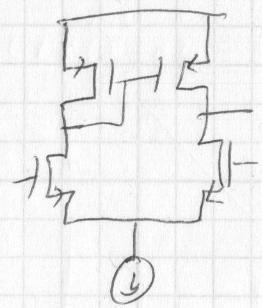
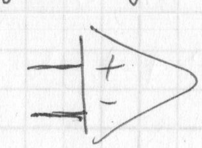
output stages – common in packaged op-amps
less common in embedded

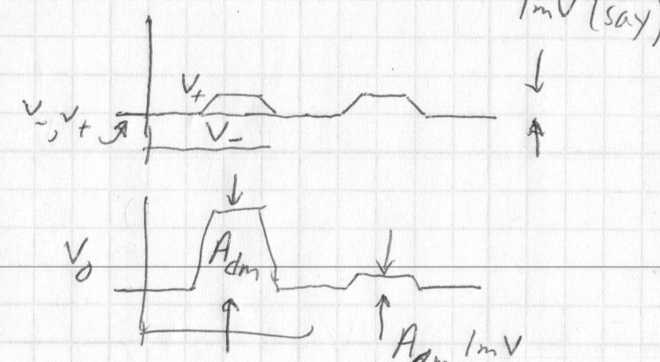
differential & common mode
signals
gain

input common mode range
output swing

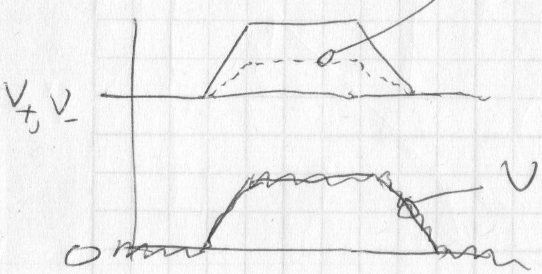
Single stage op-amp (or OTA)







$V_{id} = V_+ - V_-$ $\quad V_{icm} = \frac{V_+ + V_-}{2}$ (avg)

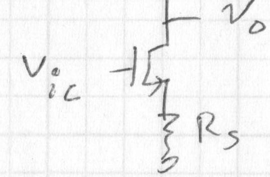


$V_{tail} = V_{S1}$ will track V_{ic} (avg input)

so $v_{gs1a} = v_+ - v_{tail} = \frac{v_{id}}{2}$ $\quad v_{gs1B} = -\frac{v_{id}}{2}$

what is the common mode gain?

Recall:



$G_m = \frac{g_m}{1 + g_m R_S}$

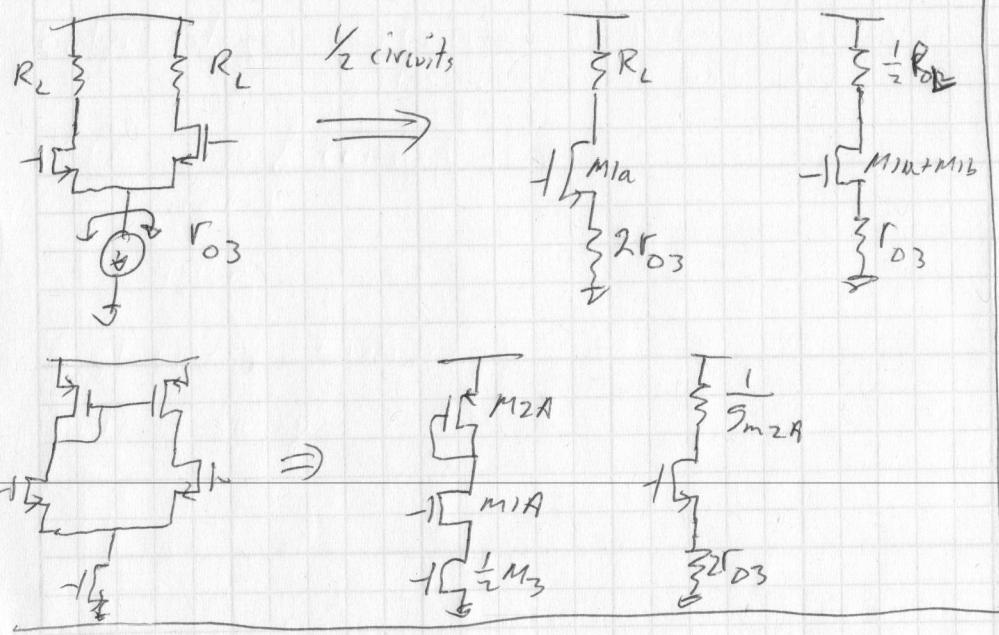
$\approx \frac{1}{R_S}$ if $g_m R_S >> 1$

$R_o = R_D || ((1 + g_m r_o) R_S + r_o)$

$\approx R_D$ if $R_D \leq R_S$

$A_V = -G_m R_o = -\frac{R_D}{R_S}$

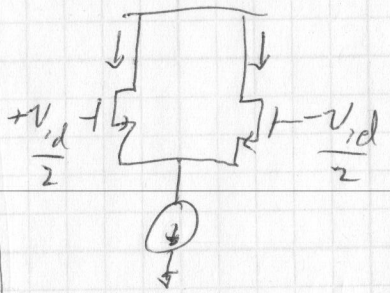
what are R_D and R_S?
(for diff amp)



$$A_{VCM} \equiv \frac{-R_D}{R_S} = \frac{1/g_{m2A}}{2r_{O3}} = \frac{-1}{2g_{m2A}r_{O3}}$$

Common mode gain $\quad v_o = A_{VCM} v_{ic}$

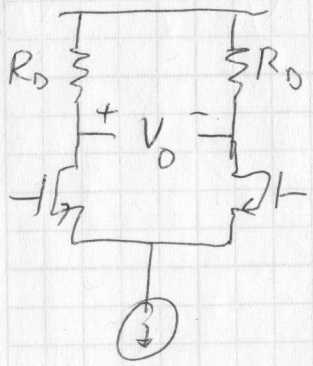
Differential mode gain $\quad v_o = A_{VDM} v_{id}$



$$i_{d1a} = g_{m1a}\left(\frac{v_{id}}{2}\right)$$

$$i_{d1b} = g_{m1b}\left(-\frac{v_{id}}{2}\right)$$

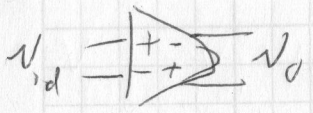
$$v_{tail} = 0$$



$$v_{o+} = -i_{d1A} R_D = -g_{m1A} R_D \frac{v_{id}}{2}$$

$$v_{o-} = -i_{d1B} R_D = +g_{m1B} R_D \frac{v_{id}}{2}$$

$$v_o = v_{o+} - v_{o-} = -g_{m1} R_D v_{id}$$

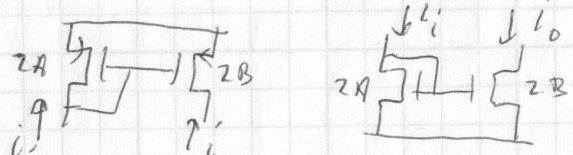


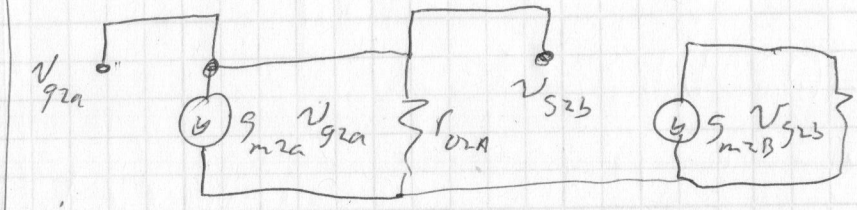
differential in, differential out

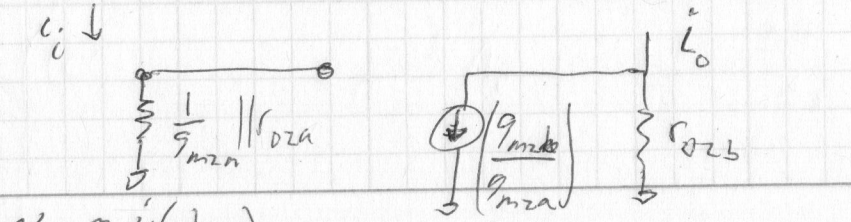
very useful, popular: 240B

common mode feedback

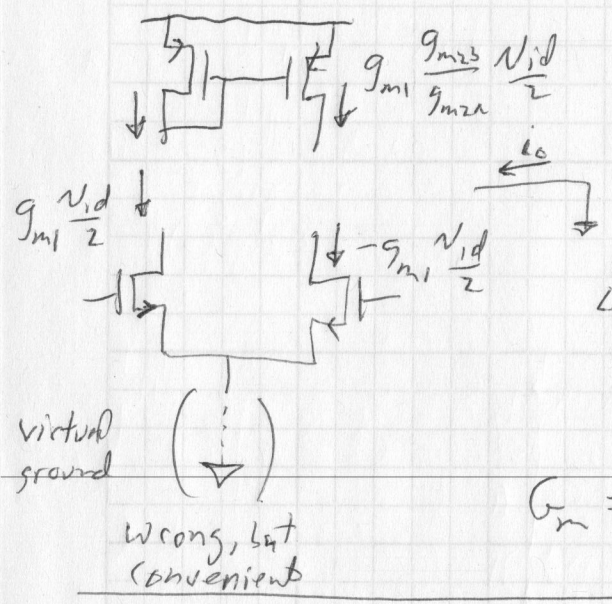
what about current mirror load?







$$v_{gs2a} \simeq i_i\left(\frac{1}{g_{m2a}}\right)$$



$$G_m = \left.\frac{i_o}{v_{id}}\right|_{v_o=0}$$

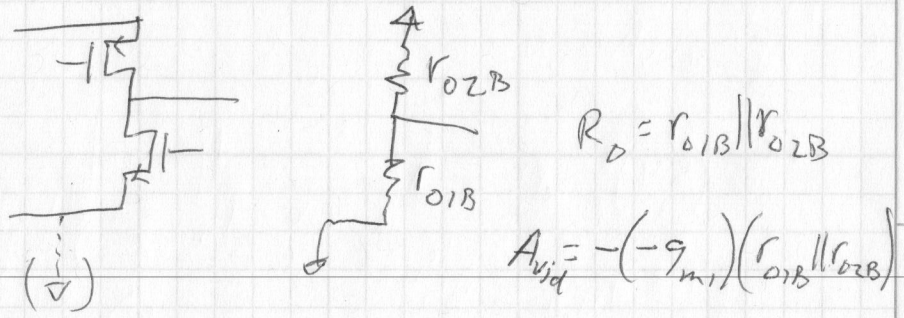
$$i_o = -g_{m1}\frac{v_{id}}{2} - g_{m1}\frac{g_{m23}}{g_{m2a}}\frac{v_{id}}{2}$$

$$\cong -g_{m1} v_{id}$$

$$G_m = -g_{m1}$$

$$R_o: \left.\frac{v_o}{i_o}\right|_{v_{id}=0}$$

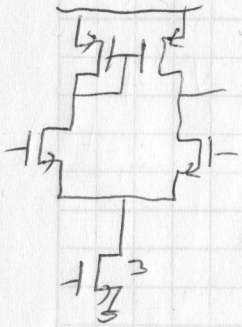
method #1: $V_{tail} = 0$ (virtual ground - wrong!)



$$R_o = r_{O1B} \| r_{O2B}$$

$$A_{vid} = -(-g_{m1})(r_{O1B} \| r_{O2B})$$

input common mode range.



$$V_{icm,min} = V_{tail,min} = V_{OV3}$$

$$V_{icm,min} = V_{tail,min} + (V_{tn} + V_{OV1})$$

max:

$$V_{G2} = V_{DD} - |V_{tp}| - |V_{OV2}|$$

$$= V_{D1,max}$$

$$V_{ic,max} = V_{G2,max} = V_{D1,max} + V_{tn}$$

$$= V_{DD} + \underbrace{V_{tn} - |V_{tp}|}_{typ \cong 0} - V_{OV2}$$

output swing

$$V_{o,max} = V_{DD} - |V_{OV2}|$$

$$V_{o,min} = V_{D1B,min}$$

$$= V_{G1B} - V_{tn}$$

$$= V_{ic} - V_{tn}$$