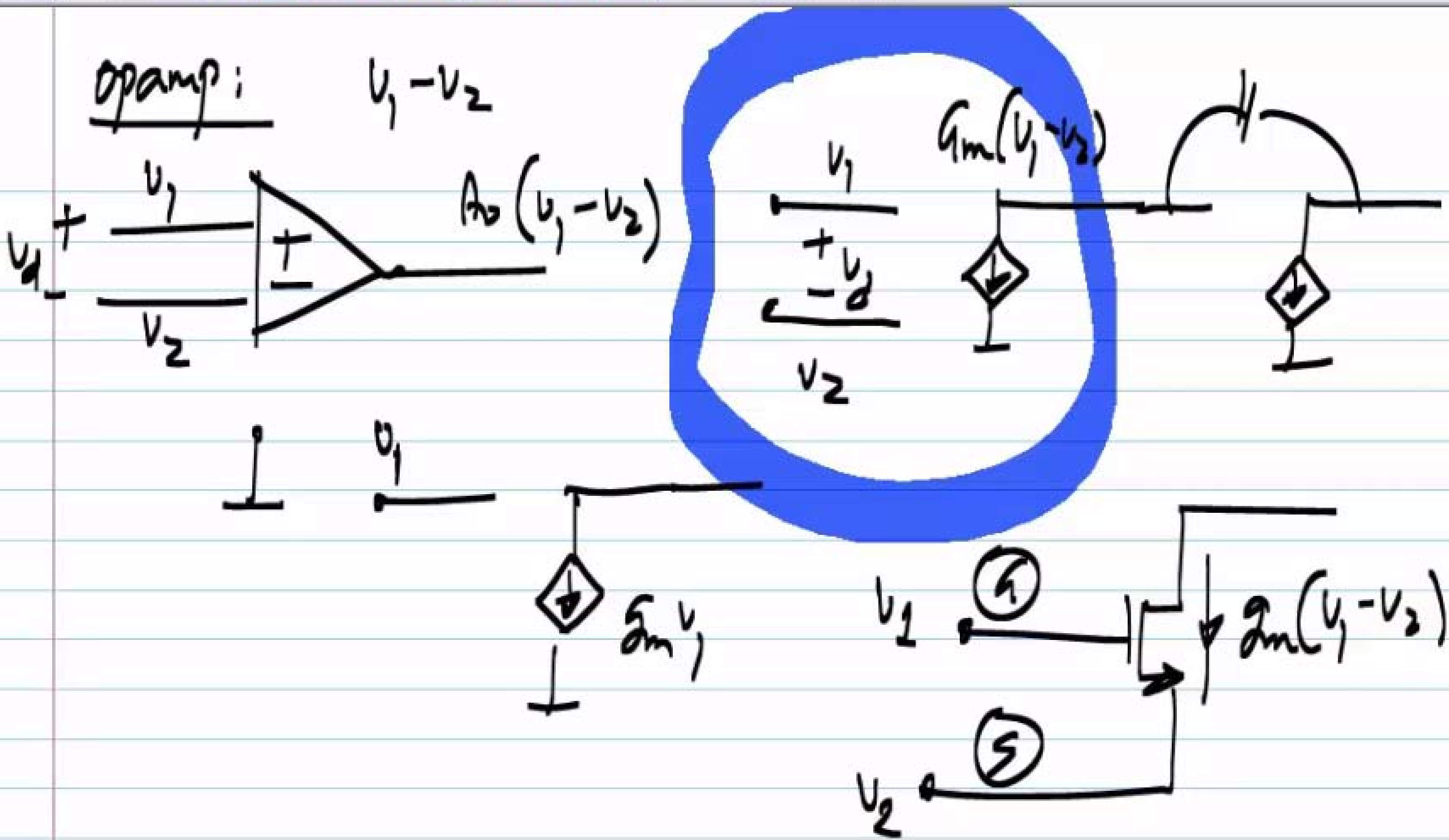
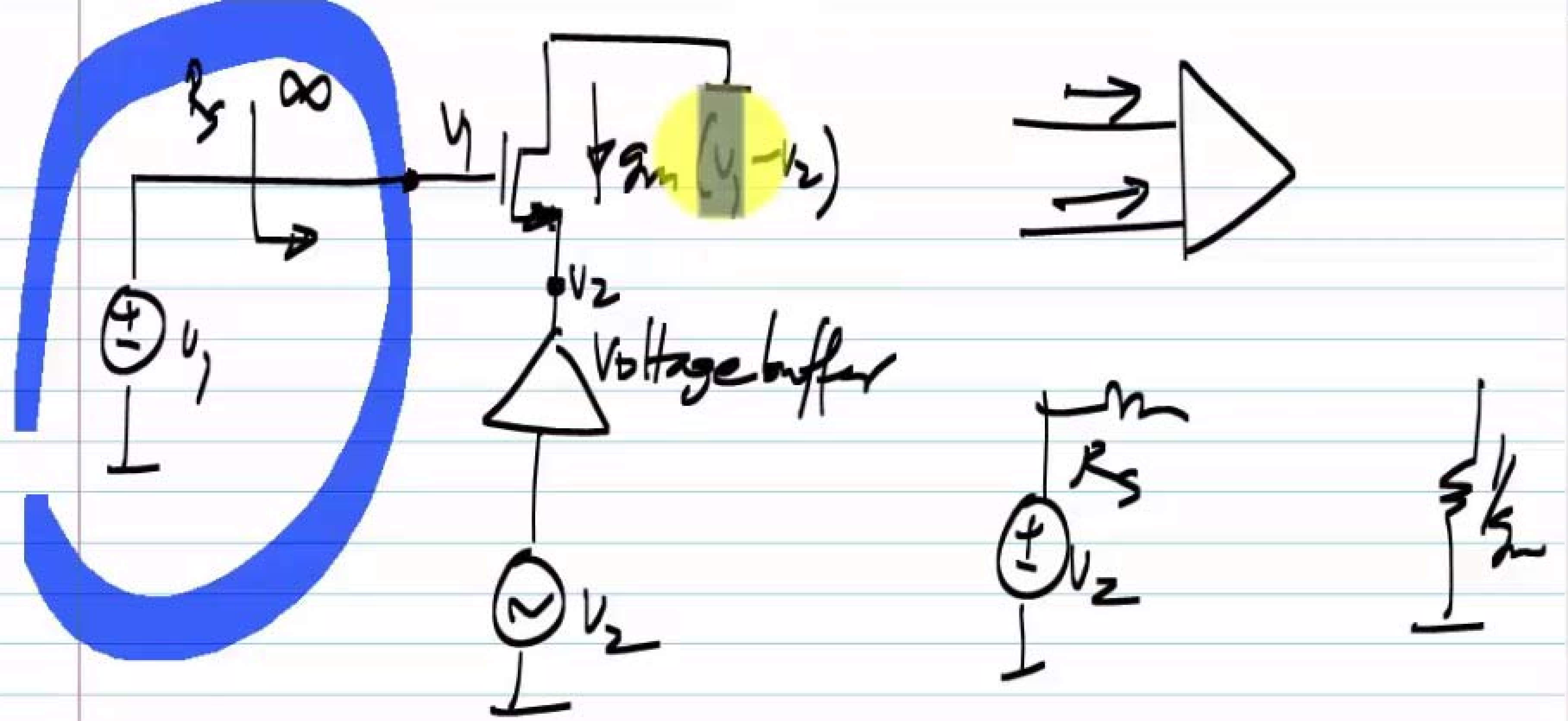
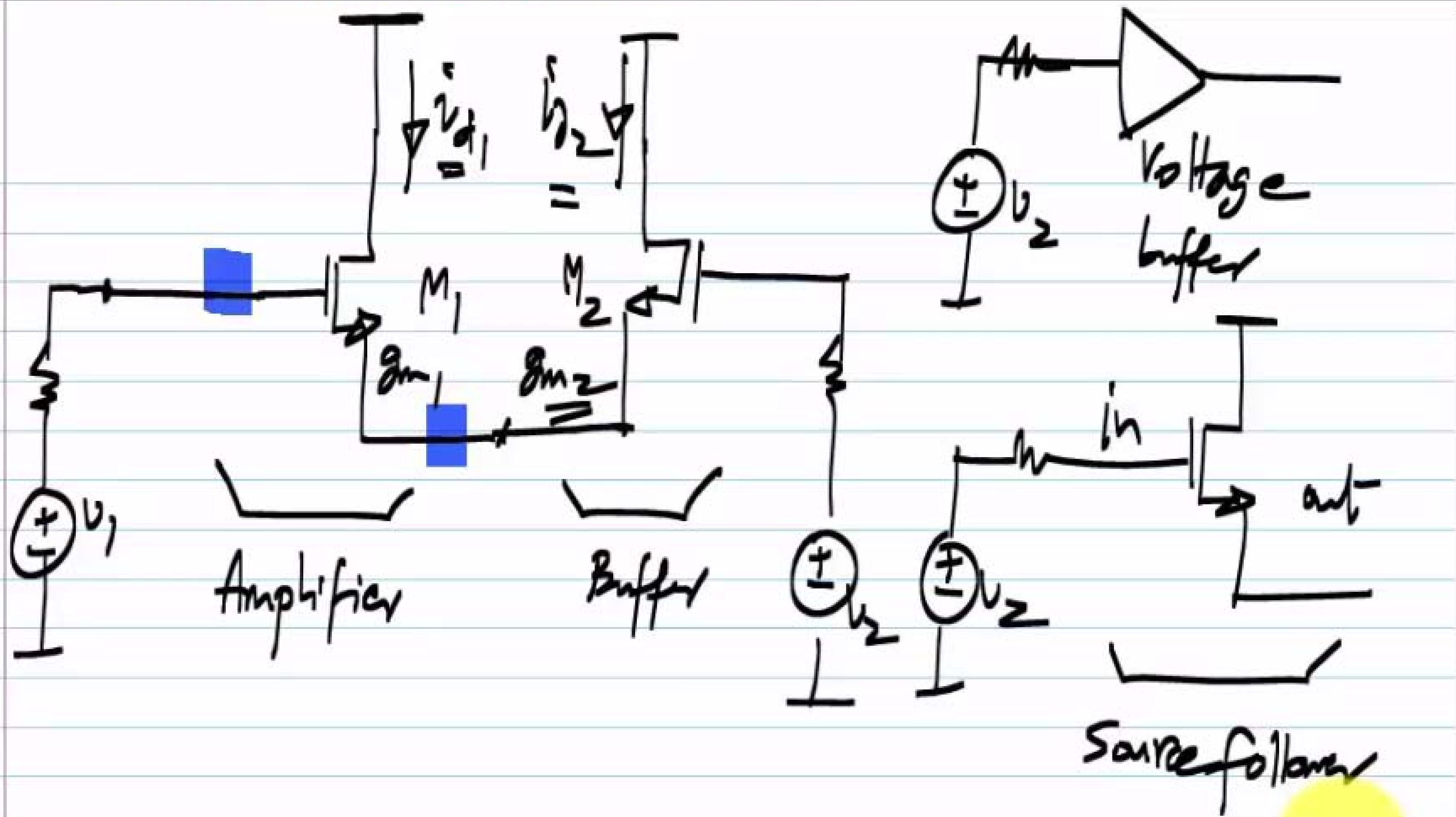
opamp:

$v_1 - v_2$



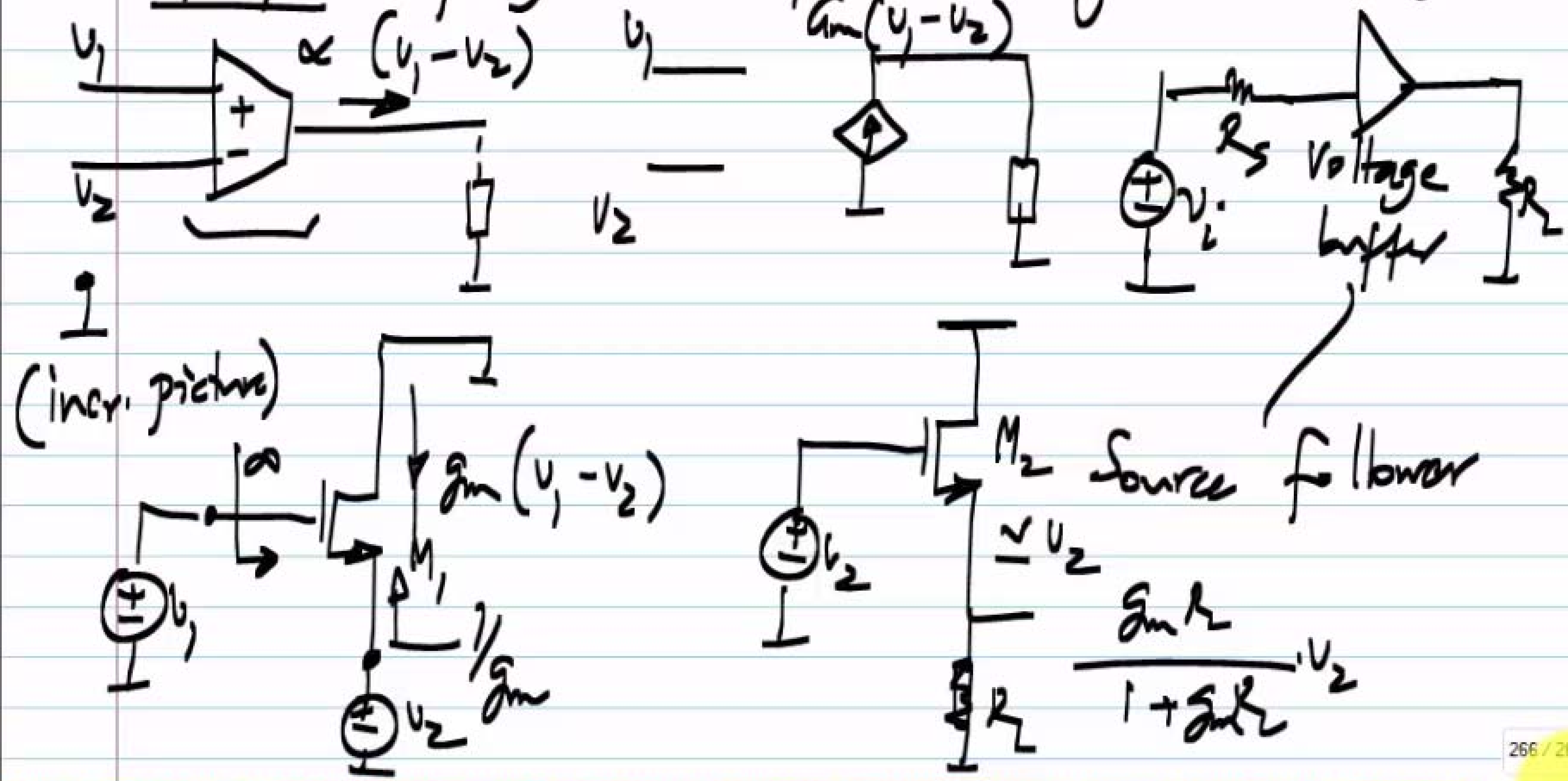


Rs
∞
v1
v1
gm(v1-v2)
v2
Voltage buffer
v2
Rs
v2
1/gm

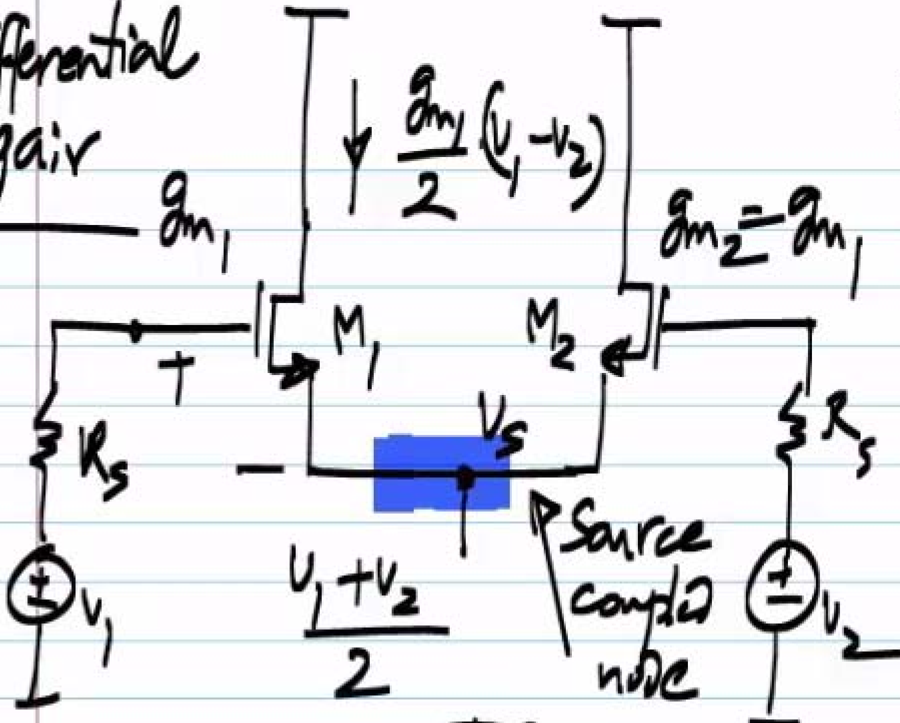


i_{d1}
i_{d2}
M_1
M_2
g_{m1}
g_{m2}
v_1
v_2
Amplifier
Buffer
Voltage buffer
in
out
Source follower

<u>opamp:</u> Amplify the difference of two voltages

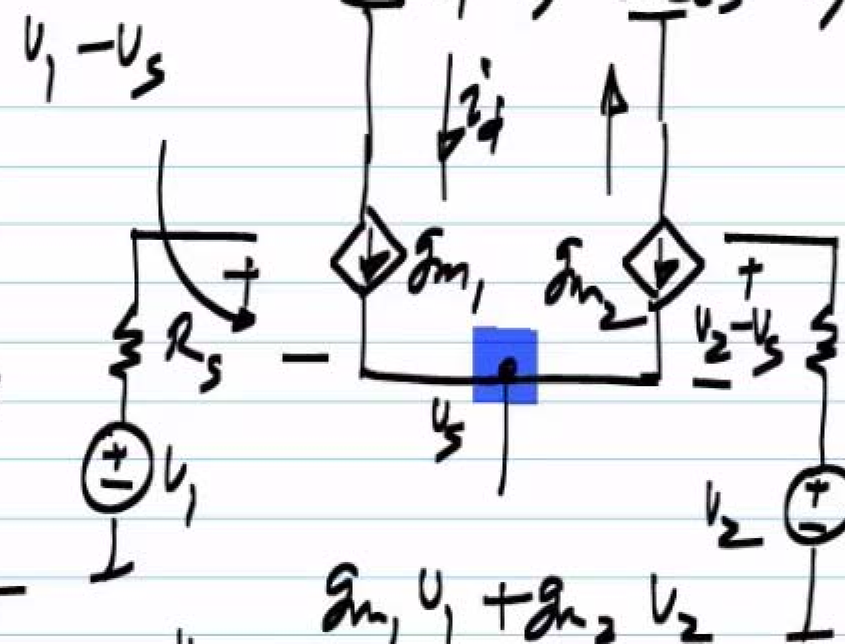


Differential pair



Tail node

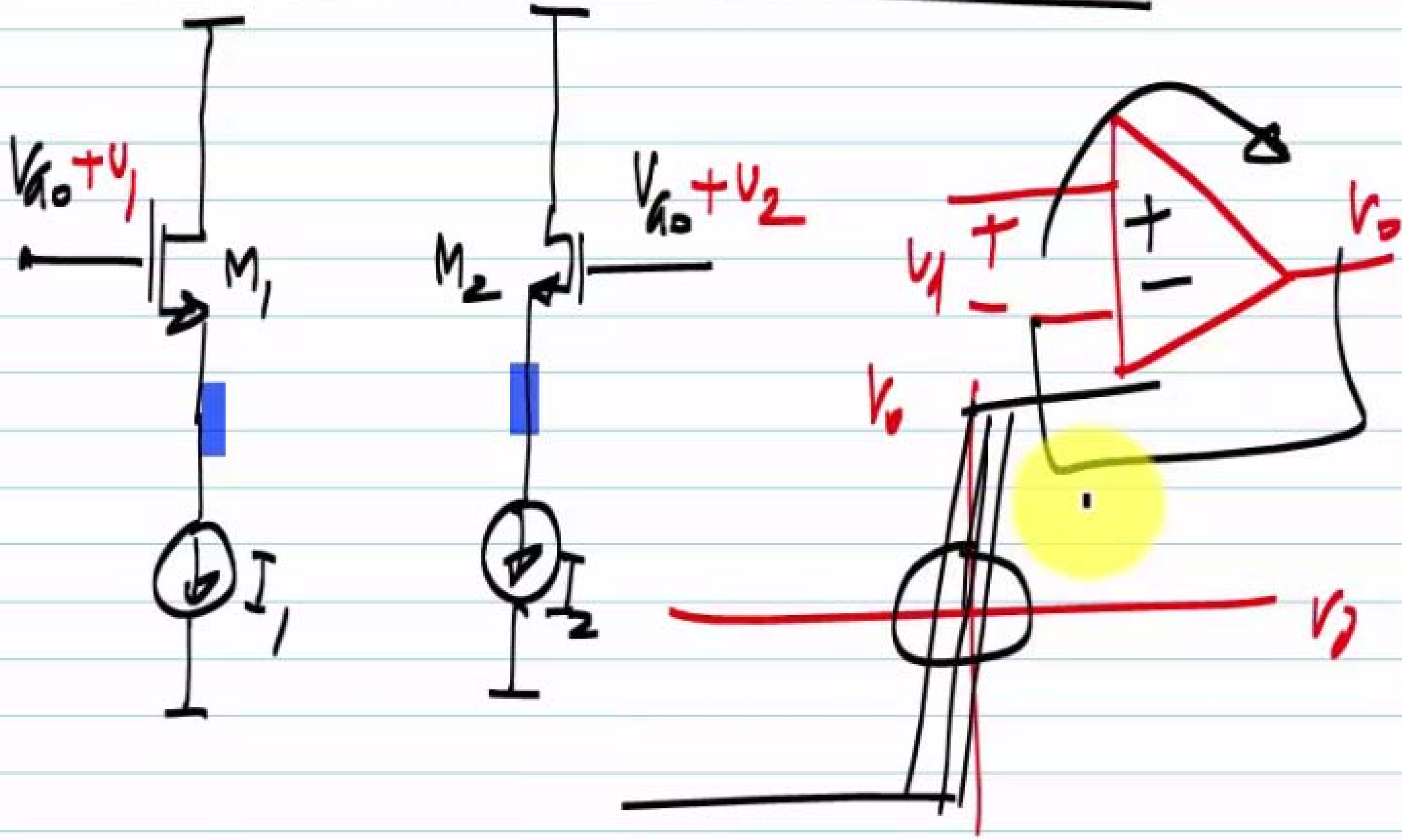
$$g_{m1}(v_1 - v_s) = g_{m2}(v_s - v_2)$$

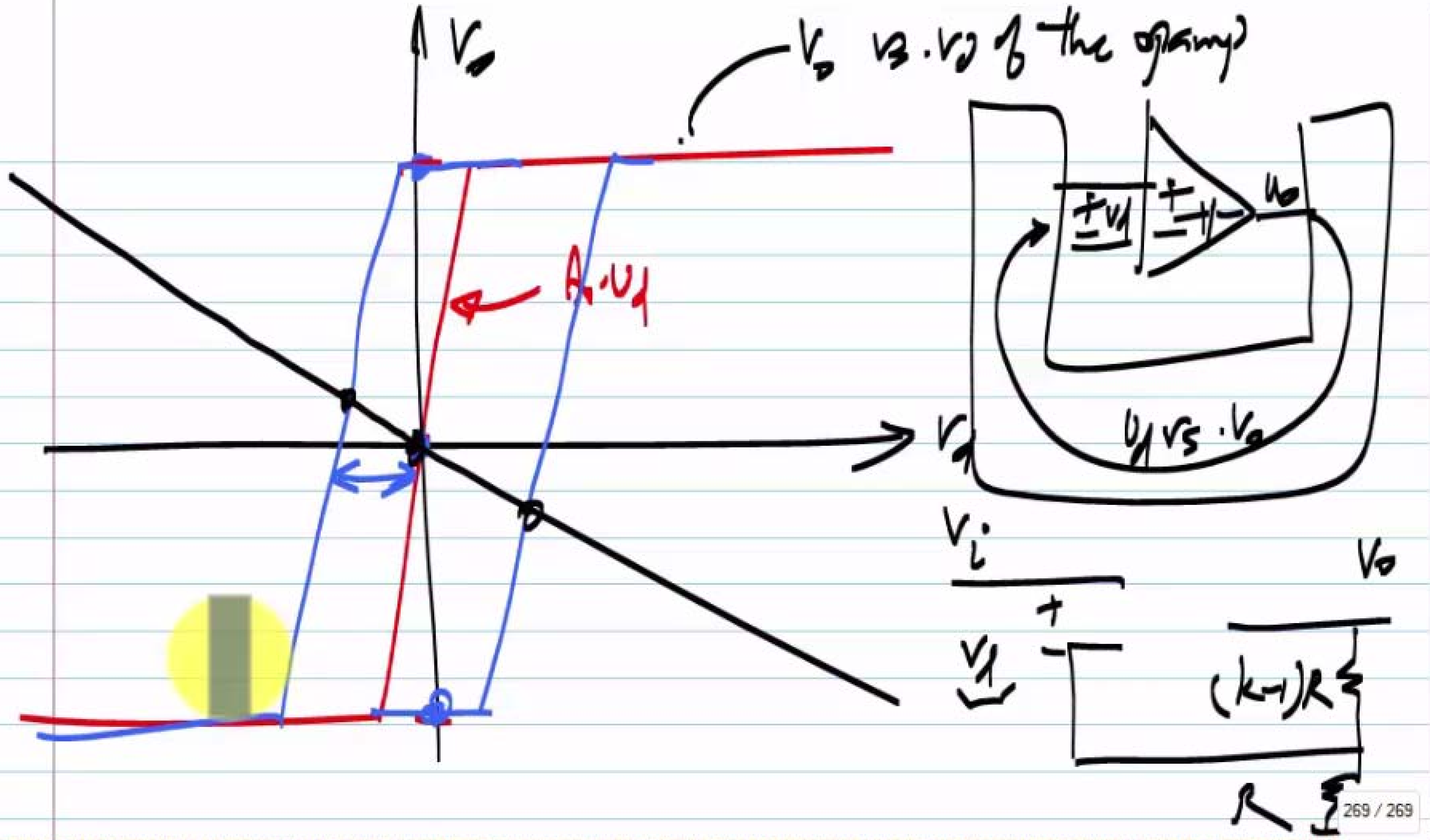


$$v_s = \frac{g_{m1} v_1 + g_{m2} v_2}{g_{m1} + g_{m2}}$$

$$i_d = \left(\frac{g_{m1} g_{m2}}{g_{m1} + g_{m2}}\right)(v_1 - v_2)$$

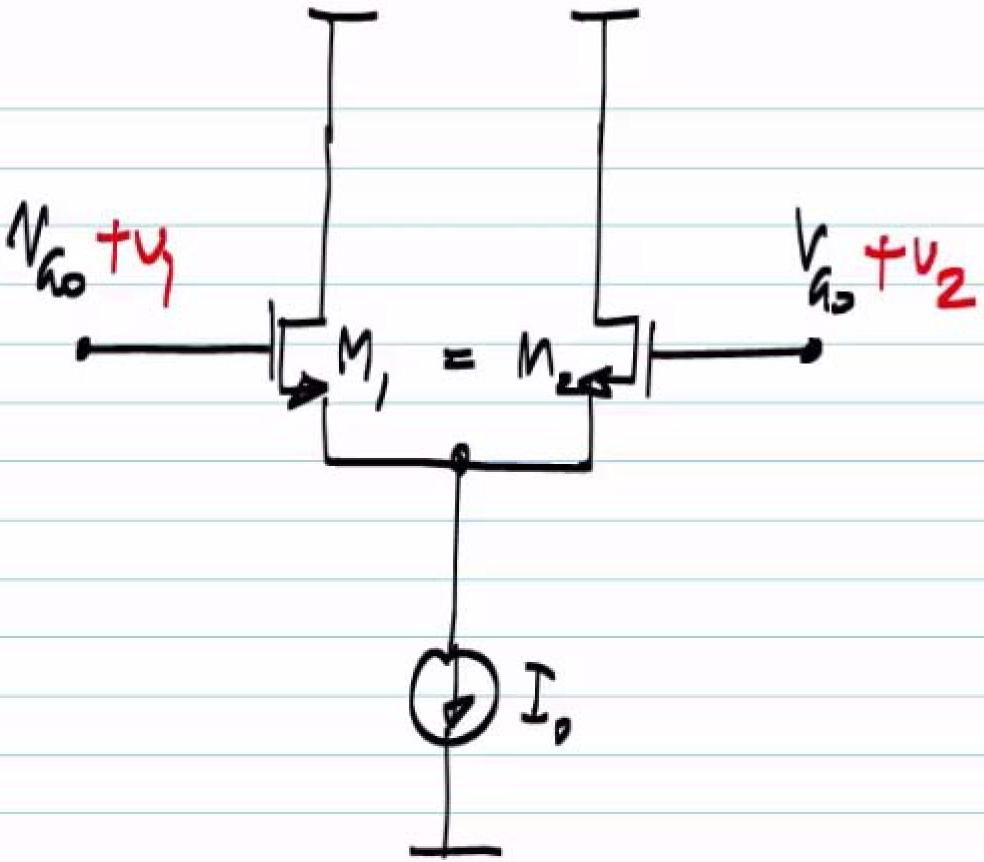
Source feedback bias : most suitable



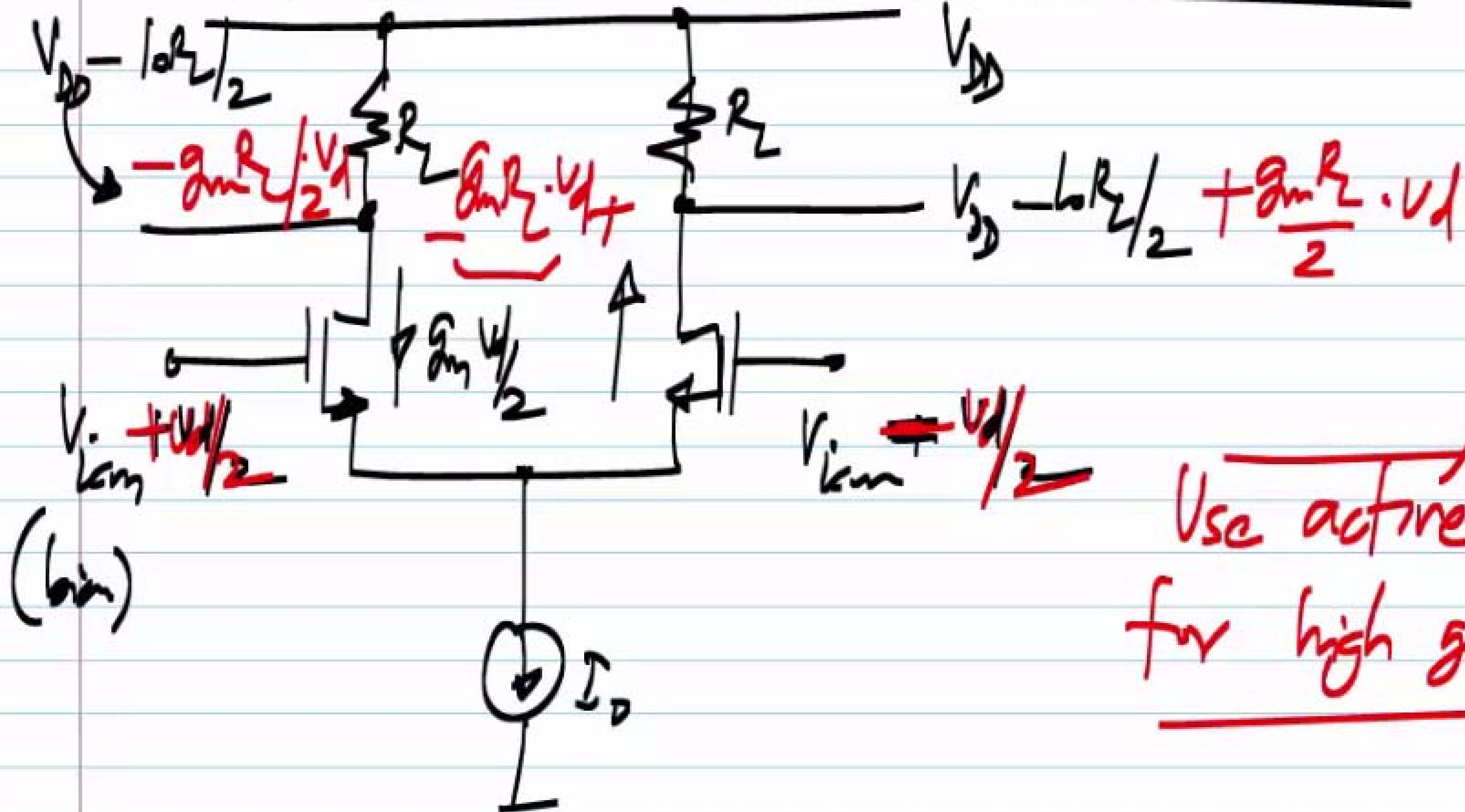

V_o
V_o vs. v_d of the opamp
$A \cdot v_d$
v_d
v_o
v_d vs. v_o
v_i
v_1
V_o
$(k-1)R$
R

Differential pair

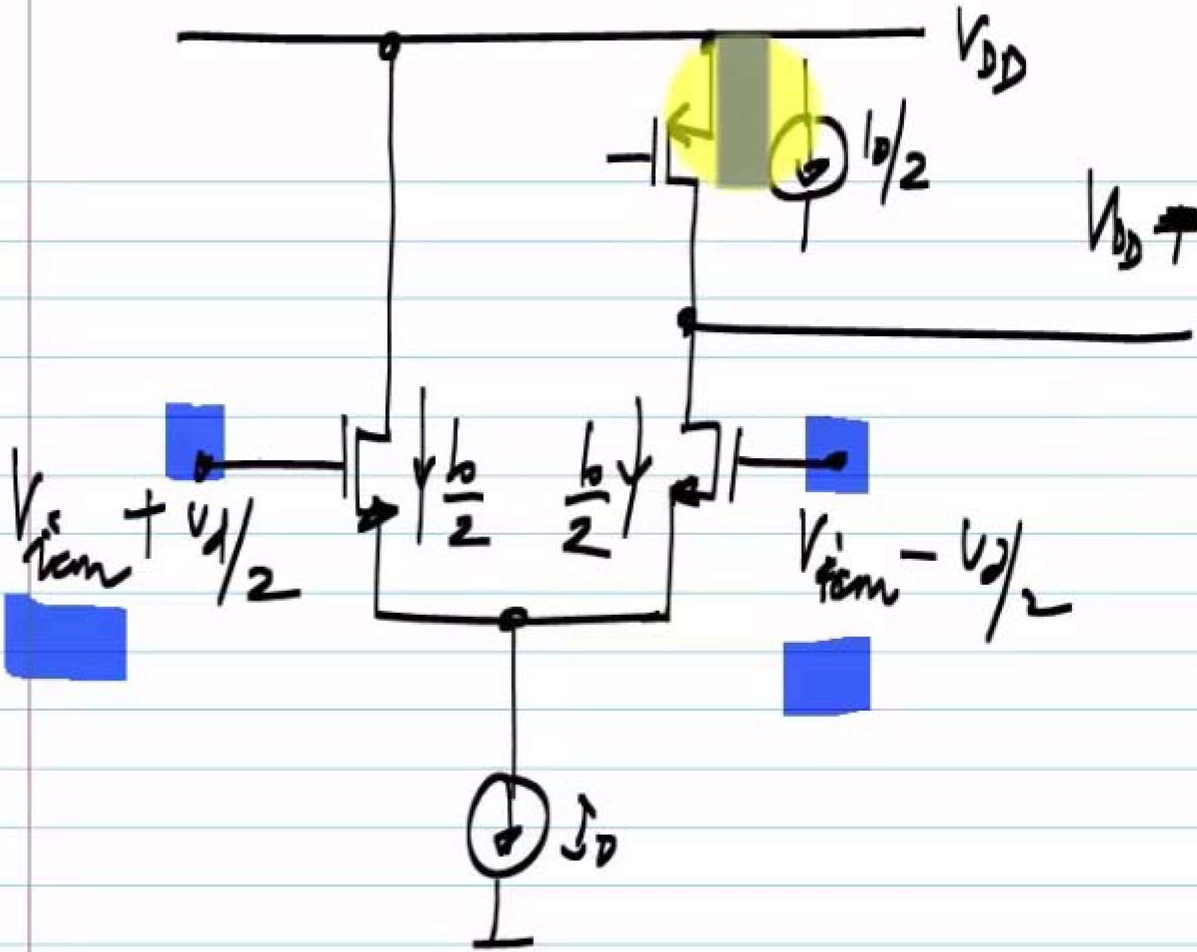
Source couple



Differential gain with differential excitation

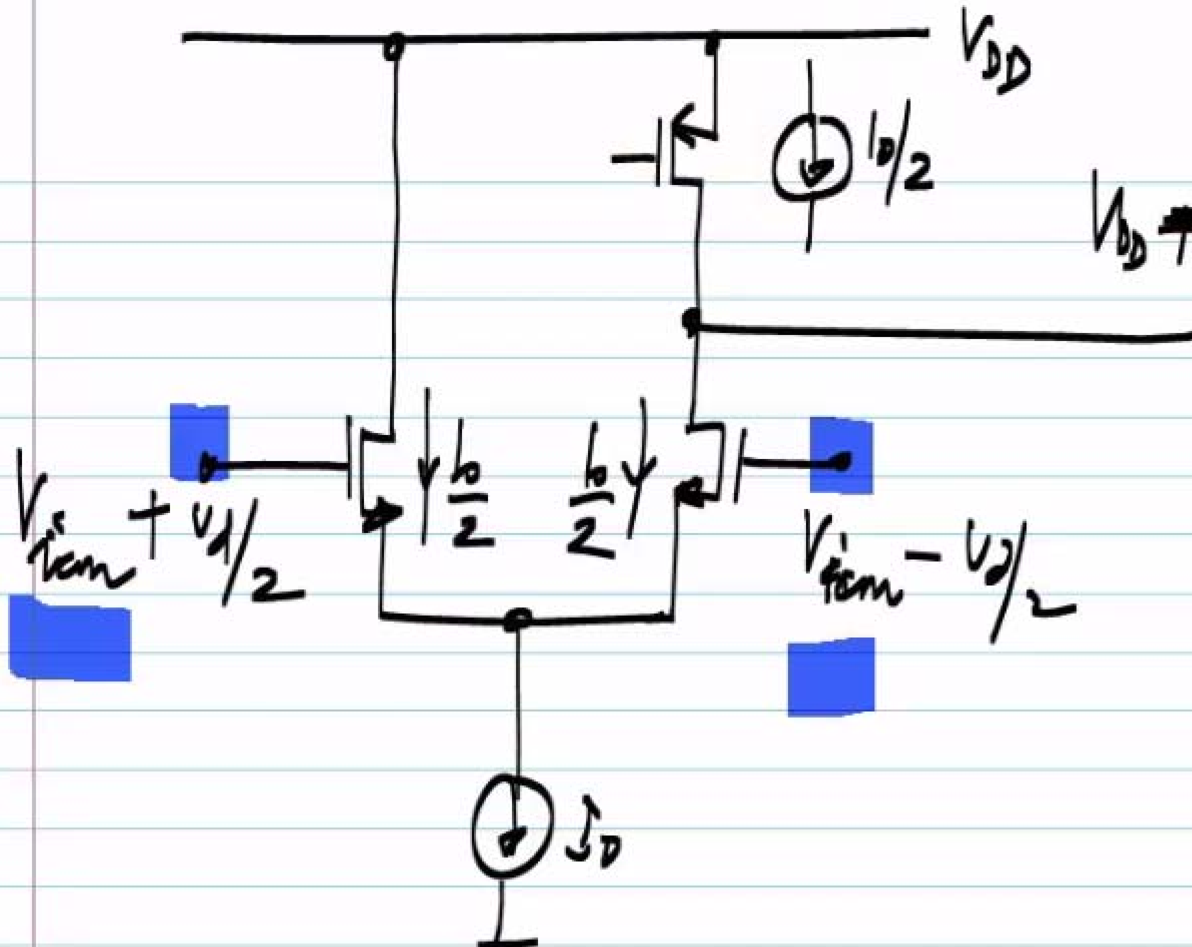


Use active load for high gain



$$V_{DD} - \frac{I_0 R_L}{2} + \underbrace{\frac{g_m R_L}{2}}\cdot v_d$$

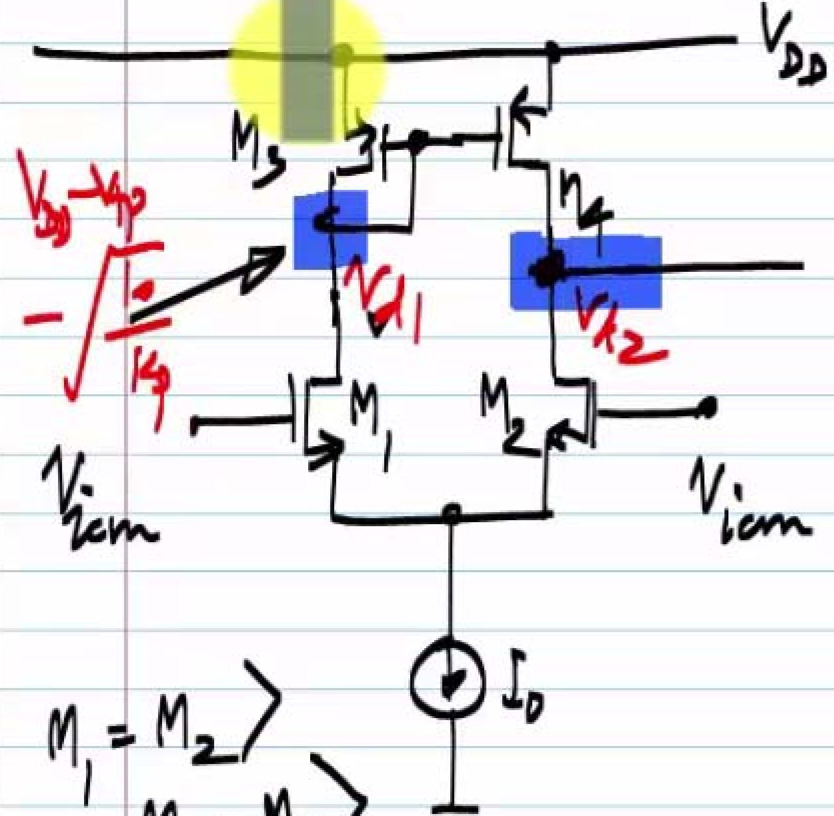
gain is limited



$$V_{DD} - \frac{I_0 R_L}{2} + \underbrace{\frac{g_m R_L}{2}} \cdot v_d$$

gain is limited

Differential pair with a current mirror load



$M_1 = M_2$

$M_3 = M_4$

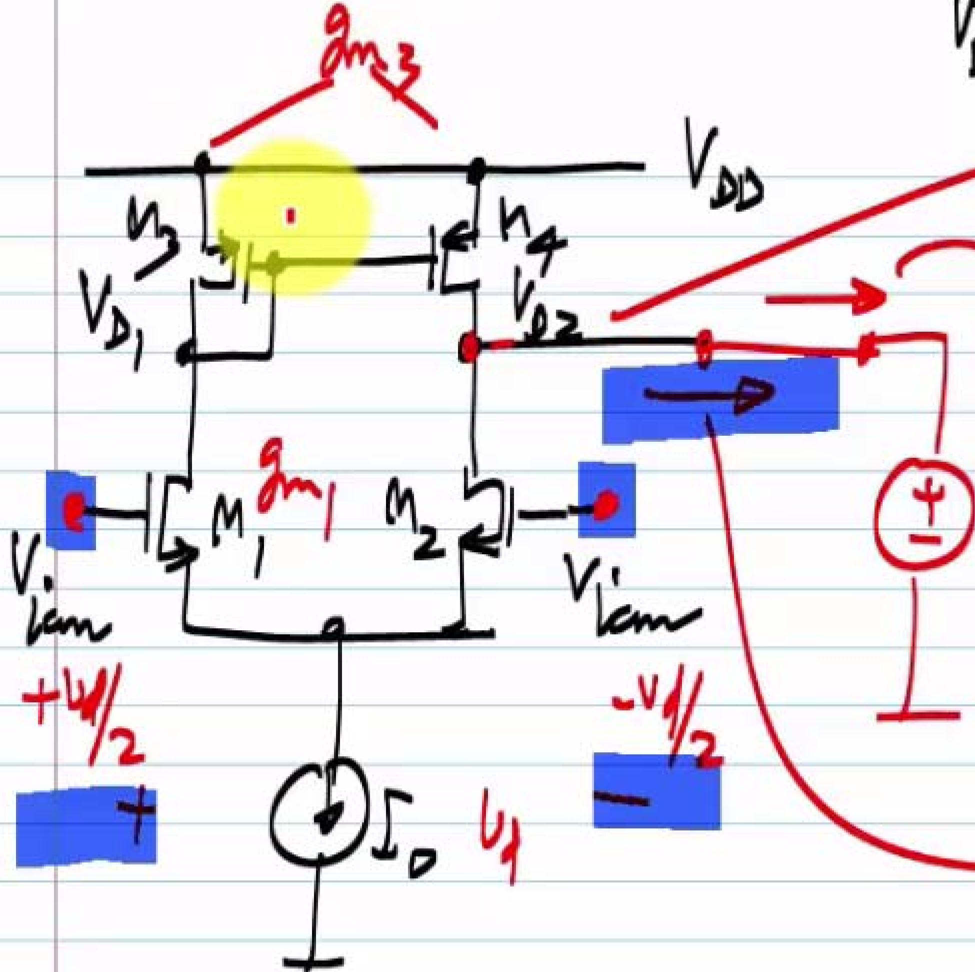
$V_{d1} > V_{d2}$

$V_{DS_1} > V_{DS_2} \Rightarrow I_{D_1} > I_{D_2}$

$V_{SD_3} < V_{SD_4} \Rightarrow I_{D_3} < I_{D_4}$

$$V_{D1} = V_{D2} = V_{DD} - V_{Tp} - \sqrt{\frac{I_0}{k_p}}$$

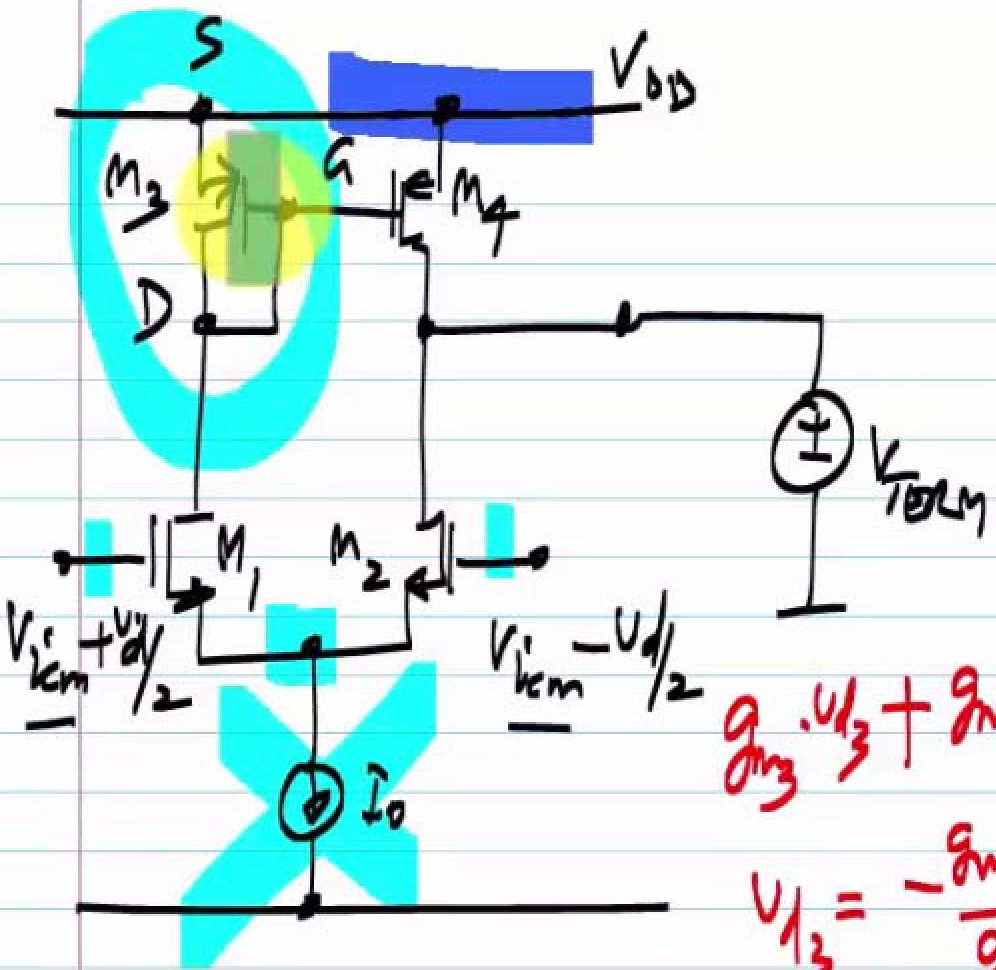
(Quiescent)



zero quiescent current

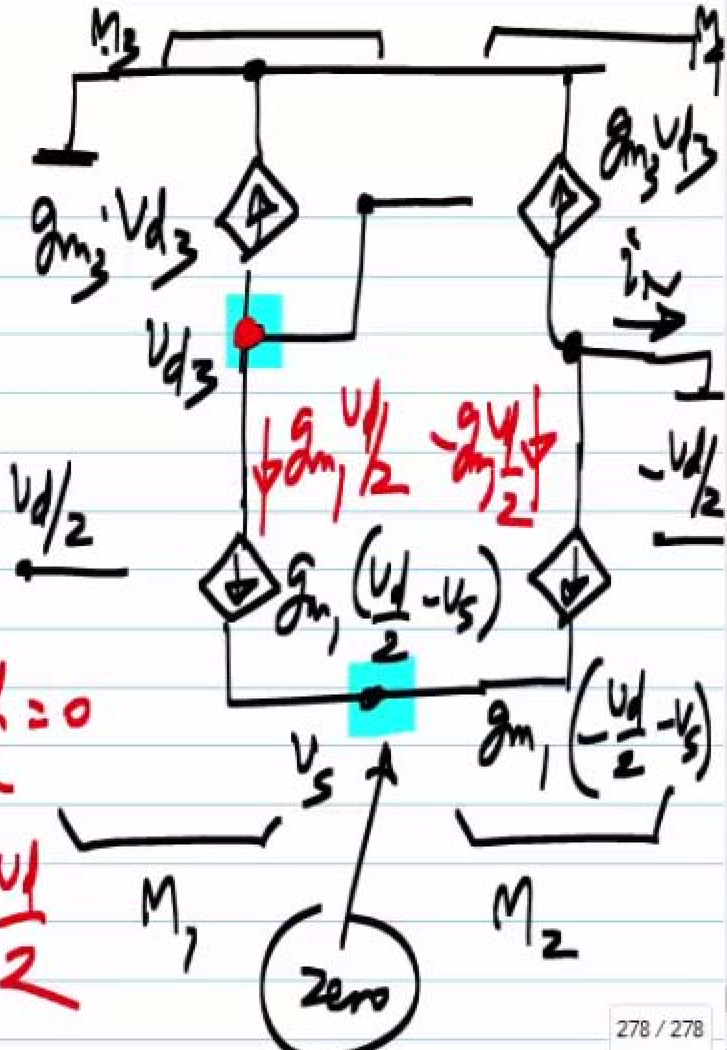
$$V_{DD} - V_{Tp} - \sqrt{\frac{I_0}{k_p}}$$

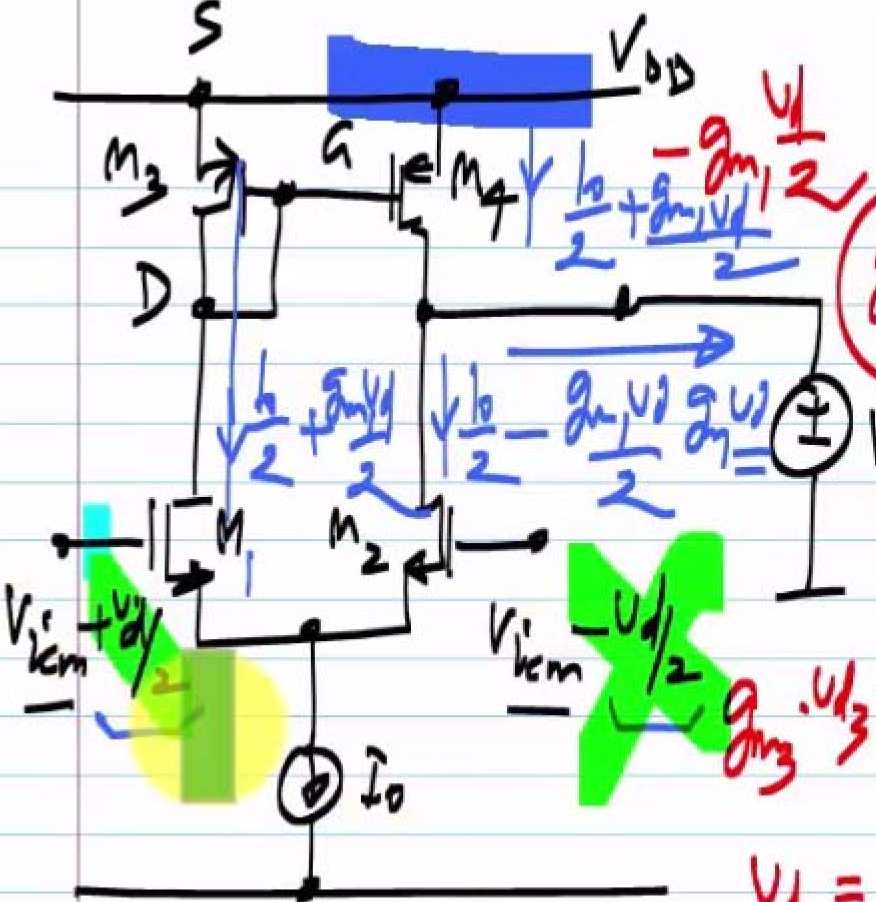
Find the incremental current



$$g_{m_3} \cdot v_{d_3} + g_{m_1} \frac{v_d}{2} = 0$$

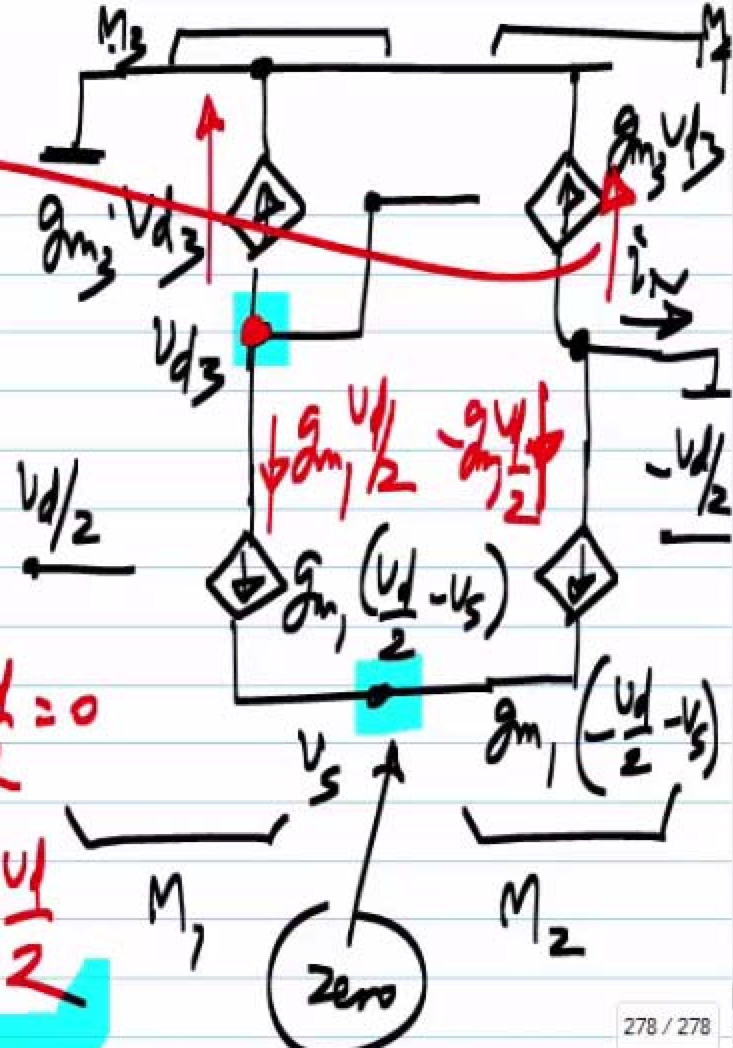
$$v_{d_3} = -\frac{g_{m_1}}{g_{m_3}} \cdot \frac{v_d}{2}$$



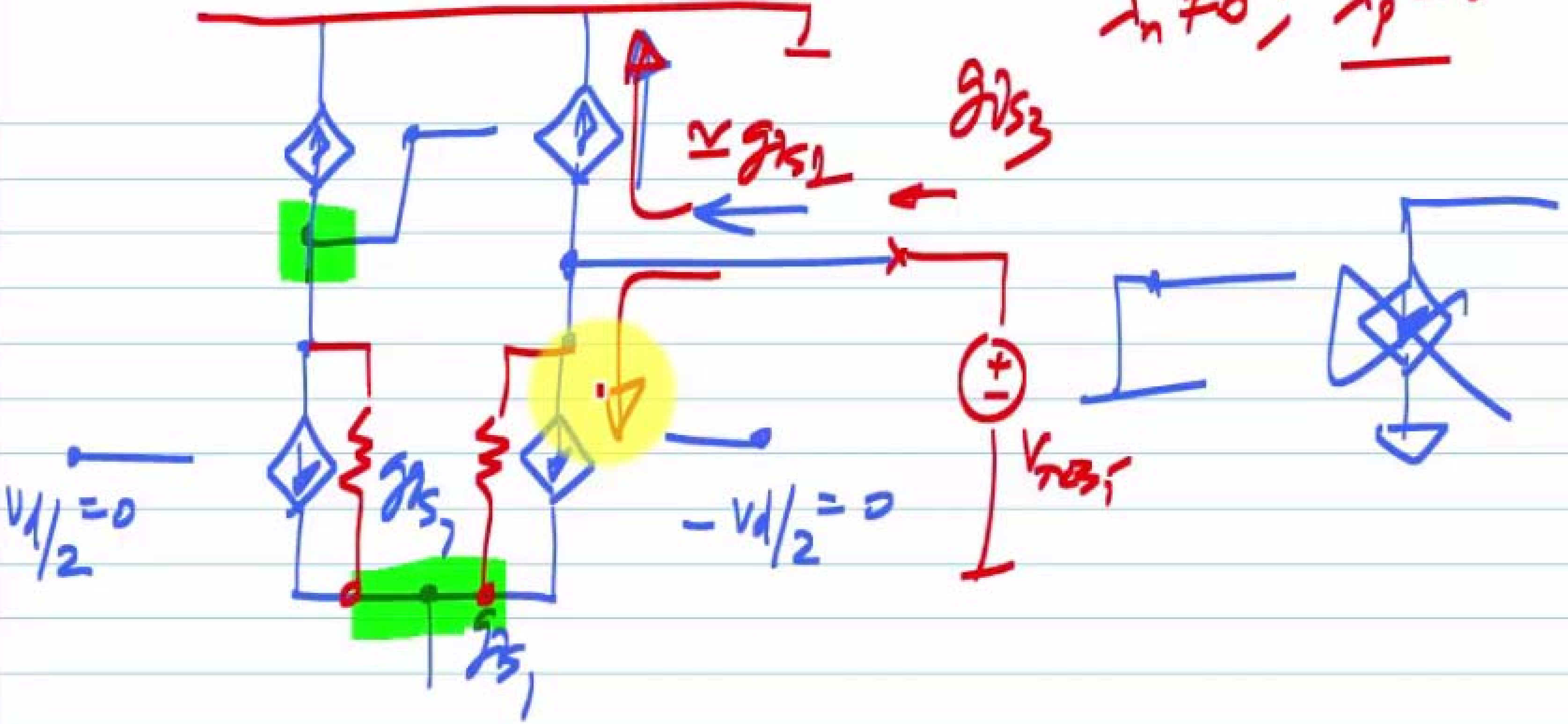


$$g_{m3}\cdot v_{d3}+g_{m1}\frac{v_d}{2}=0$$

$$v_{d3}=-\frac{g_{m1}}{g_{m3}}\cdot\frac{v_d}{2}$$

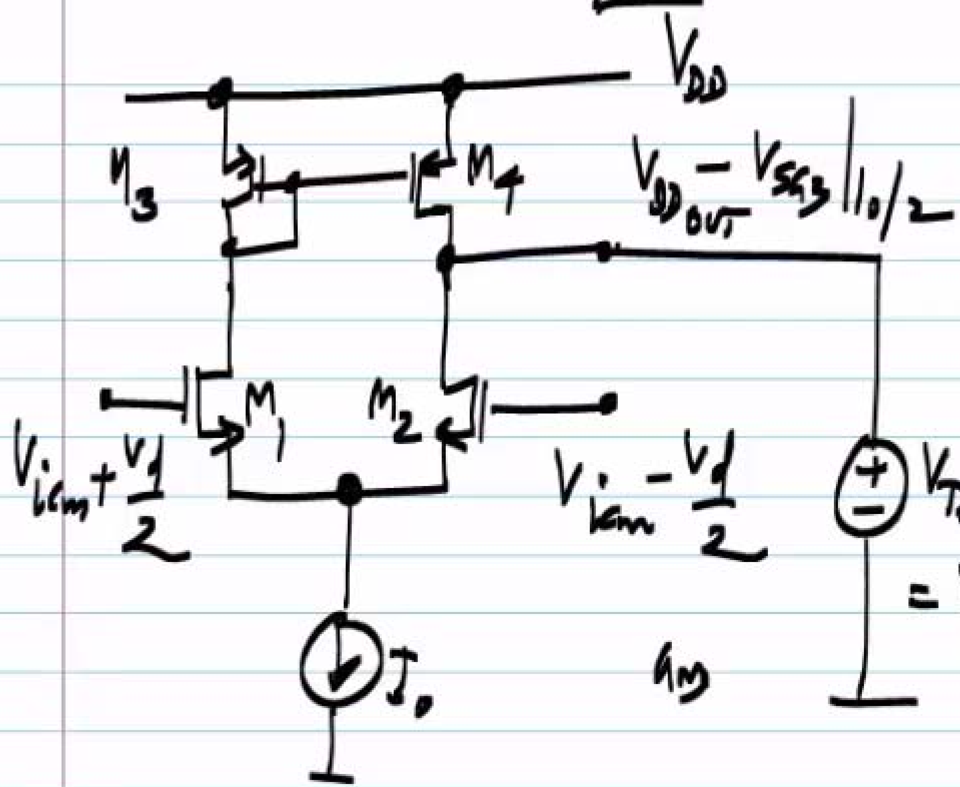


$\lambda_n \neq 0$; $\lambda_p = 0$



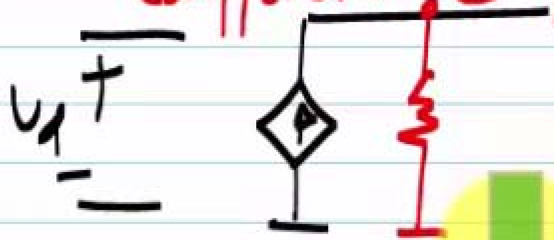
Small signal model of a differential pair (differential inputs)

$\lambda_n = 0;\ \lambda_p \neq 0$



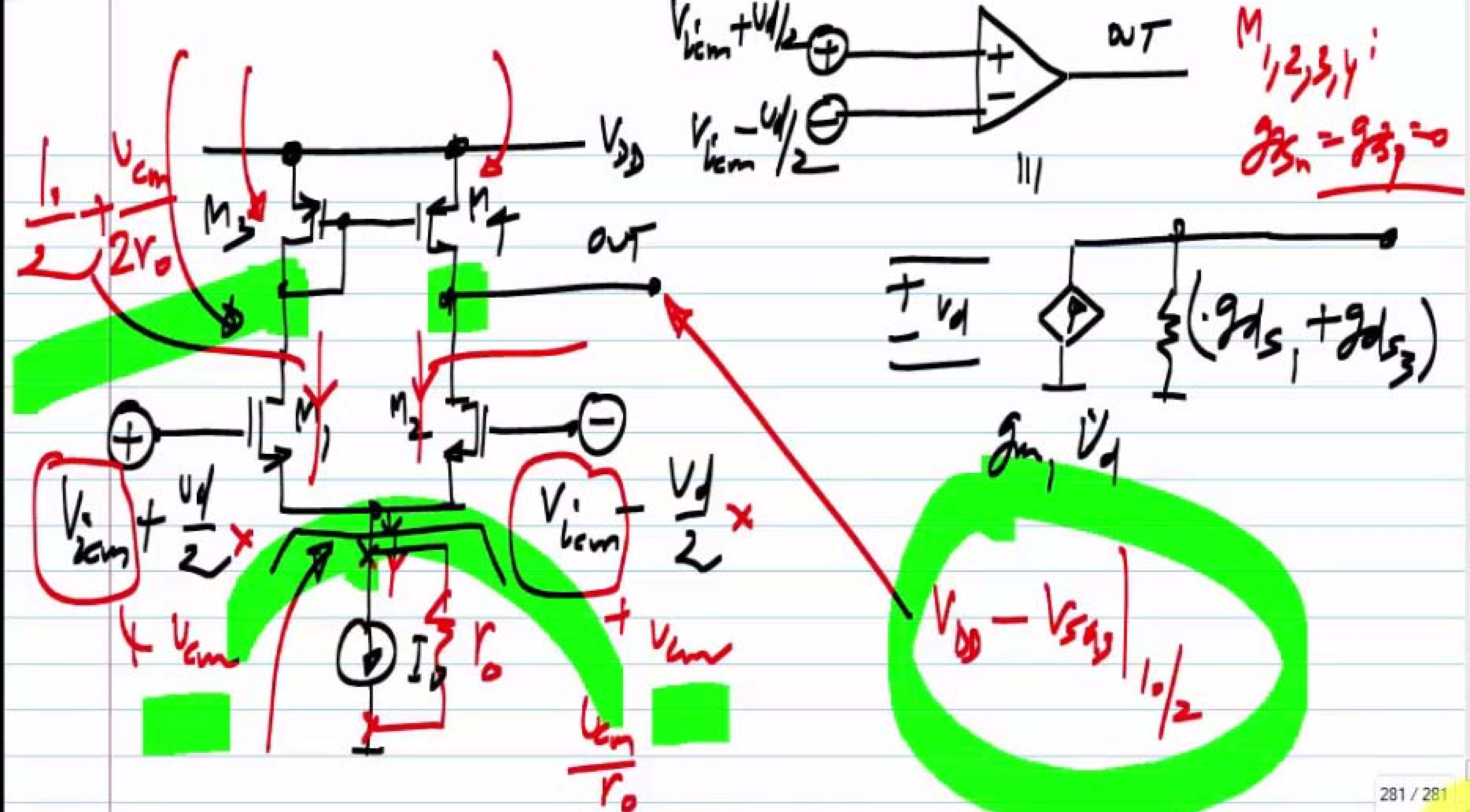
$V_{DD_{OUT}} - V_{SG3}\big|_{I_0/2}$

$= V_{DD} - V_{SG3}\big|_{I_0/2}$



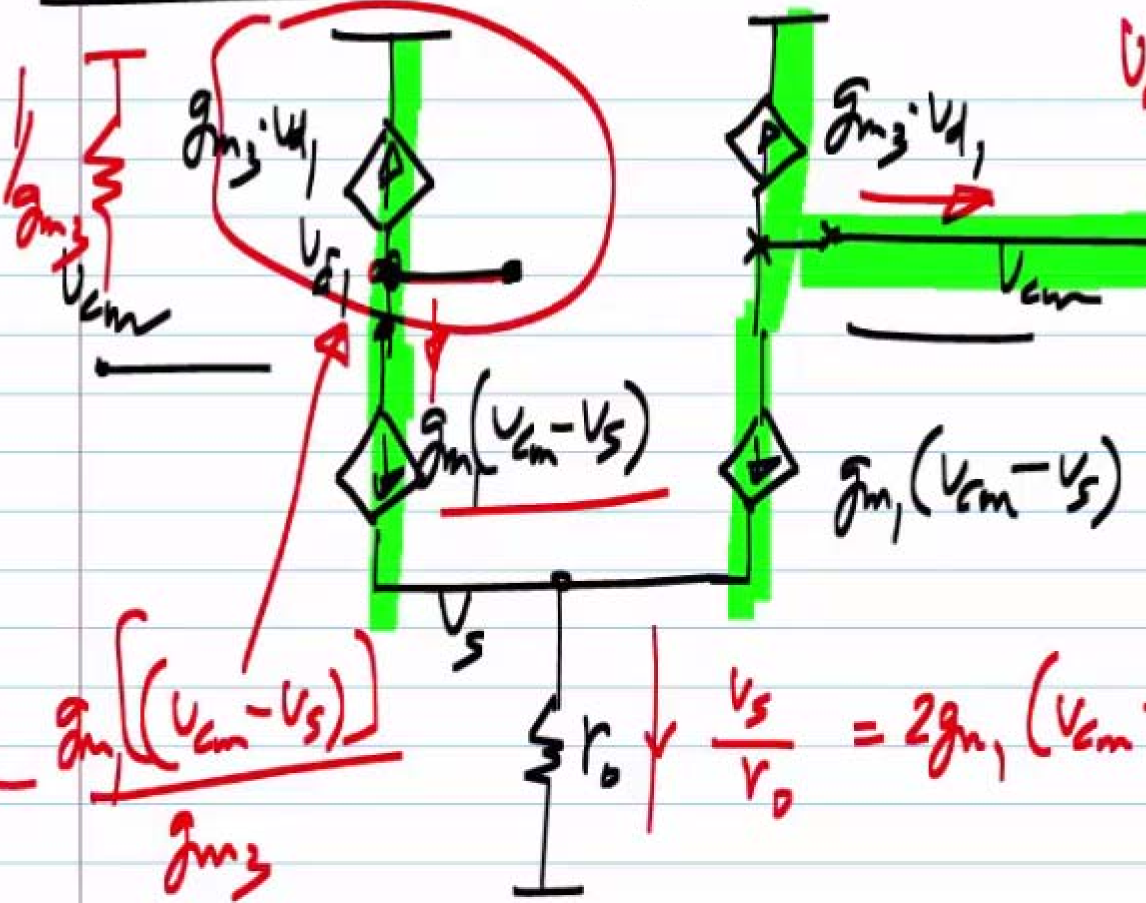
$g_{m1} v_d$ $\quad g_{ds3} + g_{ds1}$

$g_m(M_1\big|_{I_0/2})$



V'icm + vd/2
V'icm − vd/2
OUT
VDD
M3
M4
M1
M2
OUT
M1,2,3,4 :
gds_n = gds_p = 0
I1/2 + vcm/2r0
+ vd
(gds1 + gds3)
gm1 v'd
VDD − VSG3 | I0/2
I0
r0
+ vcm
vcm/r0

Common mode input



$$\frac{v_s}{r_0} = 2g_{m1}(v_{cm} - v_s)$$

$$v_{d1} = -\frac{g_{m1}}{g_{m3}} \frac{1}{2g_{m1}r_0 + 1} \cdot v_{cm}$$

$$v_s = \frac{2g_{m1}r_0}{2g_{m1}r_0 + 1} \cdot v_{cm}$$

Voltage gain of a diff pair

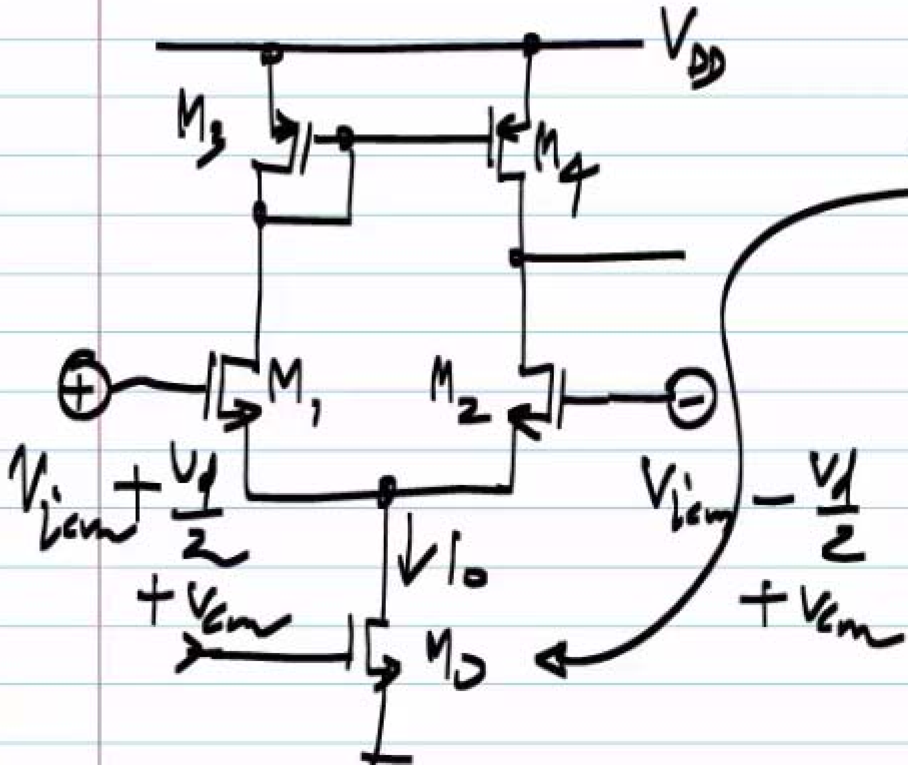
for differential signals: $A_d = \dfrac{v_o}{v_d} = \left[\dfrac{g_{m_1}}{g_{ds_1} + g_{ds_3}}\right]$

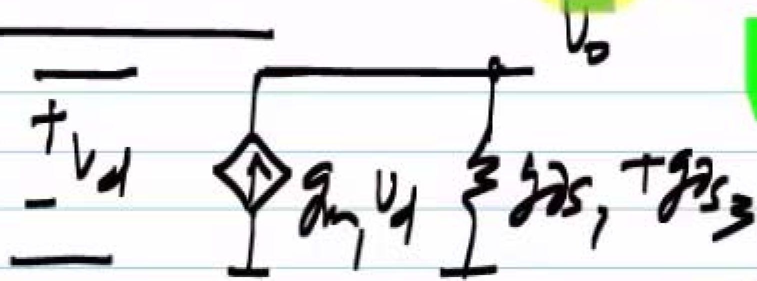
for CM signals $A_{cm} = \dfrac{v_o}{v_{cm}} = \left[-\dfrac{g_{m_1}}{g_{m_3}} \cdot \dfrac{1}{\underbrace{2g_{m_1} r_o + 1}_{\gg 1}}\right]$

Common mode rejection ratio

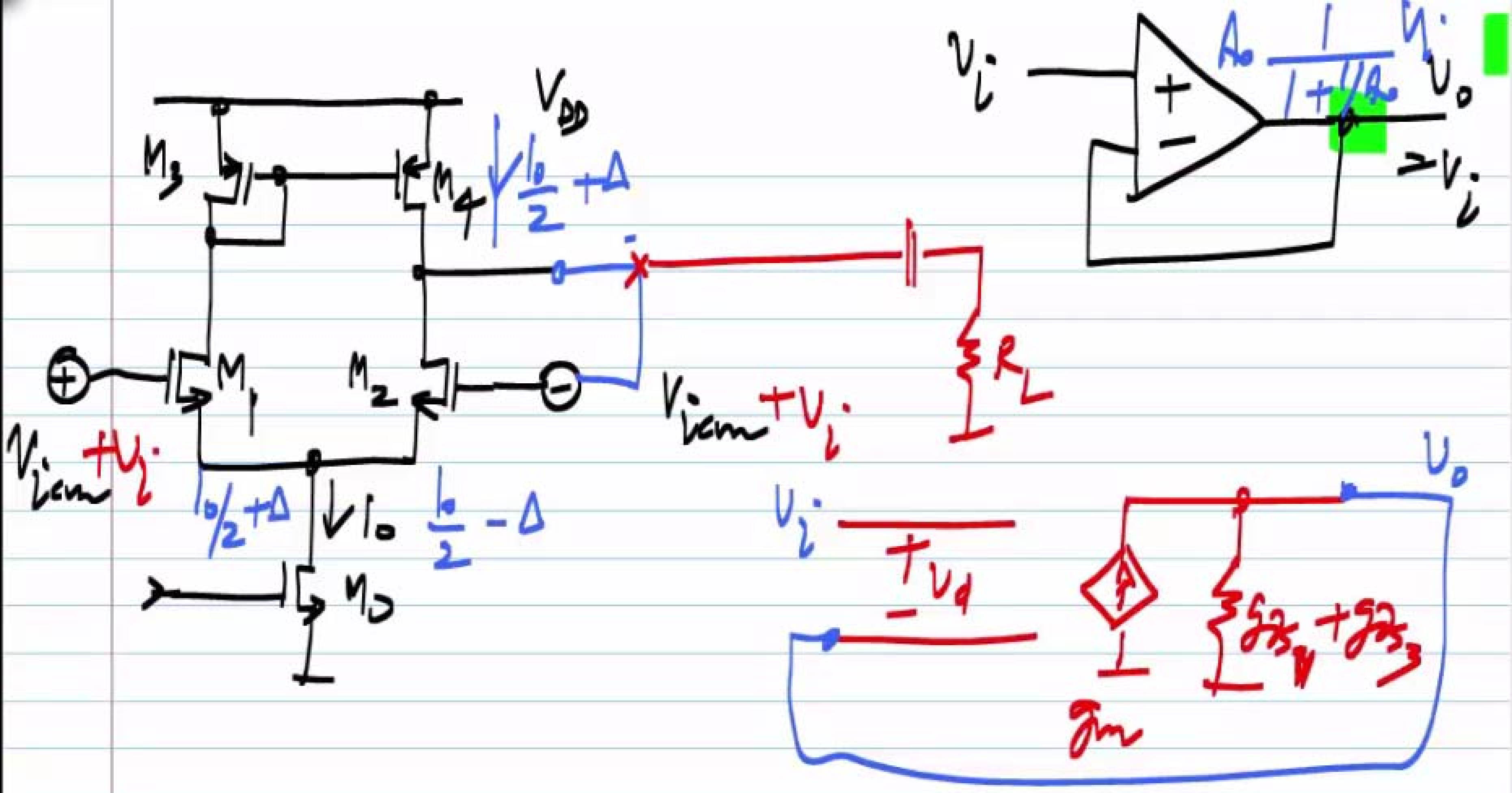
$$CMRR = \left|\frac{A_d}{A_{cm}}\right| = \frac{2g_{m_1} r_o + 1 \cdot (g_{m_3})}{(g_{ds_1} + g_{ds_3})} = \frac{1}{2g_{m_3} r_o}$$

Diff. pair with current mirror load

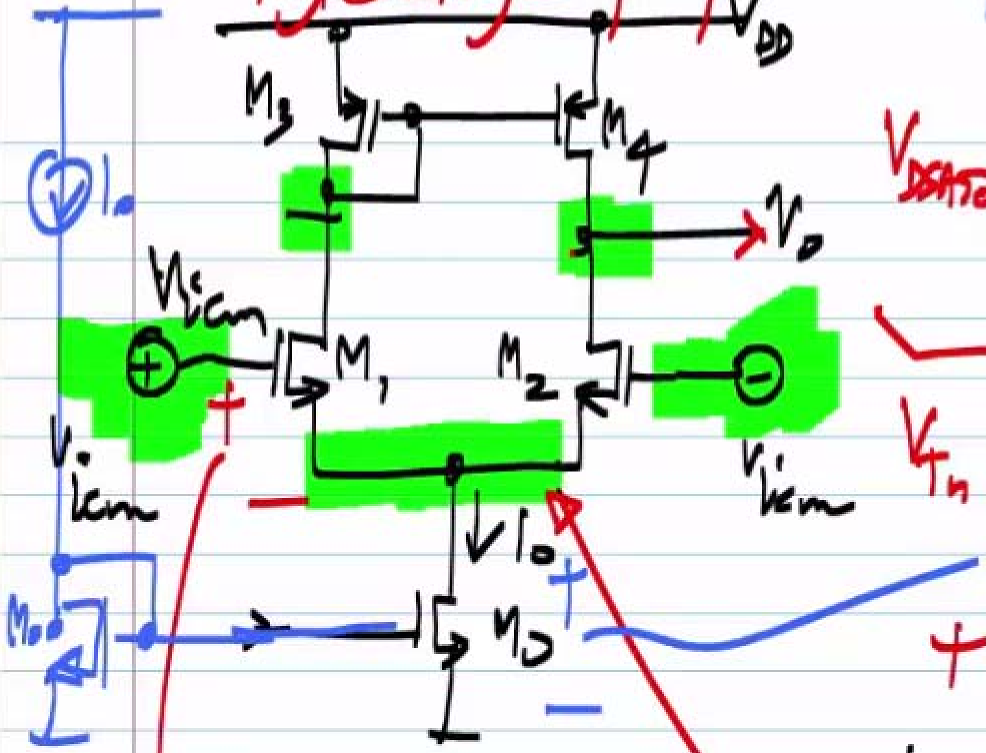




$$\frac{v_o}{v_{cm}} \simeq -\frac{g_{ds0}}{2g_{m3}}$$


V_DD
M_3
M_4
I_0/2 + Δ
M_1
M_2
V_icm + v_i
I_0/2 + Δ
I_0
I_0/2 − Δ
M_0
R_L
v_i
v_o
A_0 1/(1 + 1/A_0) v_i
≈ v_i
v_d
g_m
g_ds4 + g_ds3

Single stage opamp

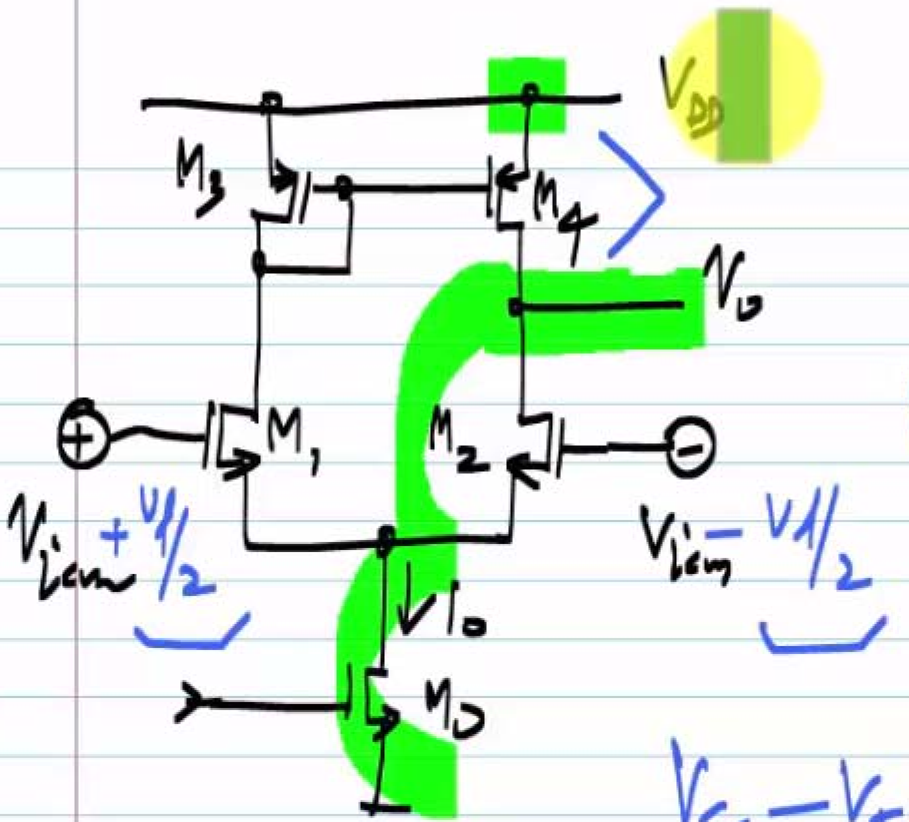


$$K_{n,0} = \mu_n C_{ox} \frac{W_0}{L_0}$$

$$\underbrace{V_{DSAT0}\Big|_{I_0} + V_{GS1}\Big|_{I_0/2}}_{V_{Tn} + \sqrt{\frac{I_0}{K_{n,1}}} + \sqrt{\frac{2I_0}{K_{n,0}}}} < V_{icm} < \underbrace{V_{DD} - V_{SG3}\Big|_{I_0/2} + V_{Tn}}_{V_{DD} - V_{Tp} - \sqrt{\frac{I_0}{K_{p,3}}} + V_{Tn}}$$

$$V_{icm} < V_{DD} - V_{SG3}\Big|_{I_0/2} + V_{Tn}$$

$$\left(V_{Tn} + \sqrt{\frac{I_0}{K_{n,1}}}\right)$$

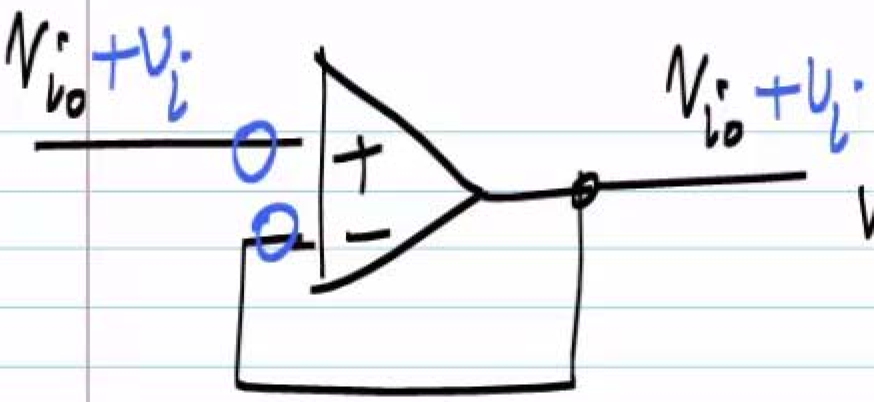


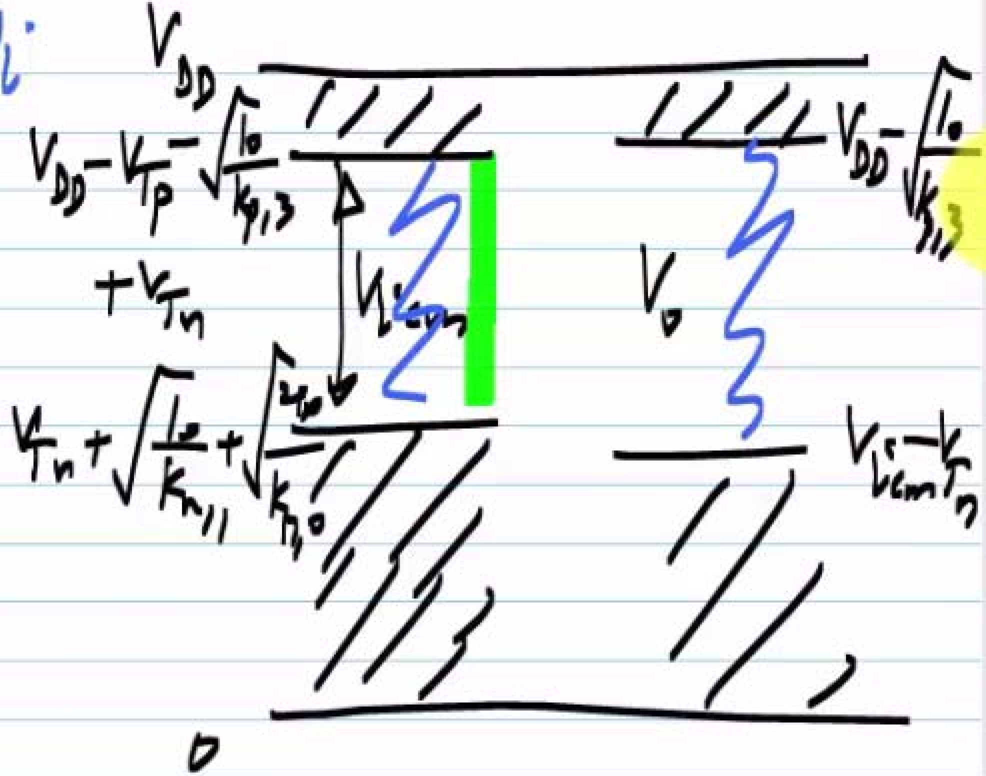
$$V_{DS} > V_{GS} - V_T$$

$$\underbrace{V_D > V_G - V_T}$$

$$V_{icm} - V_{Tn} < V_o < V_{DD} - \sqrt{\frac{I_o}{K_{p,3}}}$$

$$V_{SG,3} - V_{Tp} = \sqrt{\frac{I_o}{K_{p,3}}}$$





$$V_{icm} = \underbrace{V_{i0} + v_i}$$

$$v_o = \underbrace{V_{i0} + v_i}$$