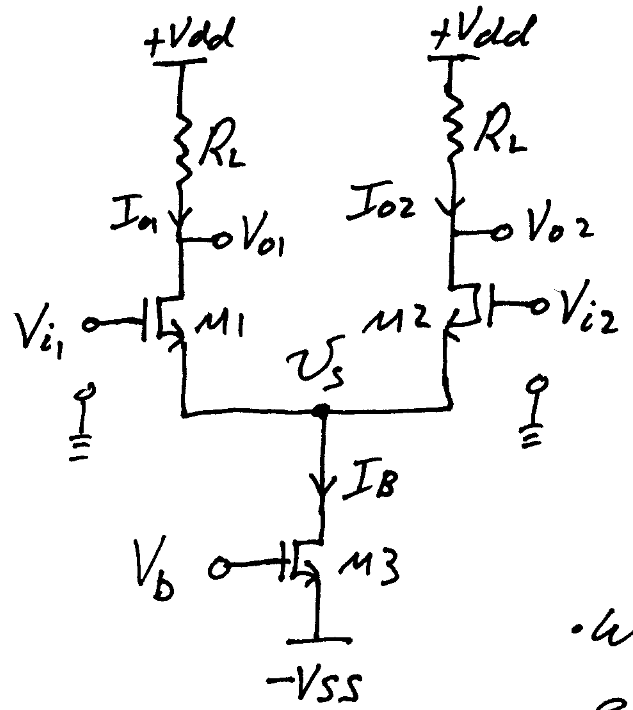
Differential Pair

- Consider a basic source-coupled diff-pair:



- Can solve ssm w/ superposition:

$$v_{o1} = A_{v1} \cdot v_{i1} + A_{v2} \cdot v_{i2}$$

$$A_{v1} = \left.\frac{v_{o1}}{v_{i1}}\right|_{v_{i2}=0} \qquad A_{v2} = \left.\frac{v_{o1}}{v_{i2}}\right|_{v_{i1}=0}$$

solutions may be difficult

- We will show that it is easier to solve if we take advantage of symmetry by re-defining the inputs:

Common-Mode:

$$V_{ic} = \frac{V_{i1} + V_{i2}}{2}, \quad V_{oc} = \frac{V_{o1} + V_{o2}}{2}$$

Diff-mode

$$V_{id} = V_{i1} - V_{i2}, \quad V_{od} = V_{o1} - V_{o2}$$

$$V_{i1} = V_{ic} + V_{id}/2$$
$$V_{i2} = V_{ic} - V_{id}/2$$
$$V_{o1} = V_{oc} + V_{od}/2$$
$$V_{o2} = V_{oc} - \frac{V_{od}}{2}$$

• From here, there are two key equations that govern circuit operation:

$$\left.\begin{aligned} &(1) \quad V_{id} = V_{gs1} - V_{gs2} \\ &(2) \quad I_{o1} + I_{o2} = I_B \end{aligned}\right\} *$$

- Consider first the DC response:

1) <u>Common-mode only:</u> $V_{id} = 0 \Rightarrow V_{GS1} = V_{GS2}$

$\Rightarrow$ if $K_1 = K_2$ (matched devices) & all devices active.

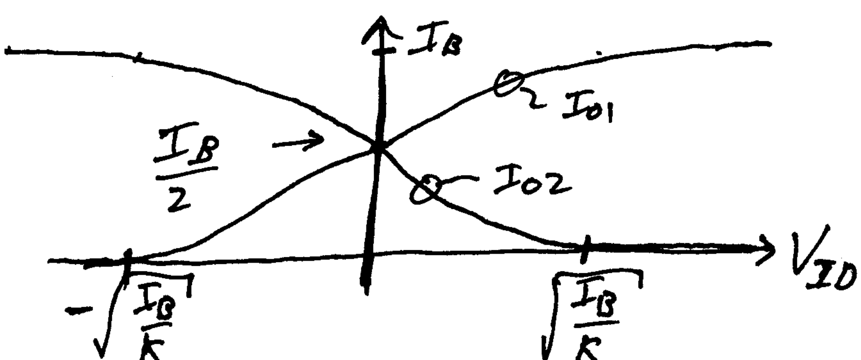
$\Rightarrow I_{o1} = I_{o2} = I_B/2$

$\Rightarrow V_{o1} = V_{o2} = V_{oc} = V_{dd} - \dfrac{I_B R_L}{2}$; $\underline{V_{OD} = 0}$

* <u>Note</u>: ideally, both CM & DM output are indep. of the CM input

$\Rightarrow$ This allows simple cascading of stages & if true in ssm results in rejection of common noise.

2) <u>Differential-Mode:</u> V_{IC} = constant, sweep V_{ID}



$$V_{id} = V_{ov1} - V_{ov2} = \frac{\sqrt{I_{o1}} - \sqrt{I_{o2}}}{\sqrt{K_{1,2}}}$$

• As we $\uparrow V_{ID}$, the bias current is diverted from M2 to M1, this continues until

$I_{D1} = I_B$, $I_{D2} = 0 \Rightarrow$ M2 cut-off boundary.

$$\Rightarrow @ \; V_{ID} = \begin{cases} +\sqrt{\dfrac{I_B}{K_{1,2}}} \Rightarrow \text{M2 cutoff boundary} \\ -\sqrt{\dfrac{I_B}{K_{1,2}}} \Rightarrow \text{M1 cutoff boundary} \end{cases}$$

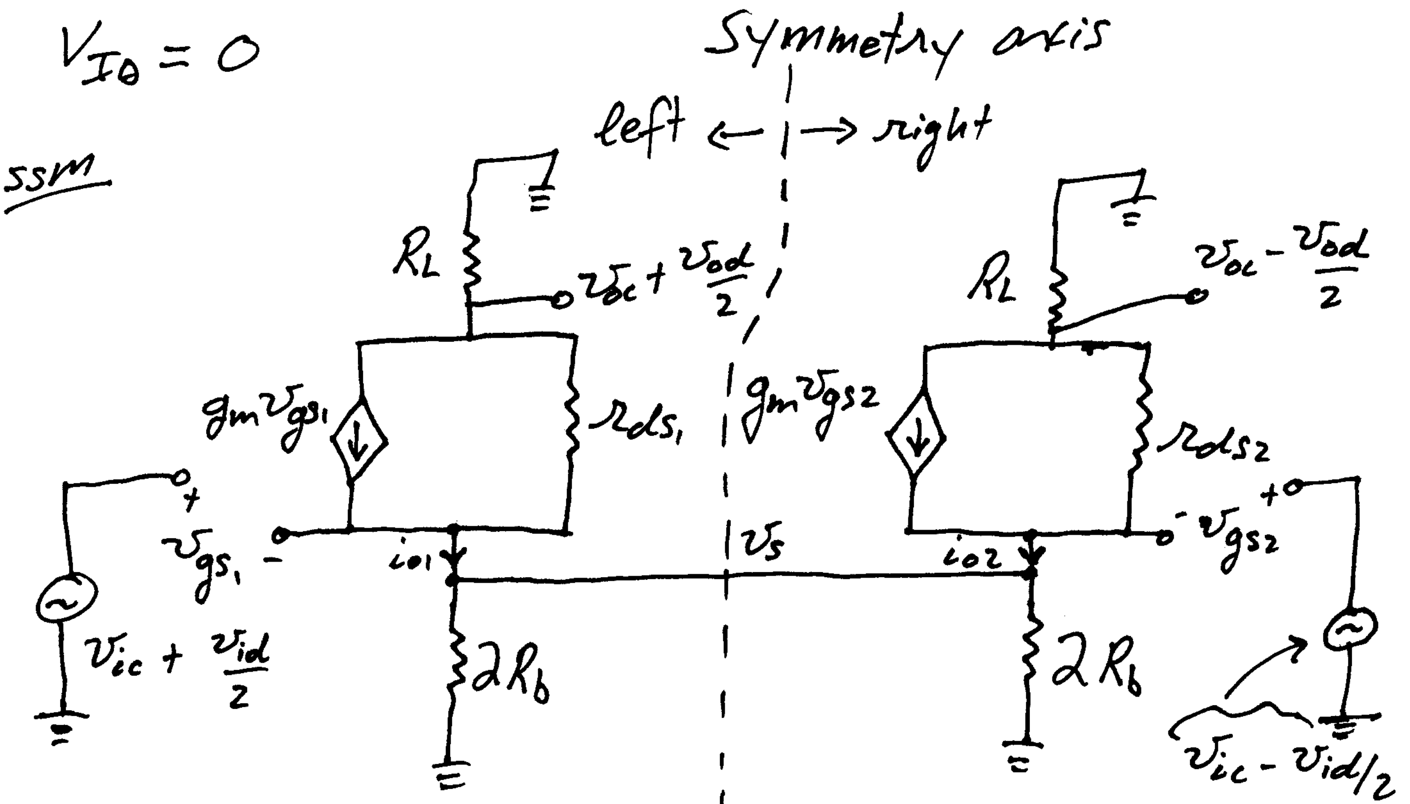
$\Rightarrow$ Therefore, we can control the sensitivity of the input stage by adjusting I_B & $K_{1,2}$.

• Next, consider the ssm at the DC op-point:

V_{IC} = constant (all devices active)

$V_{ID} = 0$

ssm



- The output resistance of the bias current source I_B (M3) has been modeled as R_b & split into two $2 \cdot R_b$ in parallel to create a symmetric circuit.

- Now, we can use super-position to analyze CM & DM small-signal inputs seperately:

$$A_{dm} = \left.\frac{v_{od}}{v_{id}}\right|_{v_{ic}=0} , \quad A_{cm} = \left.\frac{v_{oc}}{v_{ic}}\right|_{v_{id}=0}$$

} with perfect symmetry, there is no coupling CM→DM or DM→CM.

- For CM only: $v_{id}=0 \Rightarrow v_{od}=0$

$$\Rightarrow i_{o1} = i_{o2} = -\frac{v_{oc}}{R_L}$$

} since currents are matched, zero current flows between left & right half circuits.

- For DM only: $v_{ic}=0 \Rightarrow v_{oc}=0 \Rightarrow i_{o1} = -i_{o2} = -\frac{v_{od}}{2} \cdot \frac{1}{R_L}$

$\Rightarrow$ Since $i_{o1} = -i_{o2}$, zero current flows into bias resistor $2 \cdot R_b \Rightarrow$ zero volts at source node v_s on axis of symmetry.

- These results are true in general for fully symmetrical circuits & allow "half-circuit analysis" by:

(1) for CM only: all branches crossing the axis of symmetry become open-circuit. (since zero current flows in them)

(2) for DM only: all nodes on the axis of symmetry become small-signal ground. (since they have zero volts).

- Now, the A_{dm} & A_{cm} gains can be solved using general CS-amp gain equations "by inspection".

$$A_{dm} = -g_{m1,2} R_{out} \ ; \ R_{out} = r_{ds1} \| R_L$$ (with $v_s = gnd$)

$$A_{cm} = \frac{-g_{m1,2} \cdot r_{ds1} \cdot R_L}{R_L + r_{ds1} + 2R_b + g_{m1,2} \cdot r_{ds1}(2R_b)}$$ (w/ open circuit at v_s axis)

- Ideally: $A_{dm} \to \infty$ (high DM gain)

  $A_{cm} \to 0$ (reject all CM noise)

- Figure of merit is how well ~~DM~~ DM is amplified over CM ⇒ "Common-Mode Rejection Ratio" = CMRR.

$$CMRR = \frac{A_{dm}}{A_{cm}} \to \infty \text{ ideally.}$$

- From pg 5, for circuit of Fig. on pg. 1,

$$\underline{\underline{CMRR}} = \frac{R_L + r_{ds1} + 2R_b + g_{m1,2}\, r_{ds1,2}\,(2R_b)}{R_L + r_{ds1}}$$

⇒ Dominated by $g_m r_{ds} (2R_b)$ term

⇒ need good bias I_b for good CMRR!

- note: $R_B = r_{ds3}$ for case of pg 1.

- Next: How to achieve large A_{dm}? ⇒ large R_L.

  ⇒ active loading (same as CS amp before)