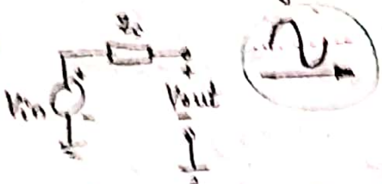
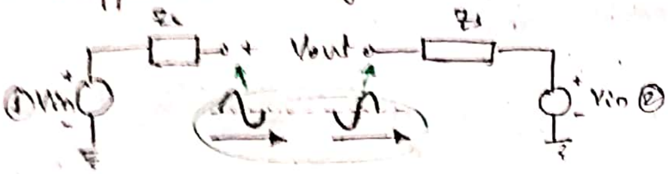
Differential Amplifiers

Single-ended and differential operation

- Single ended signals



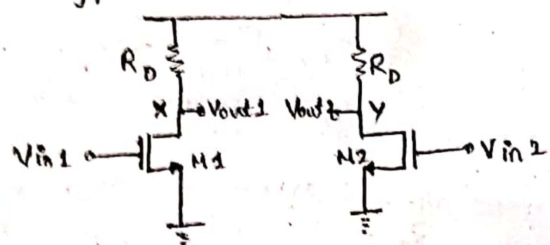
- Differential signals.



- Advantages of differential
  - (i) Reduction of coupling
  - (ii) Common mode rejection occurs with noisy supply voltages
  - (iii) Reduction of coupled noise by differential operation.
  - (iv) Increase in maximum achievable voltage swing!
  - (v) Simpler biasing
  - (vi) Higher linearity.

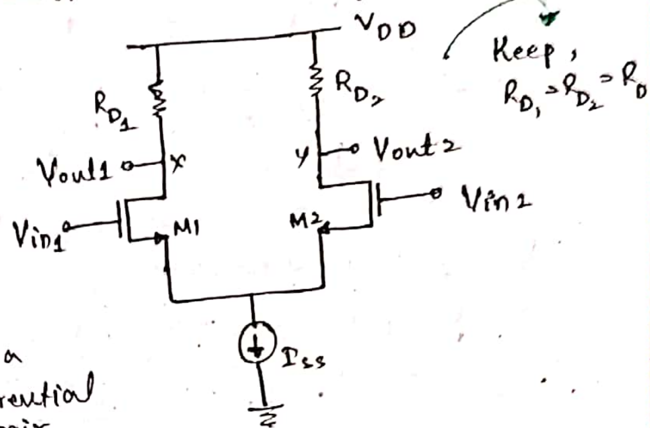
Basic Differential Pair

→ Simple differential circuit



This circuit has issues!
- if CM level changes, bias current of M_1 & M_2 changes, so gm of M_1 & M_2 changes.
when gm of M_1 & M_2 changes, there is variation in small-signal gain and lowers the maximum allowable output swings.

→ To solve this issue, consider the below circuit.

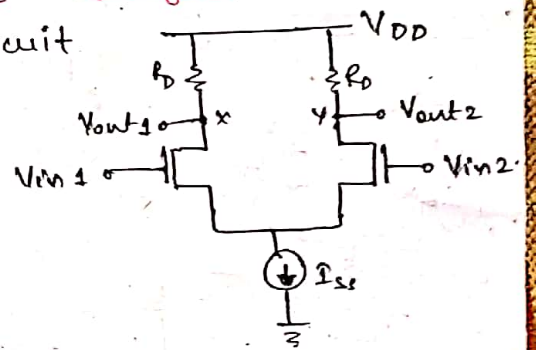


This is a differential pair.

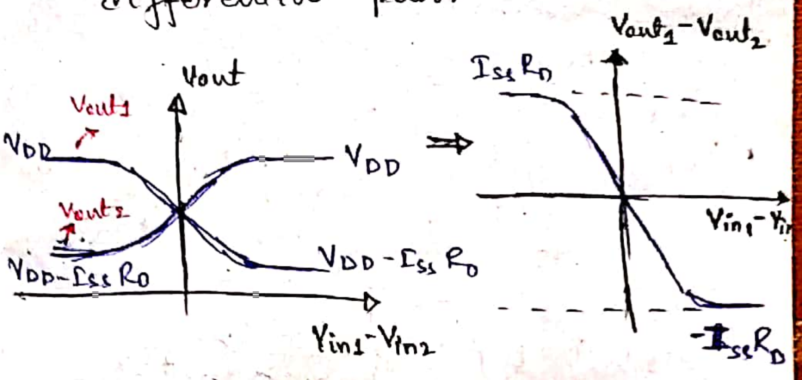
- The differential pair employs a current source I_{ss} to make $I_{D_1} + I_{D_2}$ independent of $V_{in,CM}$.
- Thus, if $V_{in1} = V_{in2}$, the bias current in each transistor equals to $\frac{I_{ss}}{2}$ and output common-mode level is $V_{DD} - \frac{R_D I_{ss}}{2}$

Qualitative Analysis

- For the circuit



Input-output characteristics of differential pair.

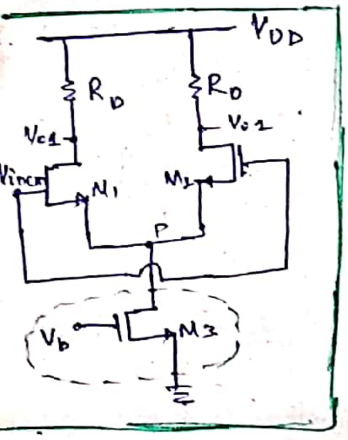


→ Conclusions from I/p - O/p characters.

- For $\frac{I_{ss}}{2}$ to be current from mosfets then $V_{in_1} = V_{in_2}$
- If V_{in1} ↑ than V_{in2}, M1 carries greater current than M_2. Hence V_{out1} drops below V_{out2}
- If V_{in1} is very large, then M_2 is off, hence $V_{out1} = V_{DD} - I_{ss}R_D$ (Min o/p)
  $V_{out2} = V_{DD}$ (Max o/p)
- Small signal gain is maximum for $V_{in1} = V_{in2}$.
  The small signal gain ↓ if $V_{in1} - V_{in2}$ ↑

So, have a common mode behaviour, i.e connect V_{in1} and V_{in2} to a single source called $V_{in,cm}$

case 1 : $V_{in,cm} = 0$, both M_1 and M_2 are off. ∴ $I_{D_3} = 0$ making $I_{D_1} = I_{D_2} = 0$



Hence, M_3 can be replaced with resistor R_{on}, since M_3 is in deep triode region

case 2 : $V_{in,CM}$ becomes more positive.

- both M_1 and M_2 turns on, if $V_{in,cm} > V_{th}$. Then later I_{D_1} and I_{D_2} ↑
- hence V_P ↑
- For a significant high $V_{in,cm}$, the V_{DS} of M_3 exceeds $V_{gs3} - V_{th3}$, thus allowing it to operate in saturation!
- Hence, for proper operation,
  $\boxed{V_{in,cm} \geq V_{gs1} + (V_{gs3} - V_{th3})}$

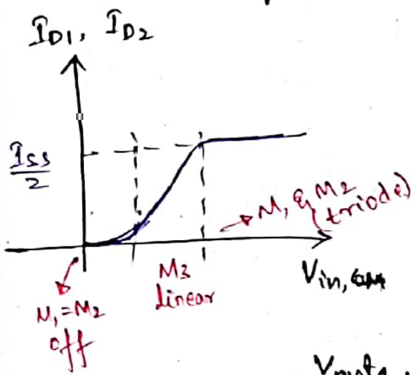
case 3 : What if $V_{in,cm}$ further ↑ !

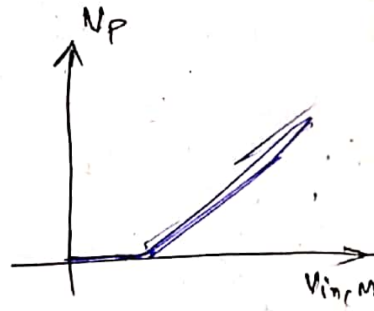
- M_1 & M_2 enters triode region. if
  $V_{incm} > V_{out1} + V_{th}$
  $V_{incm} > V_{DD} - \frac{R_D I_{ss}}{2} + V_{th}$
- This ~~sets~~ restricts the maximum value V_{incm} to be minimum b/w. $\left[V_{DD} - \frac{R_D I_{ss}}{2}, V_{DD}\right]$

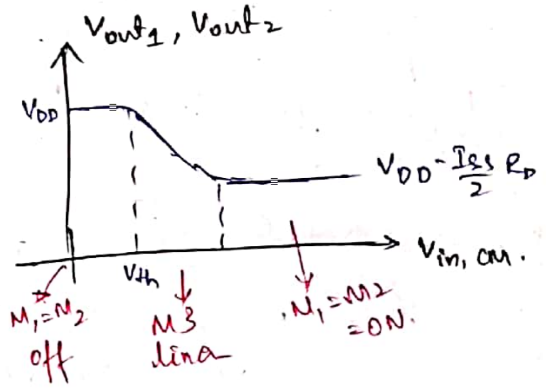
conclusion of formulae

$$\boxed{V_{gs1} + (V_{gs3} - V_{th3}) \leq V_{in,cm} \leq \min\left[V_{DD} - \frac{R_D I_{ss}}{2} + V_{th},\ V_{DD}\right]}$$

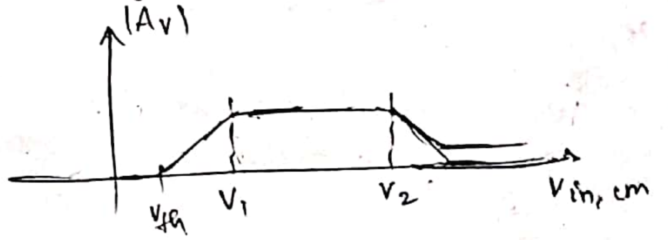
- Graphs:



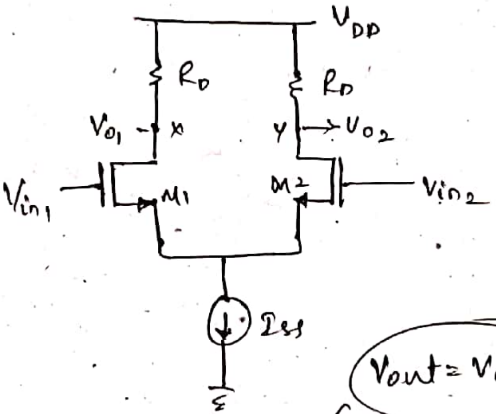




→ Small-signal differential gain of D.P.



→ Small Signal - (half circuit analysis only)



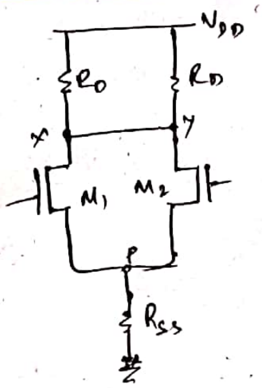
$Vout = V_x - V_y$

$$\boxed{A_v = \frac{V_{out}}{V_{in_1} - V_{in_2}} = -g_m R_D}$$

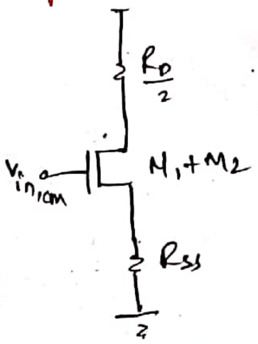
⇒ for half circuit

$$\boxed{A_v = \frac{V_{out}}{V_{in_1} - V_{in_2}} \times \frac{1}{2} = \frac{-g_m R_D}{2}}$$

Common-Mode Response



⇒



gain

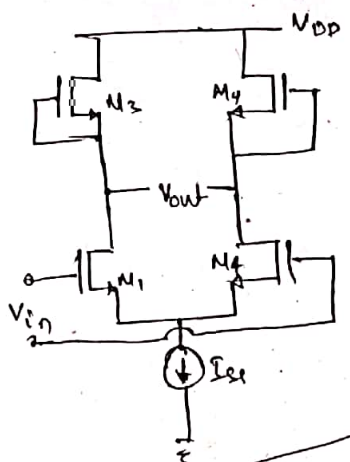
$$\boxed{A_{v_{cm}} = \frac{V_{out}}{V_{in,cm}}} \quad \boxed{A_v = \frac{R_D/2}{\frac{1}{2g_m} + R_{ss}}}$$

① Common-mode response due to mismatch in R_D ($R_{D1} \neq R_{D2}$).

② Common-mode response due to mismatch in transistor ($M_1 \neq M_2$)

$$\boxed{A_v = \frac{-\Delta g_m R_D}{1 + (g_{m_1} + g_{m_2}) R_{ss}}}$$

Differential Pair with MOS Loads



$$\boxed{A_v = \frac{-g_{mN}(r_{oN} \| r_{op})}{-g_{mp}}}$$

↓ if $\lambda = 0$

$$\boxed{A_v = \frac{-g_{mN}}{-g_{mp}}}$$

$$\boxed{A_v \approx -\sqrt{\frac{\mu_n (\frac{W}{L})_N}{\mu_p (\frac{W}{L})_p}}}$$