Analog integrated Circuits
Lec16, Frequency Compansiation.

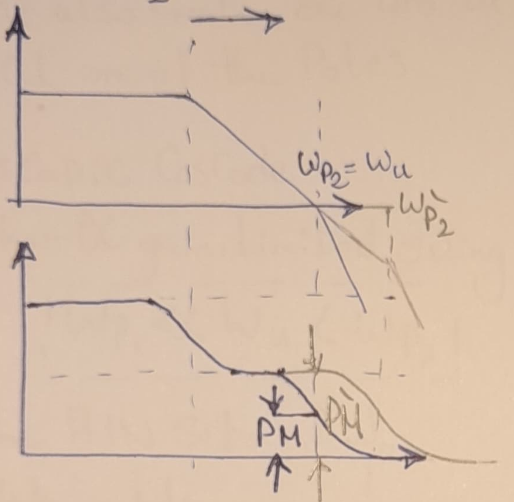
① Freq Compansiation

- is the modification of the System, to achive a specific PM, to Control the Peaking and ringing.
- We Want

$$G_x < P_x \rightarrow \omega_u < \omega_{P_2}$$

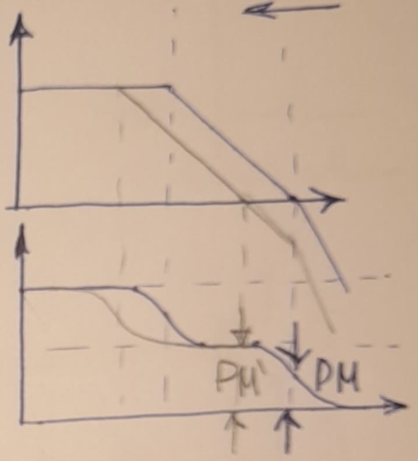
we Can achive this by

[1] Push ω_{P_2} outwards →



achived by Lowering resistance or Caps @ P_2 node
↳ not always feasible for free

[2] Push $G_x / \omega_{P_1} / \omega_u$ in ←



Lower GBW
∴ Lower speed

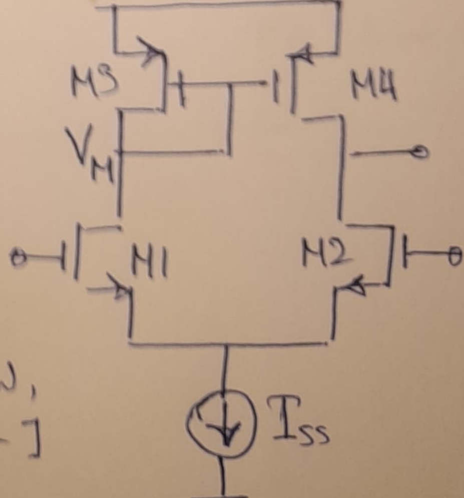
② Single Stage OTA

[1] 5T_OTA

- we always want

$$\omega_{P_1} \ll \omega_u < \omega_{P_2}$$

- The HIN sets open loop BW = $\omega_{P_{out}}$
- The First non-dominant Pole [mirror node] sets ultimate GBW, ultimate Closed loop BW [Buffer]



$$\omega_{P_2} = \omega_{P_M} = \frac{g_{m3}}{C_M} = \omega_T / 3$$

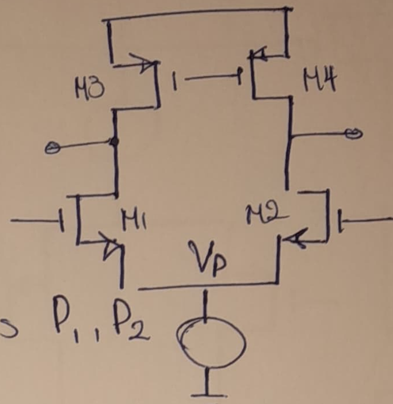
→ higher Caps

C_M → $C_{dB1} + C_{dB2} + f(C_{gdM}) + C_{gs4} + C_{gs3} + C_{dB1}$

- The LHP zero:

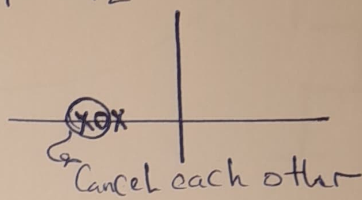
$$\omega_z = 2\omega_{P_2} \rightarrow \text{reduce the effect of } P_2$$

- if Fully diff.?



* out^+ and out^- Contribute 1 Pole
* $\omega_{P_2} = \frac{g_m}{\dots}$
  at V_P
* if there is a mismatch
  - out^+ and out^- Contribute two Poles P_1, P_2 which are Close to each other
  - it also Create one zero at $\omega_z = 2[\omega_{P_1} \parallel \omega_{P_2}]$

  Cancel one of the Poles

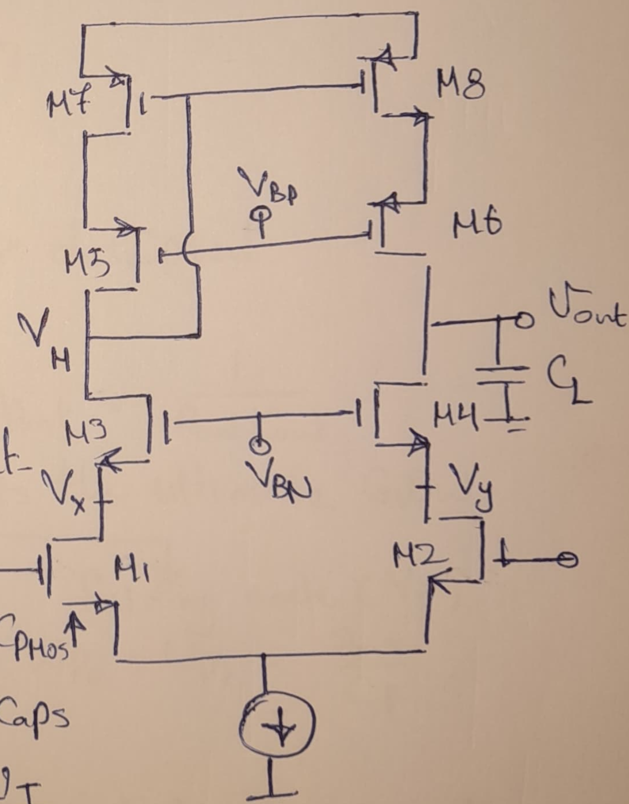


[2] Telescopic Cascode

- Higher DC gain, Limited swing, additional Poles
- $\omega_{P_1} \ll \omega_u < \omega_{P_2}$
- the HIN sets BW_{OL}

  $$\omega_{P_1} = \omega_{P_{out}} = \frac{1}{R_{out} C_{out}}$$

- V_x and V_y Contribute a Single Pole



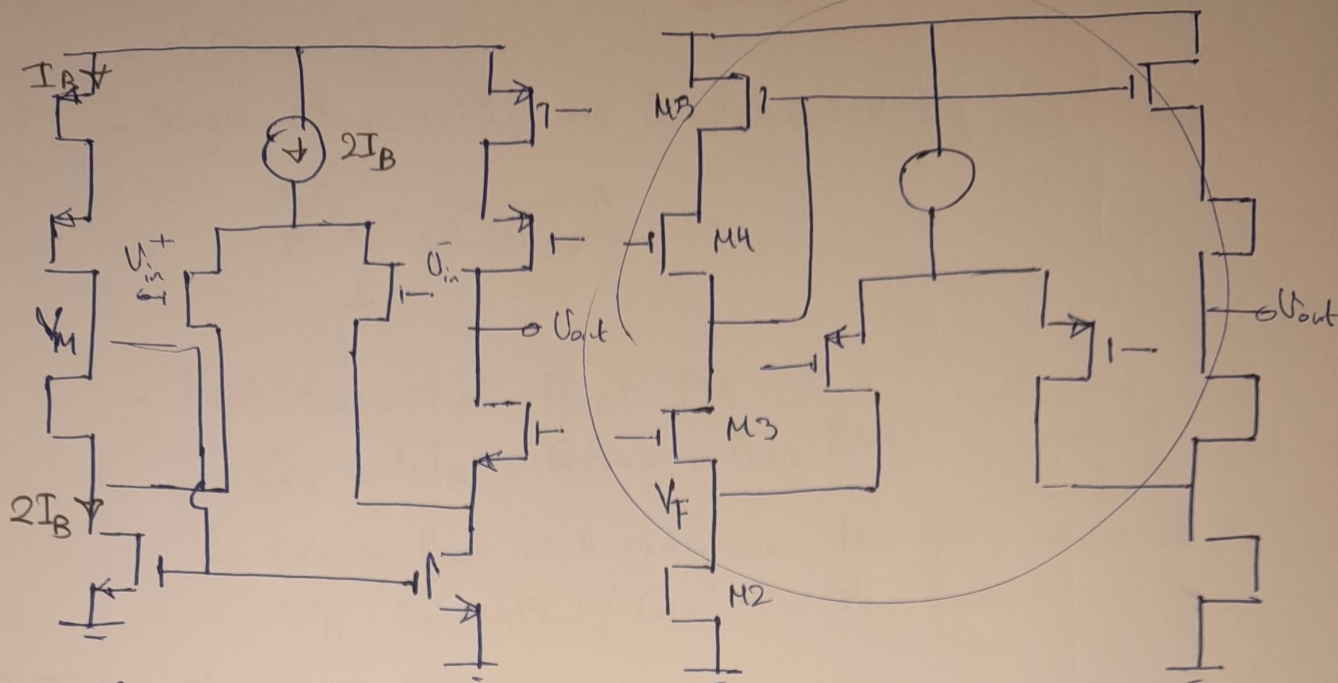
non_dominant Pole Considerations.

1. PMOS Contribute Larger Caps → for Same I_D, $W_{PMOS}\uparrow$, $C_{PMOS}\uparrow$
2. C_{gs} is Larger than other Caps

$$\therefore \omega_{P_2} = \omega_{P_M} = \frac{g_{m7}}{C_M} = \frac{\omega_T}{4}$$

[3] Folded CasCode

- Two Possible implementation for SE output



- Compared to telescopic CasCode
  * More Power 2x
  * Lower gain [$r_{o1} \parallel r_{o2}$]
  * More node / Poles
  * More Complex
  #* input and output range deCapled

- $\omega_{P1} \ll \omega_u < \omega_{P2}$
- the HIN sets BW_{OL}: $\omega_{P1} = \omega_{Pout} = \frac{1}{R_{out} C_{out}}$
- the first non-dominant Pole Sets the ultimate GBW

mirror node (V_M)
$\omega_{P2} = \omega_{PM} = \frac{g_{m5}}{C_M}$

folding node (V_F)
$\omega_{P2} = \omega_{PF} \approx \frac{g_{m3}}{C_F}$

- Consideration
  - M2 has Large CapaCitance (double the Current)

☒ Single-Stage OTAs: Compansiation.

- Push G_x / ω_u / ω_{p_1} inwards : Lower GBW ⟵
- increase C_L
- Single stage OTAs are Compansated by Load Capacitance

$$\omega_{p_1} \downarrow = \frac{1}{R_{out}\, C_{out} \uparrow}$$

??

- Rout does not affect PM

$$G_x = \omega_u = GBW = A_{OL}\, BW_{OL} = \frac{G_m}{C_{out}}$$

↳ increase Rout will increase the gain and reduce ω_{p_1}, So GBW / G_x is the same

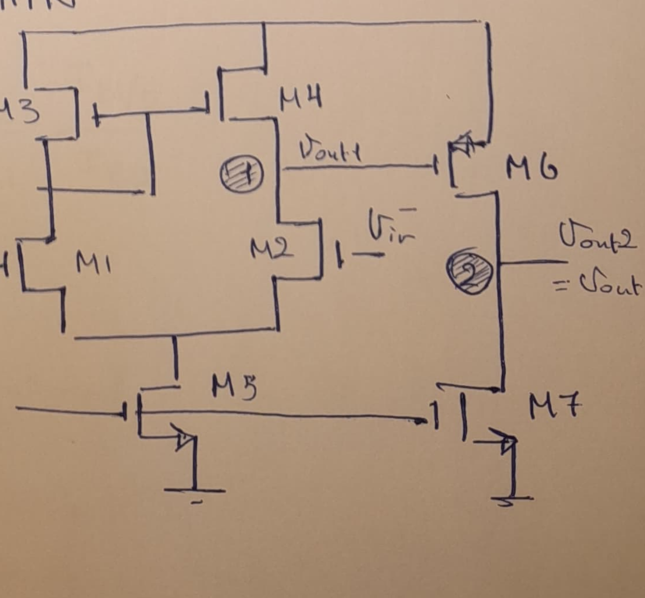
③ Two-Stage OTA

- isolates the gain and swing requirements.
  - * But much more Power Consumption
  - * And Complicates stability requirements
- Three stage OTA exists, but quite difficult to stablize
- First stage Can be 5T-OTA [Moderate gain] or CasCode [high gain]
- Scond stage is typically a simple Common-Source
  ↳ allows maximum Swing

\# → Two gain stages → two HIN
→ two dominant Poles

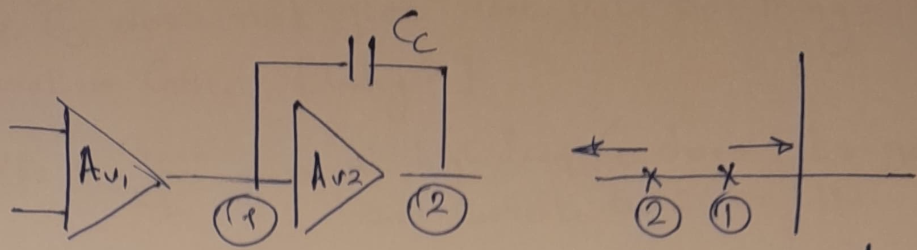
1 internal Pole, $\omega_{p_1} = \frac{1}{R_{out_1} C_1}$

2 output pole, $\omega_{p_2} = \frac{1}{R_{out_2} C_2}$



Solutions:

use miller



- Cc has miller effect at node 1 → $C_1 \uparrow$, $W_{P_1} \downarrow$

↳ Push Gx inwards # $W_{P_1} = \frac{1}{R_{out1}[G_{m2}R_{out2}]C_c}$

- Push W_{P_2} outwards [how?]

@ high freq Cc is short circuit

∴ Node 2 become LIN ~ $\frac{1}{g_m}$

$$\therefore W_{P_{nd}} = W_{P_2} = \frac{G_{m2}C_c}{C_c[C_1+C_2]+C_1C_2} \simeq \frac{G_{m2}}{C_1+C_2} = \frac{G_{m2}}{C_L}$$

- $GBW \simeq G_{m1}R_{out1}G_{m2}R_{out2} \cdot \frac{1}{R_{out1}[G_{m2}R_{out2}]C_c}$

$$= \frac{G_{m1}}{C_c}$$

- for critical damped response, $\xi = 1$, $Q = 0.5$

PM = 76°

$$\therefore W_{P_2} \simeq 4W_u \rightarrow \frac{G_{m2}}{C_L} \simeq \frac{4G_{m1}}{C_c}$$

- assume $C_c = C_L/2$

$$\therefore \frac{G_{m2}}{\cancel{C_L}} \simeq \frac{8G_{m1}}{\cancel{C_L}} \rightarrow \frac{G_{m2}}{G_{m1}} = 8$$

- for same g_m/I_D

$$\therefore \frac{G_{m2}/I_{B2}}{G_{m1}/\frac{I_{B1}}{2}} = \frac{G_{m2}}{G_{m1}} \cdot \frac{I_{B1}/2}{I_{B2}} = 1 \rightarrow \frac{I_{B1}}{I_{B2}} = \frac{1}{4}$$

$$\therefore I_{B2} = 4I_{B1}$$

- 80% of the power is consumed in the second stage to achive stability

∴ 80% of the current not contribute to GBW

∴ miller OTA is very energy <u>inefficient</u>

- Too Large C_c does not give more Pole splitting
  : Just Smaller GBW [Why?]

  ↳ $\omega_{P_2} \approx \frac{G_{m2}}{C_L}$ → at high freq C_c does its job and Converts out2 to LIN

- Reasonable starting Point $C_c \approx 0.3 : 0.5\ C_L$

- increasing G_{m2} Works even better than increasing C_c

  $$\omega_{P_1}\downarrow = \frac{1}{R_{out1}\,[G_{m1}\uparrow R_{out2}]\,C_c} \quad , \quad \omega_{P_2}\uparrow \approx \frac{G_{m2}}{C_1 + C_2} = \frac{G_{m2}\uparrow}{C_L}$$

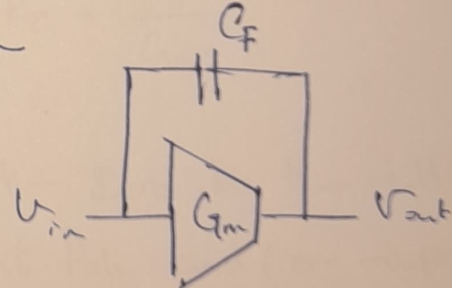
  ↳ But more Power Consumption in the Second stage

- Single ~~ended~~ stage Vs Two stage Sensitivity to C_L

  Single stage: $C_L\uparrow,\ \omega_{P_1}\downarrow,\ PM\uparrow$

  two stage: $C_L\uparrow,\ \omega_{P_2}\downarrow,\ PM\downarrow$

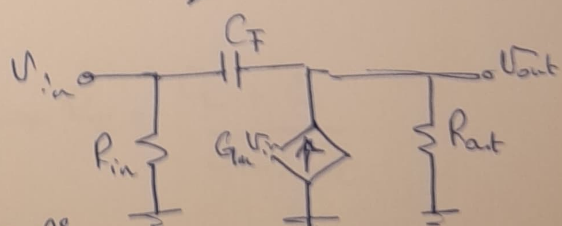
4) The feedforward zero → Reminder



$V_{out} = 0$, $I_{out} = 0$

∴ $V_{in}\, S C_F = -G_m V_{in}$

∴ $S_z = -\frac{G_m}{C_F}$



→ LHP zero if G_m is +ve [√]

→ RHP zero if G_m is -ve [X]

↳ mag increase and Phase drops

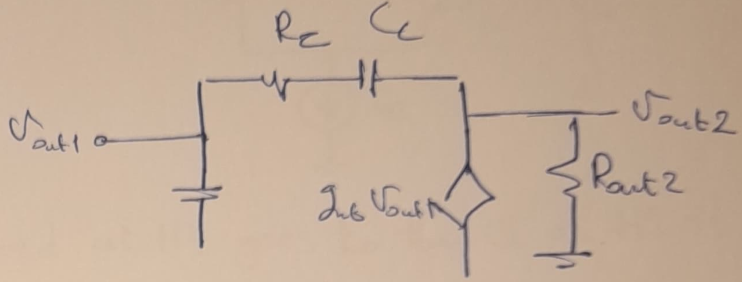
↳ Very bad for FB Loop stability

- RHP zero is bad for both magnitude and Phase
  ↳ Pushes G_x outwards and Pushes P_x inwards
  ↳ increasing C_c may hurt stability

$$\omega_z = \frac{g_{m6}}{C_c + C_{gd}} \approx \frac{G_{m2}}{C_c}$$

- Handling the RHP zero
  ↳ Add a resistance to Control the Value of the zero

$$\frac{V_{out1}}{R_z + \frac{1}{S_z C_c}} = g_{m6} V_{out}$$



$$S_z = \frac{1}{C_c\left[\frac{1}{g_{m6}} - R_z\right]}$$

- Place the zero
  [1] at ∞

$$\omega_z = \frac{1}{C_c\left[\frac{1}{G_{m2}} - R_z\right]} \longrightarrow R_z = \frac{1}{G_{m2}}$$

[2] Some designers try to move the zero to the LHP to Cancel the first non-dominant Pole and / or improve PM

$$\frac{1}{C_c\left(R_z - \frac{1}{G_{m2}}\right)} = \frac{G_{m2}}{C_L} \longrightarrow R_z = \frac{C_L + C_c}{G_{m2} C_c}$$

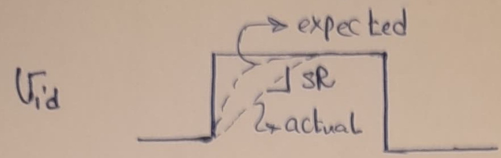
* Practically never achieved due to Variation
* actually does not Lead to faster response (Why?)
  Critical damped [Second order system]
  faster than over damped [1st order System]
* Pole - zero doublet, Pushing the LHP zero to Lower freq
  ↳ Very Poor settling time
  ↳ noise amplification

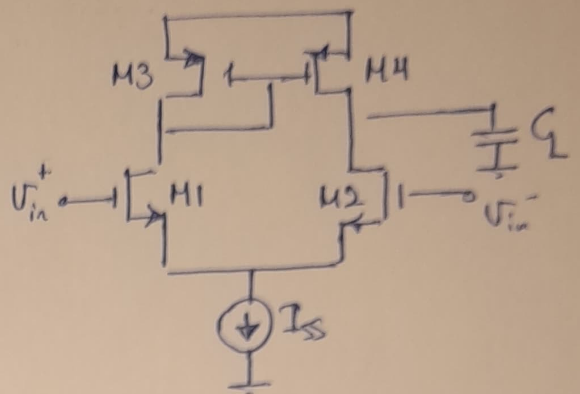
(5) Slew Rate (SR)

- is the maximum rate at which the output of an opamp changes when a large differential input signal is present

[1] Single stage Slew Rate

- if $V_{in}^{+} \uparrow$, $V_{in}^{-} \downarrow$





I_D @ $M1 \uparrow$, I_D @ $M2 \downarrow$

↳ M1 : Complitly ON

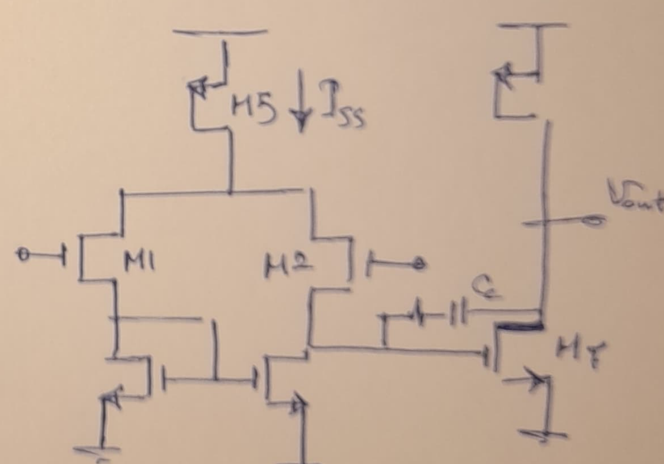
M2 : Complitly off

$\therefore I_{D1} = I_{SS}$ will be mirrored at M4 goes to the CL as M2 is off $\quad SR = I_{SS} / C_L$

and Vica Versa if $V_{in}^{+} \downarrow$, $V_{in}^{+} \uparrow$

[2] two stage OTA Slew Rate

[#] miller Companstiated



if V_{id} is Large

$$\therefore SR = \frac{I_{cc}|_{max}}{C_c} = \frac{I_{SS}}{C_c}$$

$$\because W_u = \frac{g_m}{C_c} \quad , \quad I_{SS} = 2 I_{D1}$$

$$\therefore SR = \frac{2 I_{D1} W_u}{g_{m1}} \rightarrow [1]$$

$$\because g_{m1} \simeq \sqrt{\mu C_{ox} \frac{W}{L} \cdot 2 I_{D1}}$$

$$\because V_{ov} = \sqrt{\frac{2 I_D}{\mu C_{ox} \frac{W}{L}}}$$

$$\therefore SR = \frac{2 I_{D1}}{\sqrt{\mu C_{ox} \frac{W}{L} \cdot 2 I_{D1}}} W_u = \underbrace{V_{eff}}_{V_{ov}} W_u$$

$$\because \frac{2}{V^*} = \frac{g_m}{I_D} \rightarrow \frac{2 I_D}{g_m} = V^* \longrightarrow SR = V^* W_u$$