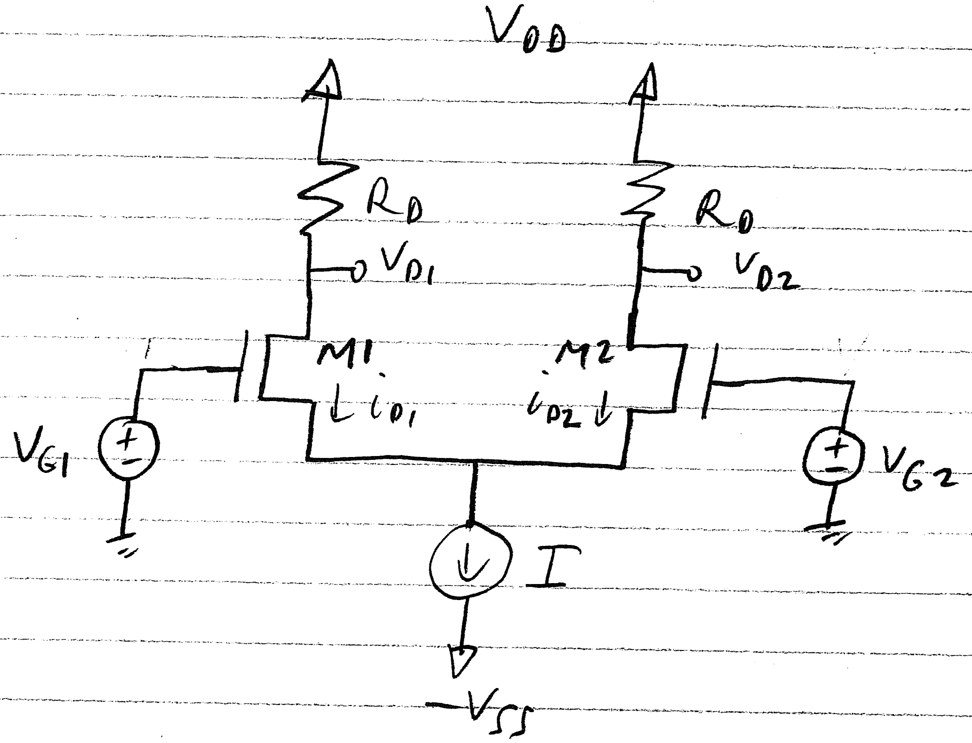
MDI

MOS DIFFERENTIAL PAIR



M_1, M_2 IDENTICAL

$i_{D_1} + i_{D_2} = I$ IF M_1 M_2 ACTIVE

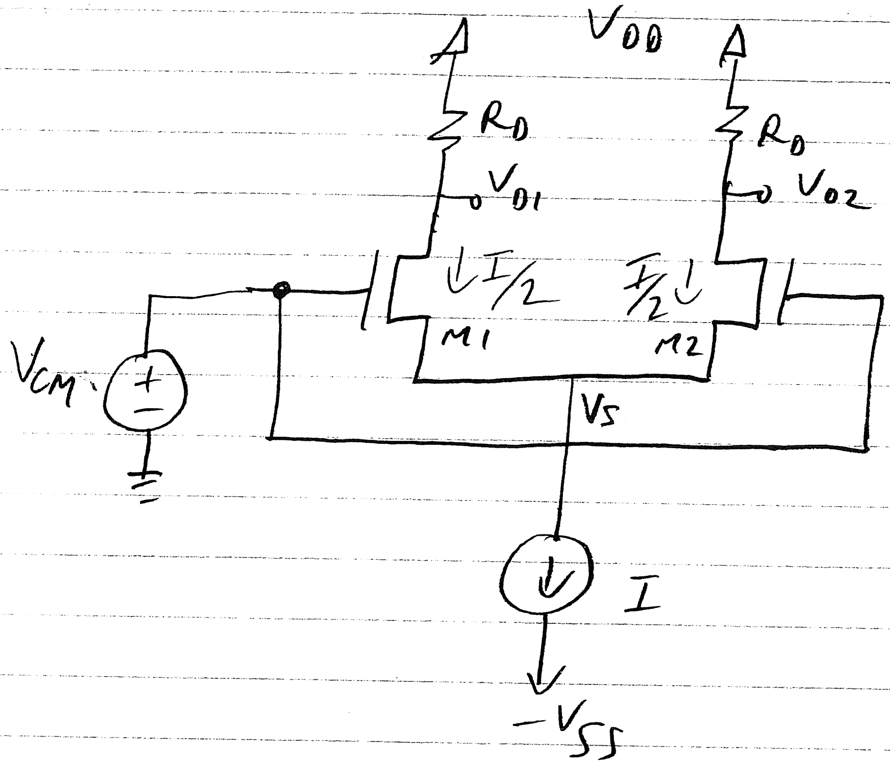
IF $V_{G1} = V_{G2} \Rightarrow i_{d1} = i_{d2} = I/2$

IF $V_{G1} > V_{G2} \Rightarrow i_{d1} > i_{d2}$

$V_{G1} < V_{G2} \Rightarrow i_{d1} < i_{d2}$

CAN "STEER" CURRENT I

COMMON-MODE INPUT OPERATION



$$V_{O1} = V_{O2} = V_{DD} - \frac{I}{2} R_D$$ WHILE M_1, M_2 ACTIVE

$$i_{D1} = \frac{I}{2} = \frac{\mu_n C_{ox}}{2} \left(\frac{W}{L}\right)\left(V_{OV}^2\right)$$

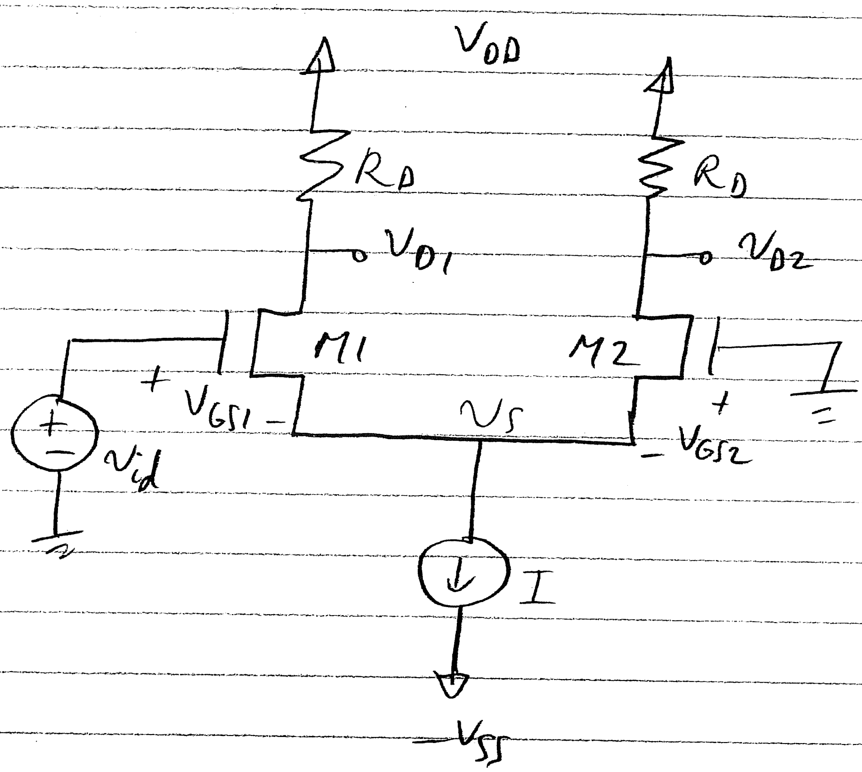
$$V_{OV(I/2)} = \sqrt{I / \left(\mu_n C_{ox} \left(\frac{W}{L}\right)\right)}$$

$$V_{CM\_MAX} = V_t + V_{DD} - \frac{I}{2} R_D$$ (ONE V_t ABOVE V_{O1})

$$V_{CM\_MIN} = -V_{SS} + V_{CS} + V_t + V_{OV(I/2)}$$

(V_{CS} IS VOLTAGE NEEDED ACROSS I CURRENT SOURCE)

LARGE SIGNAL WITH DIFFERENTIAL VOLTAGE



IF $v_{id} \gg 0$ ALL I FLOWS THROUGH M1

$v_{id} \ll 0$ " " " " M2

WHEN $i_{D2} \cong 0$ (M₂ JUST TURNS OFF)

$$V_{GS2} = V_{tn} \Rightarrow V_S = -V_{tn}$$

$V_{GS1} = V_{tn} + V_{OV(I)}$ WHERE

$$V_{OV(I)} = \sqrt{2I/(\mu_n C_{ox}(W/L))}$$

$$= \sqrt{2}\; V_{OV(I/2)}$$

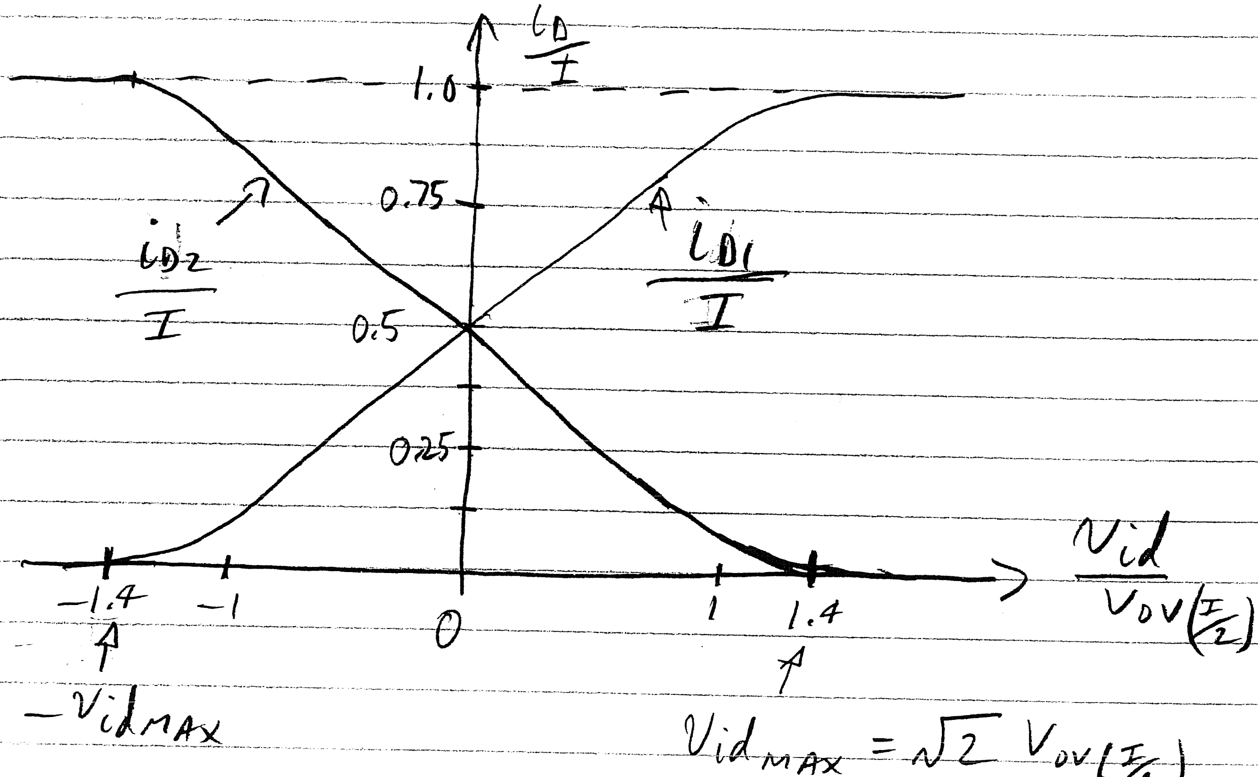
MD4

SINCE $v_{id} = v_S + V_{GS1}$

$= -V_{tn} + V_{tn} + v_{OV1}$

$$V_{id\,MAX} = \sqrt{2}\, V_{OV(I/2)}$$

WHERE CURRENT CAN BE STEERED TO M1 OR M2



CAN SHOW

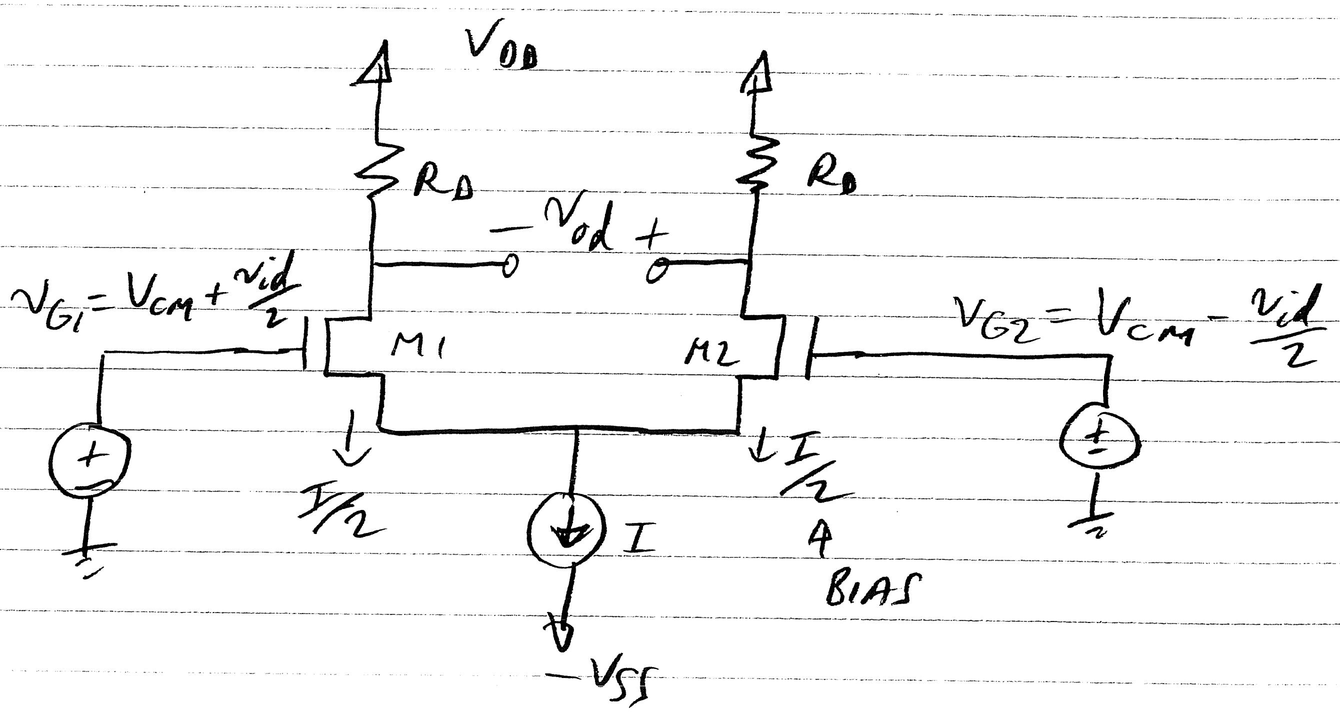
$$i_{D1} = \frac{I}{2} + \left(\frac{I}{V_{OV(I/2)}}\right)\left(\frac{v_{id}}{2}\right)\left(\sqrt{1 - \left(\frac{v_{id}/2}{V_{OV(I/2)}}\right)^2}\right)$$

i_{D2} SIMILAR EQN.

MD5

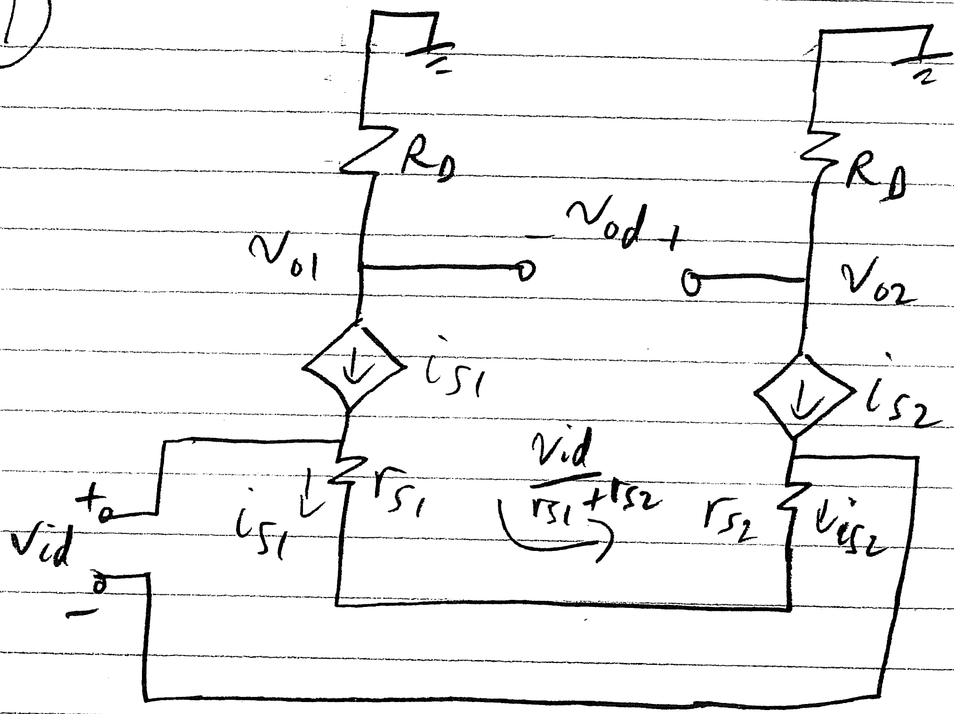
- i_D IS APPROX LINEAR RELATIONSHIP TO v_{id} NEAR $v_{id} \cong 0$
- MORE NON-LINEAR AS v_{id} INCREASES.

SMALL-SIGNAL OPERATION



2 WAYS TO LOOK AT CIRCUIT.
FOR SMALL-SIGNAL ANALYSIS

(1)



$$i_{S1} = \frac{v_{id}}{r_{S1}+r_{S2}} = \frac{v_{id}}{2 r_S}$$

ASSUME $r_S = r_{S1} = r_{S2}$

$$v_{o1} = - i_{S1} R_D \quad \& \quad i_{S2} = - i_{S1}$$

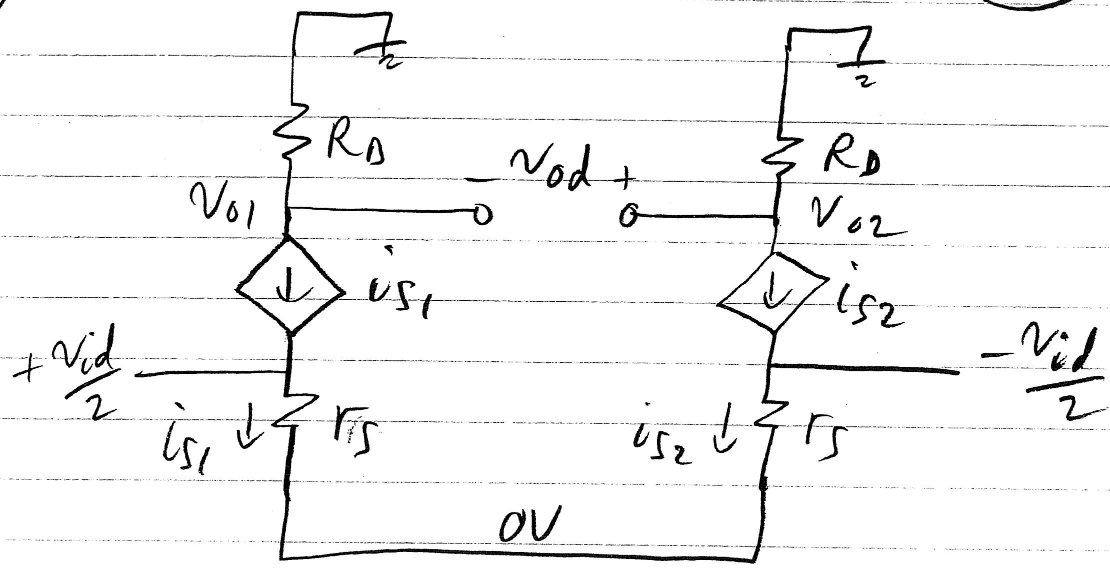
$$v_{o2} = - i_{S2} R_D = i_{S1} R_D$$

$$v_{od} = v_{o2} - v_{o1} = 2 i_{S1} R_D = \frac{R_D}{r_S} v_{id}$$

$$\frac{v_{od}}{v_{id}} = \frac{R_D}{r_S} = g_m R_D$$

(2) BALANCED VIEW

(MD7)



SINCE BALANCED CIRCUIT.

$$v_{o1} = -\left(\frac{R_D}{r_s}\right)\left(\frac{v_{id}}{2}\right)$$

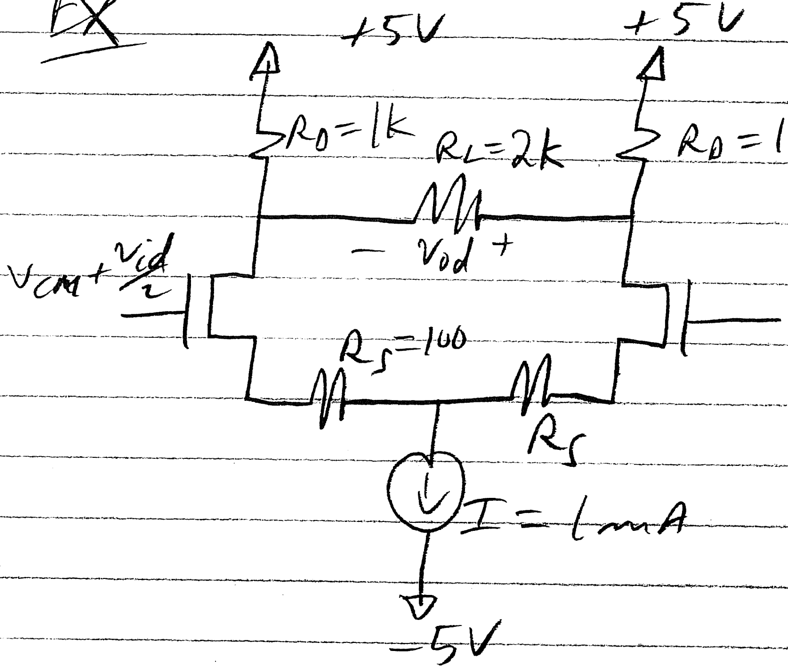
$$v_{o2} = -\left(\frac{R_D}{r_s}\right)\left(-\frac{v_{id}}{2}\right)$$

$$v_{od} = v_{o2} - v_{o1} = \left(\frac{R_D}{r_s}\right) v_{id} = g_m R_D v_{id}$$

DIFFERENTIAL HALF CIRCUIT.

IF CIRCUIT IS BALANCED ⇒ DO ANALYSIS ON HALF CIRCUIT

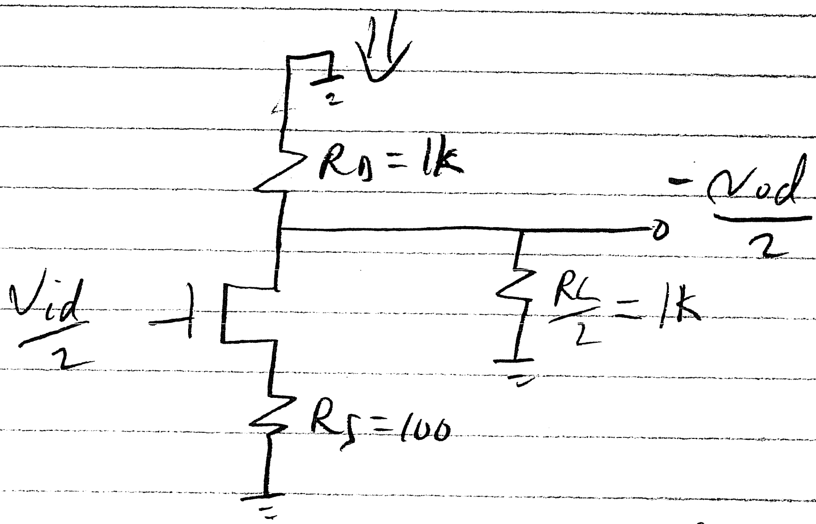
EX



ASSUME
$V_{OV} = V_{OV}\left(\frac{I}{2}\right) = 0.2V$

$\lambda = 0$

⇓



$$g_m = \frac{1}{r_S} = \frac{2 I_D}{V_{OV}} = \frac{2\left(\frac{I}{2}\right)}{V_{OV}} = \frac{2(0.5)}{0.2} = 5\,mA/V$$

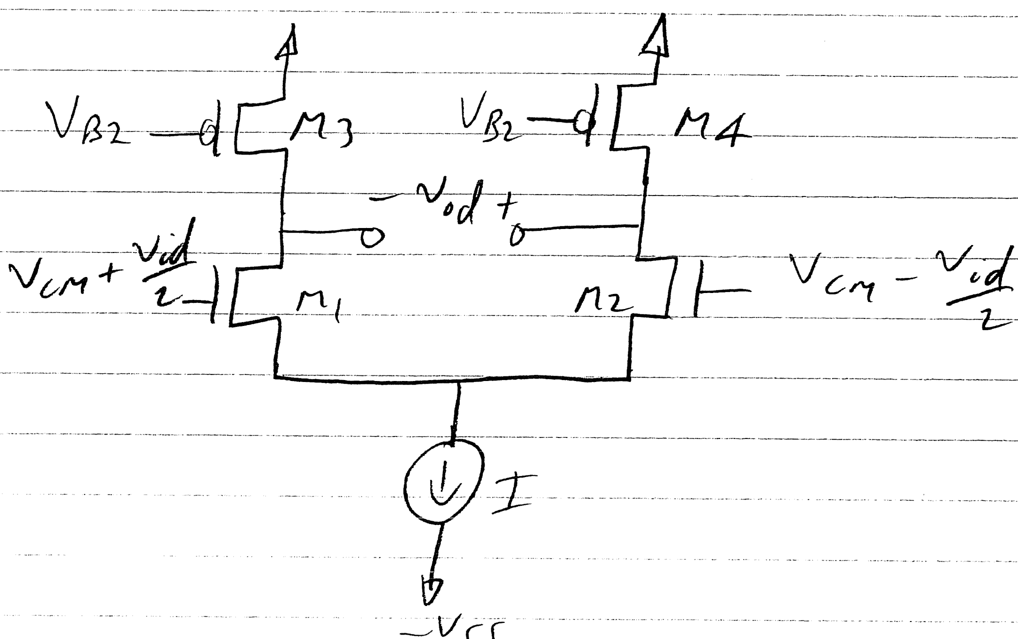
$r_S = 200\,\Omega$

$$\frac{-\frac{v_{od}}{2}}{\frac{v_{id}}{2}} = \frac{-v_{od}}{v_{id}} = \frac{-\left[R_D \,//\, \left(\frac{R_L}{2}\right)\right]}{r_s + R_s}$$

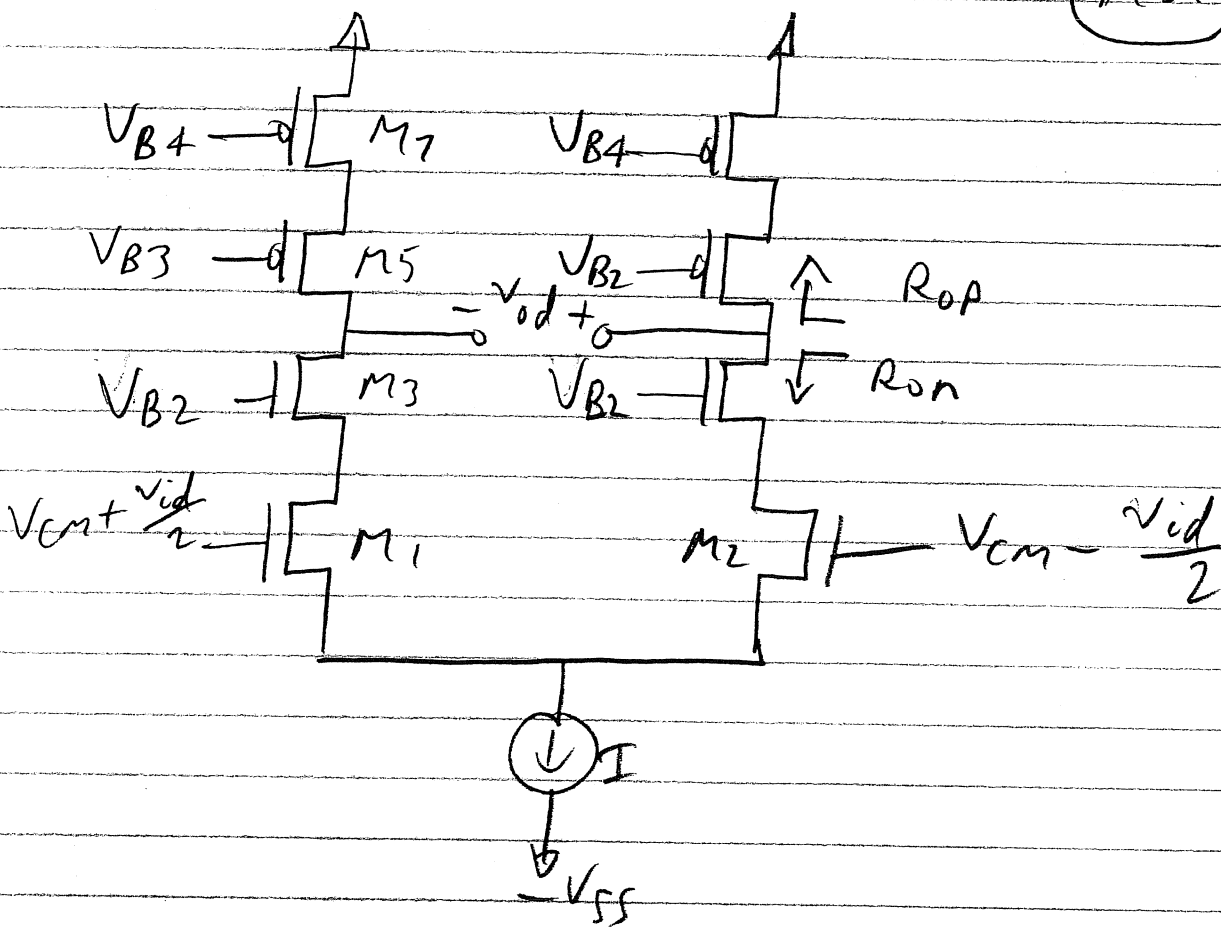
$$-\frac{v_{od}}{v_{id}} = \frac{-500}{300} = -1.67 \ V/V$$

$$\frac{v_{od}}{v_{id}} = 1.67 \ V/V$$

DIFF PAIR WITH CURRENT SOURCE LOADS



$$A_d = \frac{v_{od}}{v_{id}} = g_{m1}\left(r_{o1} \,//\, r_{o3}\right)$$



$$A_d = \frac{v_{od}}{v_{id}} = g_{m1}(R_{on} \| R_{op})$$

$$R_{on} \simeq (g_{m3} r_{o3}) r_{o1}$$

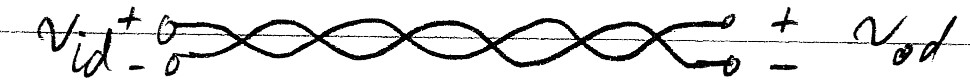
$$R_{op} \approx (g_{m5} r_{o5}) r_{o7}$$

DIFFENTIAL + COMMON-MODE SIGNALS

- MANY CIRCUITS RELY ON DIFFERENTIAL SIGNALS AS THEIR SIGNALS AND TRY TO IGNORE (OR REJECT) COMMON-MODE SIGNALS

- ETHERNET

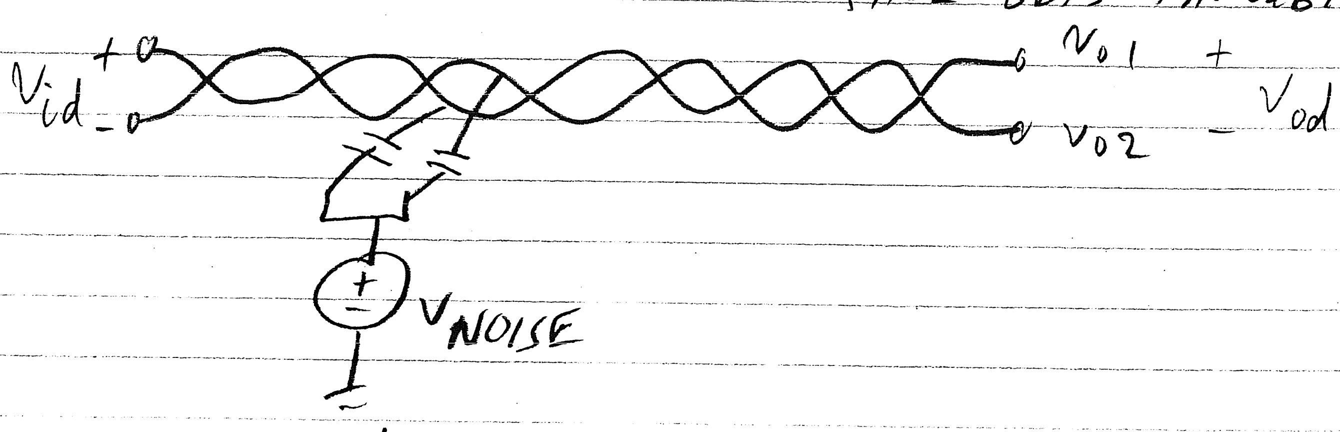
TWISTED WIRE PAIR



TRANSMIT + RECEIVE DIFF SIGNALS

SO COMMON MODE INTERFERENCE CAN BE REJECTED

- TWISTED PAIR HELPS BUT COMMON-MODE SIGNAL STILL GETS THROUGH.



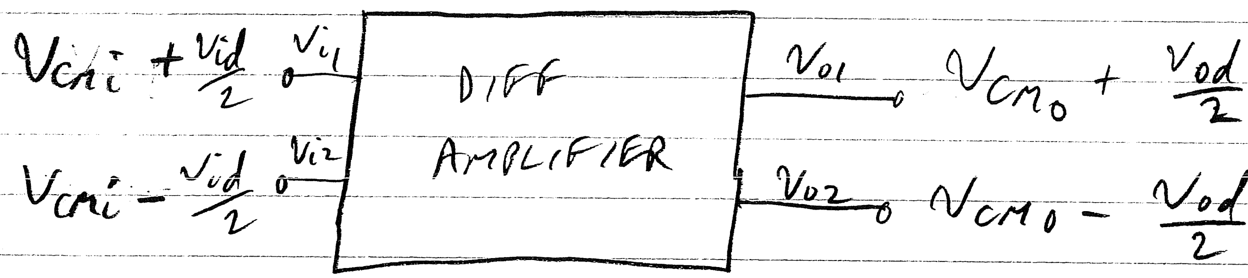
$$v_{o1} = \frac{v_{id}}{2} + V_{NOISE}$$

$$v_{o2} = -\frac{v_{id}}{2} + V_{NOISE}$$

MD12

$$V_{od} = V_{o1} - V_{o2} = V_{id}$$

DIFF AMP



$$V_{id} \equiv V_{i1} - V_{i2}$$

$$V_{cmi} \equiv \frac{V_{i1} + V_{i2}}{2}$$

$$V_{od} \equiv V_{o1} - V_{o2}$$

$$V_{cmo} \equiv \frac{V_{o1} + V_{o2}}{2}$$

DEFINE 4 GAINS THROUGH AMP

$$A_d \equiv \frac{V_{od}}{V_{id}}$$ DIFFERENTIAL GAIN

$$A_{CM-CM} \equiv \frac{V_{CMO}}{V_{CMi}}$$ COMMON MODE TO COMMON MODE GAIN

$$A_{CM} = \frac{V_{od}}{V_{cmi}}$$ COMMON MODE TO DIFFERENTIAL GAIN

$$A_{d-CM} \equiv \frac{V_{CMO}}{V_{id}}$$ DIFF TO CM GAIN (USUALLY UNIMPORTANT)

A_{CM-CM} KEEP SMALL SO COMMON-MODE SIGNALS DO NOT AMPLIFY (<1)

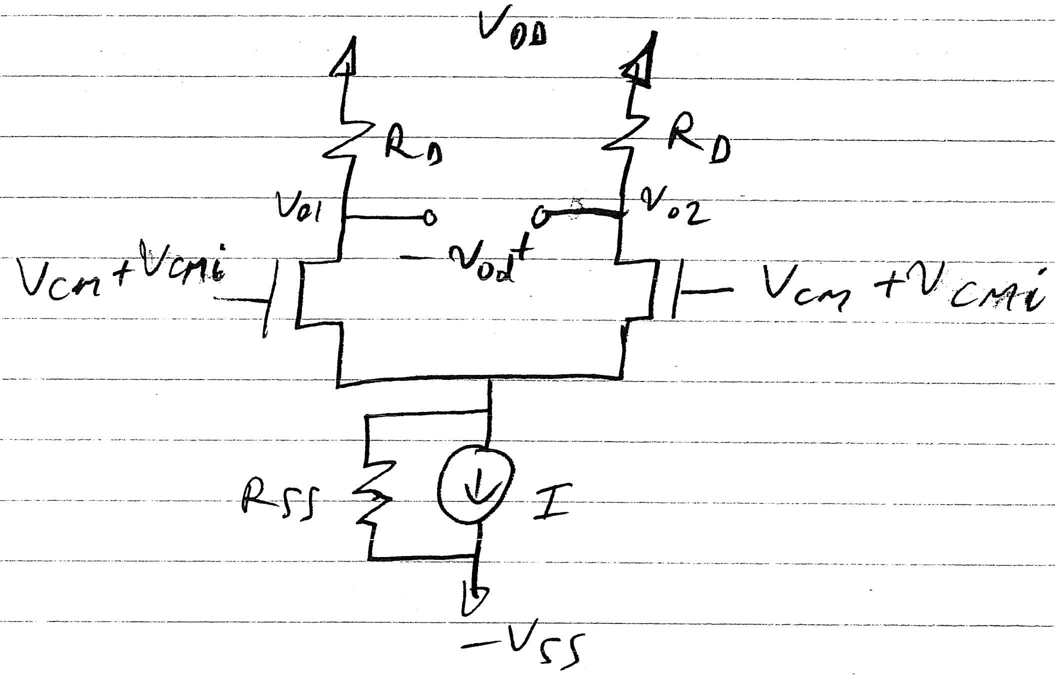
MOST IMPORTANT ARE A_d & A_{CM}

& WANT $A_d \gg A_{CM}$ SO

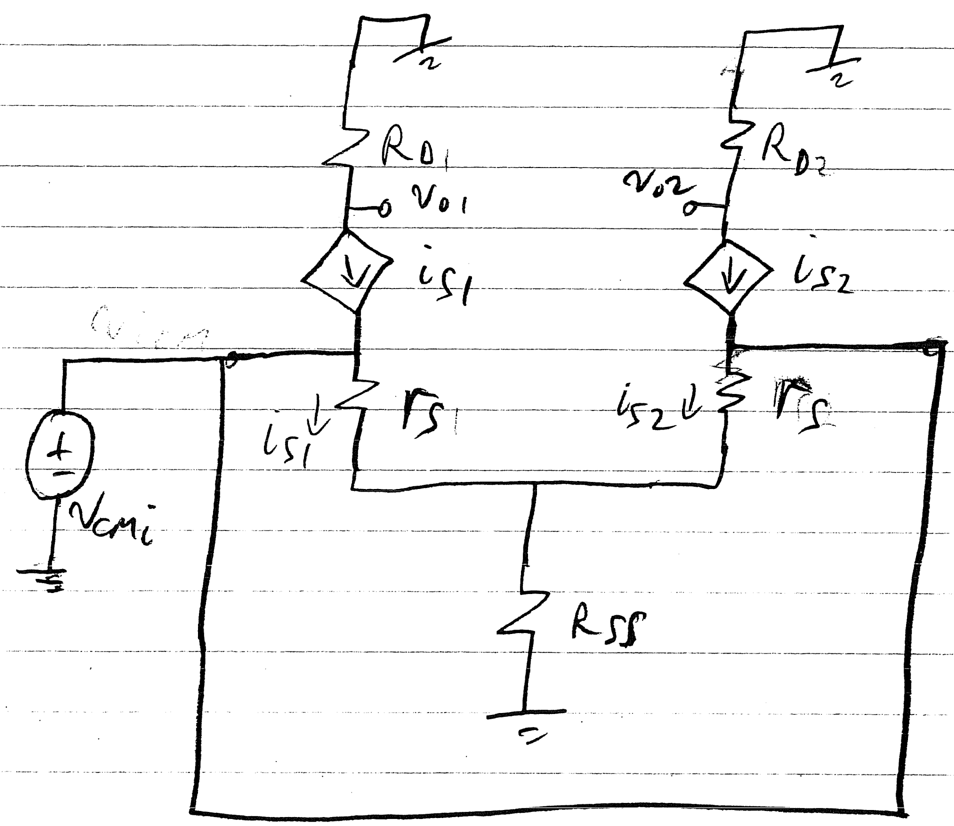
CM SIGNALS ARE REJECTED

MD 14

Ad_cm



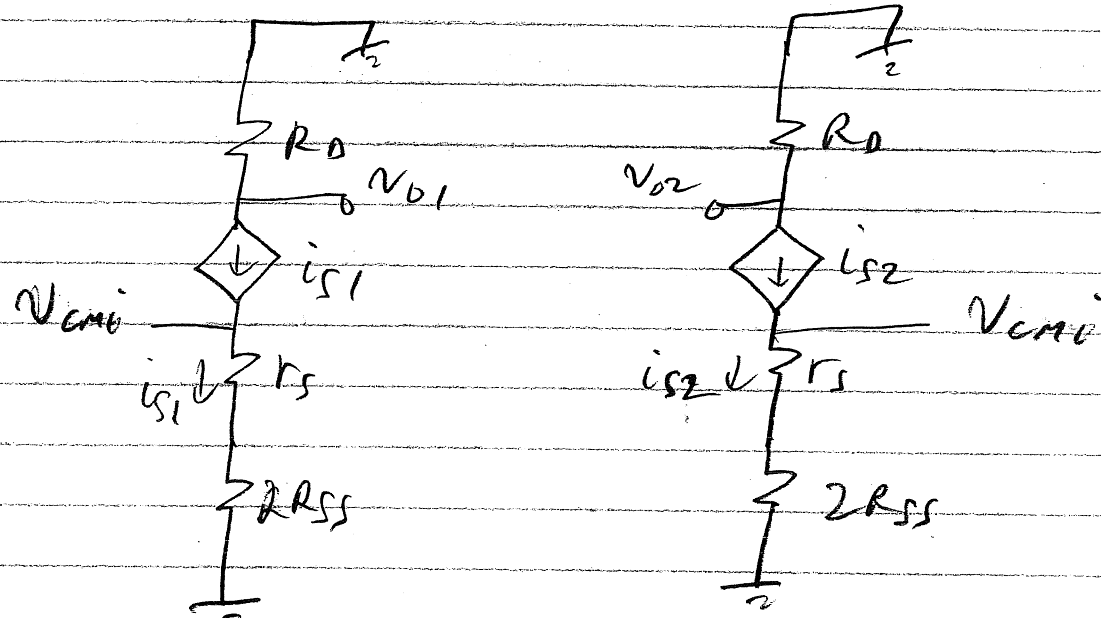
V_{DD}
R_D
R_D
V_{o1}
v_{o2}
$V_{cm}+v_{cmi}$
$-v_{od}+$
$V_{cm}+v_{cmi}$
R_{SS}
I
$-V_{SS}$



R_{D1}
v_{o1}
v_{o2}
R_{D2}
i_{s1}
i_{s2}
i_{s1}
r_{s1}
i_{s2}
r_s
v_{cmi}
R_{SS}

MD15

EQUIV TO HALF CIRCUITS



$$\frac{v_{o1}}{v_{cmi}} = -\frac{R_D}{r_s + 2R_{SS}} = \frac{v_{o2}}{v_{cmi}}$$

SO $v_{od} = v_{o1} - v_{o2} = 0$ & $A_{CM} = 0$

IF PERFECTLY MATCHED.

IF RESISTORS MISMATCHED BY ΔR_D

$R_{D1} = R_D$ & $R_{D2} = R_D + \Delta R_D$

CAN SHOW $A_{CM} = -\left(\frac{R_D}{2R_{SS}}\right)\left(\frac{\Delta R_D}{R_D}\right)$

IF TRANSISTORS g_m MISMATCHED BY $\frac{\Delta g_m}{g_m}$

CAN SHOW

$$A_{CM} \approx \left(\frac{R_D}{2R_{SS}}\right)\left(\frac{\Delta g_m}{g_m}\right)$$

<u>CMRR</u> COMMON-MODE REJECTION RATIO

USUALLY CARE ABOUT RATIO $\frac{A_d}{A_{CM}}$

SO DEFINE

$$CMRR \equiv \frac{|A_d|}{|A_{CM}|}$$

OR IN dB

$$CMRR(dB) = 20 \log \frac{|A_d|}{|A_{CM}|}$$

SINCE $A_d = g_m R_D$

THEN FOR $\Delta R \Rightarrow CMRR = \frac{2 g_m R_{SS}}{(\Delta R_D / R_D)}$

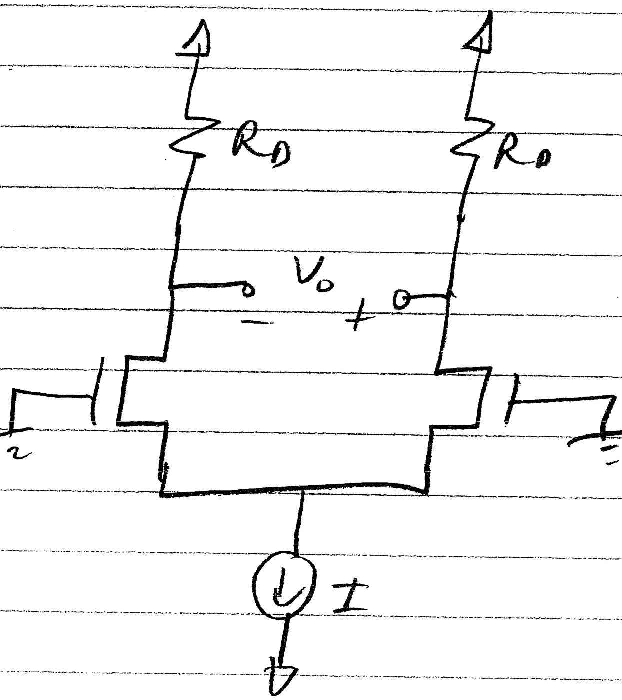
FOR $\Delta g_m \Rightarrow CMRR = \frac{2 g_m R_{SS}}{(\Delta g_m / g_m)}$

INPUT OFFSET OF DIFF PAIR (dc VALUE)

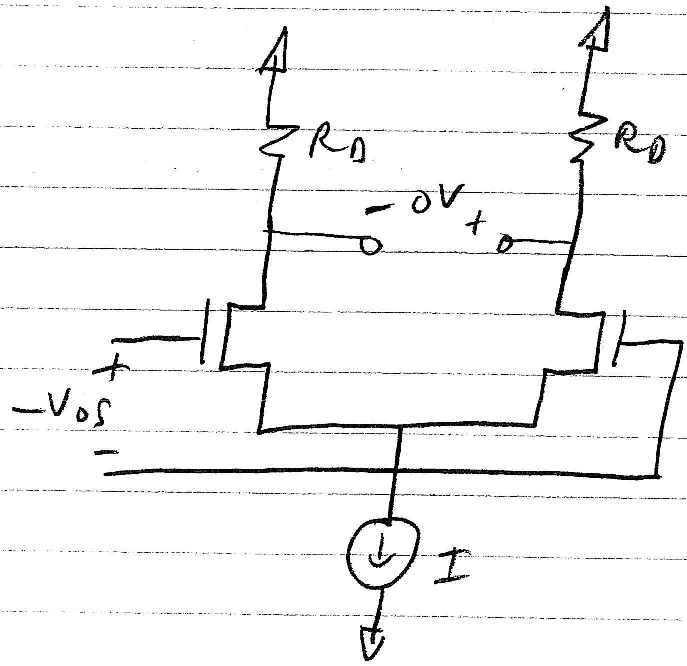
DEFINE V_{os} AS INPUT OFFSET VOLTAGE NEEDED TO SET OUTPUT OFFSET TO ZERO

V_{os} INPUT OFFSET
V_o OUTPUT OFFSET

$$V_{os} = V_o / A_d$$



IF $V_{id} = 0$
V_o IS OUTPUT OFFSET VOLTAGE



APPLY V_{OS} TO SET $V_o = 0$

OFFSET DUE TO R_D, $\left(\frac{W}{L}\right)$, V_{tn} MISMATCH

TYPICALLY V_{tn} DOMINATES

& $V_{OS} = \Delta V_{tn}$

TYPICALLY $\Delta V_{tn} \approx 1 \rightarrow 10$ mV

FOR ΔR_D

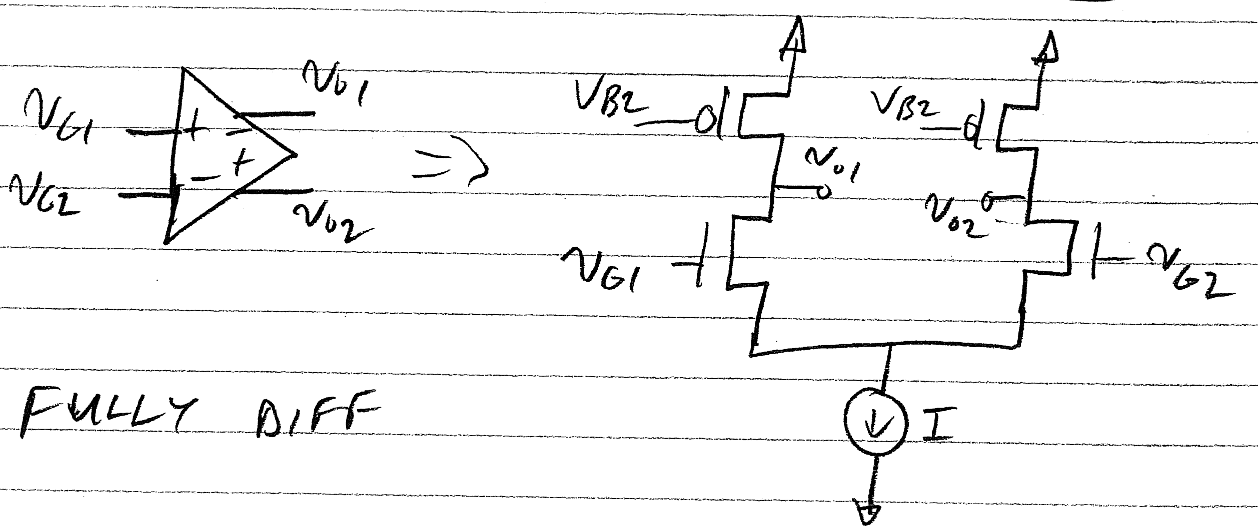
$$V_{OS} = \left(\frac{V_{OV}}{2}\right)\left(\frac{\Delta R_D}{R_D}\right)$$

FOR $\Delta\left(W/L\right)$

$$V_{OS} = \left(\frac{V_{OV}}{2}\right)\frac{\Delta(W/L)}{(W/L)}$$

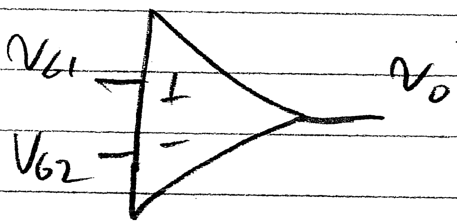
ACTIVE LOADS

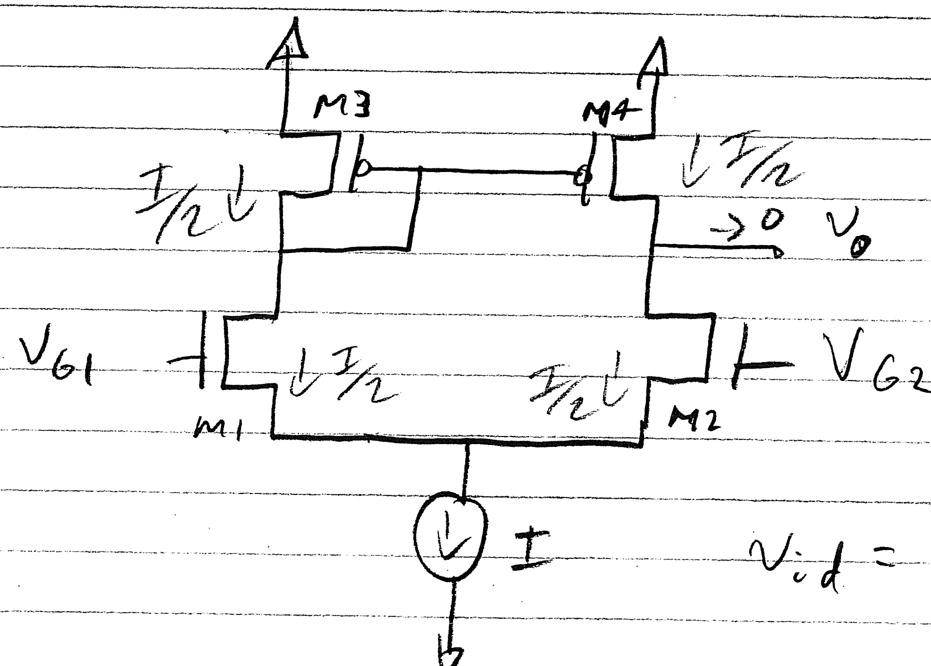
MD19



FULLY DIFF

DIFF - SINGLE-ENDED

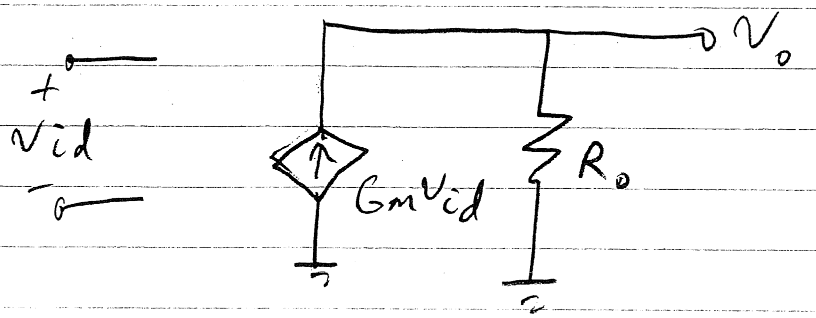




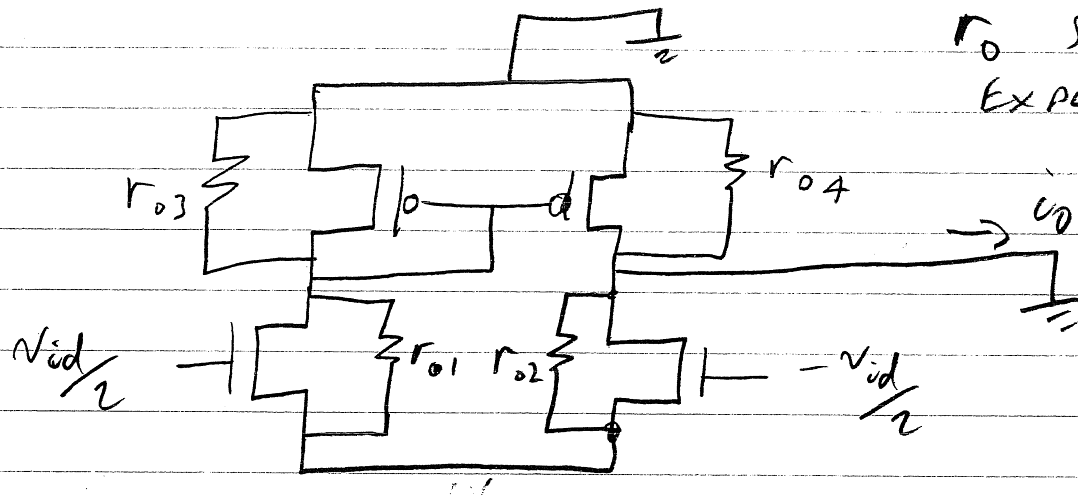
$$v_{id} = V_{G1} - V_{G2}$$

MD20

WANT TO MODEL ABOVE AS



TO FIND G_m



r_o SHOWN EXPLICITLY

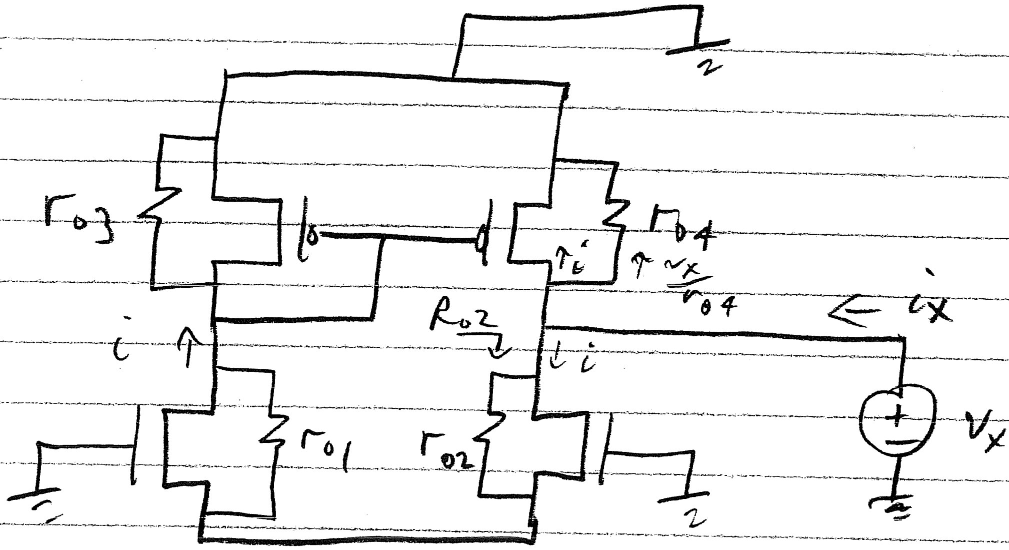
$$G_m \equiv \frac{i_o}{v_{id}} \quad \text{OR} \quad i_o = G_m v_{id}$$

CAN SHOW $G_m = g_{m_1}$ SEE TEXT

WHERE $g_m = g_{m_1} = g_{m_2}$

MD21

TO FIND R_o



$$R_o \equiv \frac{v_x}{i_x}$$

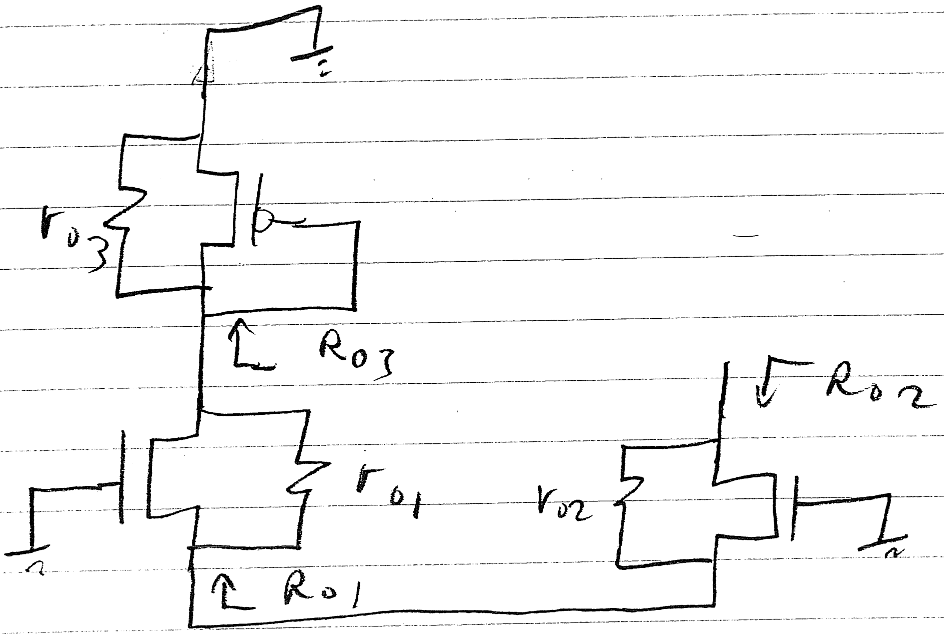
CAN SHOW $R_o \simeq r_{o2} \| r_{o4}$

$$R_{o2} \approx 2r_{o2} \Rightarrow i = \frac{v_x}{2r_{o2}}$$

$$i_x = i + i + \frac{v_x}{r_{o4}} = \frac{2V_x}{2r_{o2}} + \frac{V_x}{r_{o4}}$$

$$i_x = \frac{v_x}{r_{o2}} + \frac{V_x}{r_{o4}} \Rightarrow R_o = \frac{v_x}{i_x} = r_{o2} \| r_{o4}$$

MD21A



$$R_{o3} = \frac{1}{g_{m3}} \parallel r_{o3} \approx \frac{1}{g_{m3}}$$

$$R_{o1} = \frac{1}{g_{m1}} + \frac{R_{o3}}{g_{m1} r_{o1}} = \frac{1}{g_{m1}} + \frac{1}{g_{m1} g_{m3} r_{o1}}$$

$$R_{o1} \approx \frac{1}{g_{m1}}$$

$$R_{o2} \cong \left[1 + g_{m2}(R_{o1})\right] r_{o2} \qquad g_{m1} = g_{m2}$$

$$= \left[1 + (g_{m2})\left(\frac{1}{g_{m1}}\right)\right] r_{o2}$$

$$= \underline{\underline{2 r_{o2}}}$$

MD 22

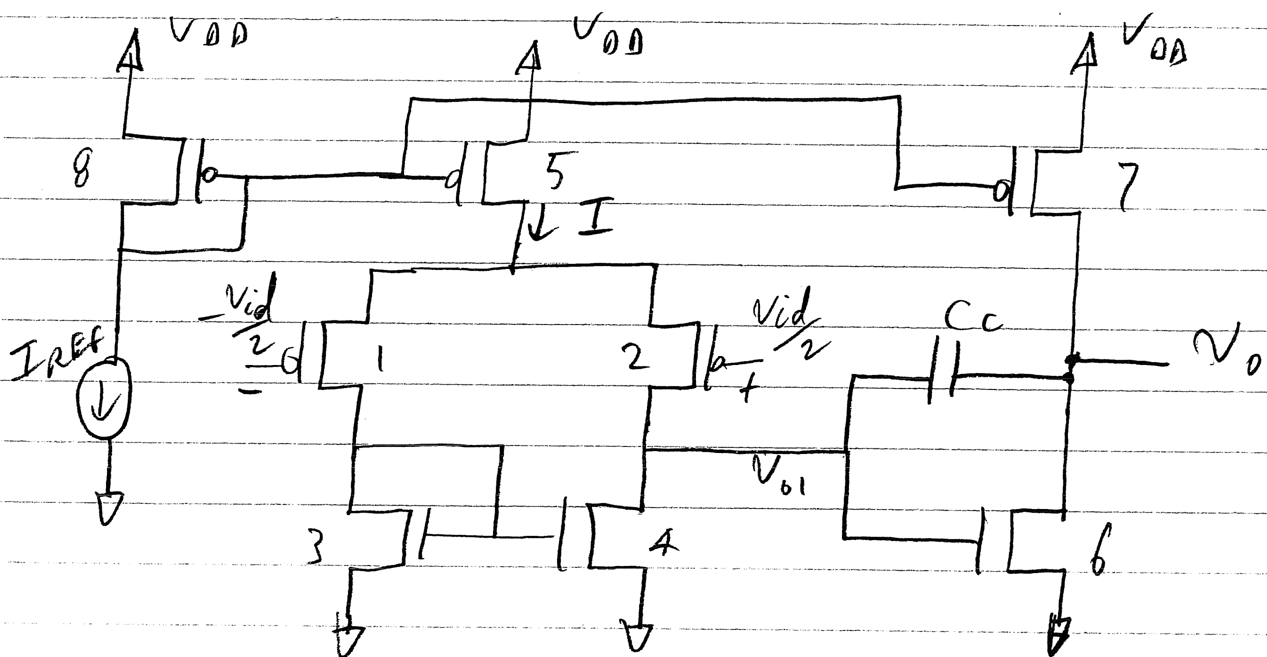
DIFFERENTIAL GAIN

$$A_d \equiv \frac{v_o}{v_{id}} = G_m R_o = g_m (r_{o2} \| r_{o4})$$

IF $r_o = r_{o2} = r_{o4}$

$$A_d = \frac{1}{2} g_m r_o$$

2 STAGE CMOS OPAMP



OVERALL GAIN $\frac{v_o}{v_{id}} = A_1 A_2$ (Cc IS A COMPENSATION CAP FOR STABILITY)

$$A_1 = \frac{v_{o1}}{v_{id}} = -g_{m1} (r_{o2} \| r_{o4})$$

$$A_2 = \frac{v_o}{v_{o1}} = -g_{m6} (r_{o6} \| r_{o7})$$

SIZING TRANSISTORS FOR ZERO SYSTEMATIC OFFSET

(RANDOM OFFSET WILL STILL OCCUR & RESULT IN 1 – 20 mV INPUT OFFSET VOLTAGE)

LET $V_{id} = 0$

SINCE M3 & M4 MATCHED

$$I_{D3} = I_{D4} = I/2 \quad \& \quad V_{DS3} = V_{DS4}$$

SO $V_{GS6} = V_{DS4} = V_{DS3} = V_{GS3}$

$$\Rightarrow \quad I_{D6} = \frac{(W/L)_6}{(W/L)_3}\left(I/2\right)$$

FOR NO SYSTEMATIC OFFSET $I_{D7} = I_{D6}$

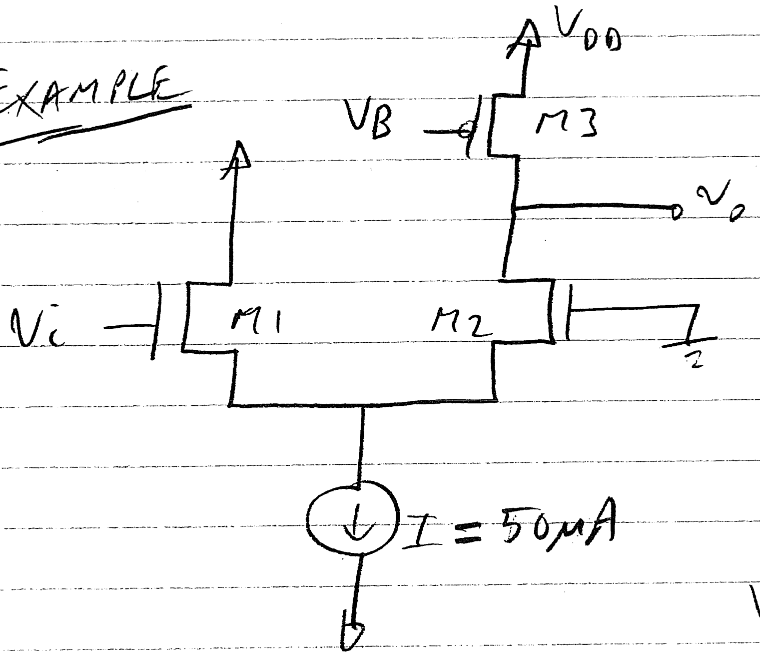
$$\& \quad I_{D7} = \frac{(W/L)_7}{(W/L)_5} I$$

SO FOR $I_{D6} = I_{D7}$

$$\frac{(W/L)_6}{(W/L)_3} = 2\,\frac{(W/L)_7}{(W/L)_5}$$

MD24

EXAMPLE



$\mu_n C_{ox} = 240\ \mu A/V^2$

$\mu_p C_{ox} = 60\ \mu A/V^2$

$\lambda' = 0.1\ \mu m/V$

$V_{tn} = 0.4V$

$W_1 = 2W_2 = 2\ \mu m$

$W_3 = 2\ \mu m$

ALL $L = 0.2\ \mu m$

V_B CHOSEN SO $I_{D3} = I_{D2}$

FIND $\frac{v_o}{v_i}$

DC

$I_{D1} = 2I_{D2}$ + $I_{D1} + I_{D2} = I = 50\mu A$

$I_{D2} = 16.7\mu A$ $\quad I_{D1} = 33.3\mu A$

$g_{m1} = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right) I_{D1}} = 400\ \mu A/V$

$r_{s1} = 2.5k\Omega$

$g_{m2} = 200\ \mu A/V$ $\quad r_{s2} = 5k\Omega$

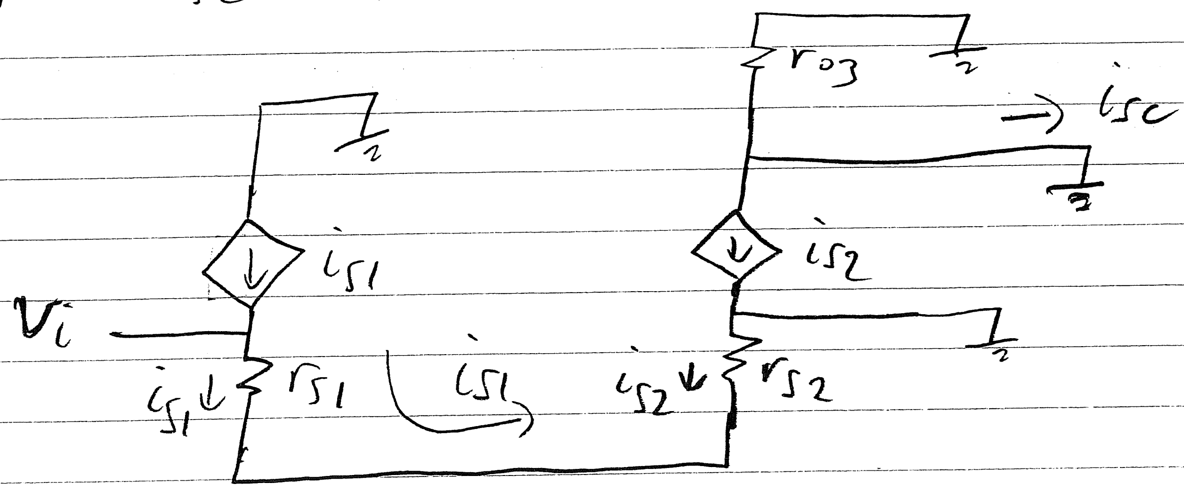
$r_{o1} = \frac{L}{\lambda' I_{D1}} = 60K$ $\quad r_{o2} = 120K$

$V_{ov1} = V_{ov2} = 167\ mV$

$r_{o3} = \frac{L}{\lambda' I_{D3}} = 120K$

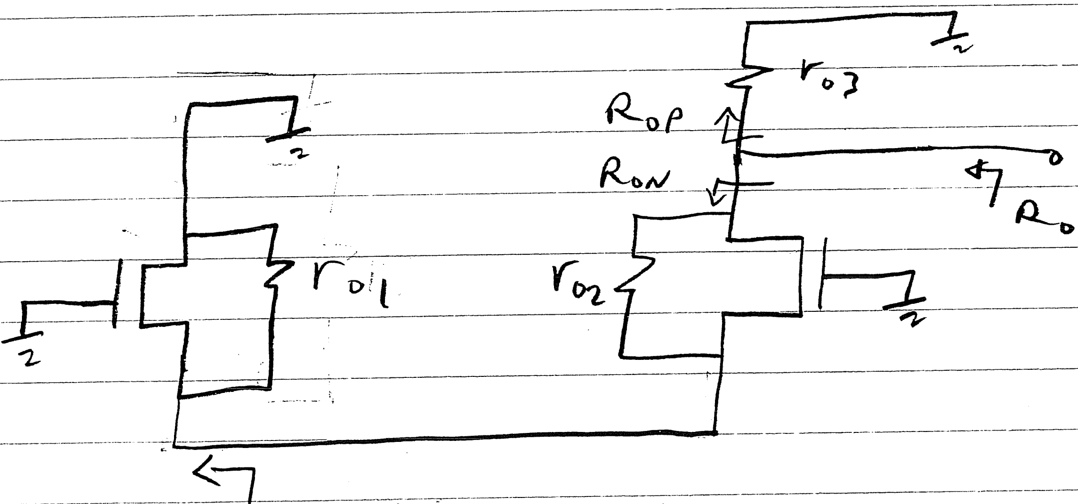
MD25

FIND i_{sc} (IGNORE r_o)



$$i_{sc} = -i_{S2} = i_{S1} = \frac{v_i}{r_{S1} + r_{S2}} = \frac{v_i}{7.5k}$$

R_o



$$R_{i1} = r_{o1} \| r_{S1} = 2.4k$$

$$R_{oP} = r_{o3} = 120k \qquad R_{oN} = R_{i1} + r_{o2} + g_{m2} r_{o2} R_{i1} = 180k$$

$$R_o = R_{oP} \| R_{oN} = 72k$$

MD26

$$v_o = i_{sc} R_o = (72k)\left(\frac{v_i}{7.5k}\right)$$

$$\frac{v_o}{v_i} = 9.6 \ V/V$$