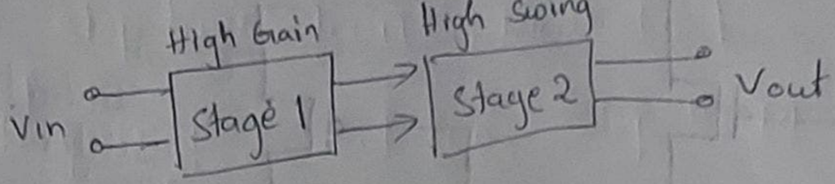
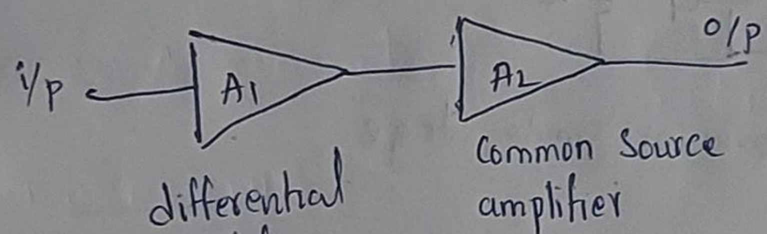
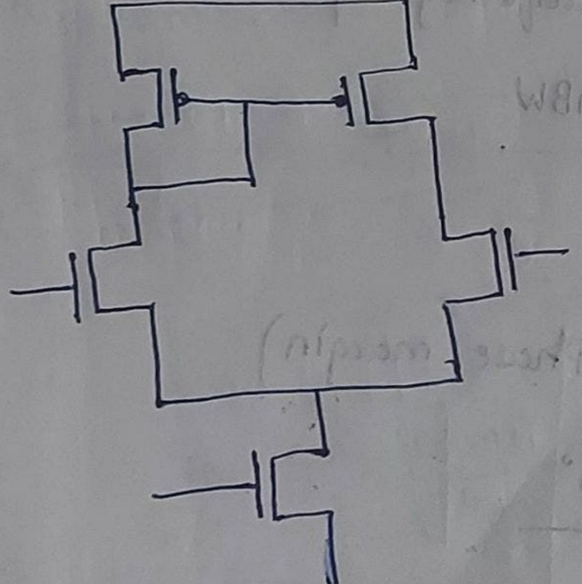
Two stage op amp :



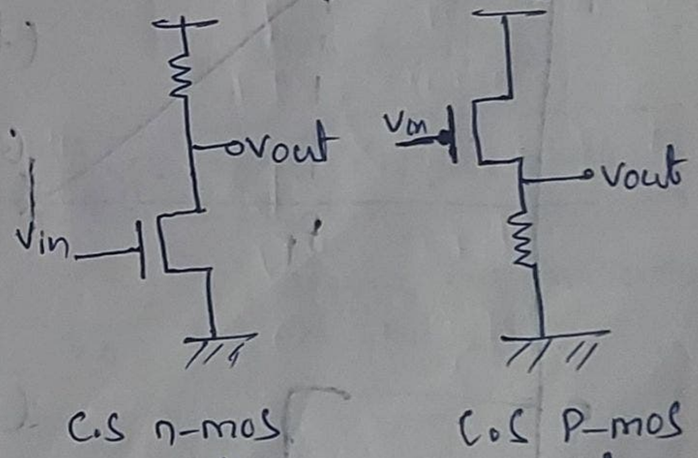
⇒ Two-stage op amp consist of first stage providing a high gain and the second providing large swing

⇒ The first stage incorporates various amplifier topologies, but the second stage is typically configured as a simple common source stage to allow maximum output swings. (maximum output swings ⇒ maximum output voltage)





differential amplifier



C.S n-mos amplifier

⇒ Swing is limited

C.S P-mos amplifier

⇒ Swing is good

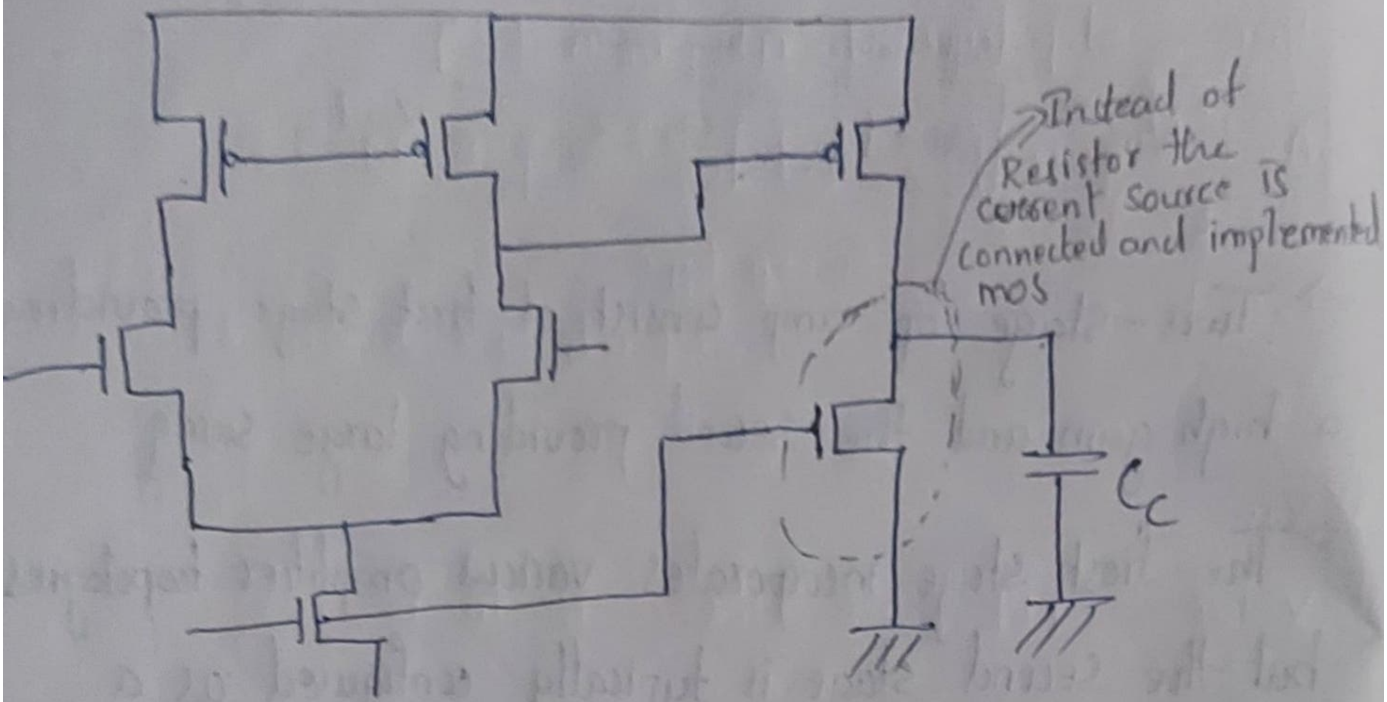


fig: Two-stage op amp

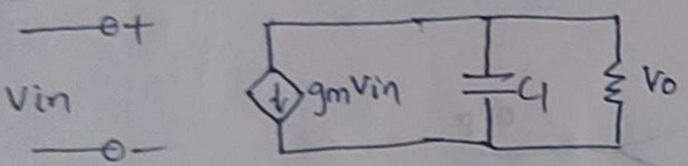


fig: Small Signal diagram of single Stage

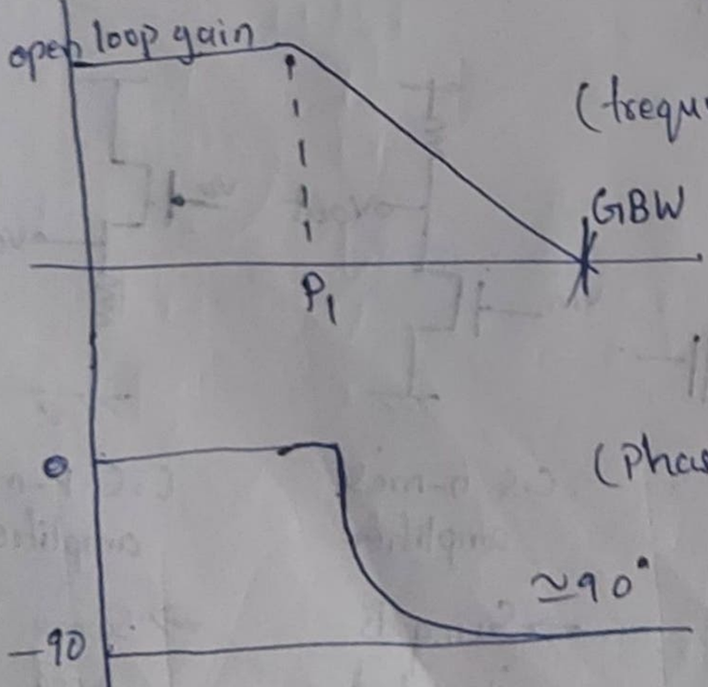


fig: Bode plot

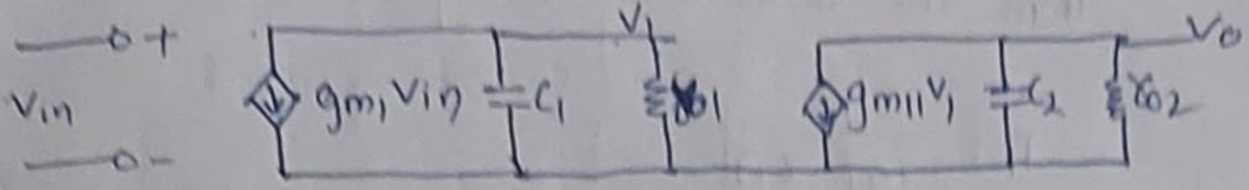


fig: Small signal diagram of two stage op amp

$$P_1 = \frac{1}{r_{o1} C_1}$$

$$P_2 = \frac{1}{r_{o2} C_2}$$

First stage output (V1):

At node v_1, impedance is

$$z_1 = \left(\frac{1}{r_{o1}}\right) // \left(\frac{1}{j\omega C_1}\right)$$

$$= \frac{1}{r_{o1} + j\omega C_1}$$

So,

$$v_1 = gm_1 \cdot v_{in} \cdot z_1$$

$$\boxed{v_1 = gm_1 \cdot v_{in} / r_{o1} + j\omega C_1}$$

Second stage output (v_0):

At node V_0:

$$z_2 = \left(\frac{1}{r_{o2}}\right) // \left(\frac{1}{j\omega C_2}\right)$$

$$= \frac{1}{r_{o2} + j\omega C_2}$$

So,

$$V_0 = gm_2 \cdot V_1 \cdot z_2$$

$$\boxed{V_0 = gm_2 \cdot v_1 / (r_{o2} + j\omega C_2)}$$

$\because$ $gm_1\, gm_2$ are transconductance of stages

Sub v_1 in v_0

$$v_0 = gm_2 \left[\frac{gm_1 \cdot v_{in}}{(r_{o1} + j\omega C_1)}\right] \cdot \left[\frac{1}{r_{o2} + j\omega C_2}\right]$$

So the overall transfer function

$$\frac{V_0}{V_{in}} = \frac{(gm_1 \cdot gm_2)}{(r_{o1} + j\omega C_1)(r_{o2} + j\omega C_2)}$$

from the denominator the poles are

$$P_1 = \frac{1}{(r_{o1} \cdot C_1)}$$

$$P_2 = \frac{1}{(r_{o2} C_2)}$$

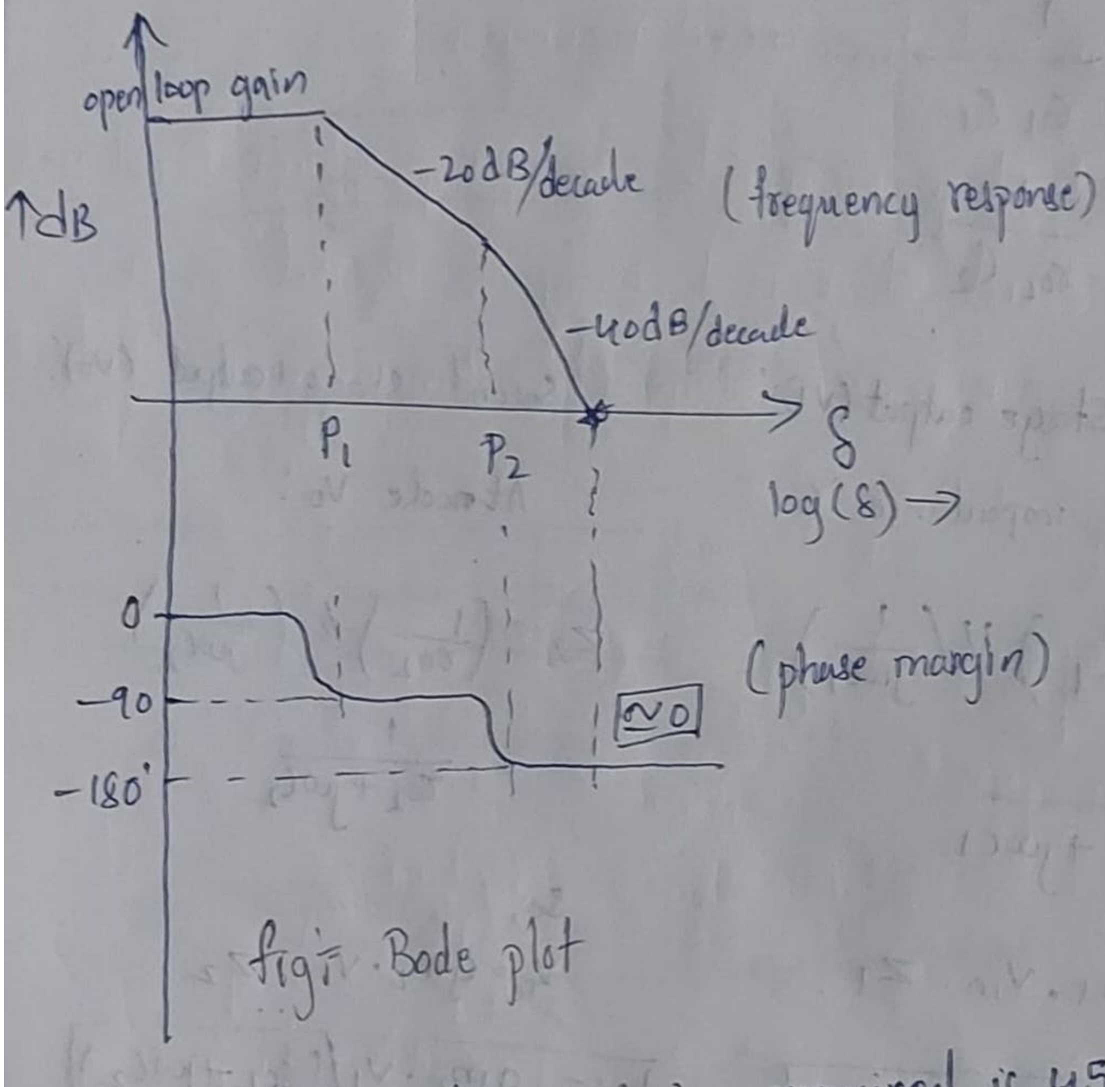


fig: Bode plot

⇒ minimum phase margin required is 45°

⇒ If it is 60° or more it is very good

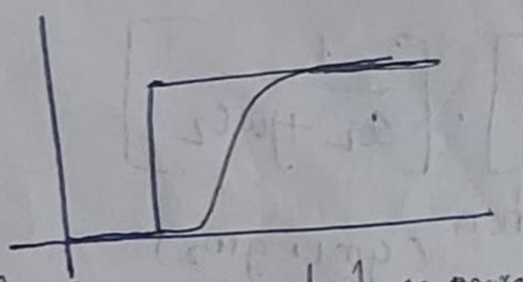


fig: for very good phase margin

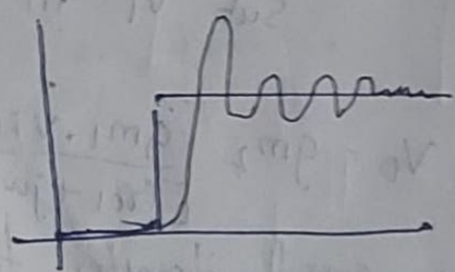
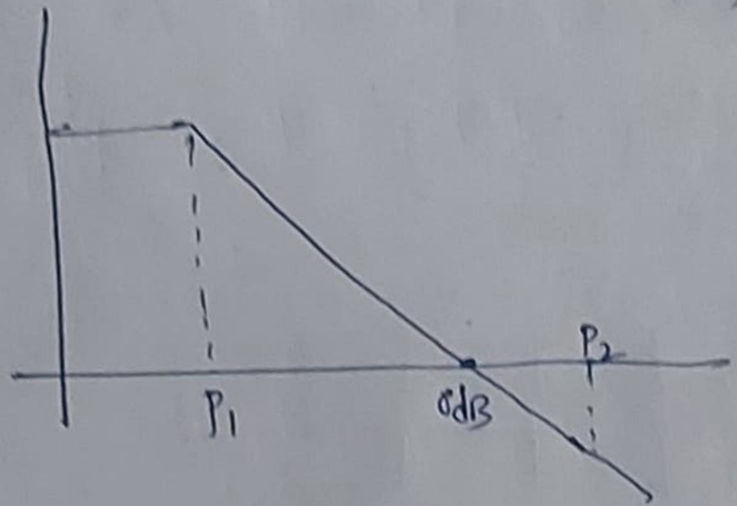


fig: for not good phase margin

⇒ Here P_1 considered as Dominal port in this the Port P_1 move backward



gain cross odB before the P_2 comes

⇒ Something that comes after odB will not have any effect so Ignore that thing

⇒ P_1 is the dominal port

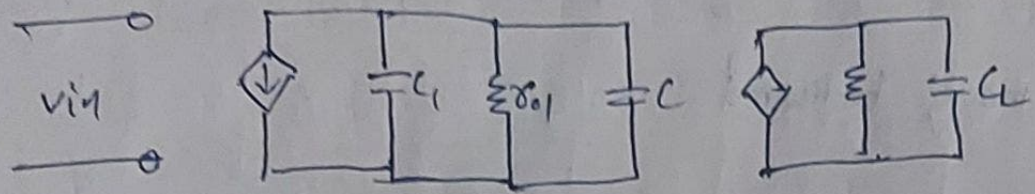
⇒ This processes is called compensation

In $P_1 = \frac{1}{r_{01} C_1}$ if we increase the value of C_1 then we can move the Pole P_1 towards left

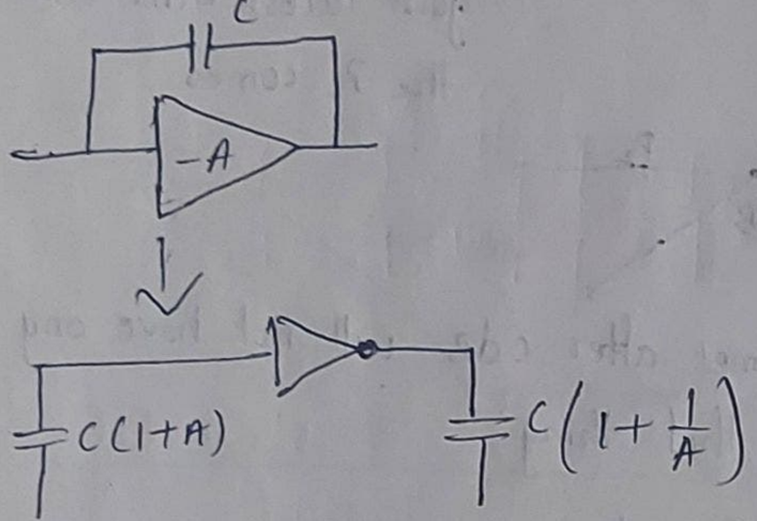
The P_1 becomes $P_1 = \frac{1}{r_1 C_1}$

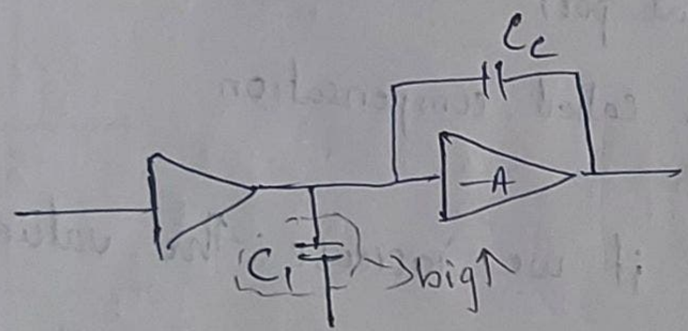
$$= \frac{1}{r_1 (C_1 + C)} \rightarrow \text{big value}$$

⇒ here the C is what we added the value to move pole towards left.

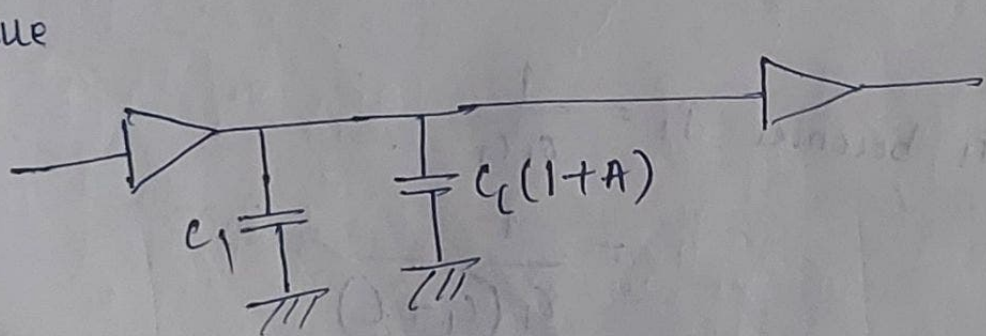


Miller effect





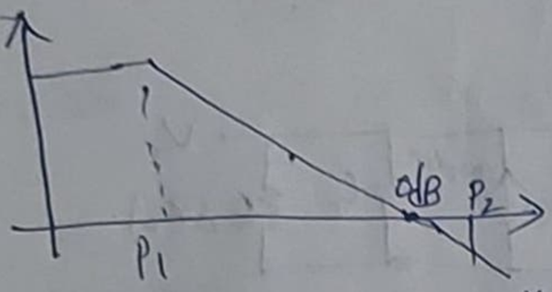
We use miller effect to get higher capacitance Value

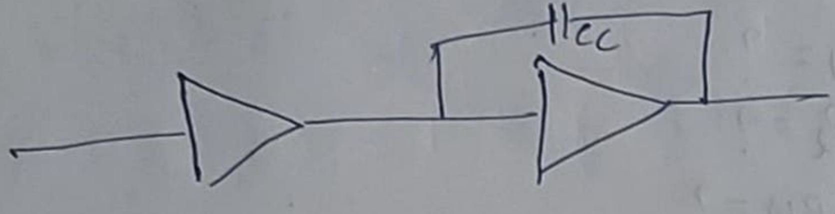


$$p_1 = \frac{1}{r_1[(C_1 + C_c(1+A)]}$$

⇒ After the miller effect is introduced the C_1 value will be high this results the P_1 to move towards left this is know as compensation

⇒ The P_2 will be after 0db avoid the P_2





$$P_1 = \frac{1}{r_{o1}\left[C_1 + C_c(1+A)\right]}$$

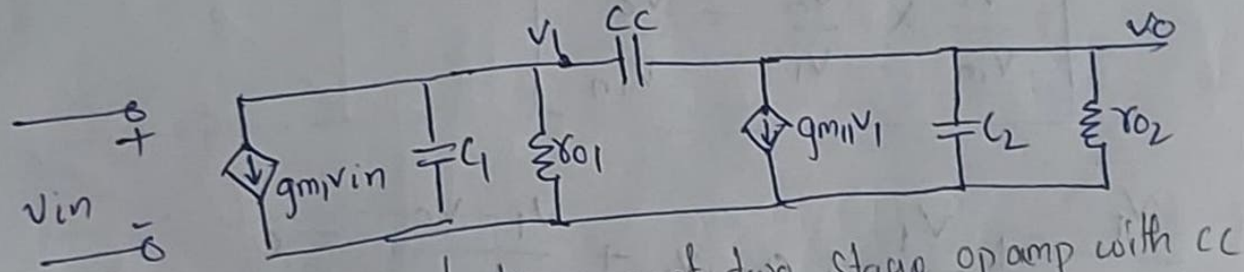
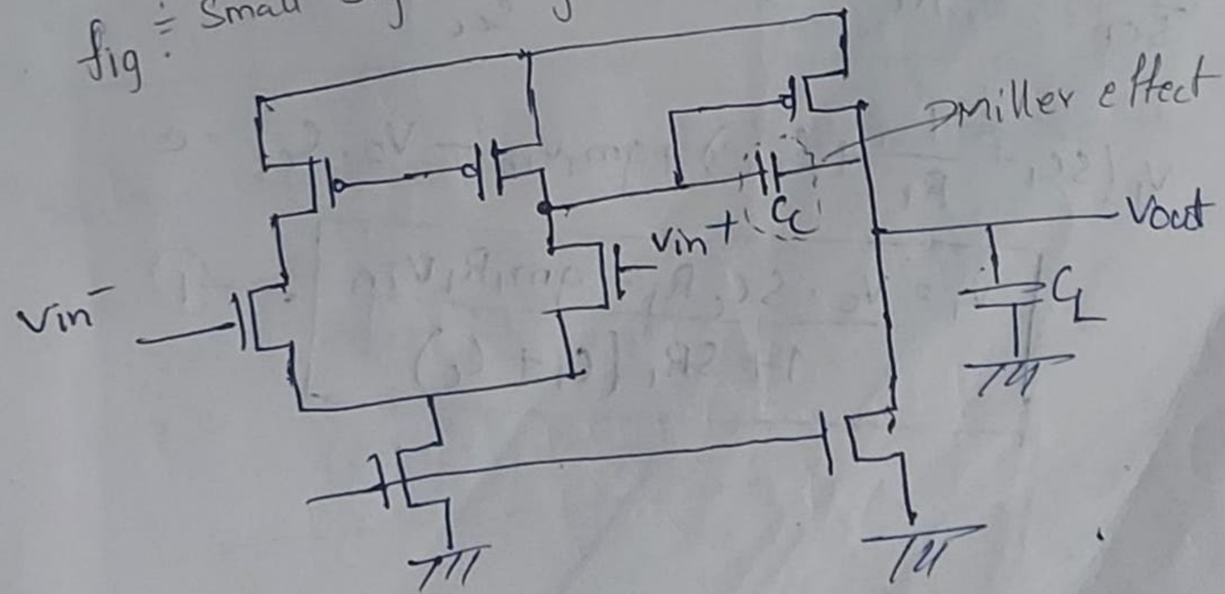


fig : Small signal diagram of two stage op amp with cc

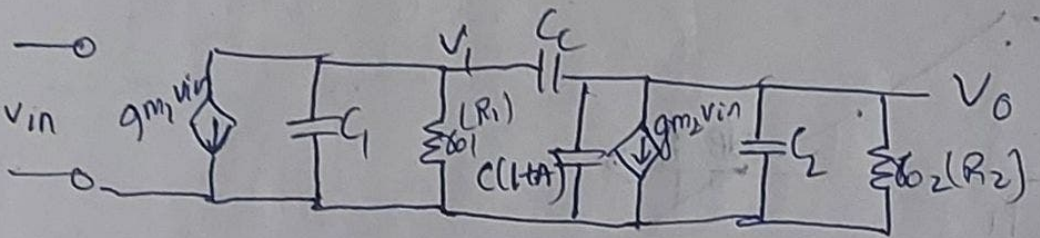


Before we go to exact design we should know the few paramaters that are :-

→ phase margin (Poles, zeroes, GBW etc ---)

→ Slew rate

→ Swing limits



$P_1 = ?$

$P_2 = ?$

$GBW = ?$

$P.m = ?$

$$\boxed{\frac{V_1}{V_{in}} \times \frac{V_o}{V_1} = \frac{V_o}{V_{in}}}$$

$$\frac{V_1}{\frac{1}{SC_1}} + \frac{V_1}{R_1} + g_{m1}V_{in} + \frac{V_1 - V_o}{\frac{1}{SC_c}} = 0$$

$$V_1\left(SC_1 + \frac{1}{R_1} + SC_c\right) + g_{m1}V_{in} - V_o . SC_c = 0$$

$$\boxed{V_1 = \frac{V_o \cdot SC_cR_1 - g_{m1}R_1V_{in}}{1 + SR_1(C_1 + C_c)}} \leftarrow 1$$

$$\frac{V_0}{\frac{1}{SC_2}} + \frac{V_0}{R_2} + gm_2 V_1 + \frac{V_0 - V_1}{1/SC_c} = 0$$

$$V_0\left[S(C_2+C_c) + \frac{1}{R_2}\right] = V_1(SC_c - gm_2) \quad \text{—②}$$

substitute eq ① in eq ②

$$V_0\left[S(C_2+C_c) + \frac{1}{R_2}\right] = \frac{(V_0 SC_cR_1 - gm_1R_1V_{in})(SC_c - gm_2)}{1+S(C_1+C_c)R_1}$$

$$V_0\left[S(C_2+C_c)R_2+1\right]\left[1+S(C_1+C_c)R_1\right] = (V_0 \cdot SC_cR_1 - gm_1R_1V_{in})(SC_c - gm_2)$$

$$\boxed{\frac{V_0}{V_{in}} = \frac{gm_1R_1\,gm_2R_2\left(1-\frac{SC_c}{gm_2}\right)}{S^2\left[R_1R_2(C_1C_2+C_1C_c+C_2C_c)\right] + S\left[R_2(C_c+C_2)+R_1(C_c+C_1) + C_c gm_2R_1R_2\right] + 1}}$$

For two pole system the standard transfer function

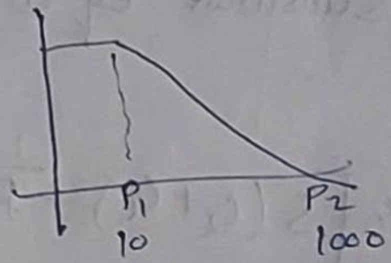
$$\boxed{\frac{V_0}{V_{in}} = \frac{A_{DC}\left(1-\frac{S}{Z}\right)}{\left(1+\frac{S}{P_1}\right)\left(1+\frac{S}{P_2}\right)}}$$

After expanding demoninator it becomes

$$= \frac{A_{DC}\left(1-\frac{s}{2}\right)}{1+s\left(\frac{1}{P_1}+\frac{1}{P_2}\right)+s^2\left(\frac{1}{P_1P_2}\right)}$$

$$s\left(\frac{1}{P_1}+\frac{1}{P_2}\right) \simeq s\,\frac{1}{P_1}$$

Ex :-



coefficient of 's' $\Rightarrow \frac{1}{P_1}$

coefficient of 's^2' $\Rightarrow \frac{1}{P_1 \cdot P_2}$

$$\frac{1}{P_1}+\frac{1}{P_2} \simeq \frac{1}{P_1}$$

$$\frac{1}{10}+\frac{1}{1000}$$

$$0.1 + 0.001$$

neglet this

$$P_1 = \frac{1}{\underbrace{R_2(C_c+C_2)+R_1(C_c+C_1)}_{\text{small} \because \text{neglected}}+g_{m2}R_2R_1C_c}$$

$$\boxed{P_1 \simeq \frac{1}{g_{m2}R_1R_2C_c}}$$

$$P_1P_2 = \frac{1}{R_1R_2(C_1C_2+C_1C_c+C_2C_c)}$$

$$P_2 = \frac{1 \quad g_{m2}\cancel{R_2R_1}C_c}{\cancel{R_1R_2}[C_1C_2+C_1C_c+C_2C_c]}$$

$$P_2 = \frac{g_{m2}C_c}{\underbrace{C_1C_2+C_1C_c}_{\text{small} \therefore \text{neglected}}+C_2C_c} \simeq \frac{g_{m2}\cancel{C_c}}{C_2\cancel{C_c}}$$

$$\boxed{P_2 \simeq \frac{g_{m_2}}{C_2}}$$ *

what comes in denominator of 's' term is zero

$$\boxed{Z = \frac{g_{m_2}}{C_c}}$$ *

$\because Z \Rightarrow$ zero
$P_1 \Rightarrow$ Pole 1
$P_2 \Rightarrow$ Pole 2

In A_{DC} all the s are '0'

So we get

$$\boxed{A_{DC} = g_{m_1} R_1 \, g_{m_2} R_2}$$ *

$$GBW = DC\,gain \times P_1$$

$$= \frac{g_{m_1} \cancel{R_1} \cancel{g_{m_2}} \cancel{R_2} \times 1}{\cancel{g_{m_2}} \cancel{R_1} \cancel{R_2} \, C_c}$$

$$\boxed{GBW = \frac{g_{m_1}}{C_c}}$$ *

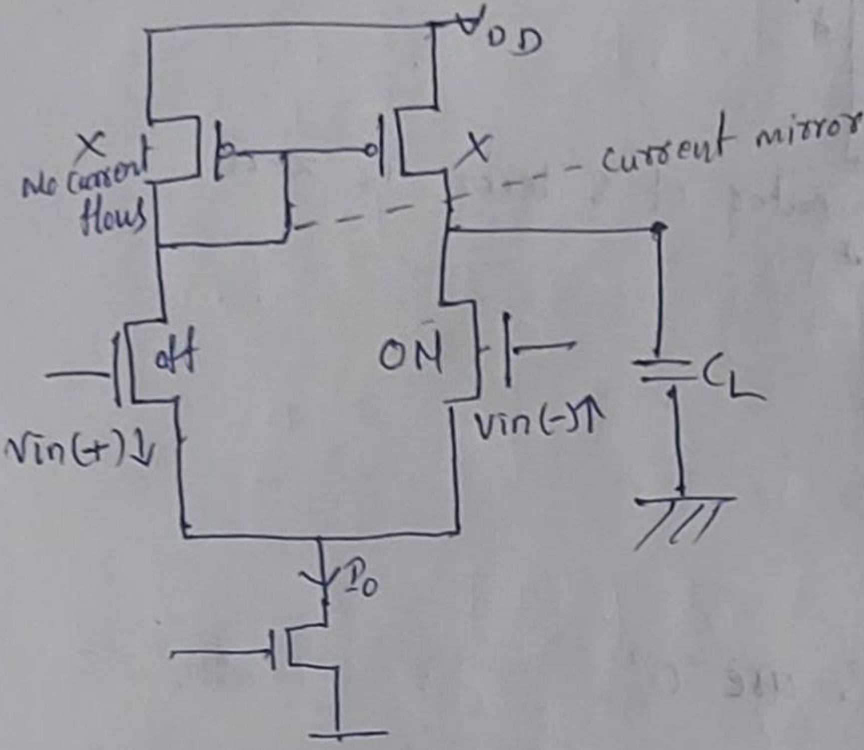
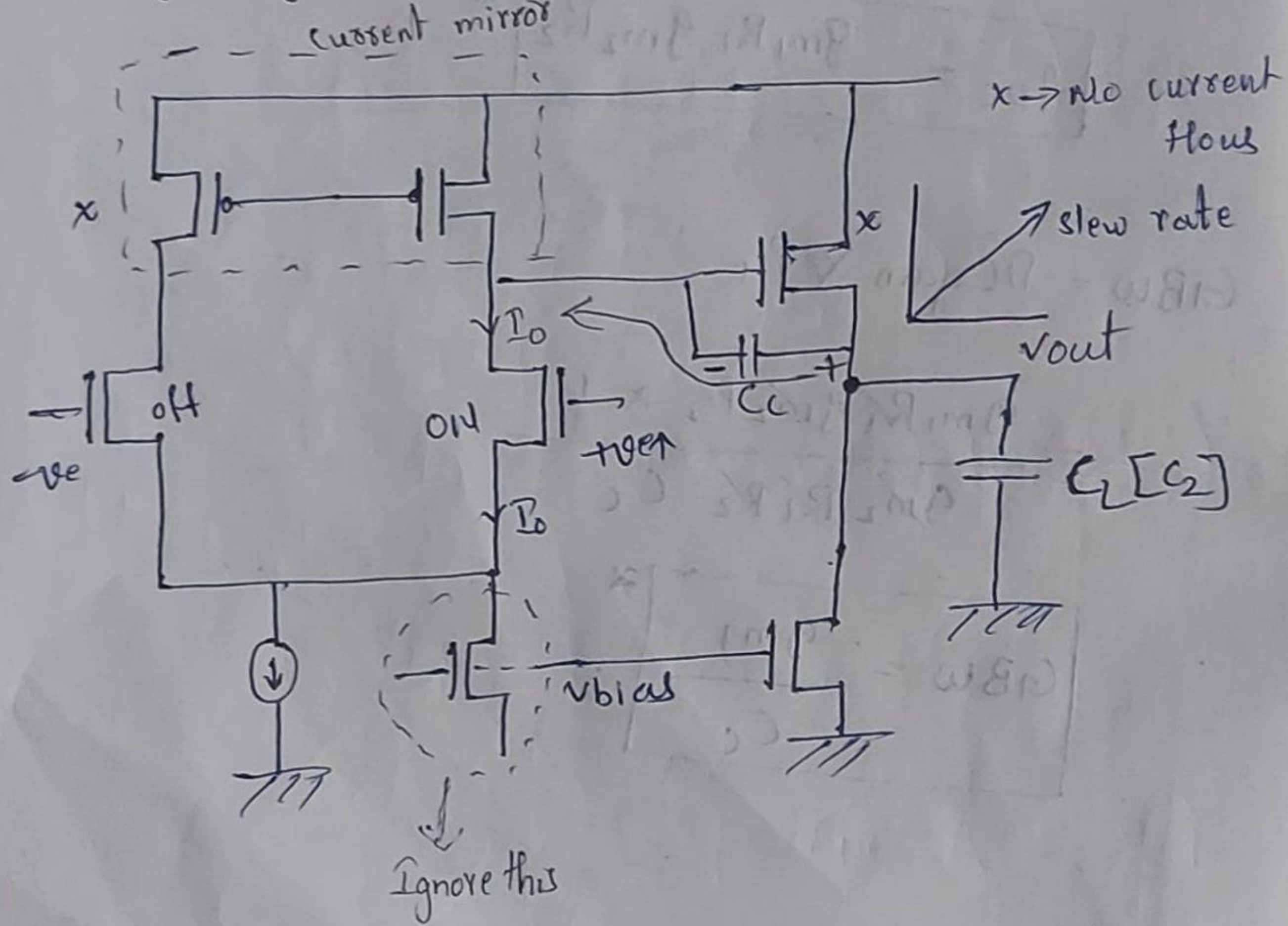
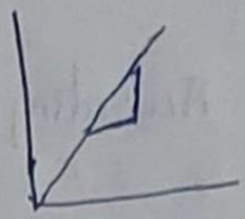


fig: Single Stage op-amp

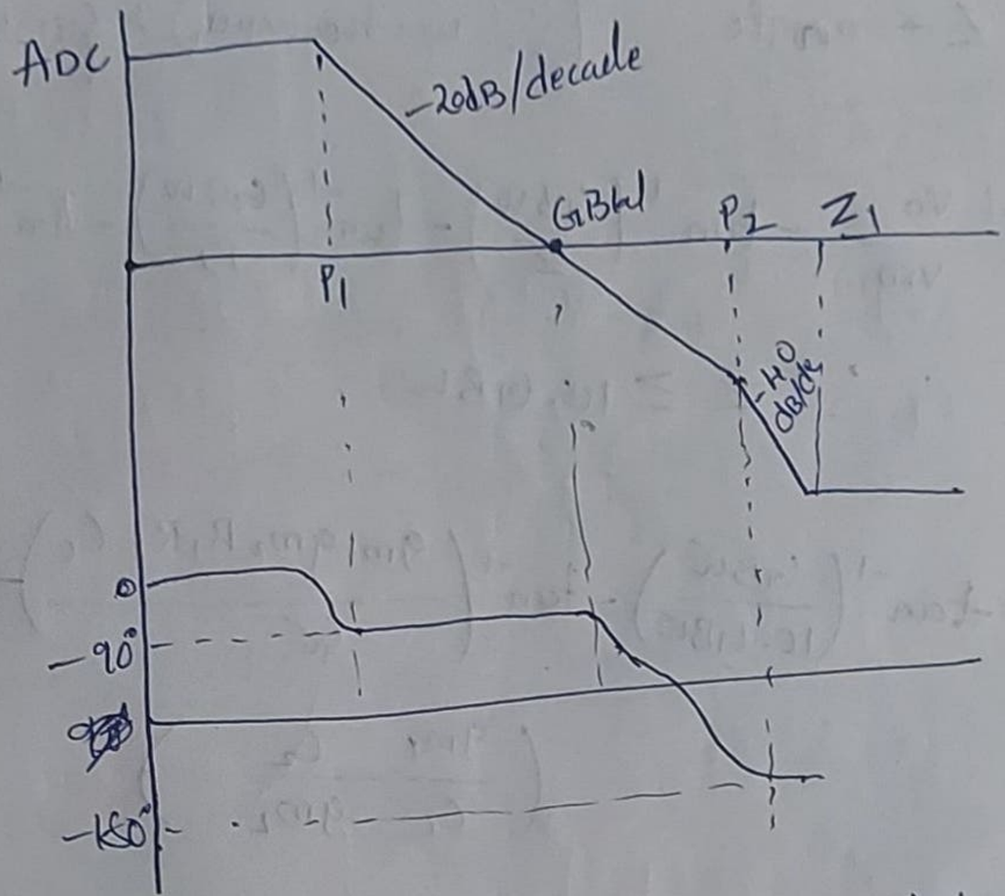


$C_c \rightarrow$ controls the current

$$\boxed{S_R = \frac{I_0}{C_c}}$$ *



Phase Margin



⇒ We should ensure that the phase margin should be 45° or more

⇒ To increase phase margin we move P_2 towards right side

$$\boxed{Z \geq 10 \cdot GBW} \quad (1)$$

According to the standard transfer function

$$\angle \frac{V_o}{V_{in}} = -\tan^{-1}\left(\frac{\omega}{Z}\right) - \tan^{-1}\left(\frac{\omega}{P_1}\right) - \tan^{-1}\left(\frac{\omega}{P_2}\right)$$

$\angle \rightarrow$ angle $\quad [\because \omega(\text{frequency}) = GBW]$

$$\angle \frac{V_o}{V_{in}} = -\tan^{-1}\left(\frac{GBW}{Z}\right) - \tan^{-1}\left(\frac{GBW}{P_1}\right) - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

$$\because Z \geq 10 \cdot GBW$$

$$= \tan^{-1}\left(\frac{GBW}{10 \cdot GBW}\right) - \tan^{-1}\left(\frac{g_{m1} g_{m2} R_1 R_2 \cancel{C_c}}{\cancel{C_c}}\right) - \tan^{-1}\left(\frac{g_{m1}}{C_c} \frac{C_2}{g_{m2}}\right)$$

$$= -\tan^{-1}\left(\frac{1}{10}\right) - \tan^{-1}(g_{m1} g_{m2} R_1 R_2) - \tan^{-1}\left(\frac{g_{m1} C_2}{C_c g_{m2}}\right)$$

$$\angle \frac{V_o}{V_{in}} = -\tan^{-1}\left(\frac{1}{10}\right) - \tan^{-1}(A_{DC}) - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

$$[\because A_{DC} = g_{m1} g_{m2} R_1 R_2]$$

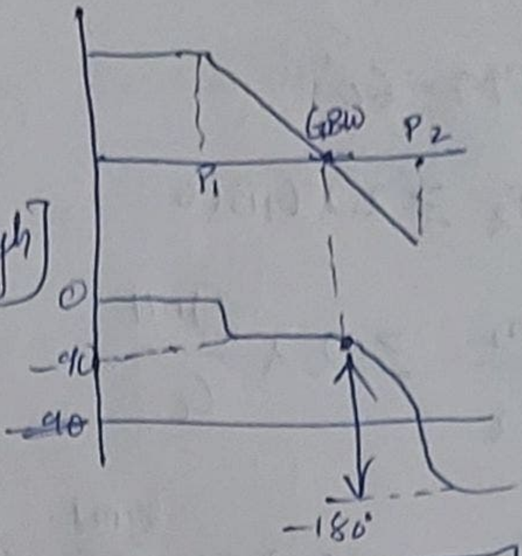
$$\angle \frac{V_o}{V_{in}} = -\tan^{-1}\left(\frac{1}{10}\right) - \tan^{-1}(A_{DC}) - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

~~$-180+PM = -5.71 - 90°$~~

Assume

$-\tan^{-1}(10000)$ [$\because A_{DC}$ is high]

$\simeq 90$



$\boxed{-180° + PM}$

$$\angle \frac{v_o}{v_{in}} = -\tan^{-1}\left(\frac{1}{10}\right) - \tan^{-1}(A_{DC}) - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

$$-180° + PM = -5.71 - 90° - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

$$PM = 180 - 5.71 - 90° - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

$$PM = 84.29 - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

For $PM = 60°$

$$60 = 84.29 - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

Apply tan on b.s

$$\left(\frac{GBW}{P_2}\right) = \tan(24.29)$$

$$\frac{GBW}{P_2} = 0.4513$$

$$P_2 = \frac{GBW}{0.4513}$$

$$P_2 = 2.2\,GBW$$

$$\boxed{P_2 \geq 2.2\,GBW}\ *$$

For $PM = 45°$

$$45° = 84.29 - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

$$\tan^{-1}\left(\frac{GBW}{P_2}\right) = 39.29$$

Apply tan on b.s

$$\frac{GBW}{P_2} = 0.8181$$

$$P_2 = \frac{GBW}{0.8181}$$

$$\boxed{P_2 \geq 1.22\,GBW}$$

$PM = 60^{\circ}$

$P_2 \geq 2.2\, GBW$

$$\frac{g_{m2}}{C_2} \geq 2.2 \frac{g_{m1}}{C_c}$$

$$\frac{g_{m2}}{C_L} \geq 2.2 \times \frac{g_{m1}}{C_c}$$

$$\frac{10 \cdot \cancel{g_{m1}}}{C_L} \geq 2.2 \frac{\cancel{g_{m1}}}{C_c}$$

$$\frac{10}{C_L} \geq \frac{2.2}{C_c}$$

$$C_c \geq \frac{2.2}{10} C_L$$

$$\boxed{C_c \geq 0.22\, C_L}^{\star}$$

$\left[\because Z = \frac{g_{m2}}{C_c}\right]$

$\left[\because P_2 = \frac{g_{m2}}{C_2}\right]$

$\left[\because GBW = \frac{g_{m1}}{C_c}\right]$

[Assumed
$Z = 10 \cdot GBW$

$$\frac{g_{m2}}{\cancel{C_c}} = \frac{10 \cdot g_{m1}}{\cancel{C_c}}$$

$$\boxed{g_{m2} = 10 \cdot g_{m1}}$$