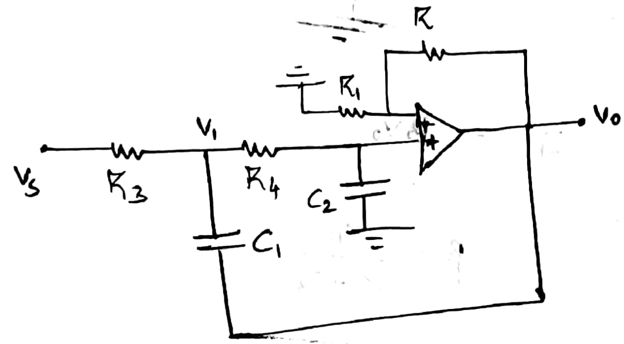
$\omega \to 0 \Rightarrow A_v \to 0$

Scanned with OKEN Scanner



$$f_L = \frac{1}{2\pi RC}$$

Second-Order Filter



$$\frac{V_s - V_1}{R} = \frac{V_1 - V_o}{1/j\omega C_1} + \frac{V_1}{R_4 + \frac{1}{j\omega C_2}}$$

$$V_p = \frac{V_1}{R_4 + \frac{1}{j\omega C_2}} \times \frac{1}{j\omega C_2}$$

$$A_{vf} = \frac{A_v}{1 + \beta A_v} \quad \text{negative feedback}$$

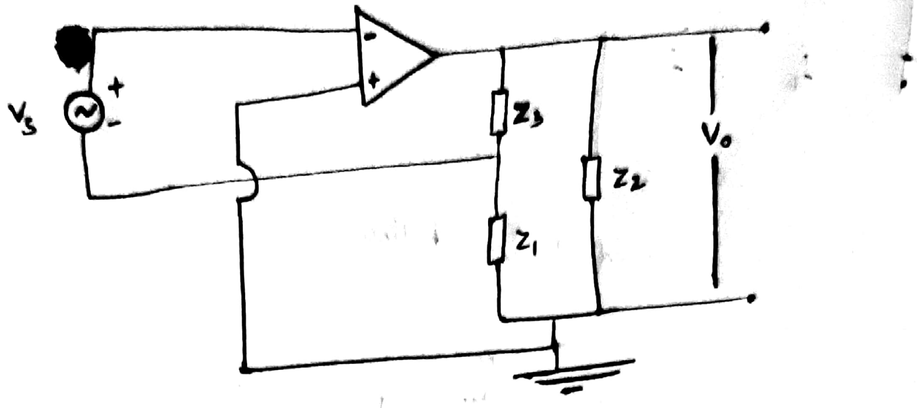
$$A_{vf} = \frac{A_v}{1 - \beta A_v} \quad \text{positive feedback}$$

$$A_{vf} = \frac{A_v}{1 - \beta A_v} = \frac{V_o}{V_s}$$

Loop gain ⇒ βA_v

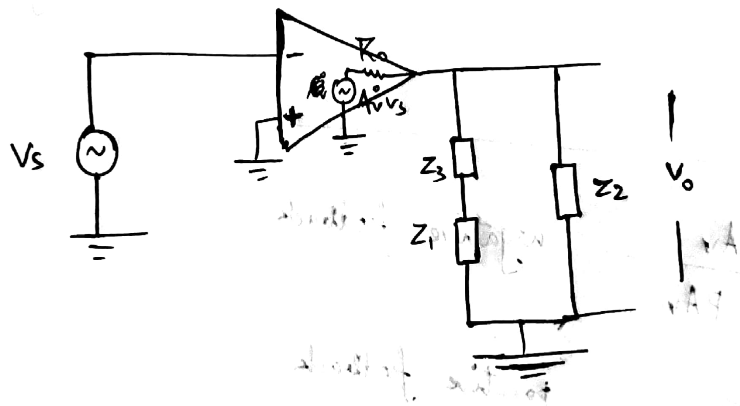
$\beta A_v = 1$ (Barkhausen criterion)

Usually βA_v taken greater than 1 due to losses in circuit.



$$V_f = \frac{V_o}{Z_1 + Z_3} Z_1 = \beta V_o$$

$$\beta = \frac{Z_1}{Z_1 + Z_3}$$



$$V_o = \frac{A_v^{\circ} V_s}{R_o + Z_L} \times Z_L \qquad Z_L = (Z_1 + Z_3) \parallel Z_2 = \frac{(Z_1 + Z_3) \cdot Z_2}{Z_1 + Z_2 + Z_3}$$

$$A_v \; \frac{V_o}{V_s} = \frac{A_v^{\circ} \dfrac{(Z_1 + Z_3) Z_2}{Z_1 + Z_2 + Z_3}}{R_o + \dfrac{(Z_1 + Z_3) Z_2}{Z_1 + Z_2 + Z_3}}$$

$$= \frac{A_v^{\circ} \, Z_2 (Z_1 + Z_3)}{R_o (Z_1 + Z_2 + Z_3) + (Z_1 + Z_3) Z_2}$$

$$\beta A_v = \frac{z_1}{z_1 + z_3} \cdot \frac{A_v^\circ z_2 (z_1 + z_3)}{R_o(z_1 + z_2 + z_3) + (z_1 + z_3) z_2}$$

$$= \frac{A_v^\circ z_1 z_2}{R_o(z_1 + z_2 + z_3) + (z_1 + z_3) z_2}$$

$$z_i = j x_i \qquad i = 1, 2, 3$$

$$\beta A_v = \frac{-|A_v^\circ| z_1 z_2}{R_o(z_1 + z_2 + z_3) + z_2(z_1 + z_3)}$$

$$= \frac{|A_v^\circ| x_1 x_2}{jR_o(x_1 + x_2 + x_3) - x_2(x_1 + x_3)}$$

$\because \beta A_v =$ Real $\Rightarrow$ $x_1 + x_2 + x_3$

$x_1 + x_3 = -x_2$ (For βA_v to be positive)

$$\beta A_v = \frac{|A_v^\circ| x_1 x_2}{x_2^2} = |A_v^\circ| \frac{x_1}{x_2}$$

$x_1, x_2 \Rightarrow$ Capacitors
$x_3 \Rightarrow$ Inductors
} Colpitt Oscillator

$x_1, x_2 \Rightarrow$ Inductors
$x_3 \Rightarrow$ Capacitors
} Hartley Oscillators