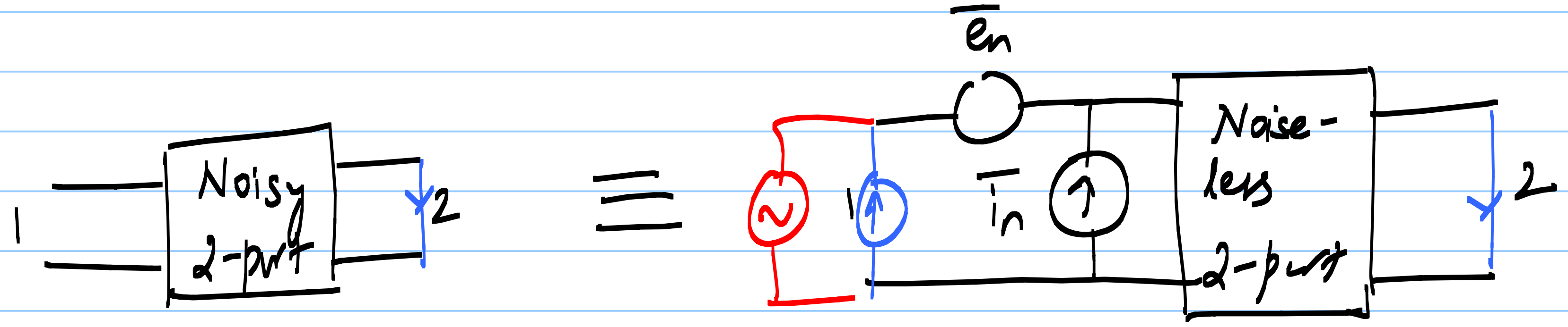
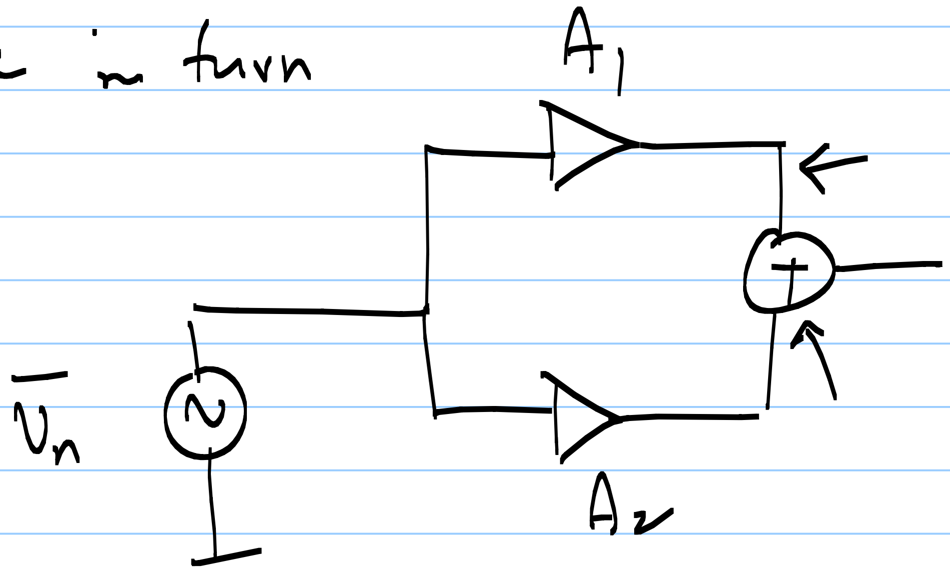
Note Title 17/1/20

17-Jan-20

EE5320 Lec3

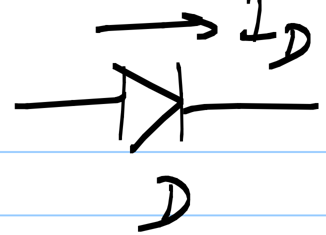


apply each noise source in turn



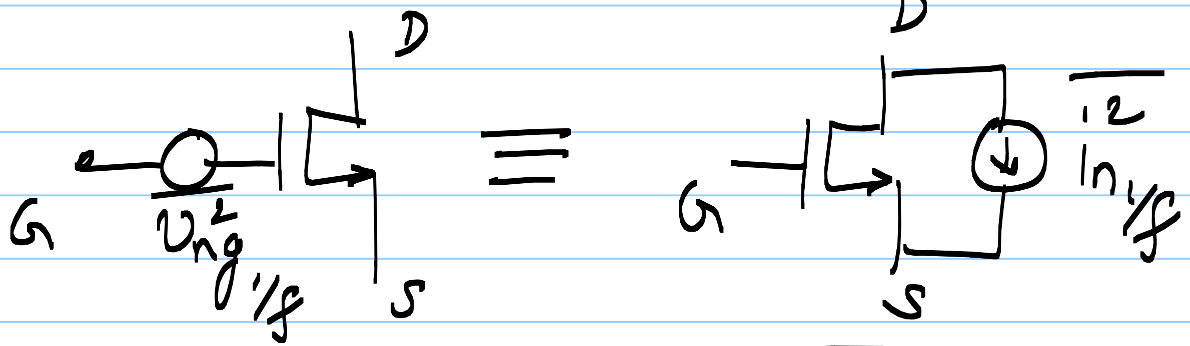
$$\overline{v_{on}} = (A_1 + A_2)^2 \cdot \overline{v_n^2}$$

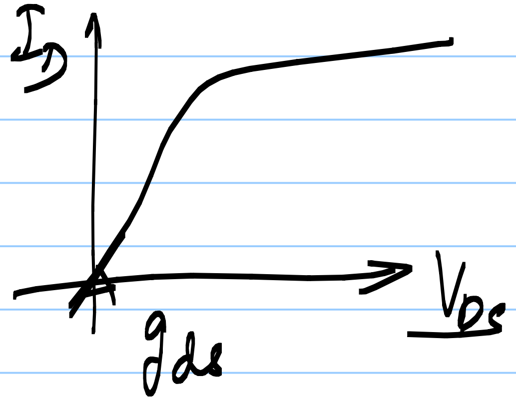
MOSFET noise in saturation



$$\overline{i_n^2} = 2qI_D\Delta f$$

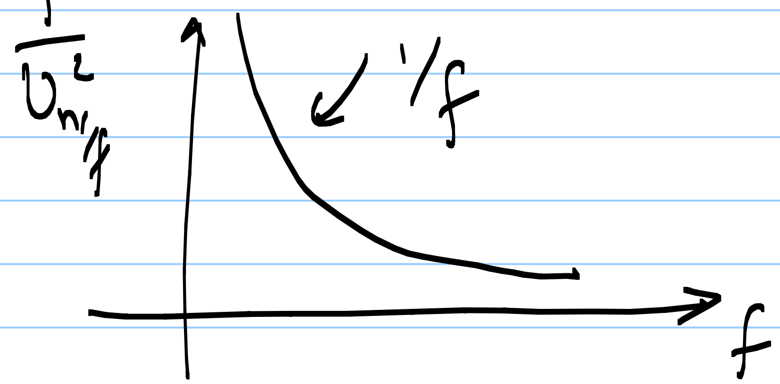
1) Flicker noise ($1/f$ noise)





$$\frac{\overline{v_{ng_{1/f}}^2}}{\Delta f} = \frac{K_{1/f}}{WLC_{ox}^2}\cdot\frac{1}{f}$$

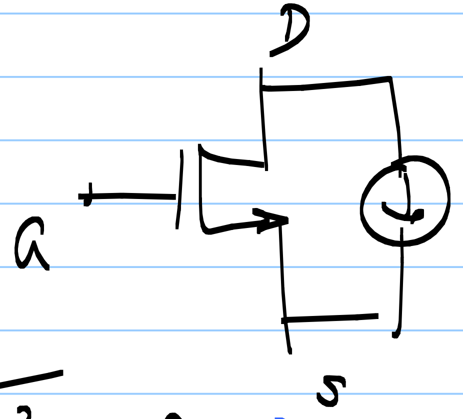
empirical parameter



$$\frac{\overline{i_{n_{1/f}}^2}}{\Delta f} = \frac{K_{1/f}\cdot g_m^2}{WLC_{ox}^2}\cdot\frac{1}{f}$$

larger device $\longleftrightarrow$ lower $1/f$ noise

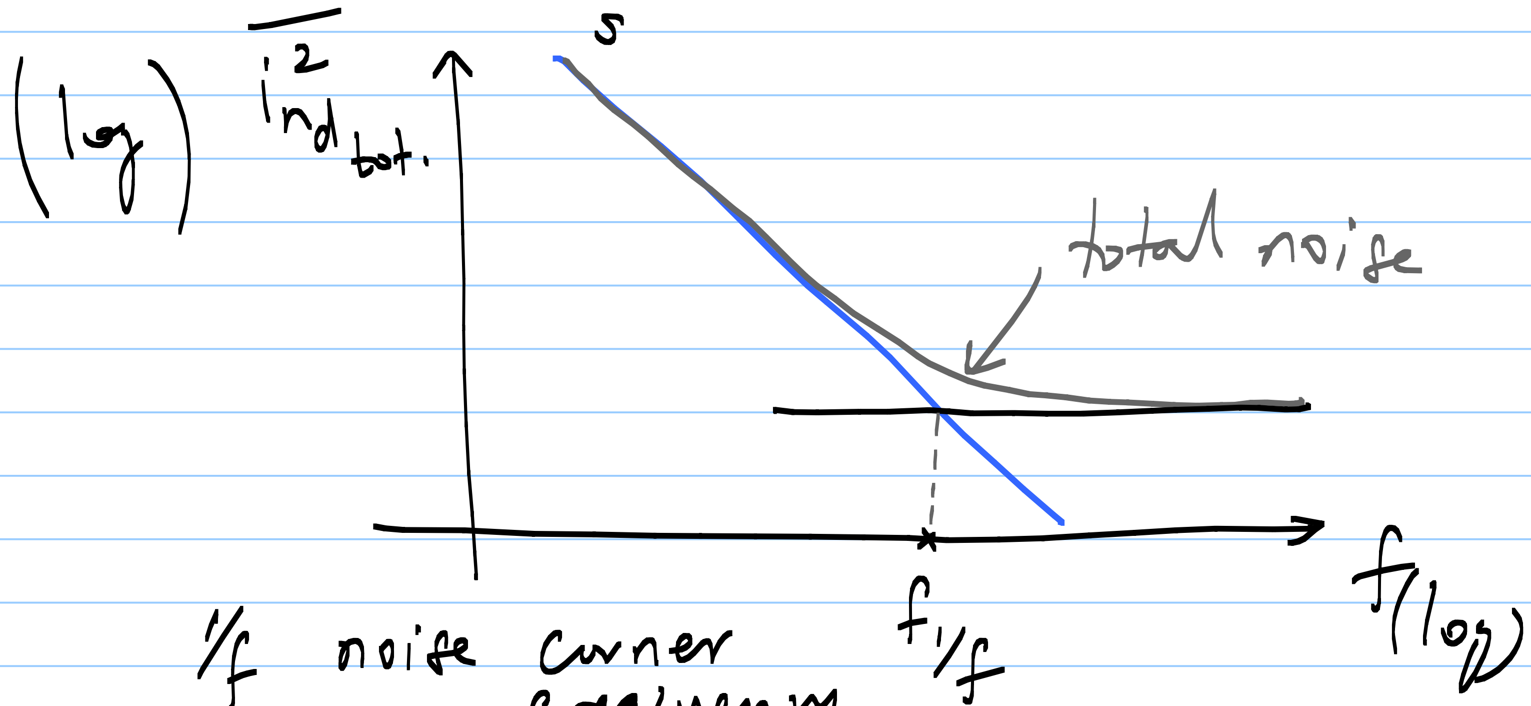
2) Thermal noise:



$$\frac{\overline{i_{nd}^2}}{\Delta f} = \frac{8kT}{3} g_m$$

$$\left(\overline{i_d^2} = g_m^2 \cdot \overline{|v_{gs}|^2}\right)$$

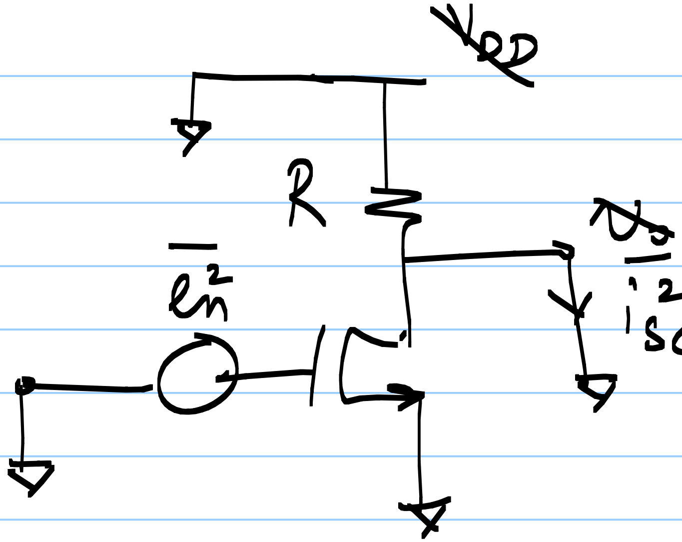
$$SNR_{output} = \frac{g_m^2 \overline{|v_{gs}|^2}}{\frac{8kT}{3} g_m}$$



$1/f$ noise corner frequency

E.g.

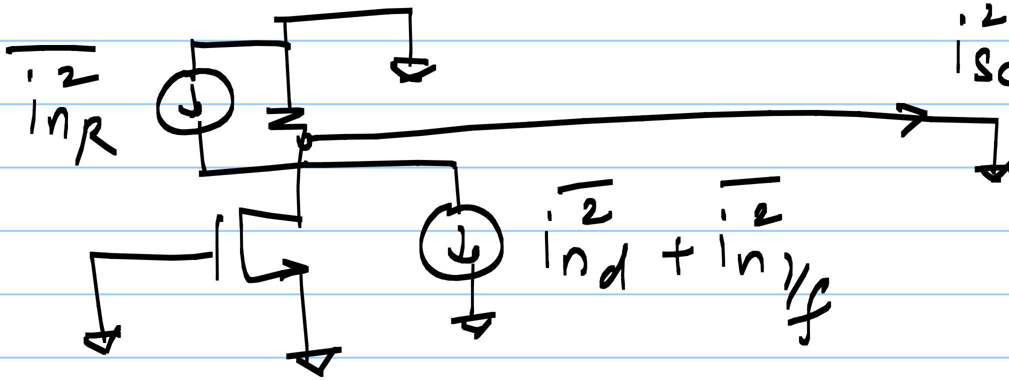
1) CSA



$\overline{i_n} = 0$

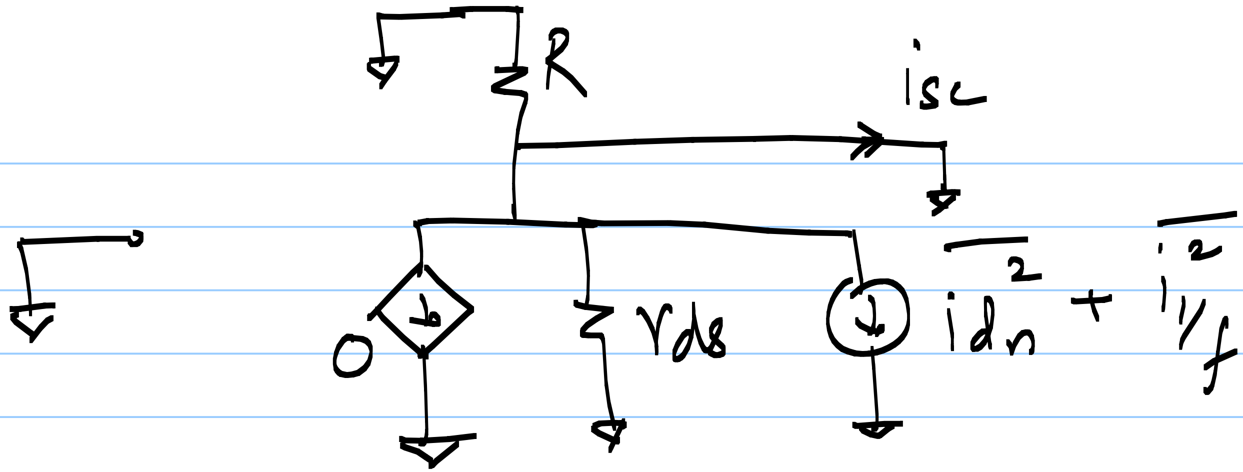
$\overline{e_n} = ?$

$\overline{i_{sc_n}^2} = g_m^2 \cdot \overline{e_n^2}$

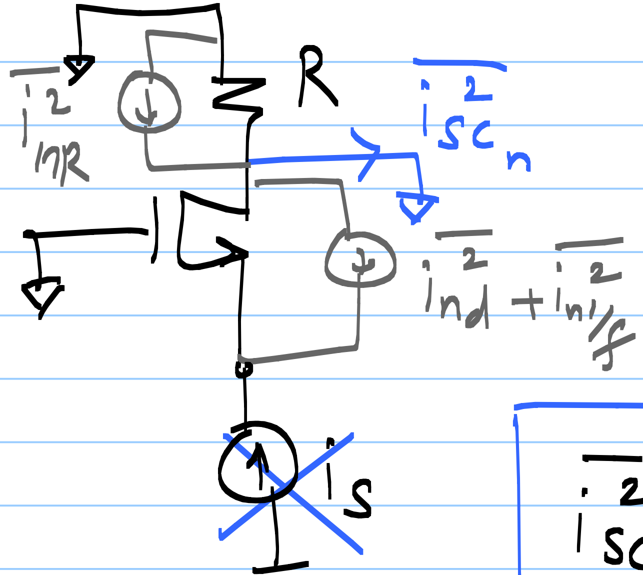


$\overline{i_{sc_n}^2} = \overline{i_{n_R}^2} + \overline{i_{n_d}^2} + \overline{i_{n_{1/f}}^2}$

$$\frac{\overline{e_n^2}}{\Delta f} = \frac{4kT}{g_m^2 \cdot R} + \frac{8kT}{3 g_m} + \frac{K_{1/f}}{W \cdot L \cdot C_{ox}^2} \cdot \frac{1}{f}$$



2) CGA

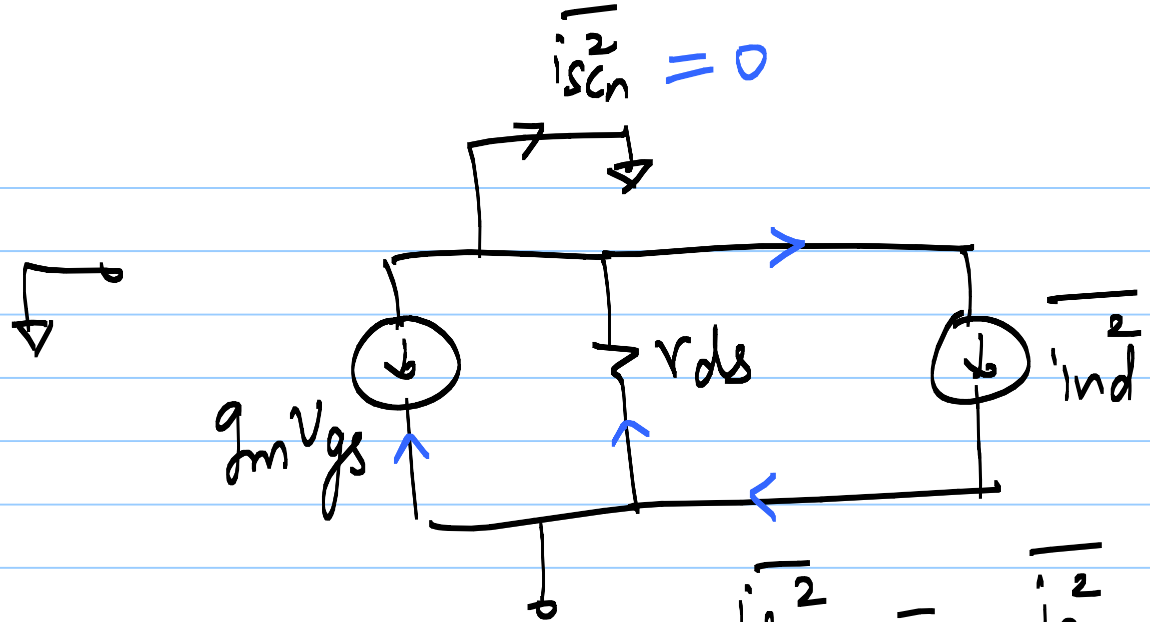


$$R_{in} = \frac{1}{g_m}$$

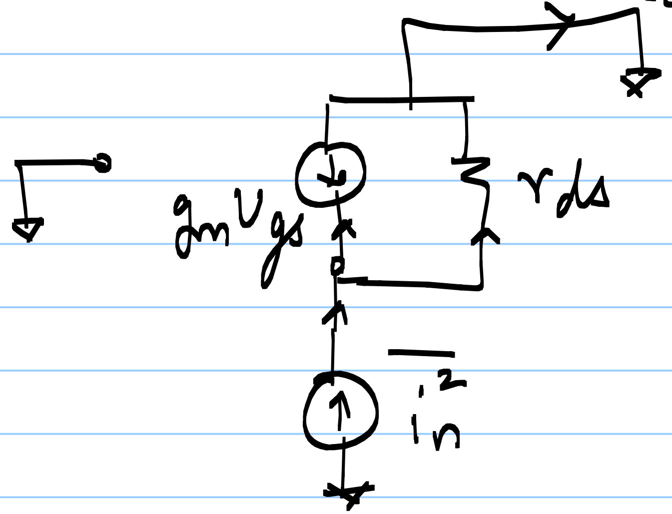
$\overline{e_n}, \overline{i_n} = ?$

HW

$$\boxed{\overline{i^2_{sc_n}} = \overline{i^2_{nR}}}$$



$$\overline{i_{scn}^2} = \overline{i_n^2} = \frac{4kT}{R}\Delta f$$



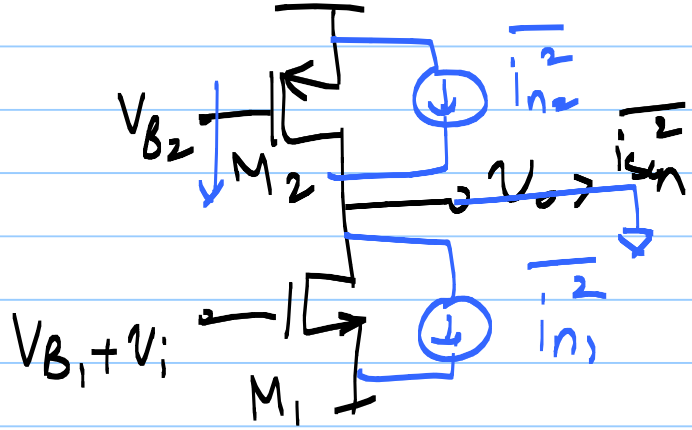
3) CDA — $\boxed{\text{HW}}$

20/1/20

Lec 4

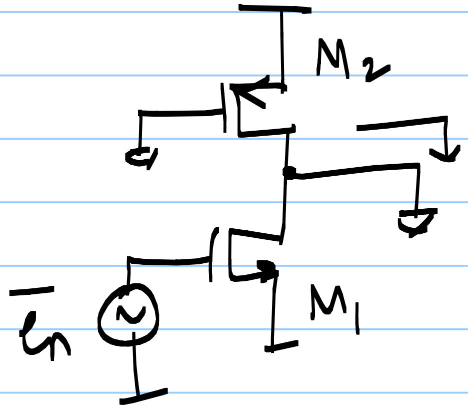
CSA w/ active load

$\equiv$



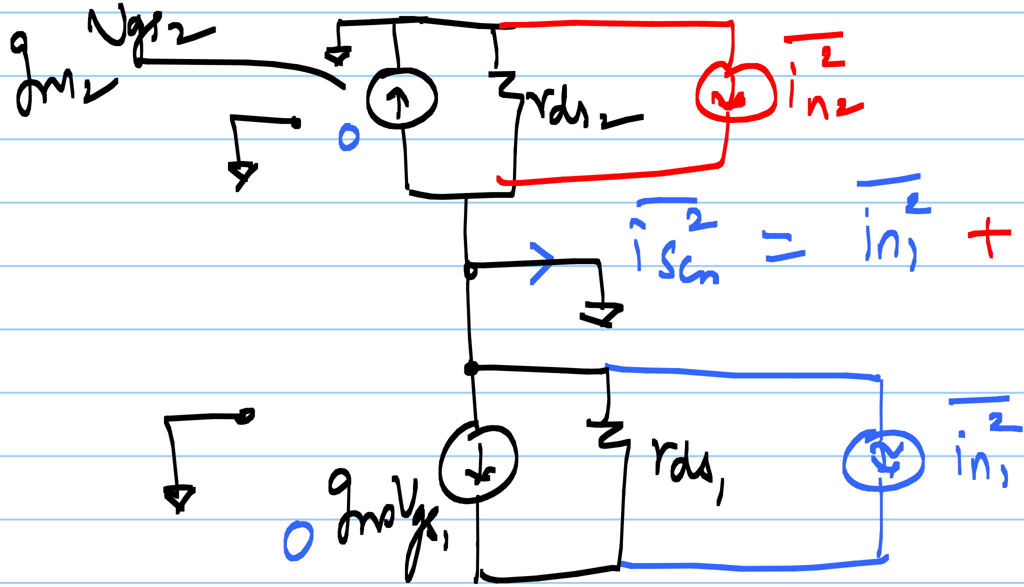
(I)

(I)



$\overline{i_{scn}^2} = g_{m_1}^2 \cdot \overline{e_n^2}$

(I)



$$\overline{i_{scn}^2} = \overline{i_{n1}^2} + \overline{i_{n2}^2} + \overline{i_{n1/f_1}^2} + \overline{i_{n1/f_2}^2}$$

$$g_{m1}^2 \frac{\overline{e_n^2}}{\Delta f} = \frac{8kT}{3}\left(g_{m1} + g_{m2}\right)$$

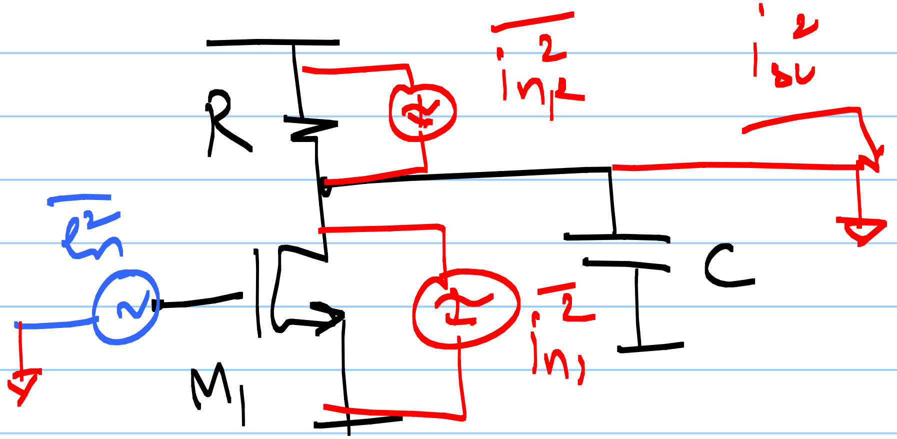
$$\frac{\overline{e_n^2}}{\Delta f} = \frac{8kT}{3 g_{m1}} + \frac{8kT}{3} \frac{g_{m2}}{g_{m1}^2}$$

large g_{m1}, small g_{m2} $\longrightarrow$ low noise

With flicker noise

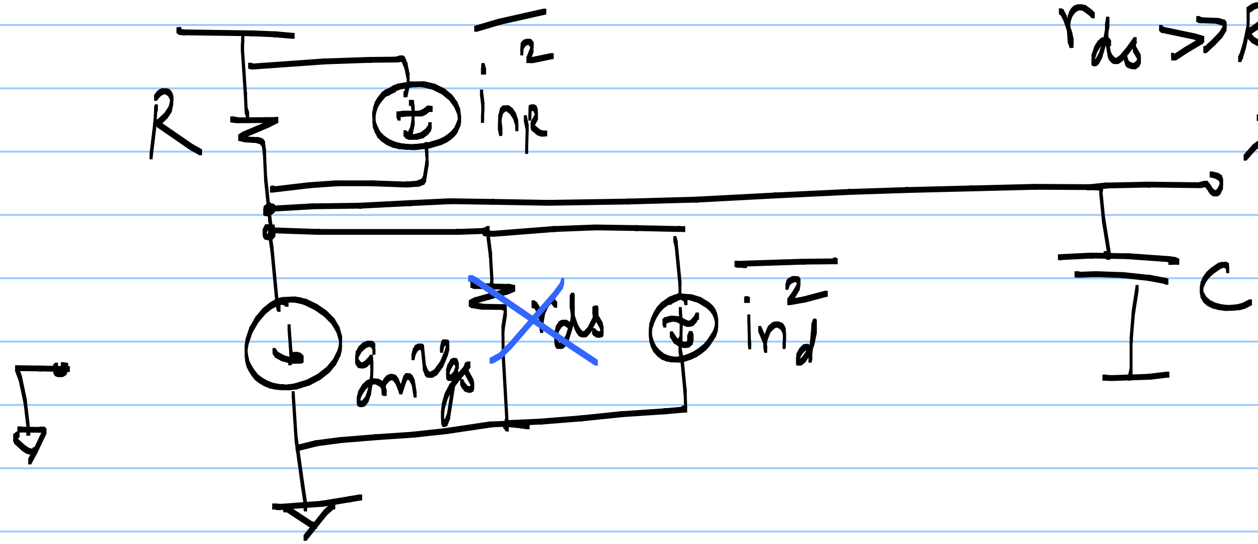
$$\frac{\overline{e_n^2}}{\Delta f} = \frac{1}{g_{m_1}^2}\left\{ \frac{8kT}{3} g_{m_1} + \frac{8kT}{3} g_{m_2} + \frac{K_{f_n}}{W_n L_n C_{ox}^2} \cdot g_{m_1}^2 \cdot \frac{1}{f} + \frac{K_{f_p}}{W_p L_p C_{ox}^2} \cdot g_{m_2}^2 \cdot \frac{1}{f} \right\}$$

$$= \frac{8kT}{3 g_{m_1}} + \frac{8kT}{3} \frac{g_{m_2}}{g_{m_1}^2} + \frac{K_{f_n}}{W_n L_n C_{ox}^2} \cdot \frac{1}{f} + \frac{K_{f_p}}{W_p L_p C_{ox}^2} \cdot \frac{g_{m_2}^2}{g_{m_1}^2} \cdot \frac{1}{f}$$



$\overline{e_n} = ?$ same as before ?!

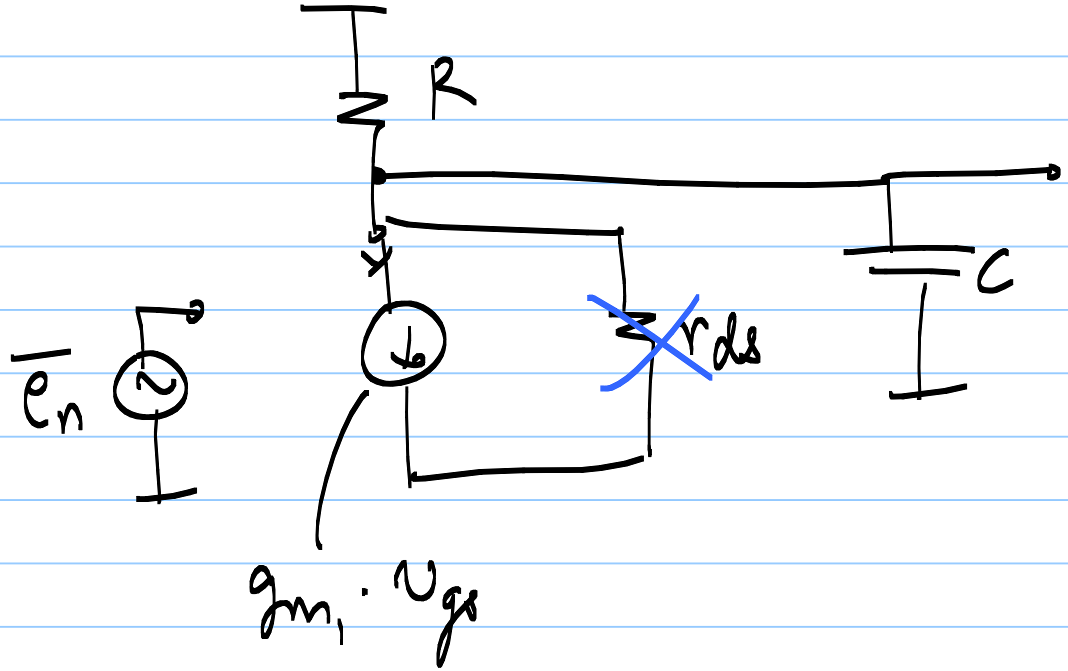
$$g_{m_1}^2 \overline{e_n^2} = \overline{i_{n_R}^2} + \overline{i_{n_{d_1}}^2} + \overline{i_{n_{1/f}}^2}$$



R
$\overline{i_{nR}^2}$
$g_m v_{gs}$
$\cancel{r_{ds}}$
$\overline{i_{nd}^2}$
C
$\overline{v_{on}^2} = ?$

$r_{ds} \gg R$ ✓

HW



$$\overline{v_{o_n}^2} = g_{m_1}^2 \cdot \overline{e_n^2} \cdot |Z|^2$$

$$Z = R \,||\, \frac{1}{j\omega C}$$

$$= \frac{R}{1 + j\omega RC}$$

$$\overline{v_{on}^2} = g_{m_1}^2 \cdot \overline{e_n^2} \cdot \frac{R^2}{1 + \omega^2 R^2 C^2}$$

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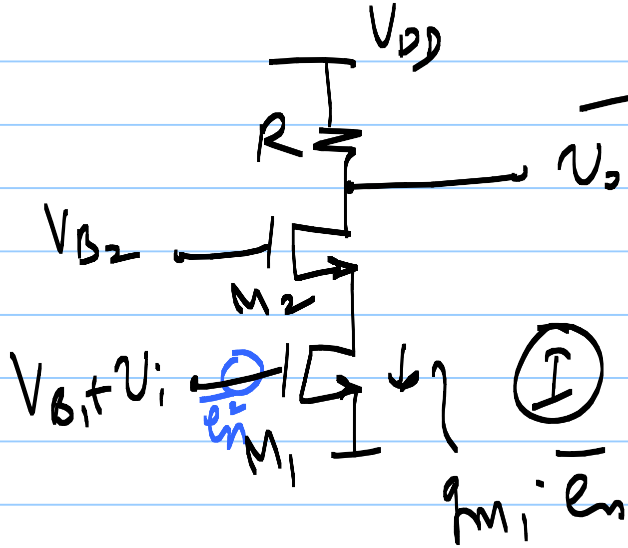
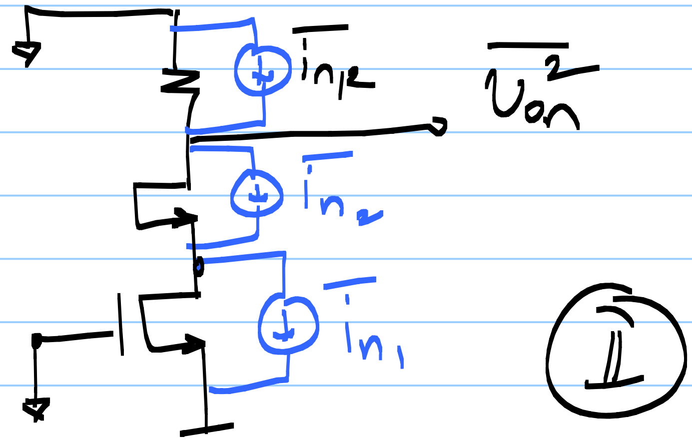
Lec 5

Cascode amplifier



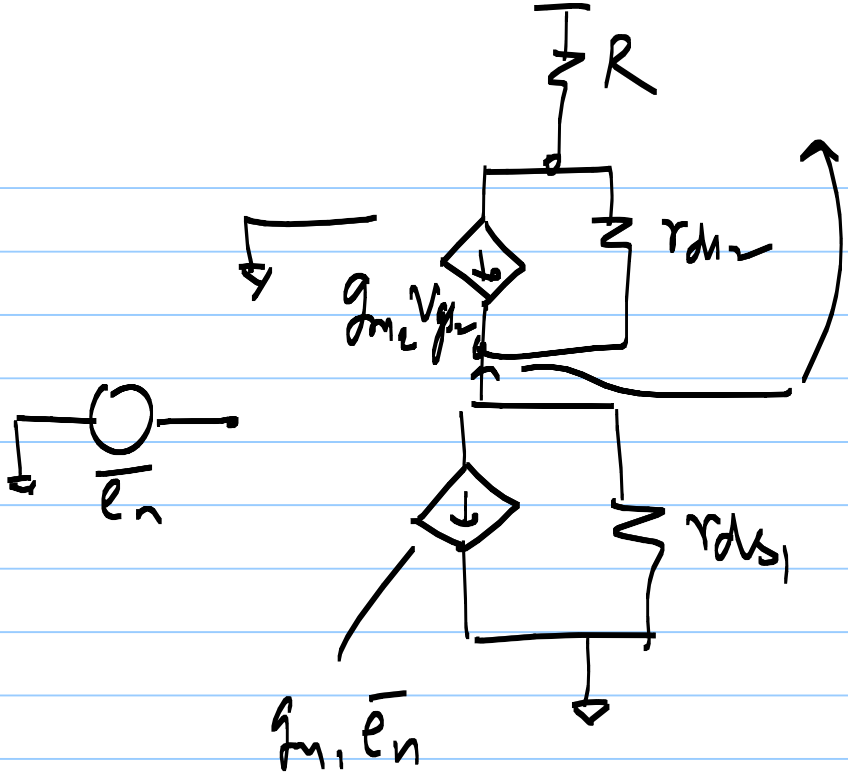
$$\overline{v_{on}^2} = g_{m_1}^2 R^2 \overline{e_n^2}$$

$\longleftrightarrow$



II : $\overline{v_{on_R}^2} = \overline{i_{nR}^2} \cdot R^2$; $\overline{v_{on_1}^2} = R^2 \cdot \overline{i_{n_1}^2}$ { assuming $g_{m_2} r_{ds_1} \gg 1$ }

$\overline{i_{n_2}} = ?$



If,

$$\frac{1}{g_{m_2}} \sim r_{ds_1}$$

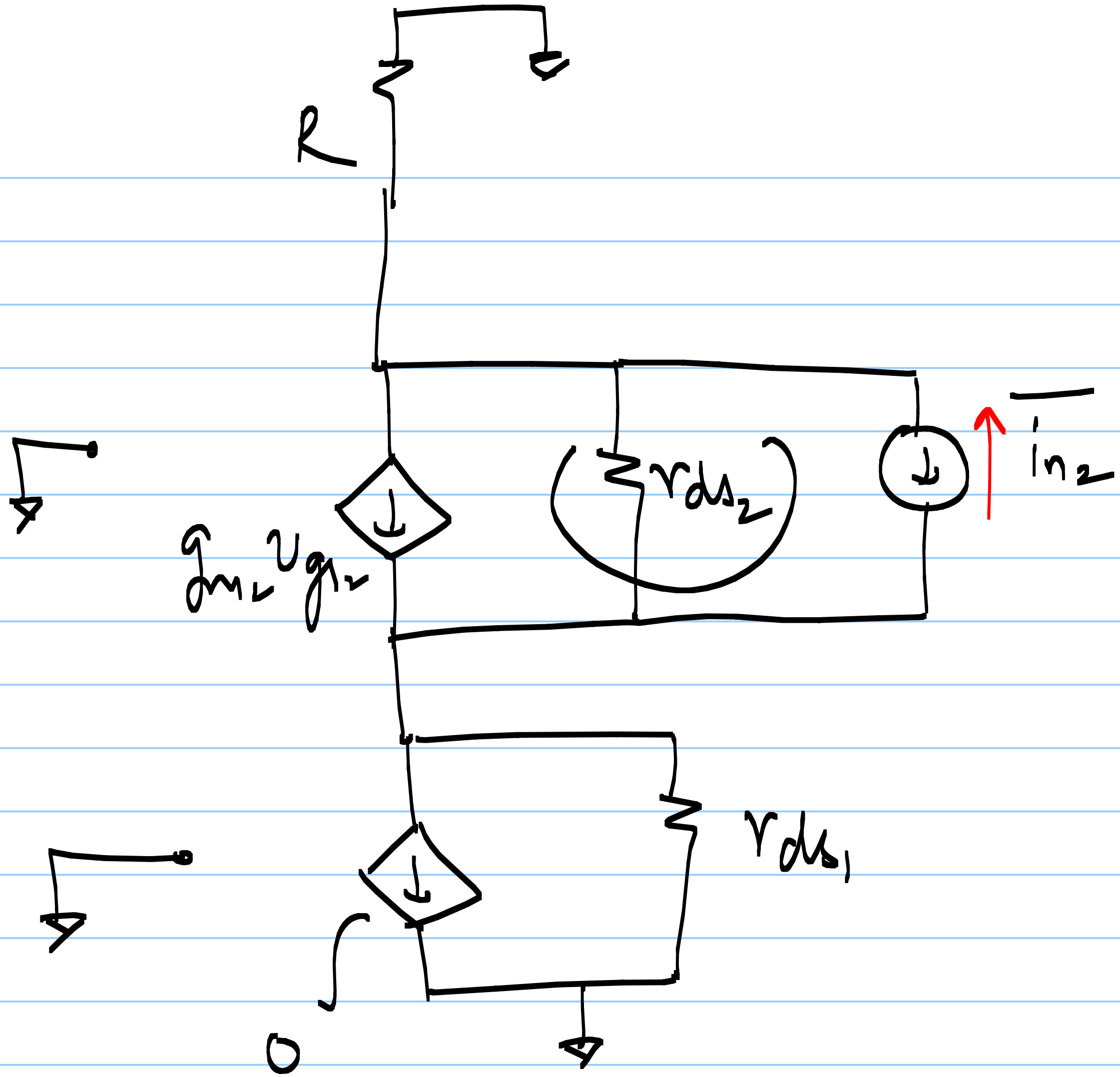
then

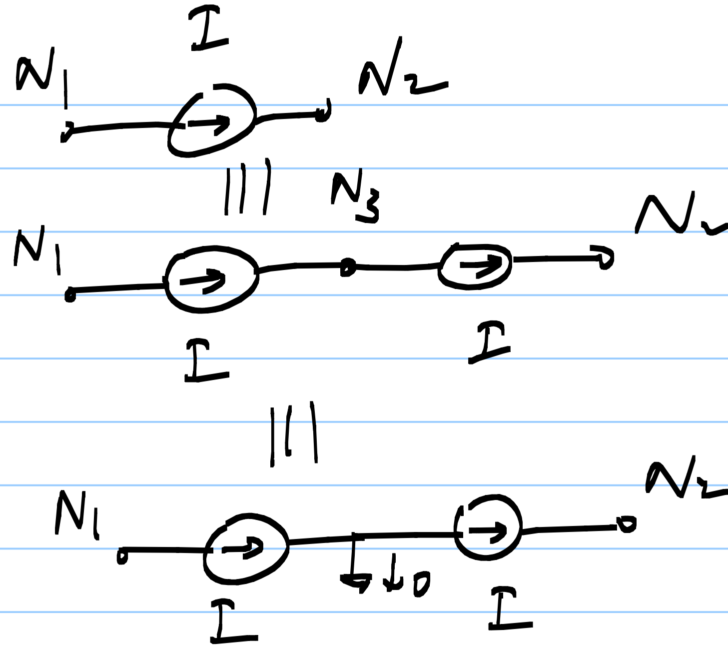
$$\overline{i_{scn}} = \frac{r_{ds_1}}{\frac{1}{g_{m_2}} + r_{ds_1}} \cdot g_{m_1} \overline{e_n}$$

If $g_{m_2} \gg \frac{1}{r_{ds_1}}$

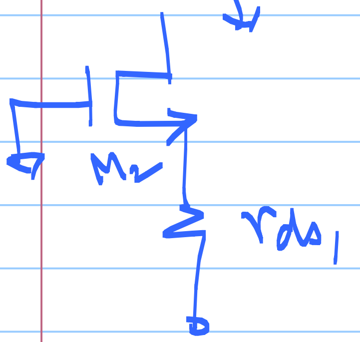
$$\overline{i_{scn}} \approx g_{m_1} \overline{e_n}$$

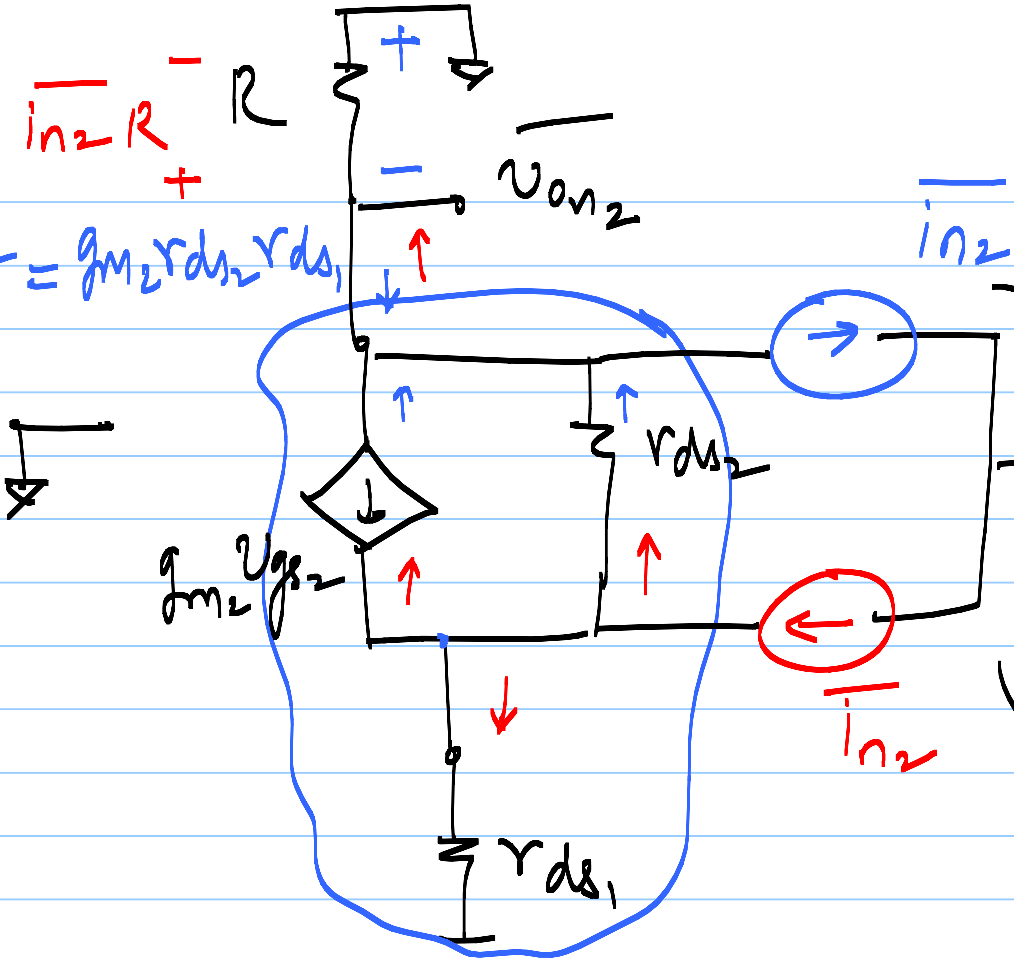
$\overline{i_{n_2}^2}$:

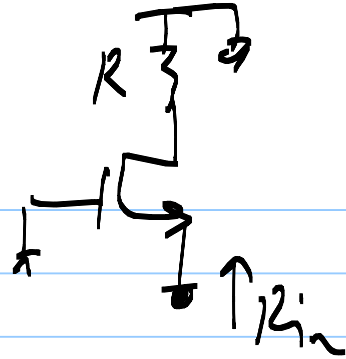




$R_{out} = g_{m_2} r_{ds_2} r_{ds_1}$







$r_{ds} \gg R$

$R_{in} \approx \dfrac{1}{g_{m_2}}$

fully correlated sources

$$\left.\begin{aligned} \overline{v_{on_2}} &= -\overline{i_{n_2}} R \\ \overline{v_{on_2}} &= +\overline{i_{n_2}} R \end{aligned}\right\} \quad \overline{v_{on_2}} = 0$$

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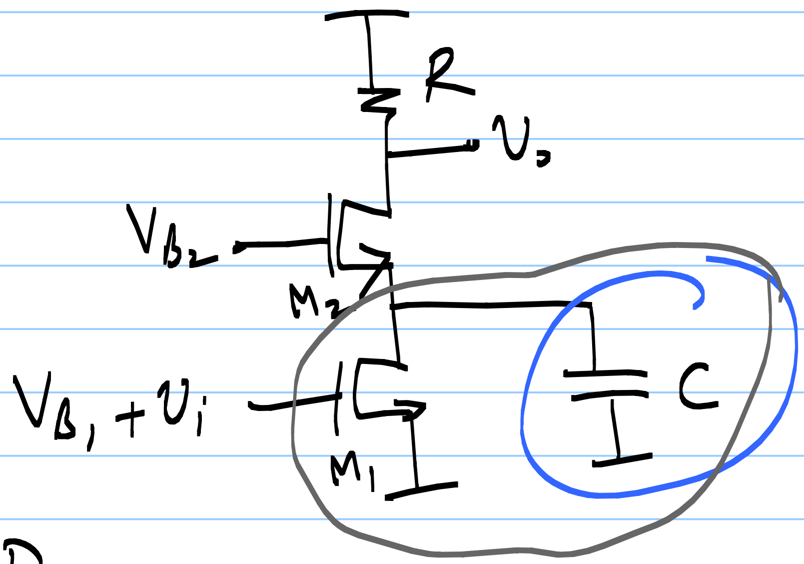
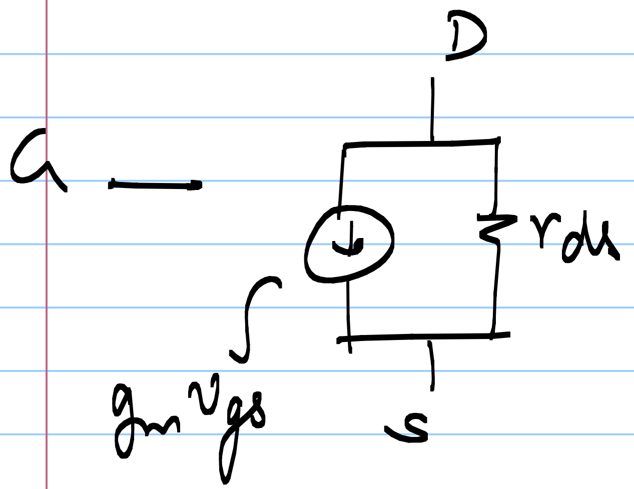
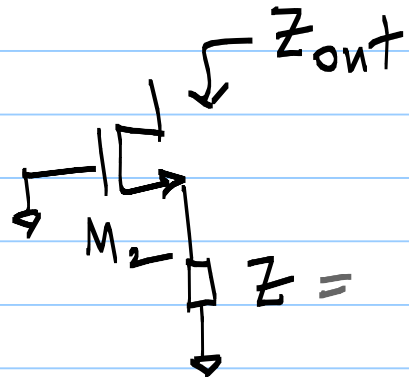
Lec 6



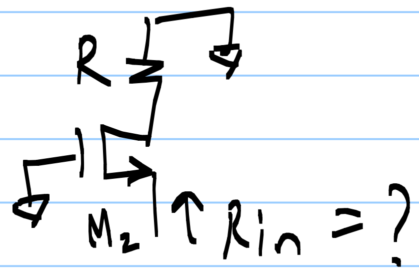
$\overline{i_n}=0$, $\overline{e_n}=?$

$$Z=\frac{r_{ds_1}}{1+j\omega C r_{ds_1}}$$



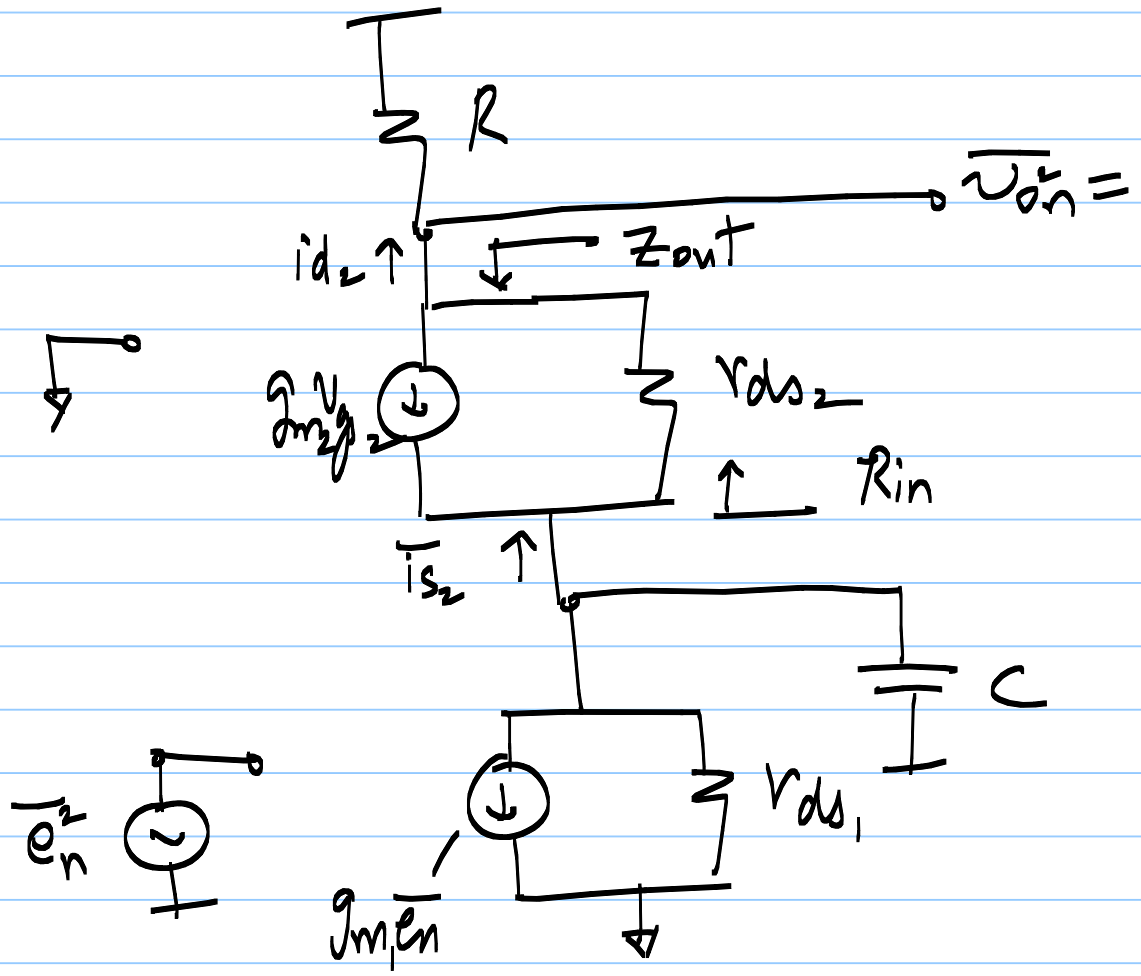


$Z = r_{ds_1} \| \frac{1}{j\omega C}$



$$R_{in}=\frac{r_{ds_2}+R}{1+g_{m_2}r_{ds_2}}$$

$$Z_{out}=g_{m_2}r_{ds_2}Z+Z+r_{ds_2}$$



$R_{in} \approx \dfrac{1}{g_{m_2}}$ if $g_{m_2} r_{ds_2} \gg 1$ and $r_{ds_2} \gg R$

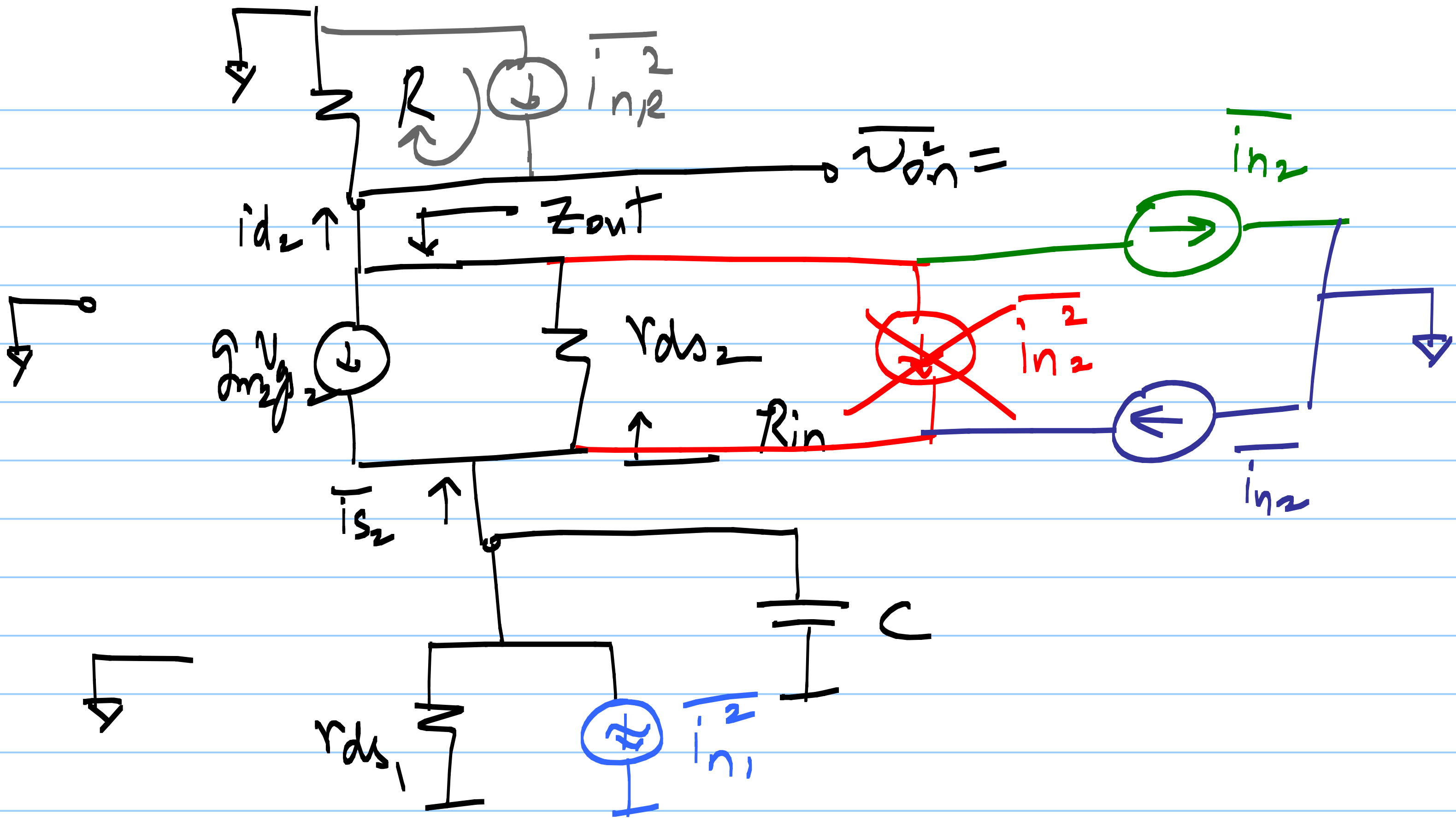
Assume $\frac{1}{g_{m_2}} \ll r_{ds_1}$

$$\overline{i_{s_2}} = \frac{1/j\omega C}{\frac{1}{g_{m_2}} + \frac{1}{j\omega C}} \cdot g_{m_1} \overline{e_n}$$

$$= \frac{g_{m_2}}{g_{m_2} + j\omega C} \cdot g_{m_1} \cdot \overline{e_n} = i_{d_2}$$

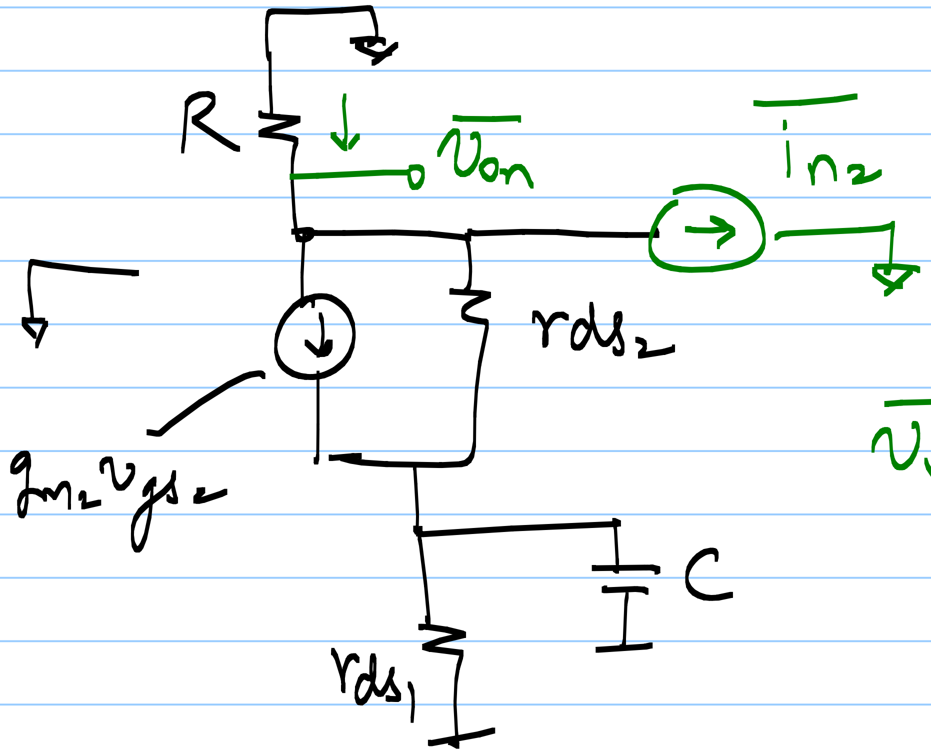
$$\overline{v_{on}} = \overline{i_{d_2}} \cdot R$$

$$\overline{v_{on}^2} = R^2 \cdot \overline{i_{d_2}^2} = \frac{g_{m_1}^2 \, g_{m_2}^2 \, R^2}{g_{m_2}^2 + \omega^2 C^2} \cdot \overline{e_n^2}$$

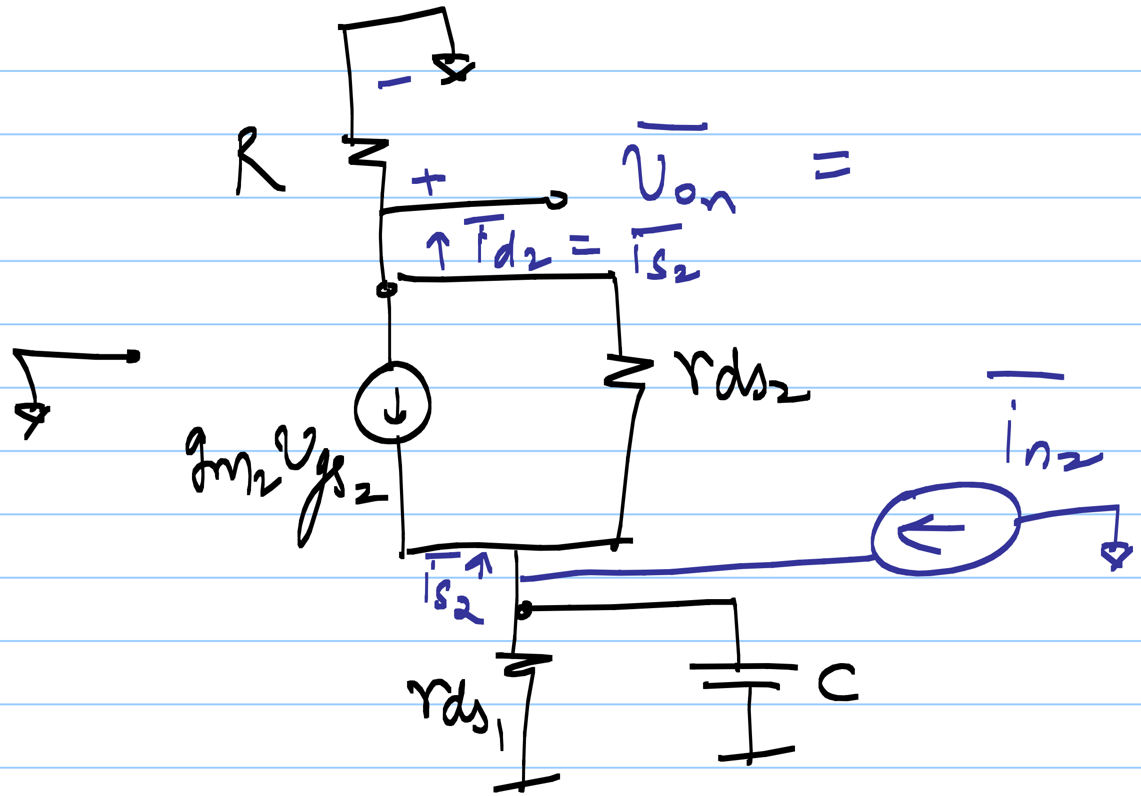


$$\overline{v_{on_1}^2} = \frac{g_{m_2}^2 R^2}{g_{m_2}^2 + w^2 C^2} \cdot \overline{i_{n_1}^2}$$

$$\overline{v_{on_R}^2} = \overline{i_{n_R}^2} \cdot R^2 \qquad \text{assuming } r_{ds_2} \gg R \leftarrow$$



$$\overline{v_{on}} = -\overline{i_{n_2}}\, R$$



$$\overline{i_{s_2}} = \frac{1/j\omega C}{1/j\omega C + 1/g_{m_2}} \cdot \overline{i_{n_2}} = \frac{g_{m_2}}{g_{m_2} + j\omega C} \cdot \overline{i_{n_2}}$$

$$\overline{v_{on}} = + \frac{g_{m_2} R}{g_{m_2} + j\omega C} \cdot \overline{i_{n_2}}$$

$$\overline{v_{on}} = \overline{v_{on}} + \overline{v_{on}}$$

$$= -\overline{i_{n2}} R + \frac{g_{m2} R}{g_{m2} + j\omega C} \cdot \overline{i_{n2}}$$

$$= \overline{i_{n2}} R \cdot \frac{-j\omega C}{g_{m2} + j\omega C}$$

$$\overline{v_{on2}^2} = \frac{\omega^2 C^2 R^2}{g_{m2}^2 + \omega^2 C^2} \cdot \overline{i_{n2}^2}$$

Total $\overline{v_{on}^2} = \overline{v_{on1}^2} + \overline{v_{on2}^2} + \overline{v_{on,R}^2}$

$$= \frac{g_{m2}^2 R^2}{g_{m2}^2 + \omega^2 C^2} \cdot \overline{i_{n1}^2} + \frac{\omega^2 C^2 R^2}{g_{m2}^2 + \omega^2 C^2} \cdot \overline{i_{n2}^2}$$

$$+ \overline{i_{nR}^2} \cdot R^2$$

$$\frac{g_{m1}^2\, g_{m2}^2\, \cancel{R^2}}{\cancel{g_{m2}^2 + \omega^2 C^2}} \cdot \overline{e_n^2}$$

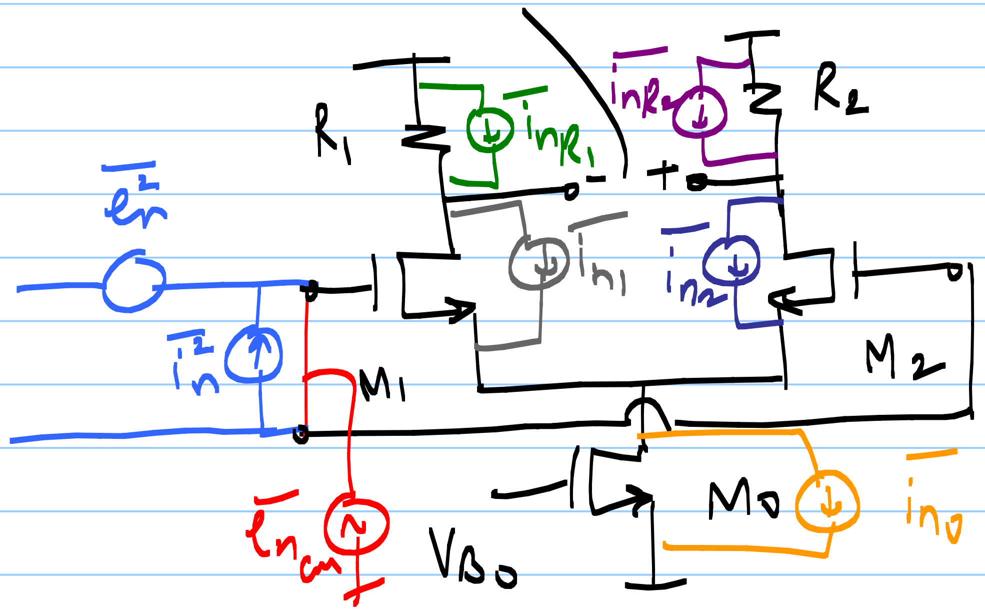
$$= \frac{g_{m2}^2\, \cancel{R^2}}{\cancel{g_{m2}^2 + \omega^2 C^2}} \cdot \overline{i_{n1}^2} + \frac{\omega^2 C^2\, \cancel{R^2}}{\cancel{g_{m2}^2 + \omega^2} C^2} \cdot \overline{i_{n2}^2}$$

$$+ \overline{i_{nR}^2} \cdot \cancel{R^2} \left(g_{m2}^2 + \omega^2 C^2 \right)$$

$$\overline{e_n^2} = \frac{\overline{i_{n1}^2}}{g_{m1}^2} + \frac{\omega^2 C^2}{g_{m1}^2\, g_{m2}^2} \cdot \overline{i_{n2}^2} + \frac{g_{m2}^2 + \omega^2 C^2}{g_{m1}^2\, g_{m2}^2} \cdot \overline{i_{nR}^2}$$

24/1/20

Lec 7 — Noise of Diff. Amplifier



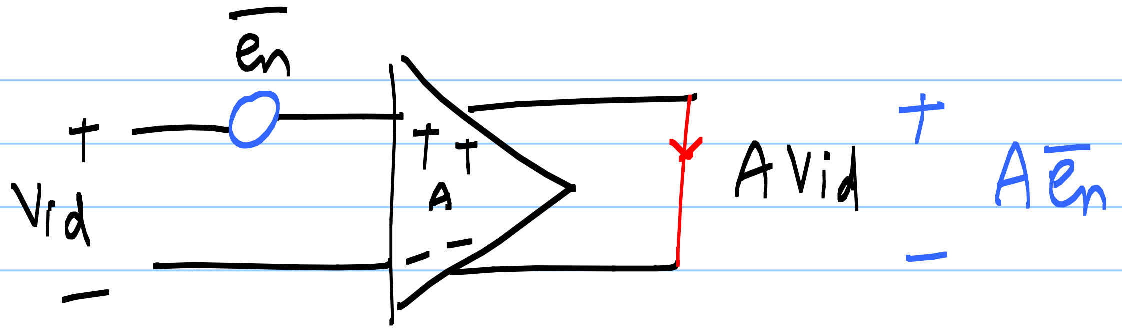
$\overline{i_n} = 0$ $\quad R_1 = R_2 = R$

$\overline{e_n} = ?$ $\quad g_{m_1} = g_{m_2} = g_m$

* Noise analysis
- cannot use "half-circuit" analysis

* Noise sources are applied asymmetrically in the diff. circuit

* Can use H.C. concepts when calculating output noise due to $\overline{e_n}/\overline{i_n}$



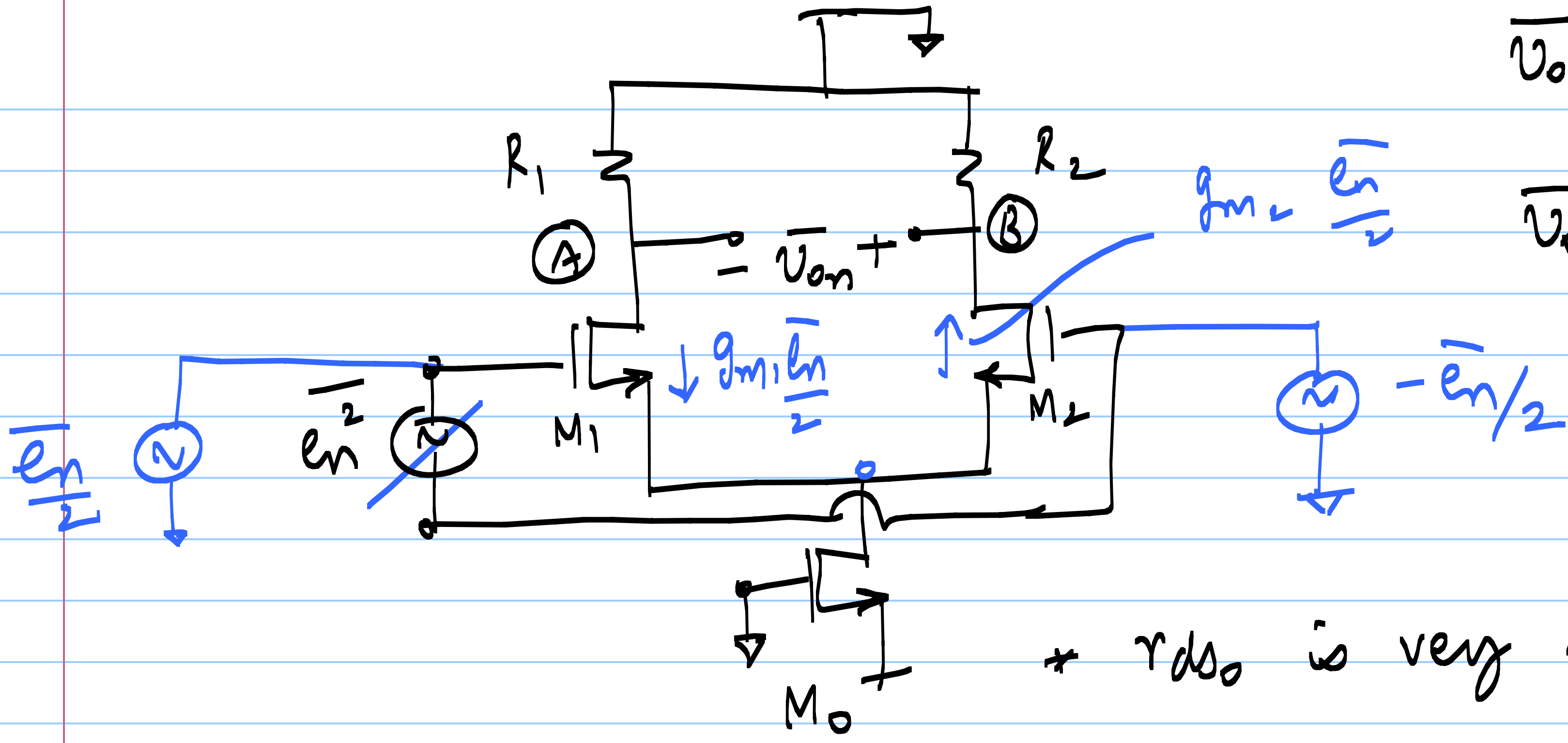
set $V_{id} = 0$ for noise analysis

case I: apply $\overline{e_n}$ only

case II: apply $\overline{i_{nR_1}}$, $\overline{i_{nR_2}}$, $\overline{i_{nO}}$, $\overline{i_{n1}}$, $\overline{i_{n2}}$ in turn

and find $\overline{V_{on}^2}$ as mean

square sum



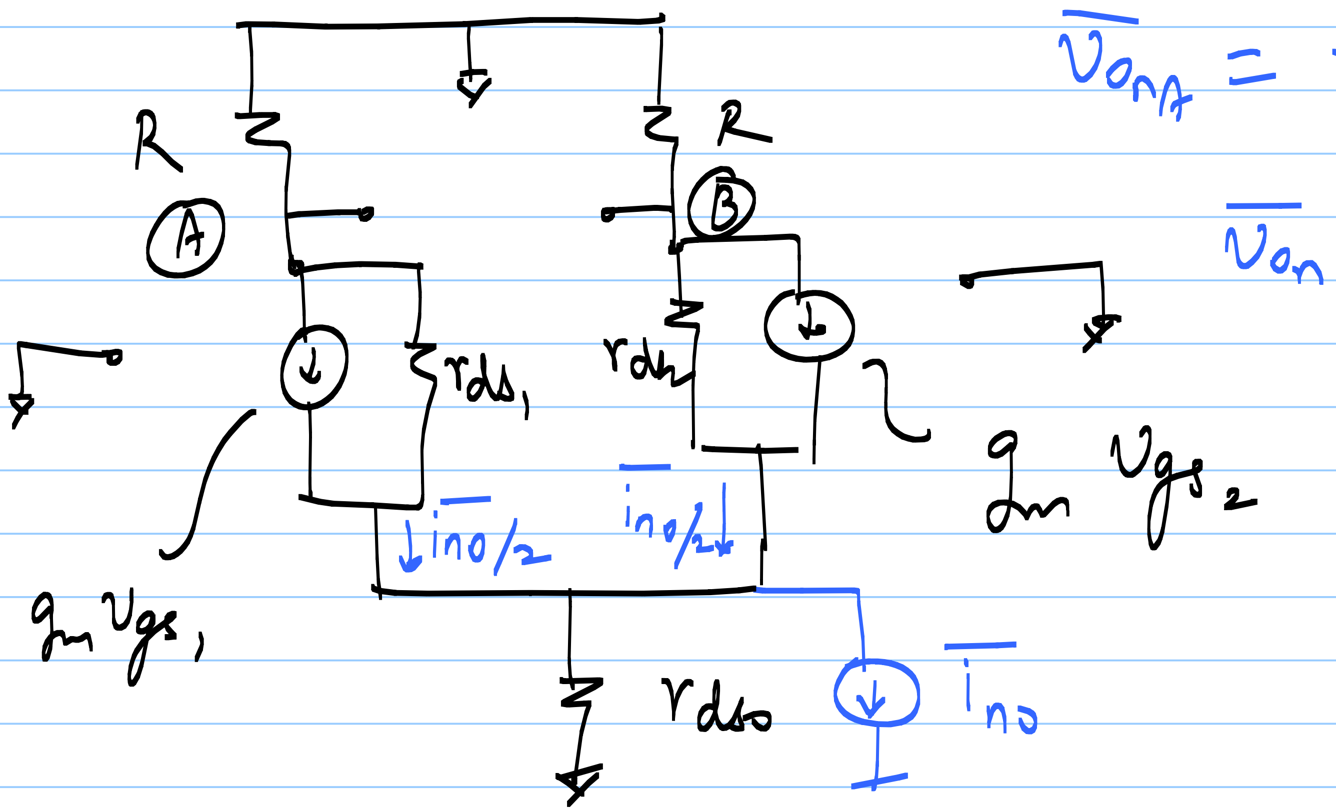
$$\overline{v_{on_A}} = -g_{m_1} R_1 \cdot \frac{\overline{e_n}}{2}$$

$$\overline{v_{on_B}} = g_{m_2} R_2 \cdot \frac{\overline{e_n}}{2}$$

* r_{ds_0} is very high

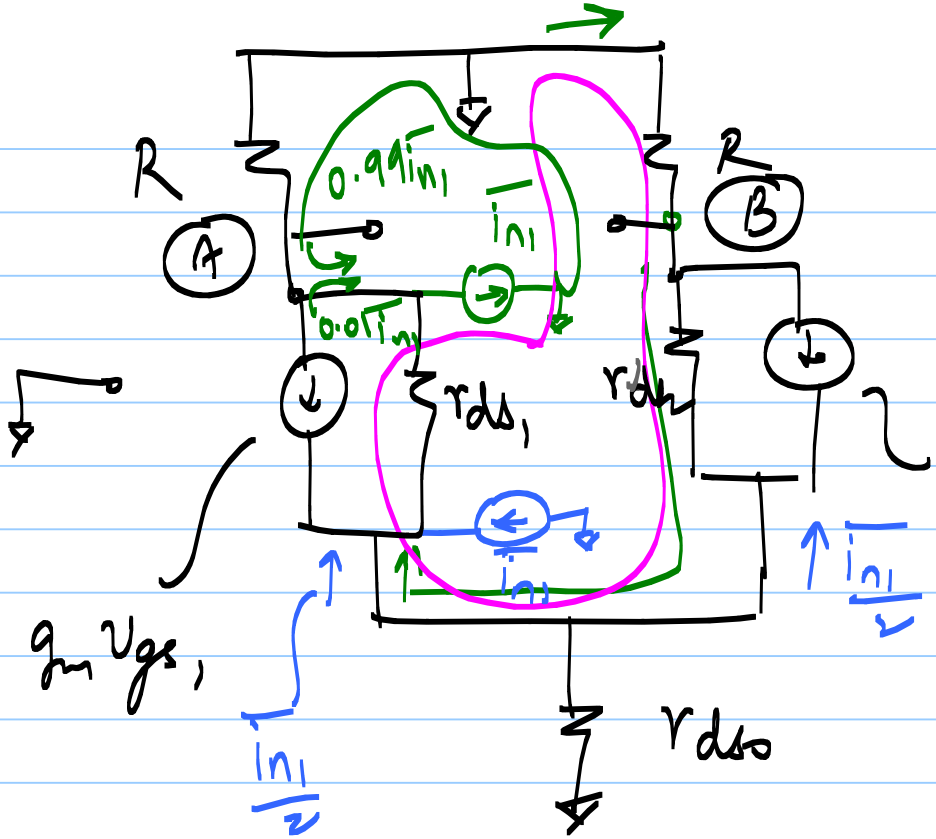
$$\overline{v_{on}} = \overline{v_{on_B}} - \overline{v_{on_A}} = g_m R \, \overline{e_n}$$

$$\overline{v_{on}^2} = g_m^2 R^2 \, \overline{e_n^2}$$



$$\overline{v_{onA}} = -\frac{R\,\overline{i_{no}}}{2} = \overline{v_{onB}}$$

$$\overline{v_{on}} = 0$$



$$\overline{v_{on_A}} = \overline{v_{on_B}} = \frac{R\overline{i_{n_1}}}{2}$$

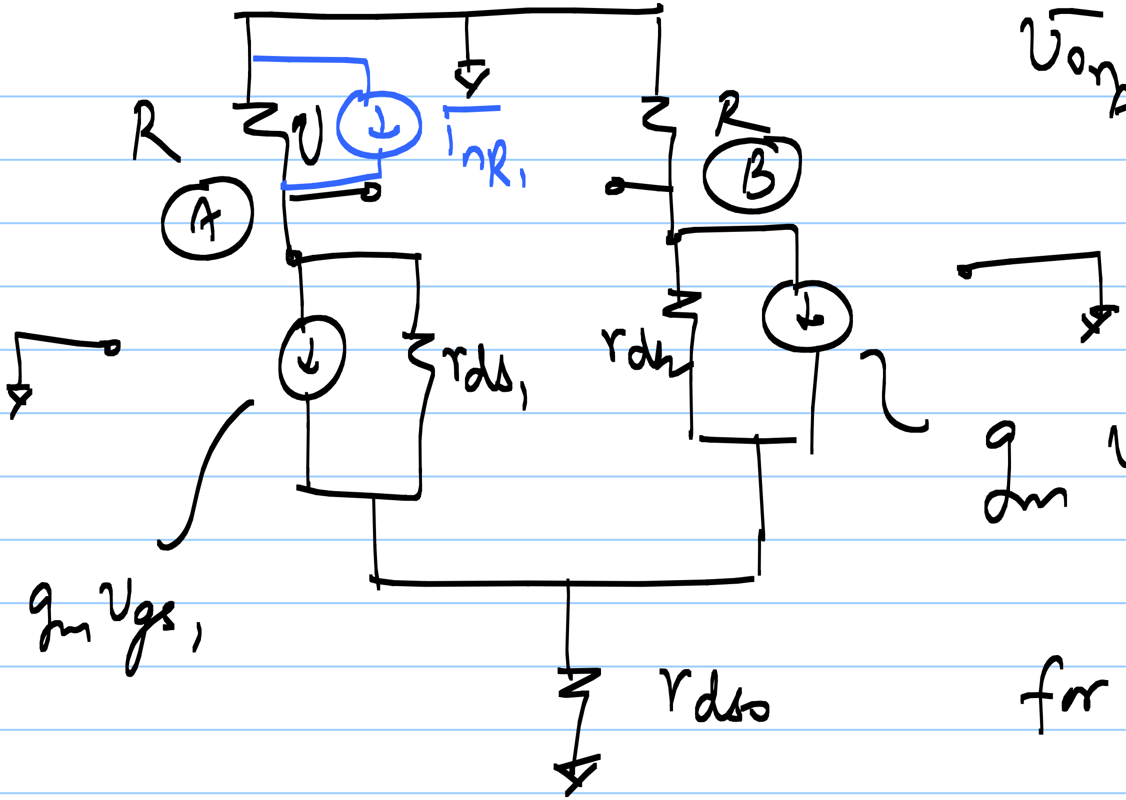
$$\overline{v_{on_A}} = -R\,\overline{i_{n_1}}$$

$$\overline{v_{on_B}} = 0$$

$$\overline{v_{on}} = R\,\overline{i_{n_1}}$$

$$\overline{v_{on}^2} = R^2\,\overline{i_{n_1}^2}$$

Due to M_2: $\overline{v_{on}^2} = R^2 \cdot \overline{i_{n_2}^2}$



$\overline{v_{on_A}} = R\,\overline{i_{nR_1}}$; $\overline{v_{on_B}} = 0$

$$\overline{v_{on}^2} = R^2 \cdot \overline{i_{nR_1}^2}$$

for $\overline{i_{nR_2}^2}$: $\overline{v_{on_A}} = 0$

$$\overline{v_{on_B}} = R \cdot \overline{i_{nR_2}}$$

$$\overline{v_{on}} = R^2 \cdot \overline{i_{nR_2}^2}$$

$$\text{Total } \overline{v_{on}^2} = R^2 \cdot \left[\overline{i_{n1}^2} + \overline{i_{n2}^2} + \overline{i_{nR_1}^2} + \overline{i_{nR_2}^2} \right]$$

$$= g_m^2 R^2 \cdot \overline{e_n^2}$$

$$\frac{\overline{e_n^2}}{\Delta f} = \frac{1}{g_m^2} \left[\frac{16kT}{3} g_m + \frac{8kT}{R} \right]$$

$$= \frac{16kT}{3 g_m} + \frac{8kT}{g_m^2 R}$$

HW : determine $\overline{e_n}$ using $\overline{i_{scn}^2}$ S.C. noise current

27/1/20

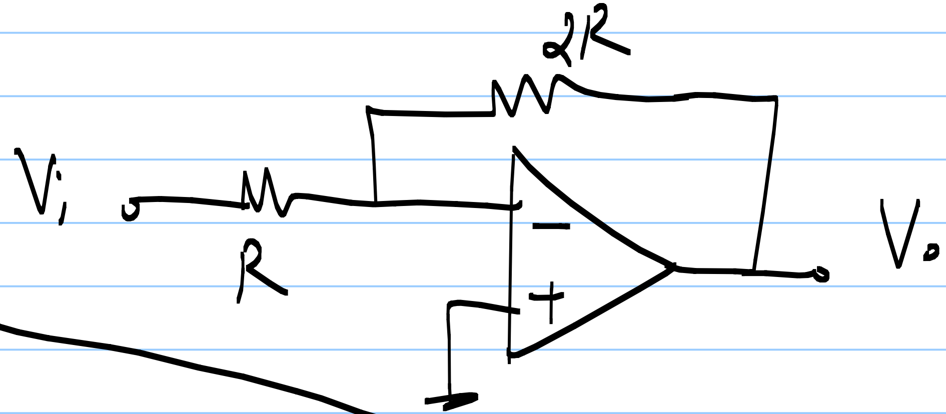
Lec 8

* $\overline{e_n}$ & $\overline{i_n}$
* Apply v_s & i_s — separate effect of $\overline{e_n}$ & $\overline{i_n}$
* Apply s.c. ($\overline{i^2_{scn}}$) or o.c. ($\overline{v^2_{on}}$) at o/p.
* Case I : $\overline{e_n}$ & $\overline{i_n}$ with ideal 2-port

  Case II : apply noise sources in turn using superposition
* equate the two

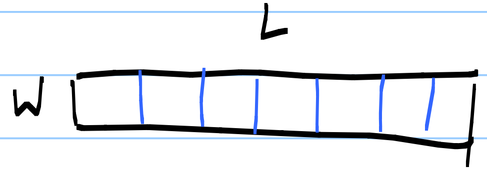
Mismatch

* Expect 2 components / circuits etc to be identical or exact multiples



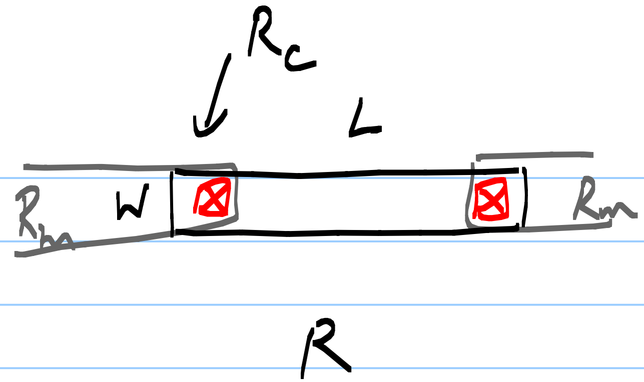
$$\frac{V_o}{V_i} = -\frac{2R}{R}$$

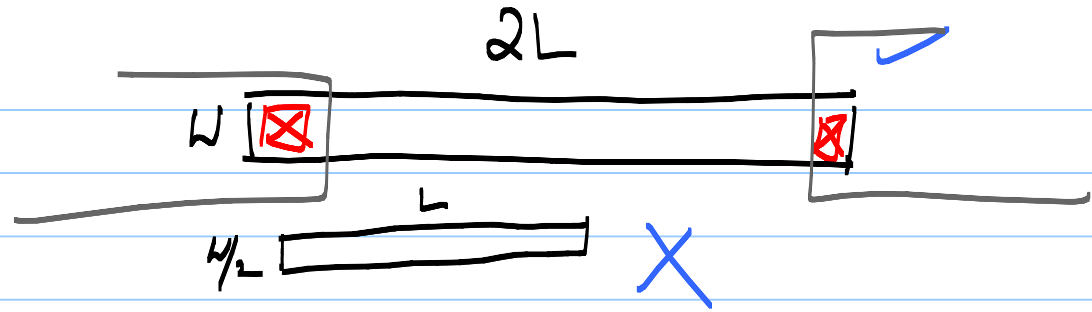
* If they are <u>not</u>, they are said to be mismatched.



$R_{sheet} = \text{---}\ \Omega/\square$

$R = R_{sheet} \times \#\text{ of }\square$



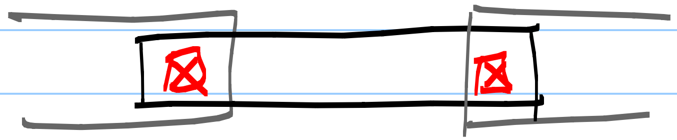
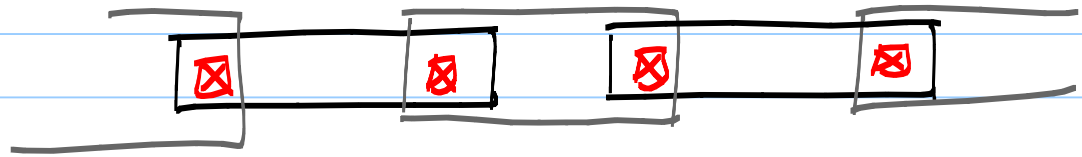


$R_{actual} = R + 2R_c$

$R'_{actual} = 2R + 2R_c$

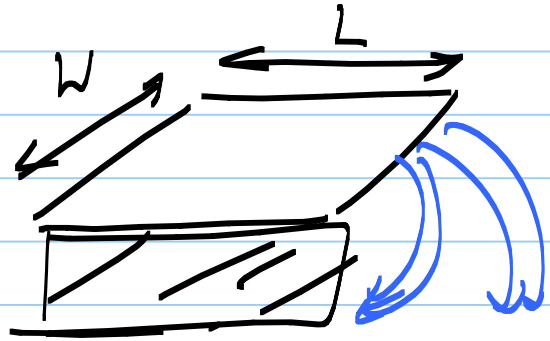
$M_x - M_y$ connection $\doteq$ Via

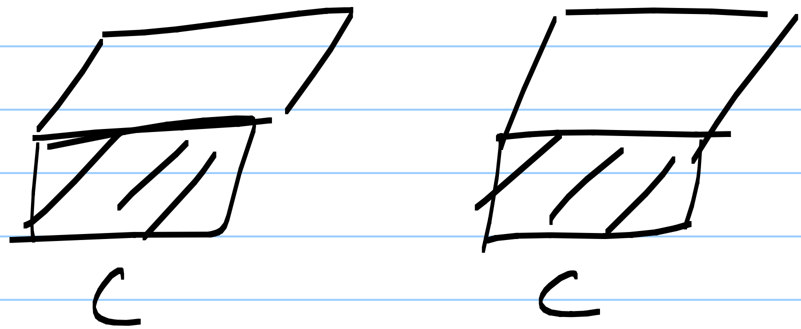
Diffusion – M_1 connection = 'contact'

$R_{ac} = R + 2R_c$ $\qquad\qquad$ $R'_{ac} = 2R + 4R_c$

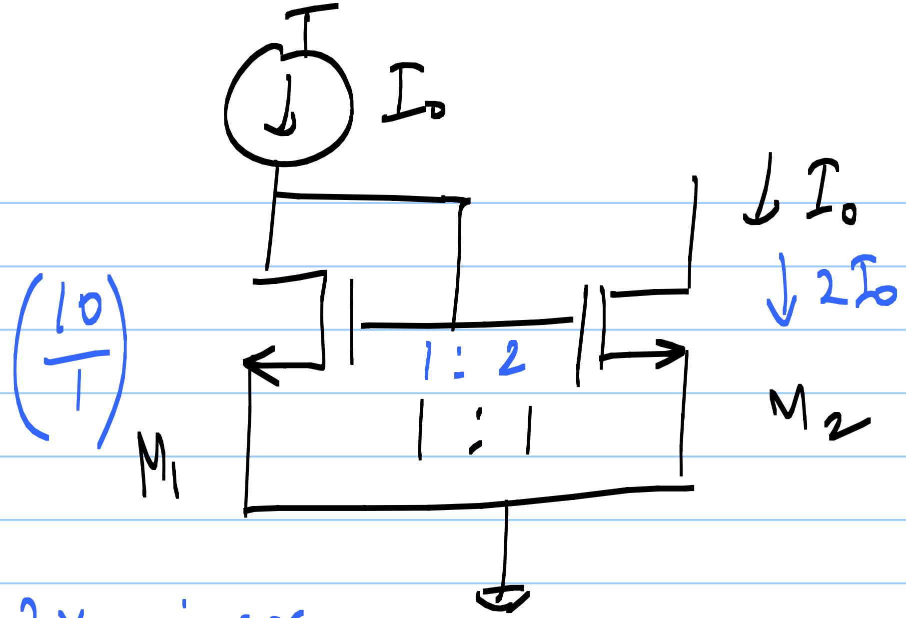
* We want C & 2C capacitances





$C = \epsilon_0 \epsilon_r A/d$

* Fringe cap. depends on perimeter; so, we 2 identical pieces



If $V_{DS_2} = V_{GS_1}$

you need to ensure

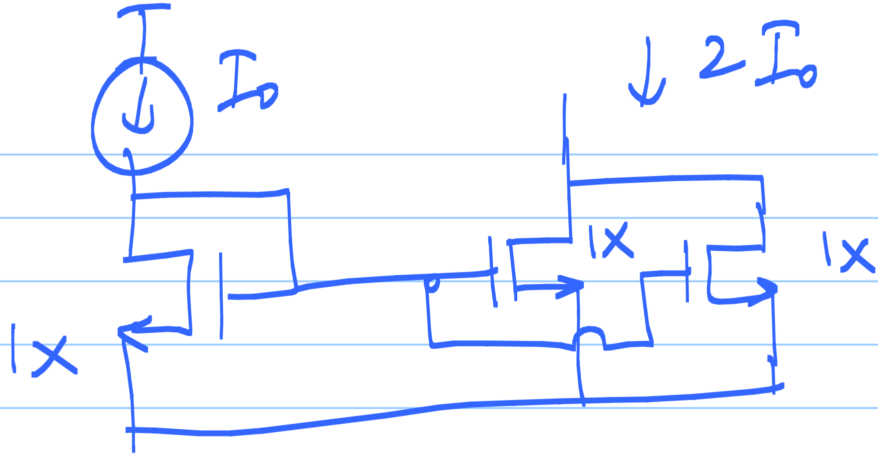
$I_2 = I_o$

$L_1 = L_2$; & $W_1 = W_2$

2x mirror

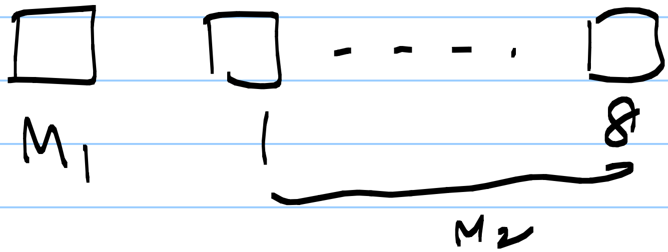
1. $\left(\frac{W}{L}\right)_2 = \left(\frac{20\mu m}{1\mu m}\right)$ ✗

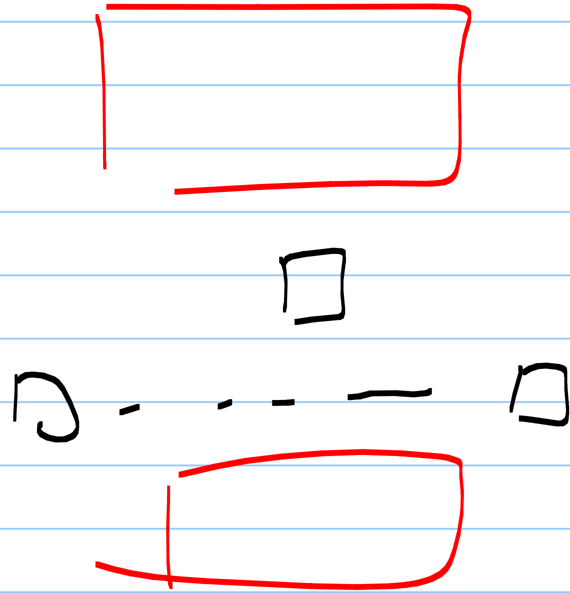
2. $\left(\frac{W}{L}\right)_2 = 2 \times \left(\frac{10\mu m}{1\mu m}\right)$ ✓

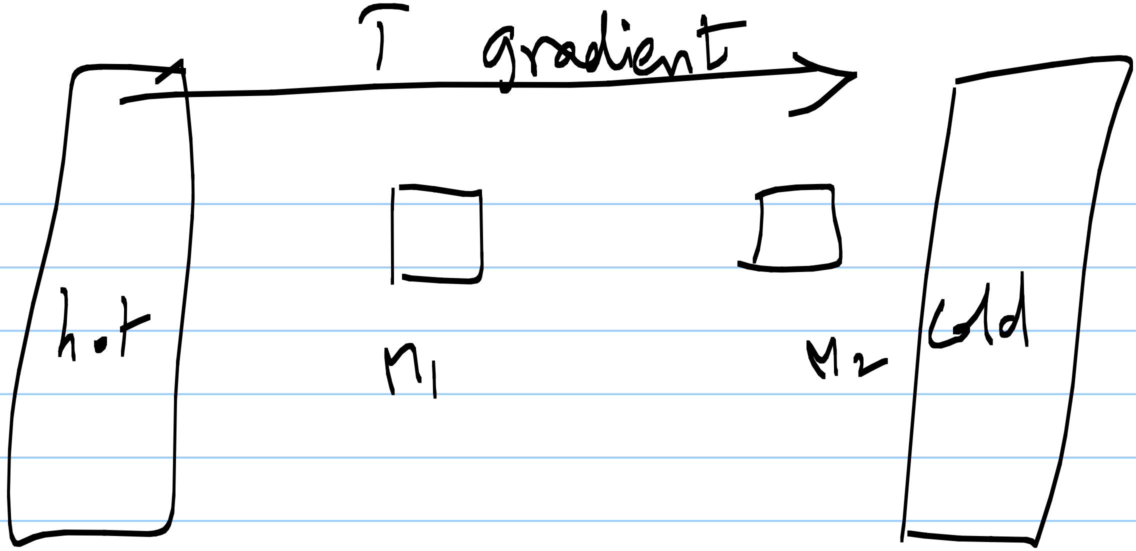


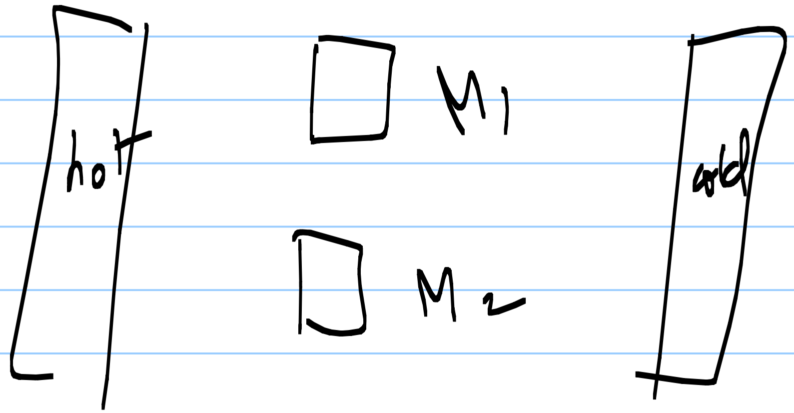
Layout :

e.g. 1 : 8 CM

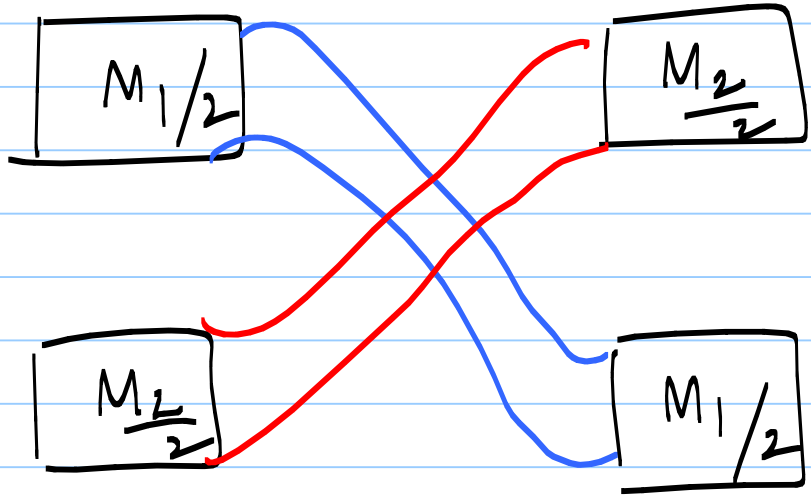





T gradient
hot
M1
M2
cold


hot
M1
M2
cold

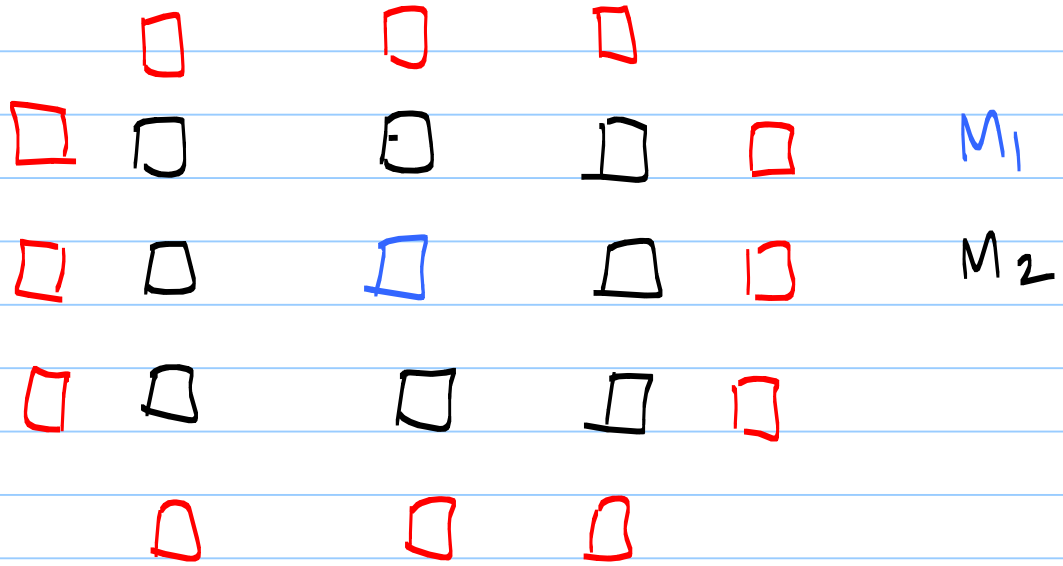
Common centroid layout

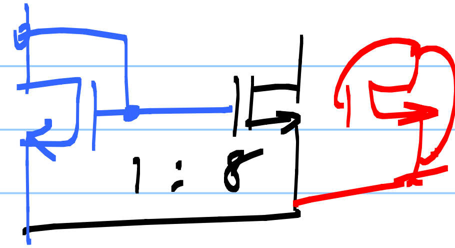


"Systematic Mismatch"

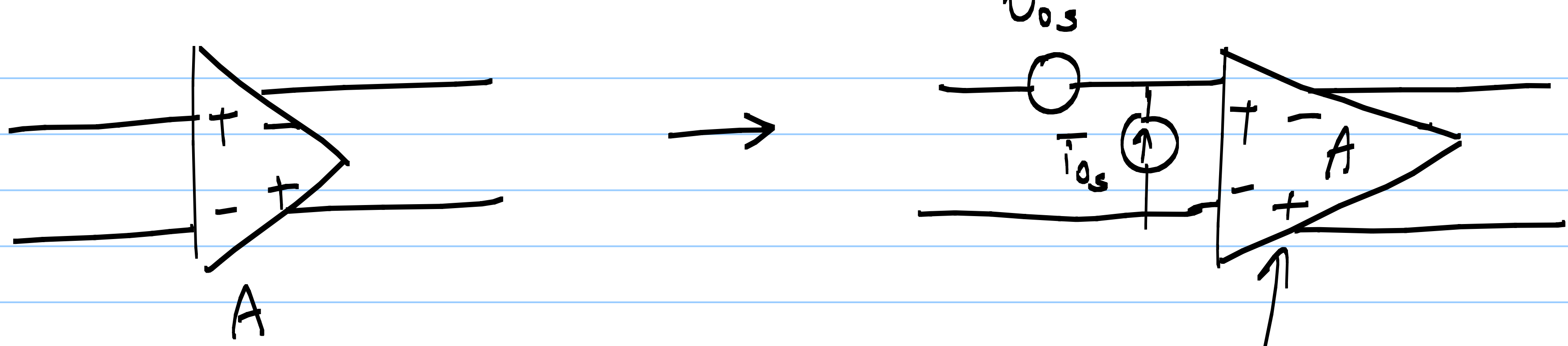
28/1/20

Lec 9



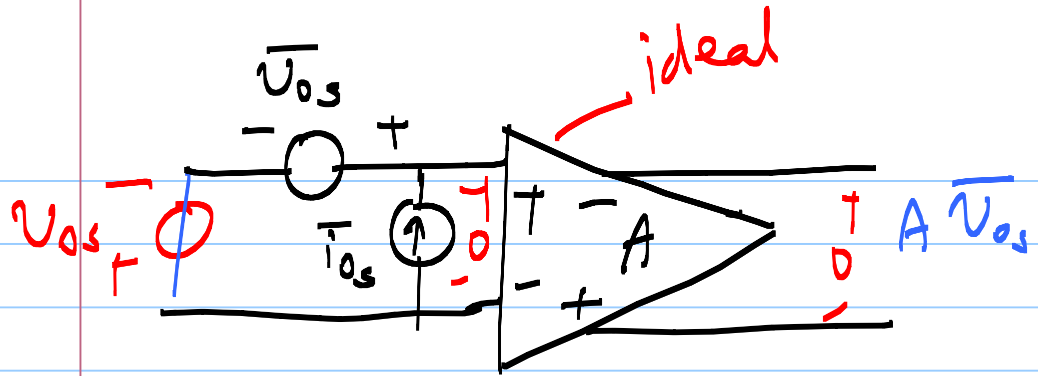


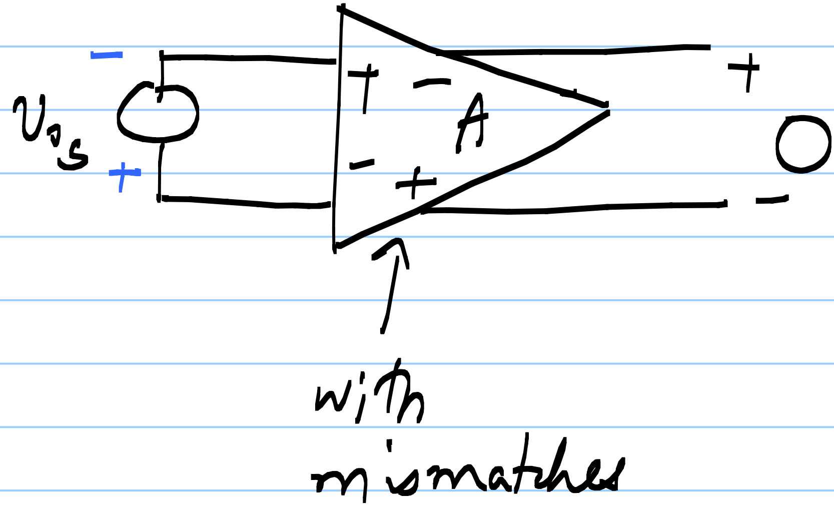
with mismatch



perfectly matched

* $\overline{v}_{os}$ & $\overline{i}_{os}$ → input-referred offset sources
* $\overline{v}_{os}$ & $\overline{i}_{os}$ → have a gaussian distribution (due to random mismatches)
* No systematic mismatch ⇒ $\overline{v}_{os}$ & $\overline{i}_{os}$ have 0 mean
* v_{os} & i_{os} are constant (or slowly varying with time) for a particular IC.

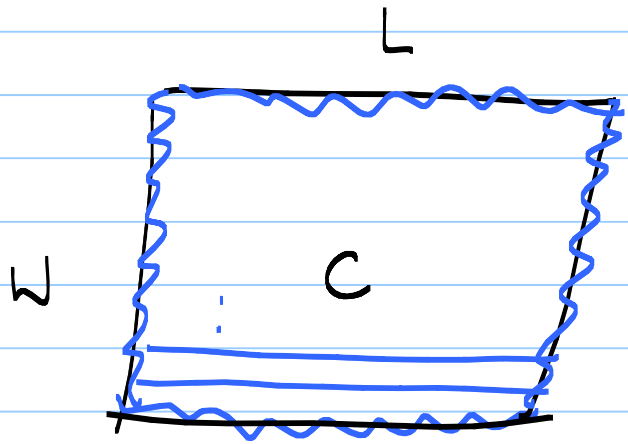




* $I_{in} = 0 \Rightarrow \bar{i}_{os} = 0$

*

Random Mismatch



$C_1 + \delta C_1$

$C_1 + \delta C_2$

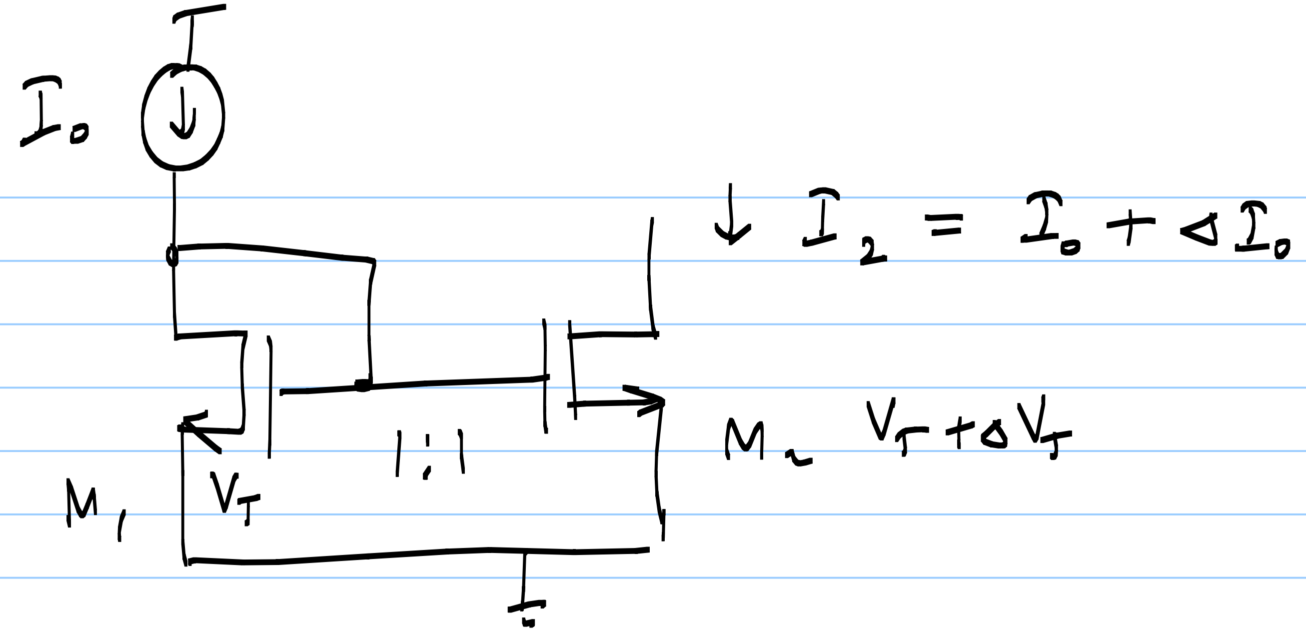
$\vdots$

$$\sigma_{\frac{\Delta C}{C}} = \frac{A_{\Delta C/C}}{\sqrt{W \cdot L}}$$

$$\sigma_{\Delta C/C} = \frac{A_{\Delta C/C}}{\sqrt{W_C \cdot L_C}} \quad ; \quad \sigma_{\frac{\Delta R}{R}} = \frac{A_{\Delta R/R}}{\sqrt{W_R \cdot L_R}}$$

$$\sigma_{V_T} = \frac{A_{V_T}}{\sqrt{W \cdot L}} \quad ; \quad \sigma_{\mu C_{ox}} = \frac{A_{\mu C_{ox}}}{\sqrt{W \cdot L}}$$

$A_{\frac{\Delta C}{C}}$, A_{V_T} etc. are empirical parameters specific to a process



* Assume ΔV_T is small

* $$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_T)^2$$

$$\frac{\partial I_D}{\partial V_T} = -\frac{\partial I_D}{\partial V_{GS}} = -g_m$$

$$\Delta I_0 = -g_m \Delta V_T$$

$$\sigma_{\Delta I_0} = -g_m \sigma_{\Delta V_T}$$

$$\sigma^2_{\Delta I_0} = g_m^2 \; \sigma^2_{\Delta V_T}$$

$$\sigma^2_{\Delta I_0/I_0} = \frac{g_m^2}{I_0^2} \cdot \sigma^2_{\Delta V_T}$$

$$g_m = \frac{2 I_D}{V_{GS} - V_T}$$

$$\frac{g_m^2}{I_0^2} = \frac{4}{V_{Dsat}^2}$$

$$\sigma^2_{\Delta I/I_0} = \frac{4}{V_{Dsat}^2} \cdot \left[\frac{A_{V_T}^2}{W \cdot L} \right]$$

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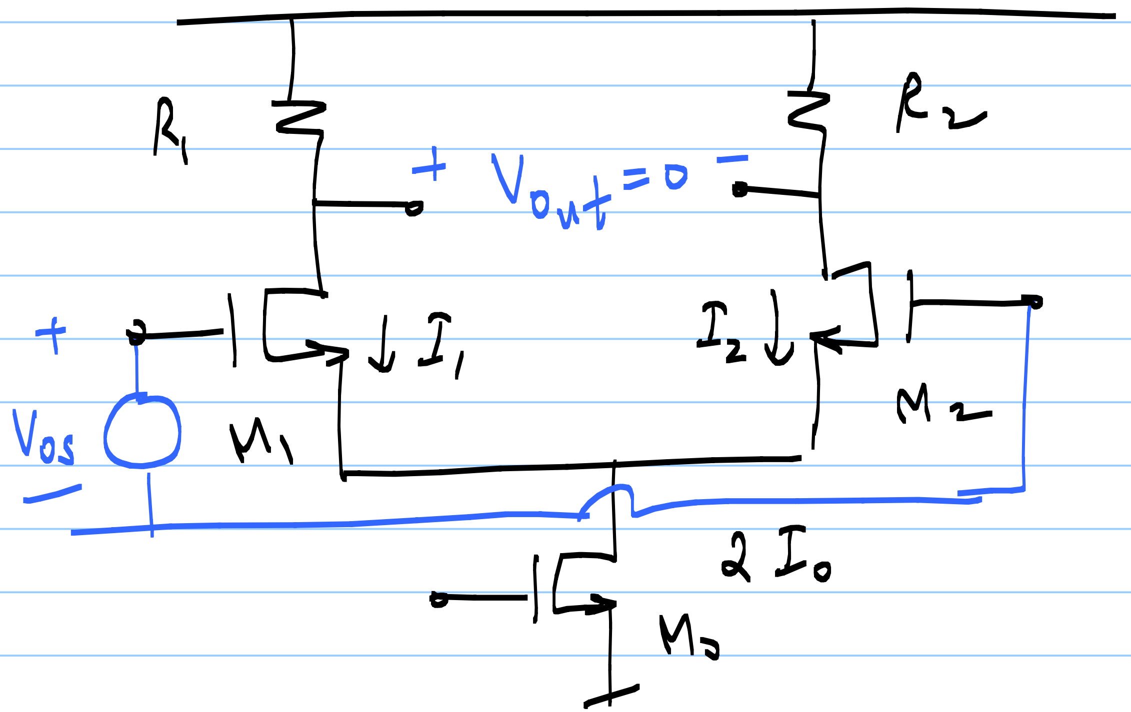
Lec 10



$R_1 \neq R_2$

$\left(\frac{W}{L}\right)_1 \neq \left(\frac{W}{L}\right)_2$

$V_{T_1} \neq V_T$

$\mu C_{ox} = \beta$

KVL

$V_{os} = V_{GS_1} - V_{GS_2}$ —— 1

$I_1 R_1 = I_2 R_2$ —— 2 → $V_{out} = 0$

$$V_{os} = V_{T_1} + \sqrt{\frac{2I_1}{\beta\left(\frac{W}{L}\right)_1}} - \left(V_{T_2} + \sqrt{\frac{2I_2}{\beta (W/L)_2}}\right)$$

$$R = \frac{R_1 + R_2}{2} \quad ; \quad \Delta R = \frac{R_1 - R_2}{2}$$

$$\Rightarrow R_1 = R + \Delta R \quad ; \quad R_2 = R - \Delta R$$

$$V_{T_1} - V_{T_2} = \Delta V_T$$

$$(W/L) = \frac{(W/L)_1 + (W/L)_2}{2} \quad ; \quad \Delta(W/L) = \frac{(W/L)_1 - (W/L)_2}{2}$$

$$\left(\frac{W}{L}\right)_1 = (W/L) + \Delta(W/L) \quad ; \quad (W/L)_2 = (W/L) - \Delta(W/L)$$

$$V_{os} = \Delta V_T + \sqrt{\frac{2 I_1}{\beta\left[(W/L) + \Delta(W/L)\right]}} - \sqrt{\frac{2 I_2}{\beta\left[(W/L) - \Delta(W/L)\right]}}$$

$$I_1 R_1 = I_2 R_2$$

$$I_1 = I_0 + \Delta I \quad , \quad I_2 = I_0 - \Delta I$$

$$(I_0+\Delta I)(R+\Delta R) = (I_0-\Delta I)(R-\Delta R)$$

$$\cancel{I_0 R} + I_0\Delta R + \Delta I R + \cancel{\Delta I \Delta R}$$

$$= \cancel{I_0 R} - I_0 \Delta R - \Delta I R + \cancel{\Delta I \Delta R}$$

$$\frac{\Delta I}{I_0} = -\frac{\Delta R}{R}$$

$$V_{os} = \Delta V_T + \sqrt{\frac{2(I_0+\Delta I)}{\beta\left((W/L)+\Delta(W/L)\right)}} - \sqrt{\frac{2(I_0-\Delta I)}{\beta\left((W/L)-\Delta(W/L)\right)}}$$

$$= \Delta V_T + \sqrt{\frac{2I_0}{\beta(W/L)}}\left[\sqrt{\frac{1+\Delta I/I_0}{1+\frac{\Delta W/L}{W/L}}} - \sqrt{\frac{1-\Delta I/I_0}{1-\frac{\Delta W/L}{W/L}}}\right]$$

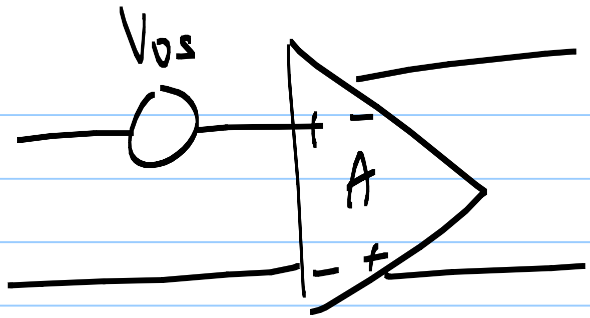
$$V_{OS} = \Delta V_T + V_{Dsat_{nom.}} \left[\left(1 + \frac{\Delta I}{2 I_0}\right)\left(1 - \frac{\Delta W/L}{2\, W/L}\right) - \left(1 - \frac{\Delta I}{2 I_0}\right)\left(1 + \frac{\Delta W/L}{2\, W/L}\right) \right]$$

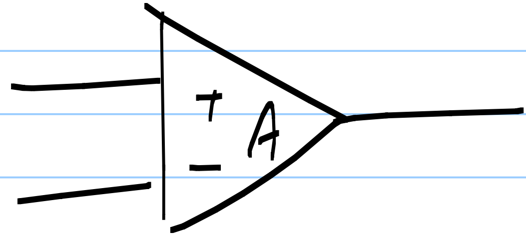
$$= \Delta V_T + V_{Dsat} \cdot \left[- \frac{\Delta W/L}{W/L} + \frac{\Delta I}{I_0} \right]$$

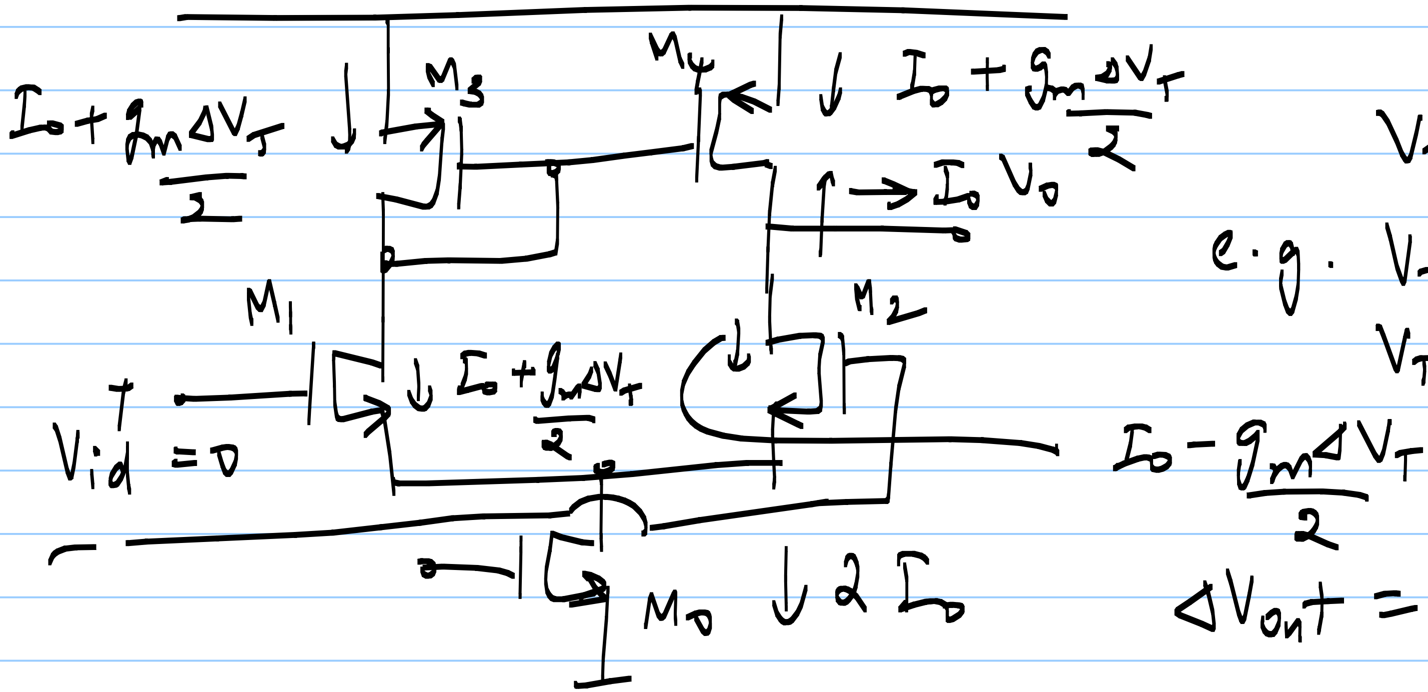
$$\boxed{V_{OS} = \Delta V_T - V_{Dsat,1} \left(\frac{\Delta W/L}{W/L} + \frac{\Delta R}{R} \right)}$$

$$\sigma_{OS}^2 = \sigma_{V_T}^2 + V_{Dsat,1}^2 \left[\sigma^2_{\frac{\Delta W/L}{W/L}} + \sigma^2_{\Delta R/R} \right]$$

$$= \frac{A_{V_T}^2}{W \cdot L} + V_{Dsat,1}^2 \left(\frac{A_{W/L}^2}{W \cdot L} + \frac{A_R^2}{W_R L_R} \right)$$







$I_o = g_m \Delta V_T$

$V_{T_2} - V_{T_1} = \Delta V_T$

e.g. $V_{T_1} < V_{T_2}$

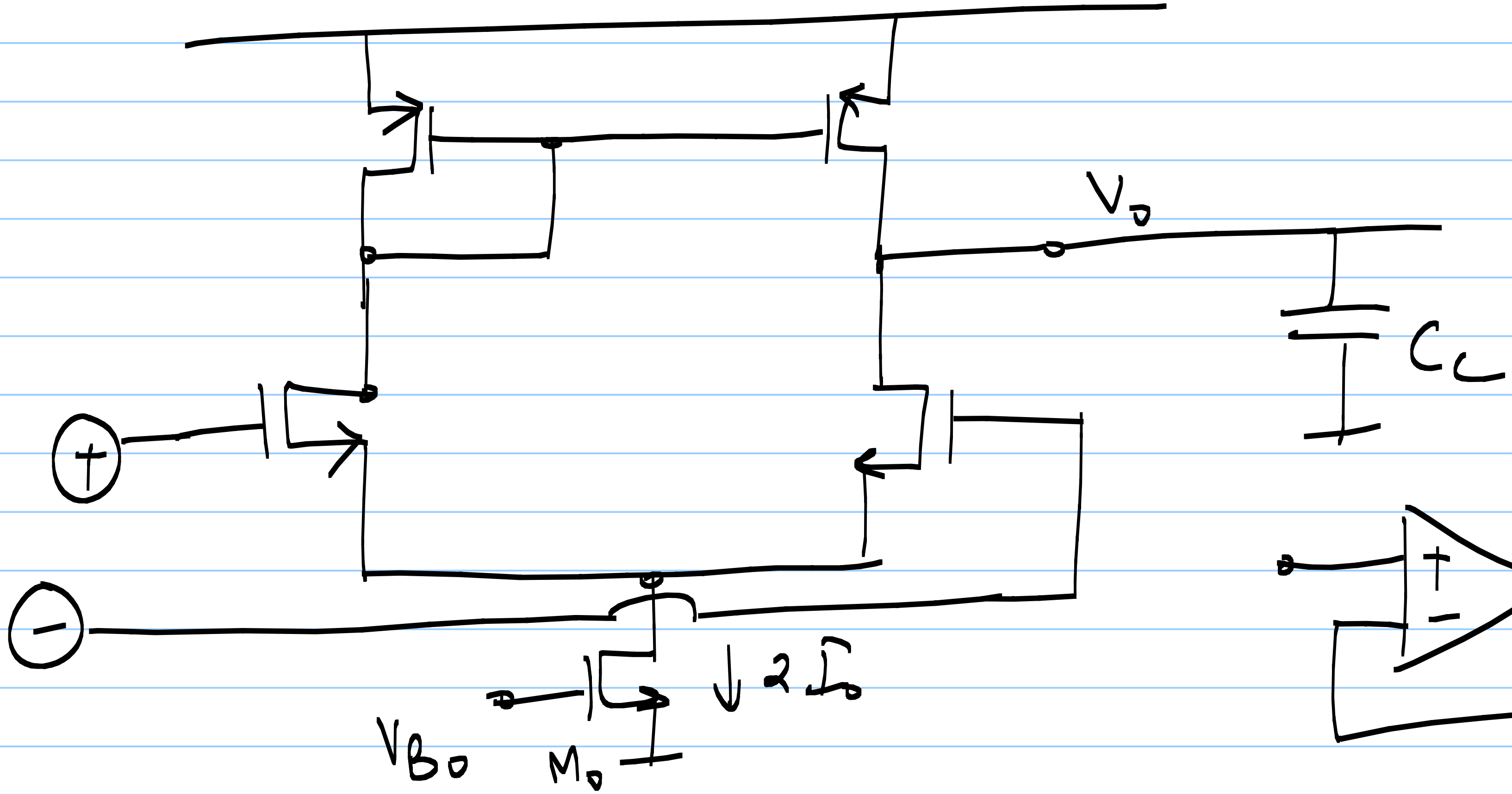
$V_{T_1} = V_T - \frac{\Delta V_T}{2}$

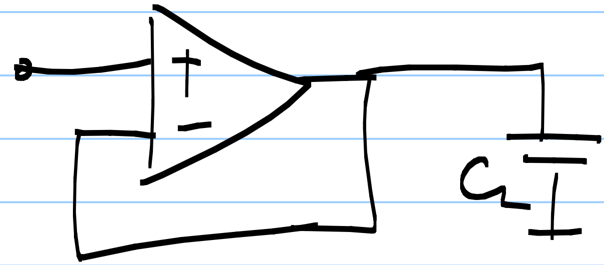
$\Delta V_{out} = g_m \Delta V_T \cdot r_{out}$

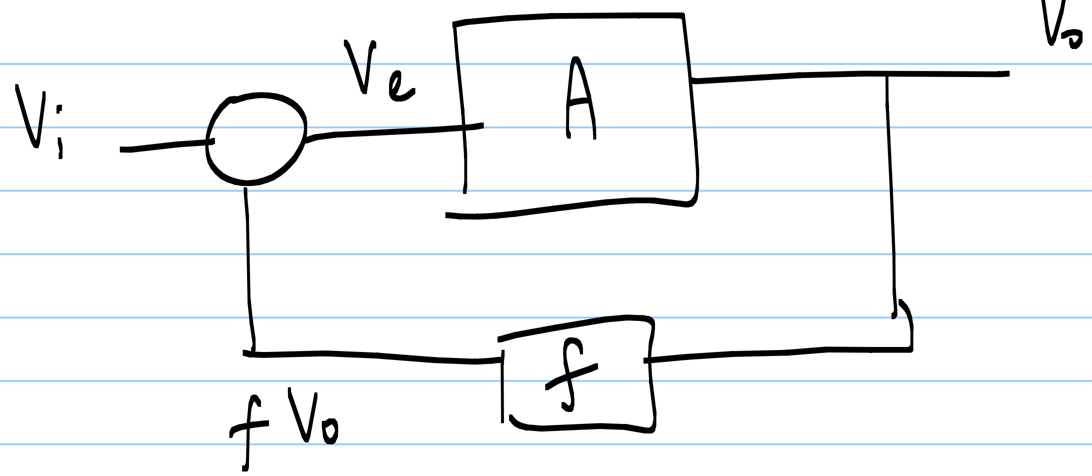
expected $V_{out} = V_{DD} - V_{SG_{34}}$

V_{os} = voltage to be applied @ input so that $\Delta V_{out} = 0$

HW : V_{os} for 1-stage opamp assuming mismatch in $V_{T_1} \leftrightarrow V_{T_2}$ & $V_{T_3} \leftrightarrow V_{T_4}$ only







$$\left|\frac{V_o}{V_i}\right| \approx \frac{1}{f}$$

$$Lh = Af$$

stability depends on $|Af|$ & $\angle Af$

$f = 1$ is worst-case

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Lec 11

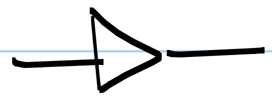
1-stage opamp datasheet

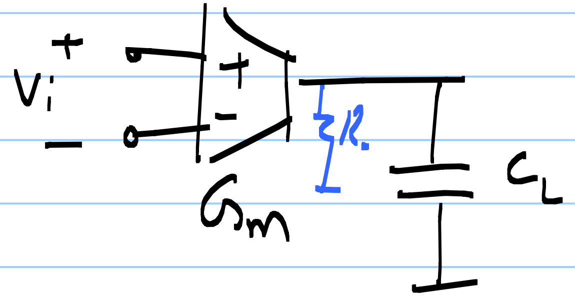
(Not recorded)

4/2/20

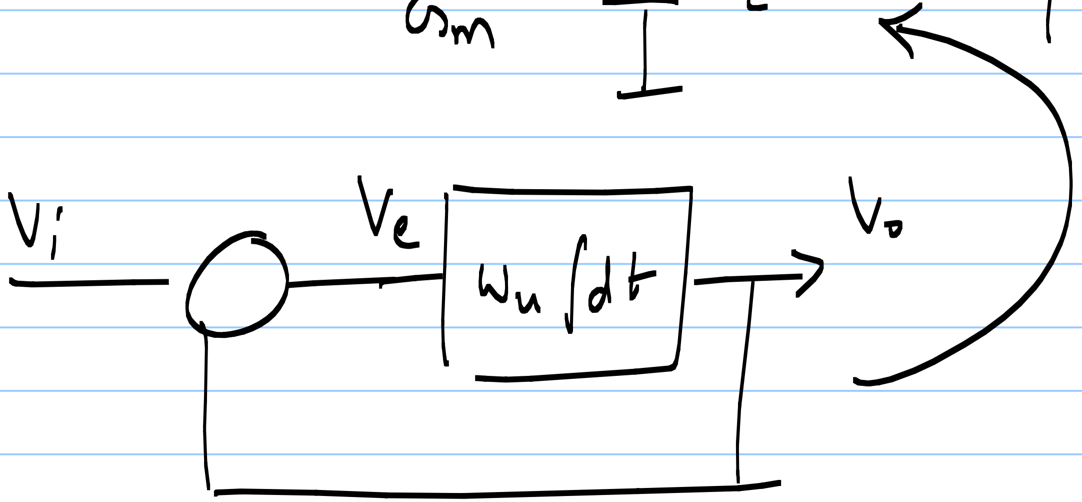
Lec 12

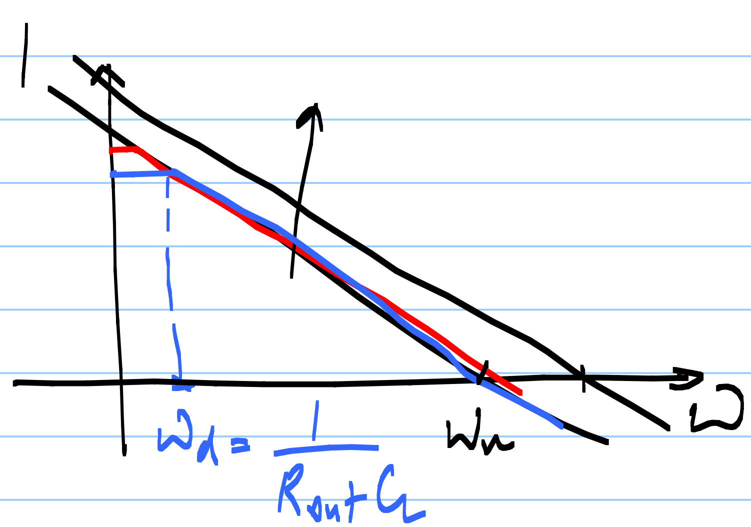
Telescopic Opamp data sheet

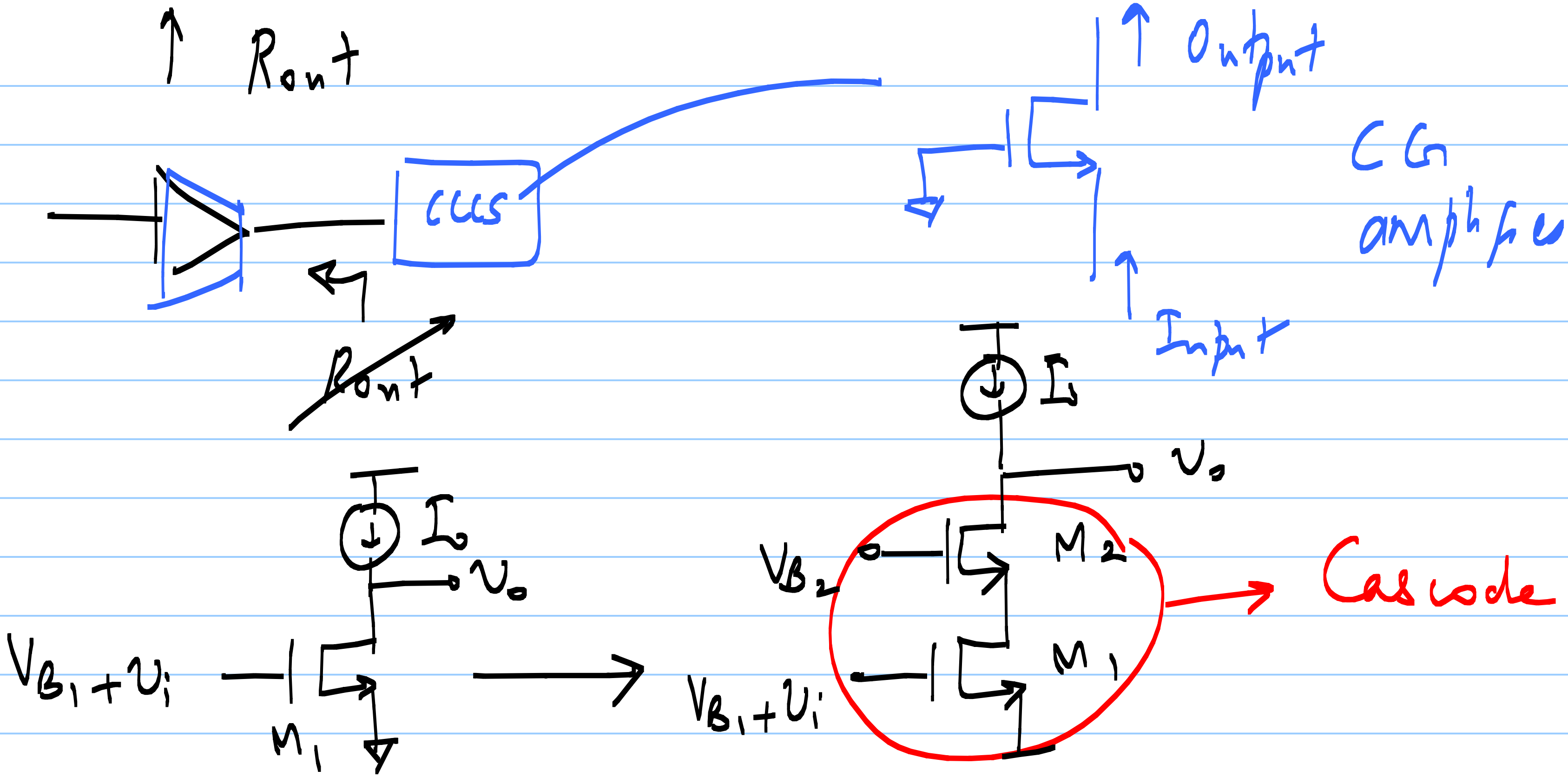




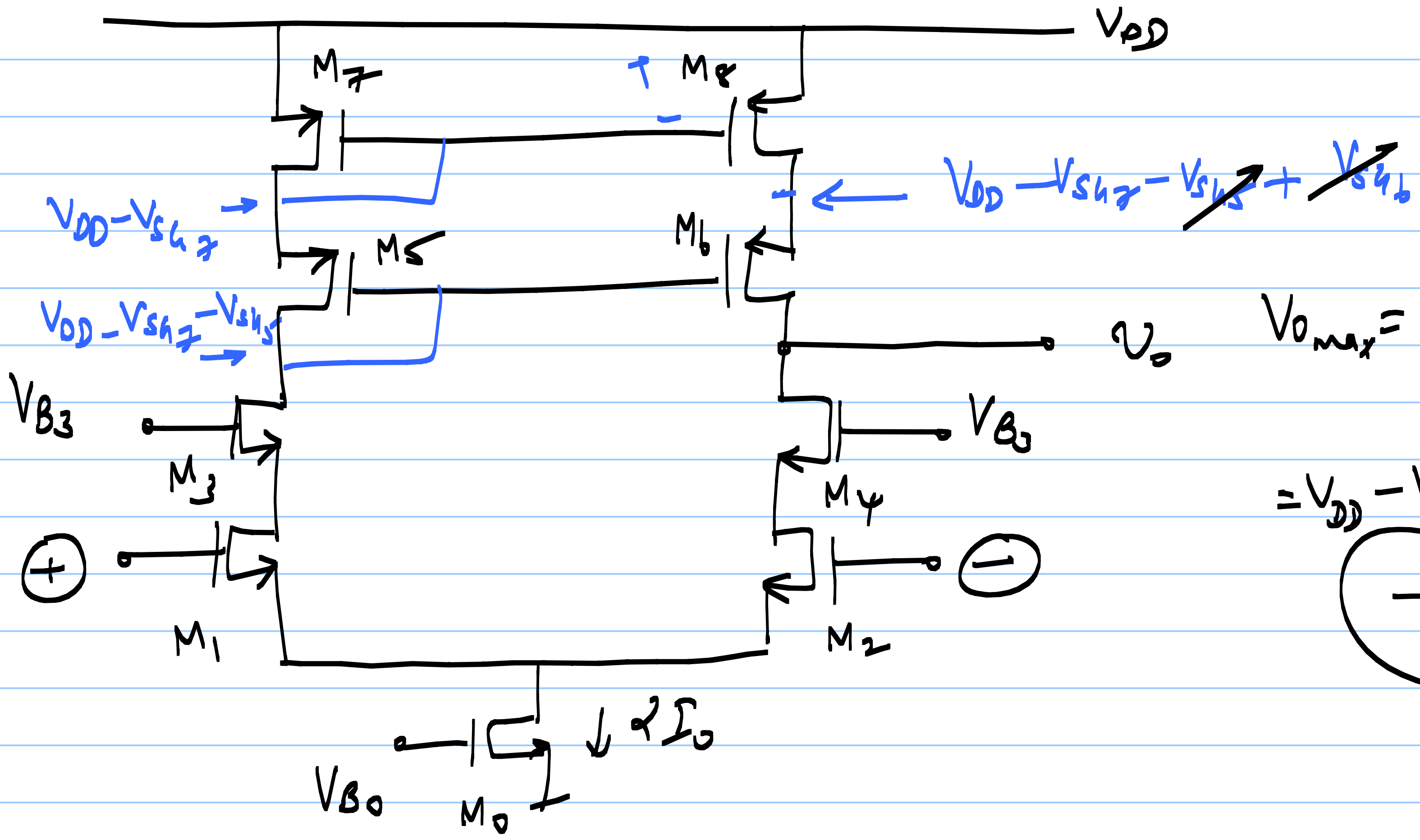
$$\omega_u = \frac{G_m}{C_L}$$





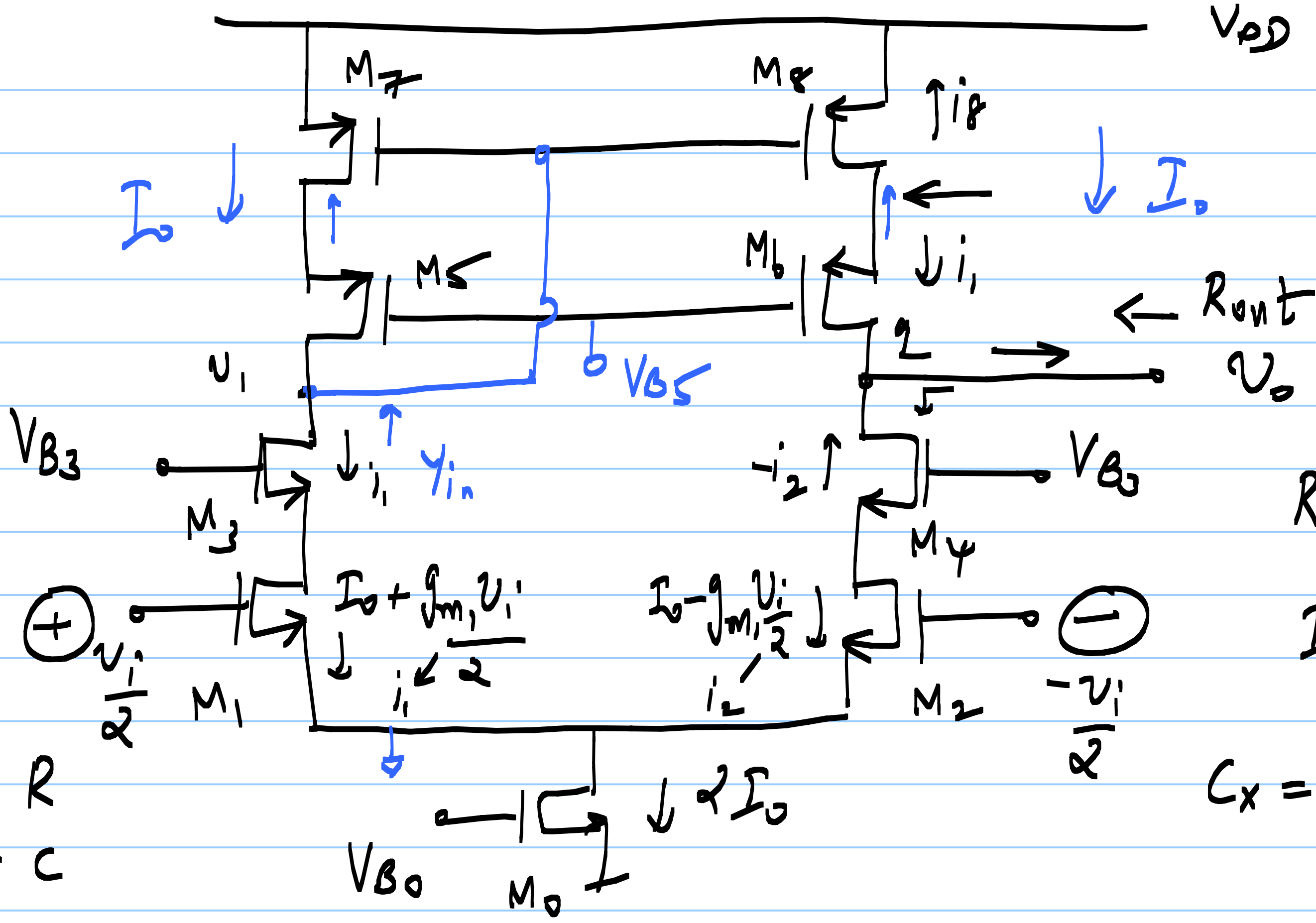


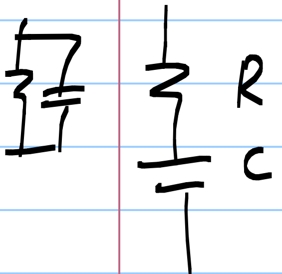
Rout
CCCS
Rout
Output
Input
CG amplifier
I0
v0
VB1 + vi
M1
VB2
M2
Cascode



$V_{O_{max}} = V_{DD} - V_{SG_7} - V_{SD_{sat_6}}$

$= V_{DD} - V_{SD_{sat_7}} - V_{SD_{sat_1}} - V_{T_7}$





$V_{B5} \le V_{DD} - V_{SDsat8} - V_{SG6}$

$Re(Y_{in}) = g_{m7}$

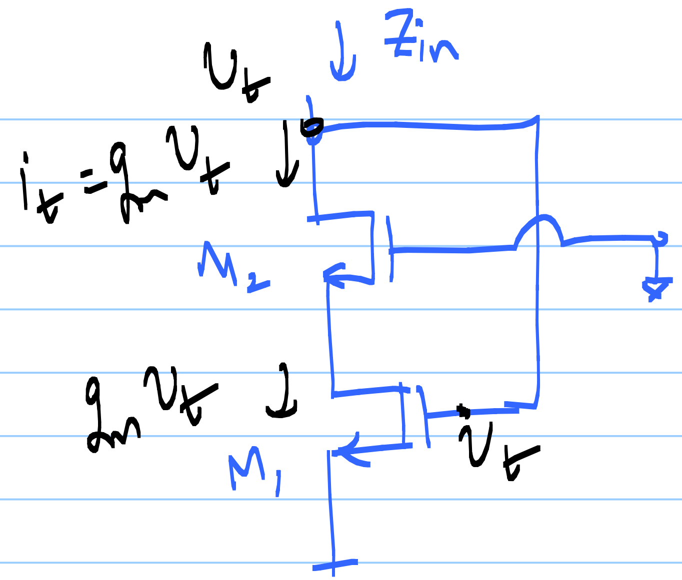
$Im(Y_{in}) = s C_x$

$C_x = C_{gs7} + C_{gs8} + C_{db3} + C_{db5}$

@ low freq., $v_1 = -\dfrac{i_1}{g_{m7}}$

$i_8 = g_{m8} \cdot v_1 = -i_1$

$i_{out} = i_1 - i_2 = g_{m1} v_i \Longrightarrow G_m = g_{m1}$



$$Z_{in} \approx \frac{1}{g_{m_1}}$$

$$R_{out} = r_{up} \parallel r_{dn} \approx (g_{m6} r_{ds_6} r_{ds_8}) \parallel (g_{m4} r_{ds_4} r_{ds_2})$$

$$\underset{\text{(telescopic)}}{R_{out}} \gg \underset{\text{(1-stage)}}{R_{out}}$$

Data sheet

1) DC gain $= g_{m_1} R_{out}$

$$R_{out} = r_{up} \| r_{dn} \approx (g_{m6} r_{ds_6} r_{ds_8}) \| (g_{m4} r_{ds_4} r_{ds_2})$$

2) $\omega_u = g_{m_1} / C_L$

3) Dominant pole $\omega_d = \dfrac{1}{R_{out} C_L}$

4) ND poles & zeroes (next class)

5) ICMR $= \left\{ V_{Dsat_0}\Big|_{2I_0} + V_{GS_1}\Big|_{I_0},\ V_{B_3} - V_{GS_3}\Big|_{I_0} + V_{T_1} \right\}$

6) $OCMR = \left\{ V_{B3} - V_{T3} ,\quad V_{B5} + V_{T6} \right\}$

7) $\overline{e_n} = \dfrac{16kT}{3 g_{m1}^2} \left[g_{m1} + g_{m7} \right]$

Same as 1-stage opamp @ low freq.

@ high freq., noise of $M_3 - M_4$ & $M_5 - M_6$ add to $\overline{e_n}$

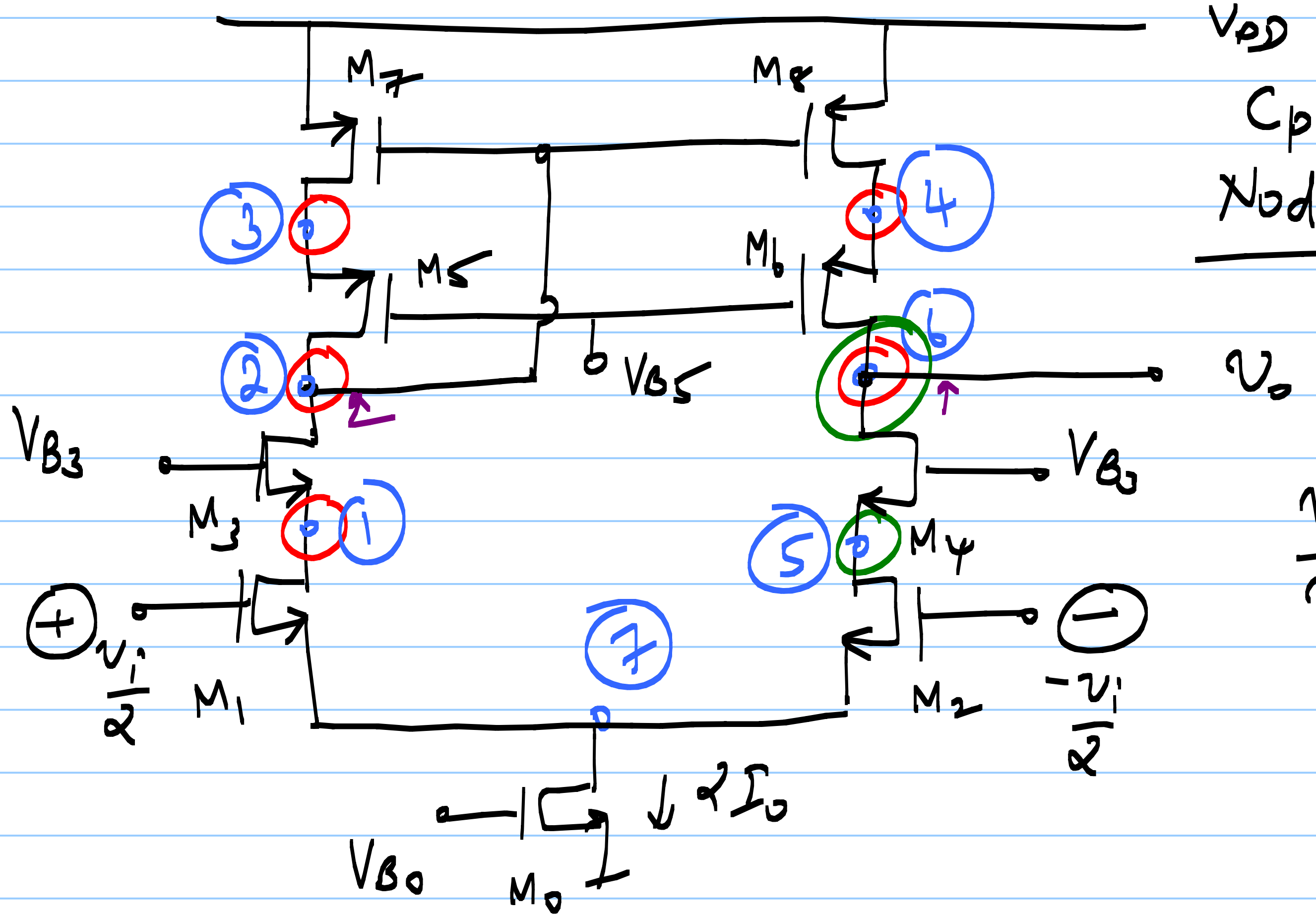
8) $\sigma_{os}^2 = \sigma_{V_{T1-2}}^2 + \dfrac{g_{m7}^2}{g_{m1}^2} \cdot \sigma_{V_{T7-8}}^2$

9) Slew rate $= \pm \dfrac{2 I_0}{C_L}$

05/2/20

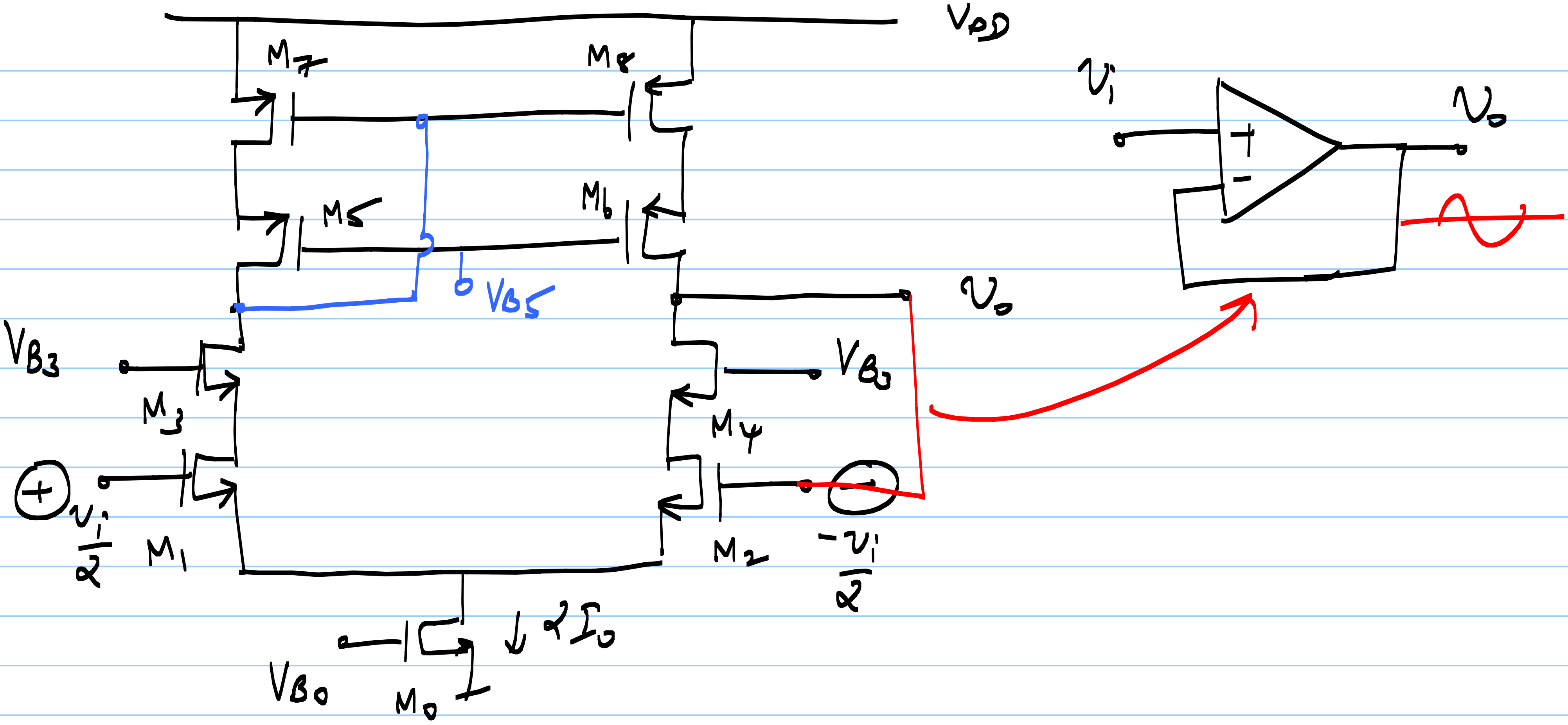
Lec 13

4) ND poles & zeroes of telescopic opamp

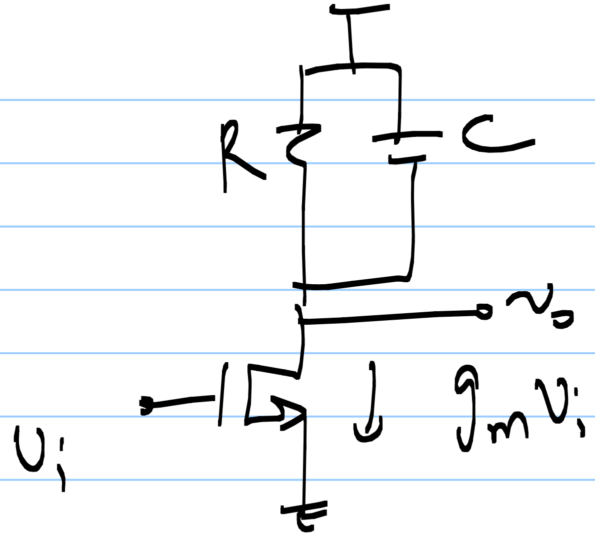


Cpar @ Node 7 : affects A_{cm} & CMRR

$$\frac{v_o}{v_{id}}(s) = \frac{N(s)}{D(s)}$$



V_{DD}
M_7
M_8
M_5
M_6
V_{B5}
V_{B3}
M_3
M_4
v_o
M_1
M_2
$\frac{v_i}{2}$
$-\frac{v_i}{2}$
$2I_0$
V_{B0}
M_0
v_i
v_o
+
−



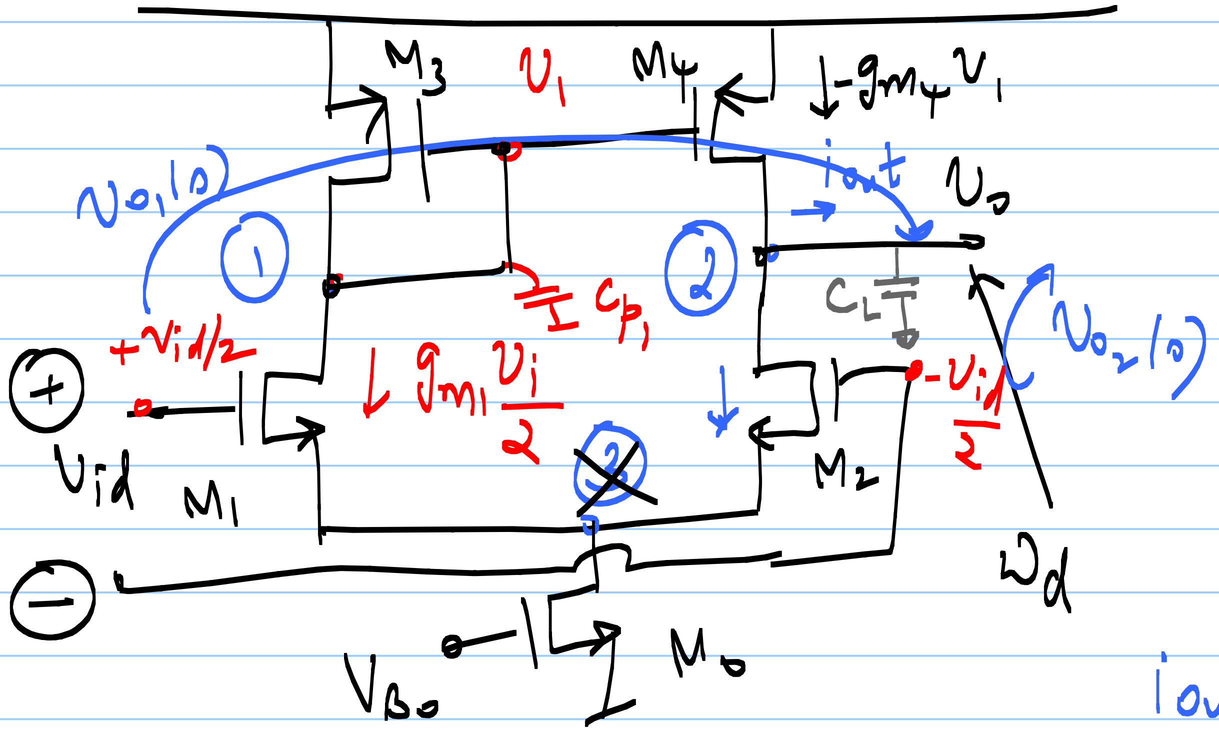
$$\frac{v_o}{v_i}(s) = -\frac{A_o}{1+\frac{s}{\omega_p}}$$

$A_o \rightarrow g_m \cdot R$

$$\omega_p = \frac{1}{RC}$$

$$v_o = -g_m v_i \cdot \frac{R \cdot \frac{1}{sC}}{R + 1/sC}$$

$$= -g_m v_i \cdot \frac{R}{1+\underbrace{sCR}_{1/\omega_p}}$$

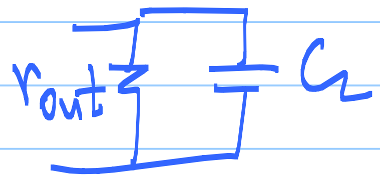


$$\frac{v_o}{v_i}(s) = \frac{N(s)}{D(s)}$$

1 zero

degree 2

i_{out} flows through



$$v_o(s) = v_{o1}(s) + v_{o2}(s)$$

$$v_{o2}(s) = +g_{m2}\frac{v_i}{2}\times\left(\frac{r_{out}}{1+\underbrace{s\,r_{out}C_L}_{\omega_{p2}}}\right)$$

$$v_{o_1}(s) = -g_{m_1}\frac{v_i}{2} \cdot \frac{\frac{1}{g_{m_3}} \cdot \frac{1}{sC_{p_1}}}{\frac{1}{g_{m_3}} + \frac{1}{sC_{p_1}}}$$

$$= -\frac{g_{m_1}}{g_{m_3}}\,\frac{v_i}{2} \cdot \frac{1}{1 + s\underbrace{\frac{C_{p_1}}{g_{m_3}}}_{\omega_{p_1} = \frac{g_{m_3}}{C_{p_1}}}}$$

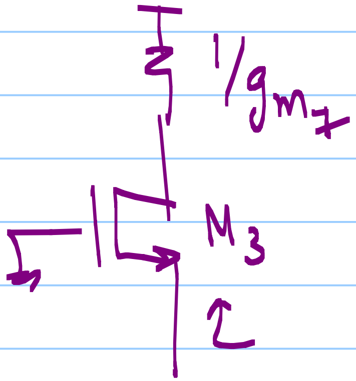
$$v_{o_1}(s) = g_{m_1}\frac{v_i}{2} \cdot \frac{1}{1 + s/\omega_{p_1}} \cdot \frac{r_{out}}{1 + s/\omega_{p_2}}$$

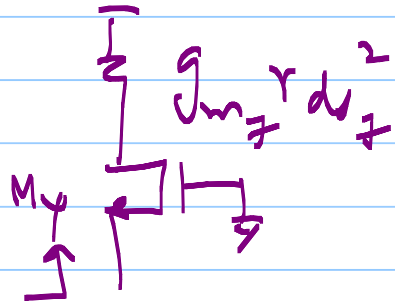
$$v_o(s) = g_{m_1} r_{out} \frac{v_i}{2}\left[\frac{1}{1 + s/\omega_{p_2}} + \frac{1}{(1 + s/\omega_{p_1})(1 + s/\omega_{p_2})}\right]$$

$$\frac{v_o}{v_i} = \frac{A_o}{2}\left[\frac{1}{(1+s/p_1)(1+s/p_2)\cdots} + \frac{1}{(\;)(\;)}\right]$$

<u>Telescopic opamp:</u>

$$\frac{v_o}{v_i}(s) = k\left[\underbrace{\frac{1}{(1+s/p_1)\cdots}}_{+\frac{v_i}{2}\text{ has } p_1,p_2,p_3,p_4,p_6} + \frac{1}{(1+s/p_5)(1+\frac{s}{p_6})}\right]$$

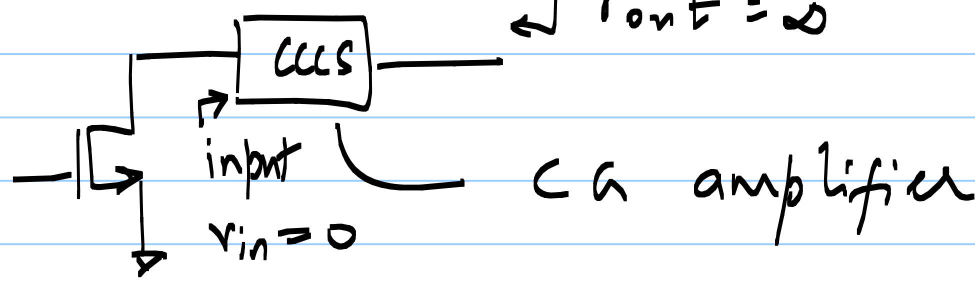


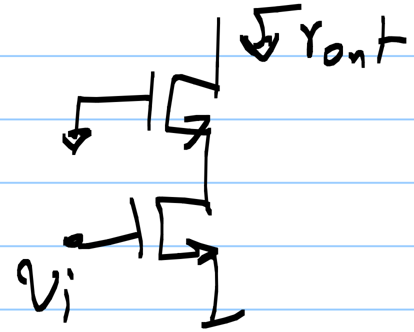


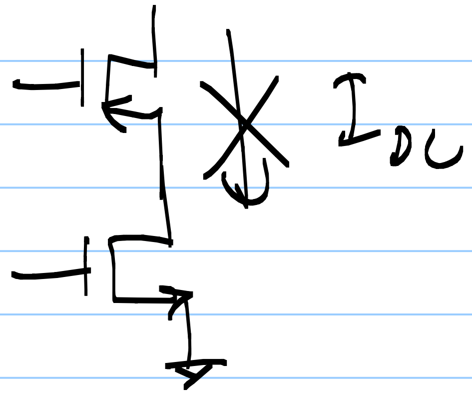
$p_1 \neq p_5$

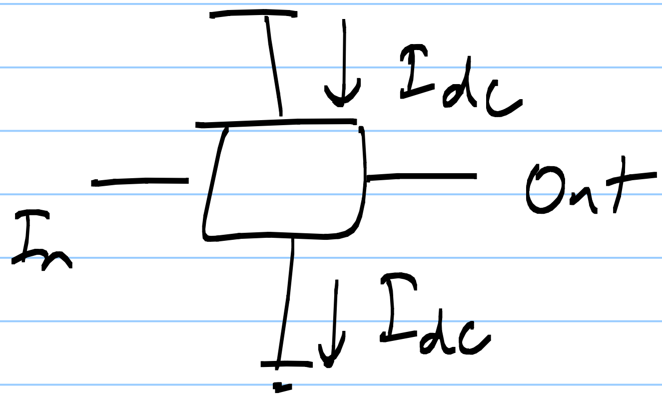
* 6 poles, 4 zeroes

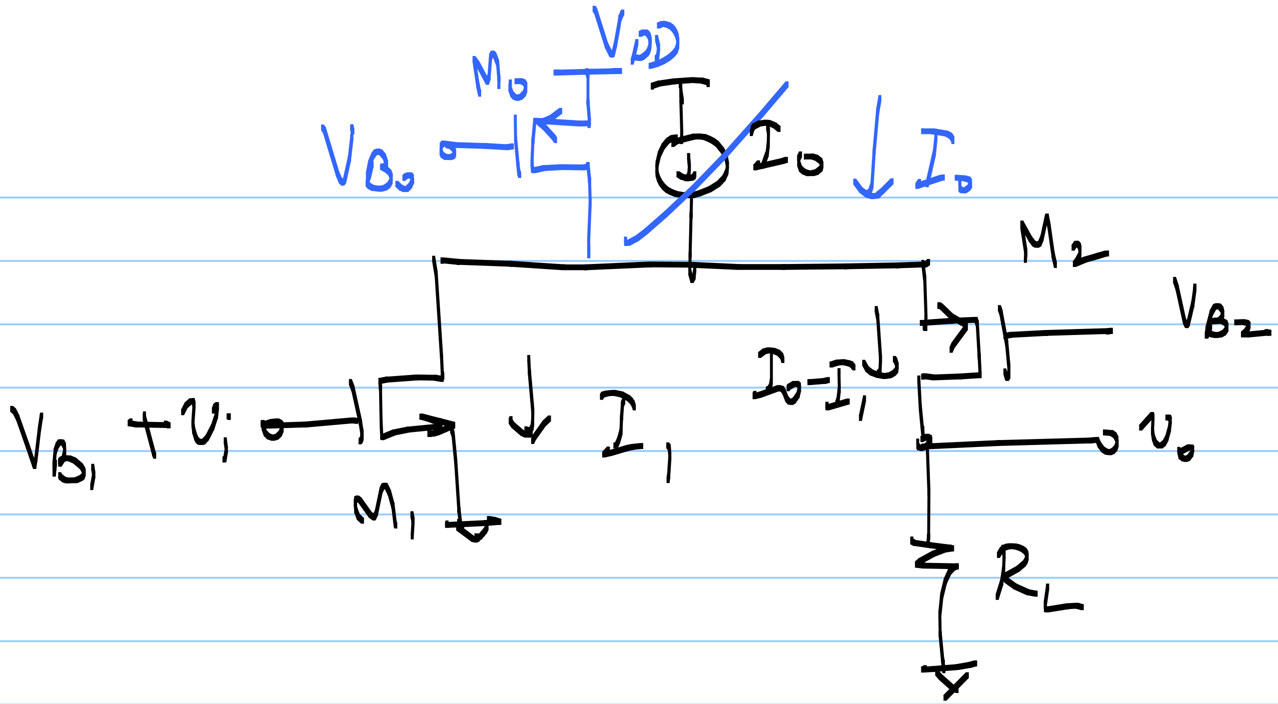
↳ 5 ND poles & 4 ND zeroes









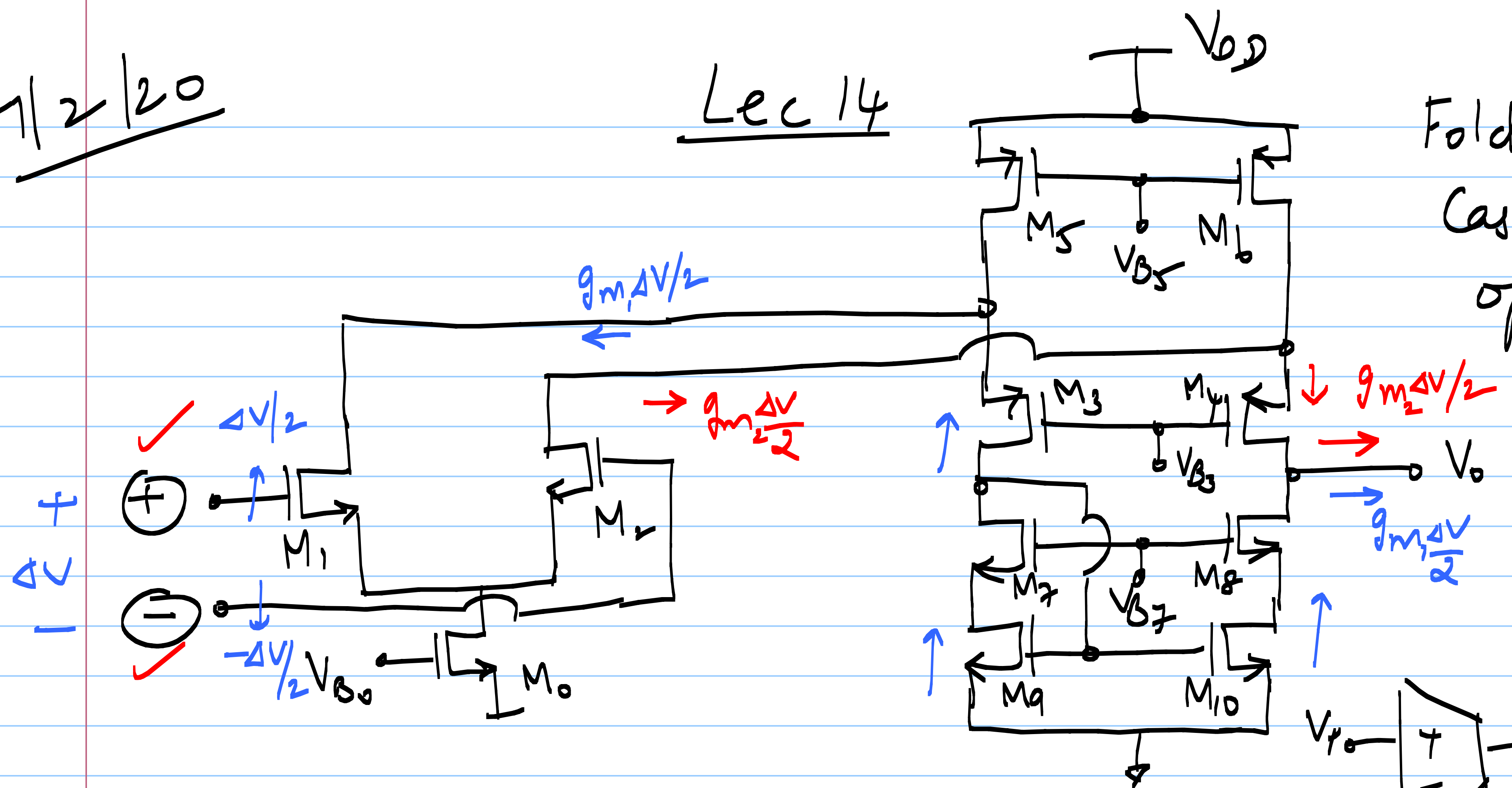


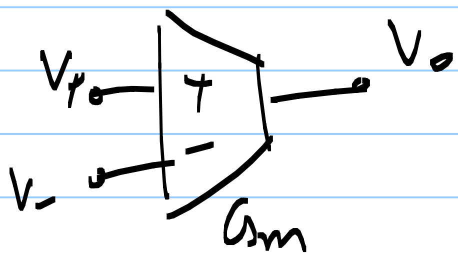
Folded cascode amplifier

7/2/20

Lec 14

Folded Cascode opamp





$G_m = g_{m_1}$

Folded Cascode Opamp datasheet

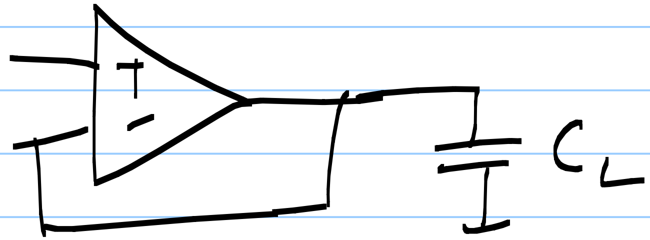
1) $G_m = g_{m_1}$;

$r_{out} = \left[g_{m_4} r_{ds_4} \left(r_{ds_2} \| \underbrace{r_{ds_6}}_{} \right) \right] \| \left[g_{m_8} r_{ds_8} r_{ds_{10}} \right]$

↳ additional term

gain = $g_{m_1} r_{out}$ – slightly lower than that of telescopic opamp

2)



$\omega_u = \dfrac{g_{m_1}}{C_L}$

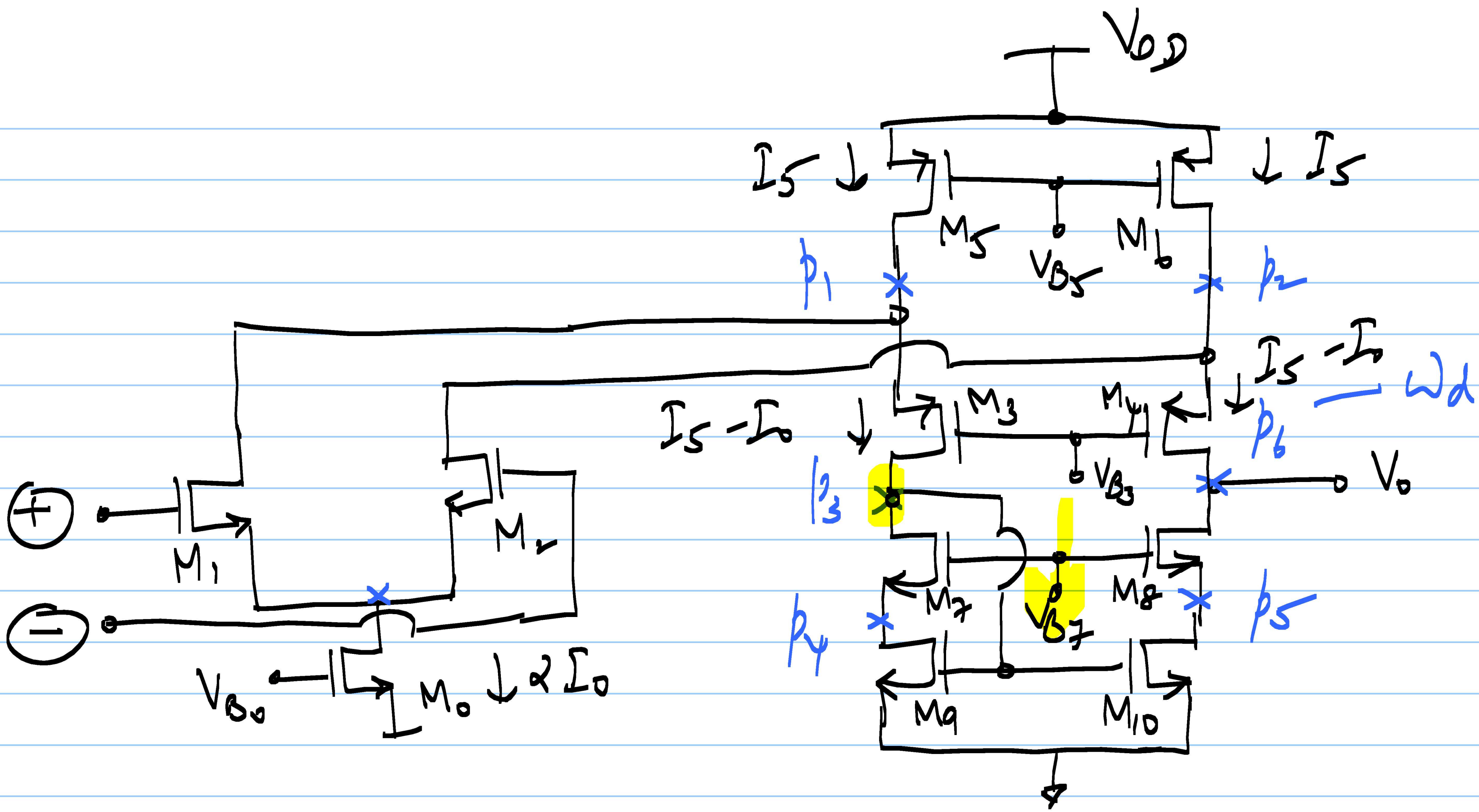
3) Dominant pole $\omega_d = \dfrac{1}{r_{out} C_L}$

4) ND poles & zeroes: 5 non-dominant poles @ $p_1 - p_5$

zeroes: 4 ND zeroes

$+V/2$ path: p_1, p_3, p_4, p_5, p_6

$-V/2$ path: p_2, p_6

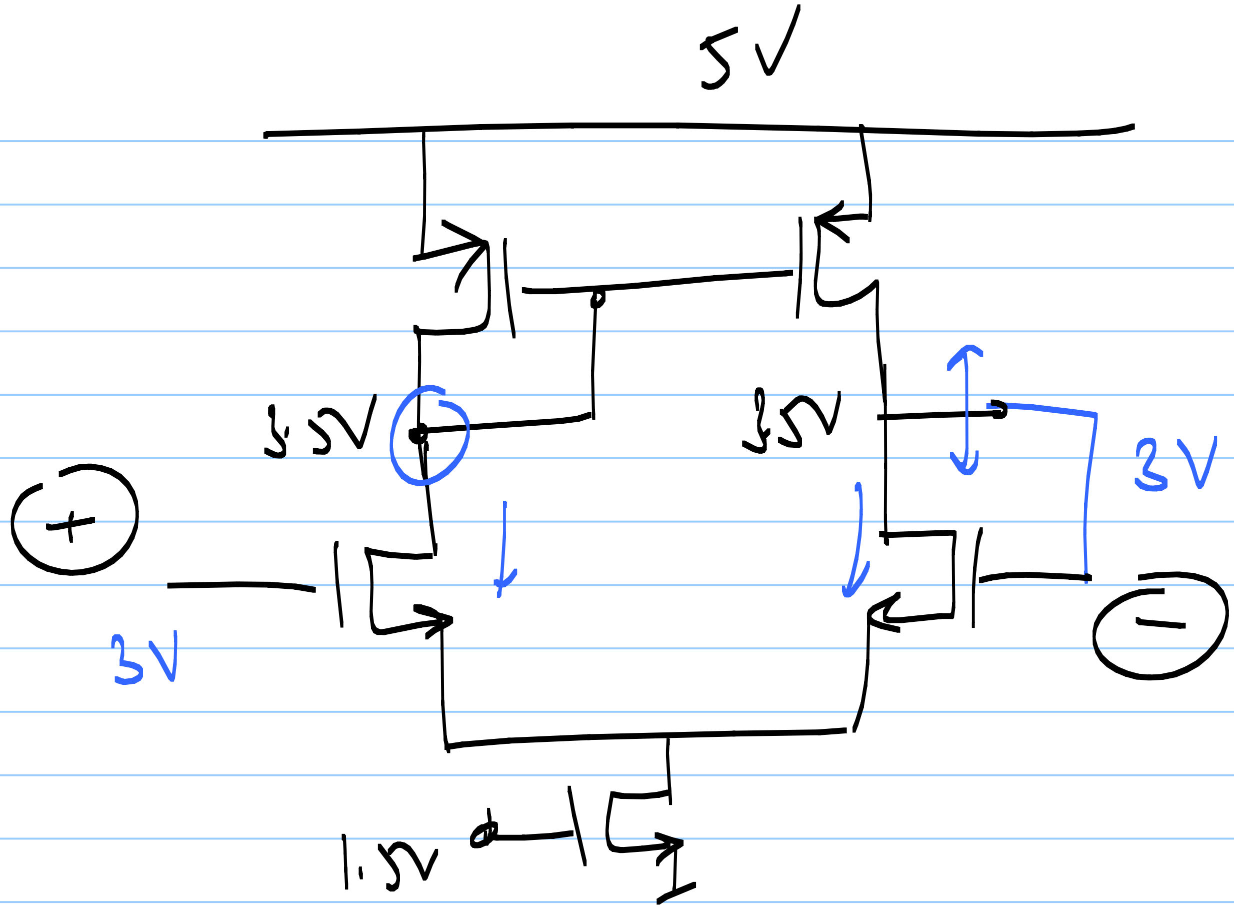


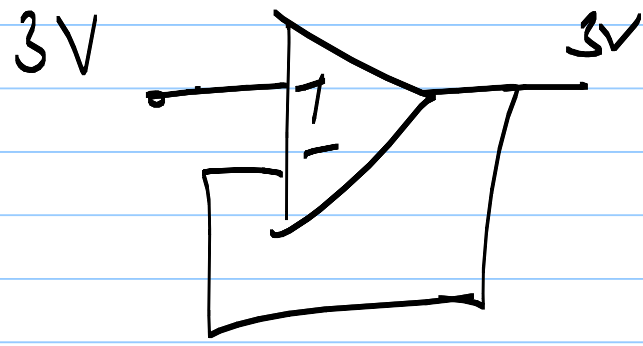
5) $$ICMR = \left\{ V_{Dsat_0}\Big|_{2I_0} + V_{GS_1}\Big|_{I_0} \; , \; V_{B_3} + V_{SG_3}\Big|_{I_5 - I_0} + V_{T_1} \right\}$$

6) <u>OCMR:</u> $\left\{ V_{B7} - V_{T8} \; , \; V_{B3} + V_{T4} \right\}$

$$\begin{cases} V_{B7\,min} = V_{Dsat_{10}}\Big|_{I_5 - I_0} + V_{GS_8}\Big|_{I_5 - I_0} \\ \\ V_{B3\,max} = V_{DD} - V_{SDsat_6} - V_{SG_4} \end{cases}$$

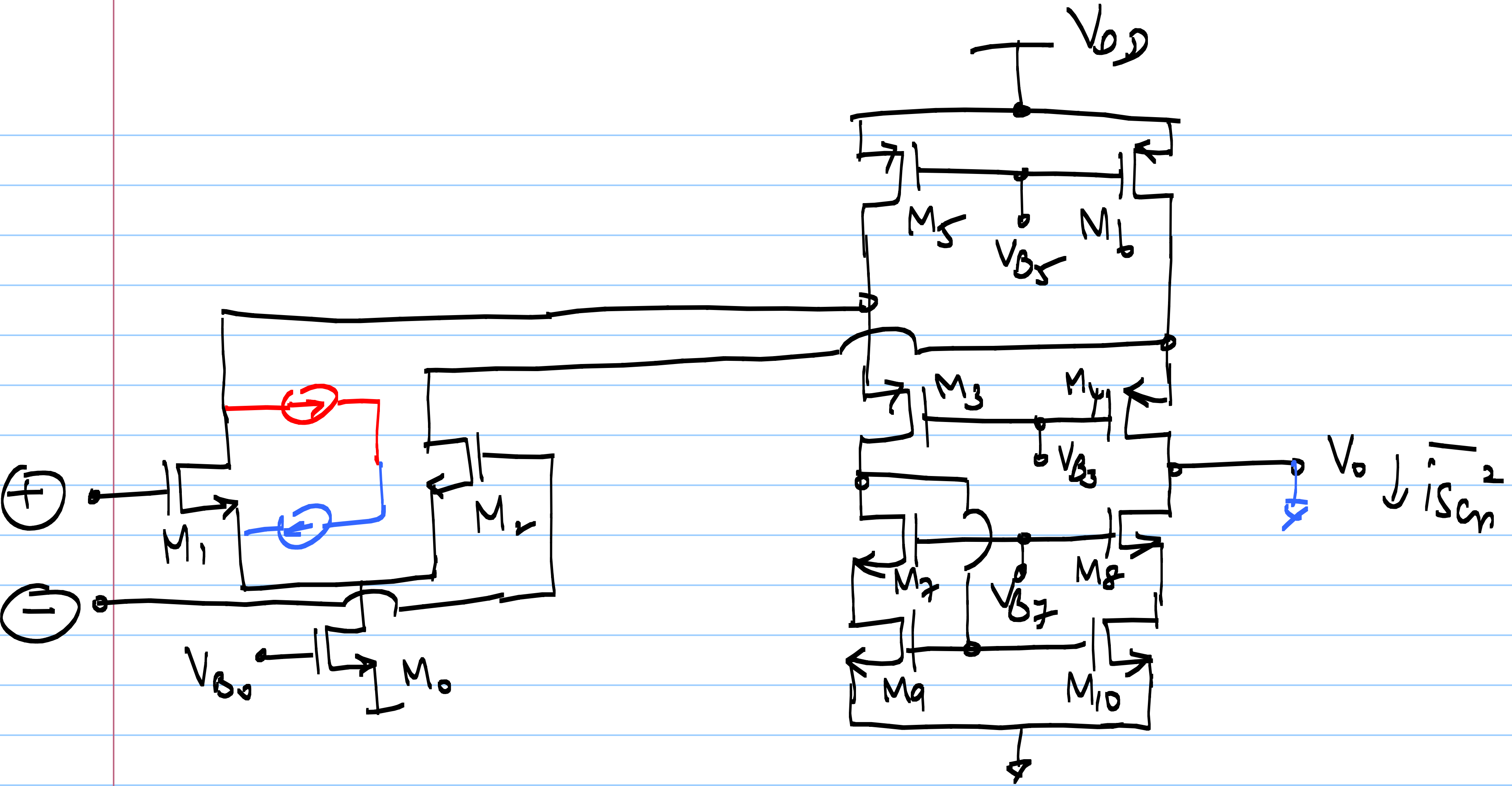
$$OCMR = \left\{ V_{Dsat_8} + V_{Dsat_{10}} \, , \; V_{DD} - V_{SDsat_6} - V_{SDsat_4} \right\}$$


5V
3.5V
3.5V
3V
+
−
3V
1.5V
I


3V
1
3V

7) $$\overline{e_n^2} = \frac{\overline{i_{sc_n}^2}}{g_{m_1}^2}$$

$$\overline{i_{sc_n}^2} = \overline{i_{n_1}^2} + \overline{i_{n_2}^2}$$

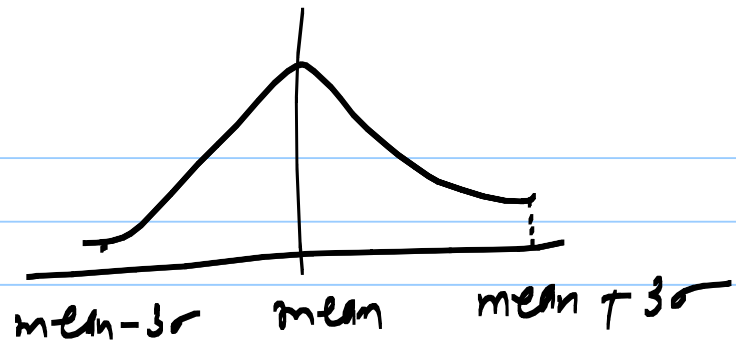


V_{DD}
M_5
M_6
V_{B5}
M_3
M_4
V_{B3}
V_o
$\overline{i_{Scn}^2}$
+
−
M_1
M_2
M_7
M_8
V_{B7}
M_9
M_{10}
V_{B0}
M_0

10/2/20

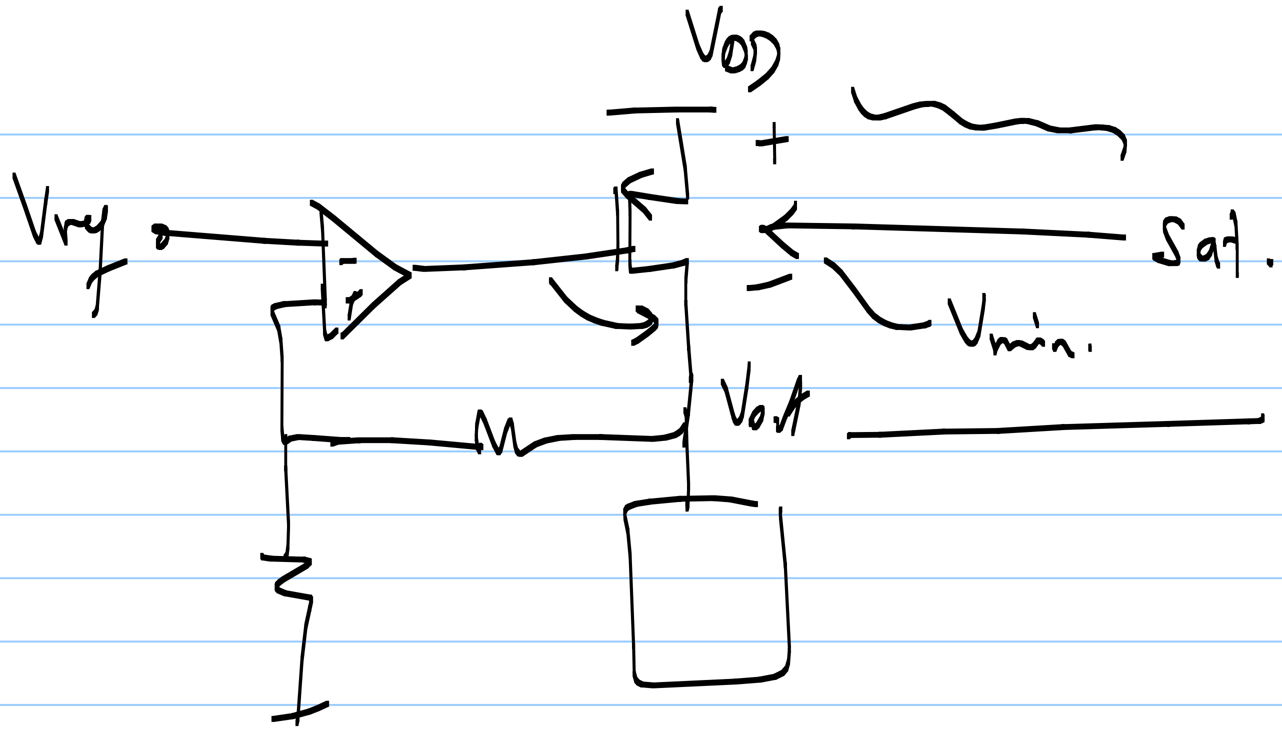
Lec 15

1) "Process corners" :

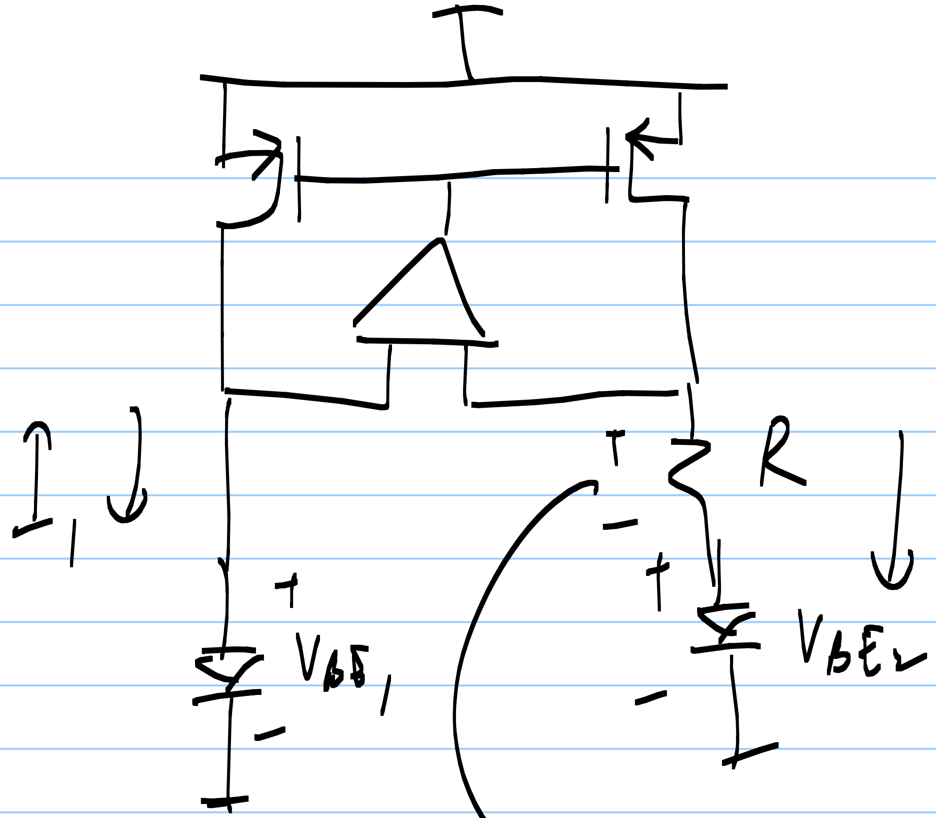


s t f

ss tt ff sf fs

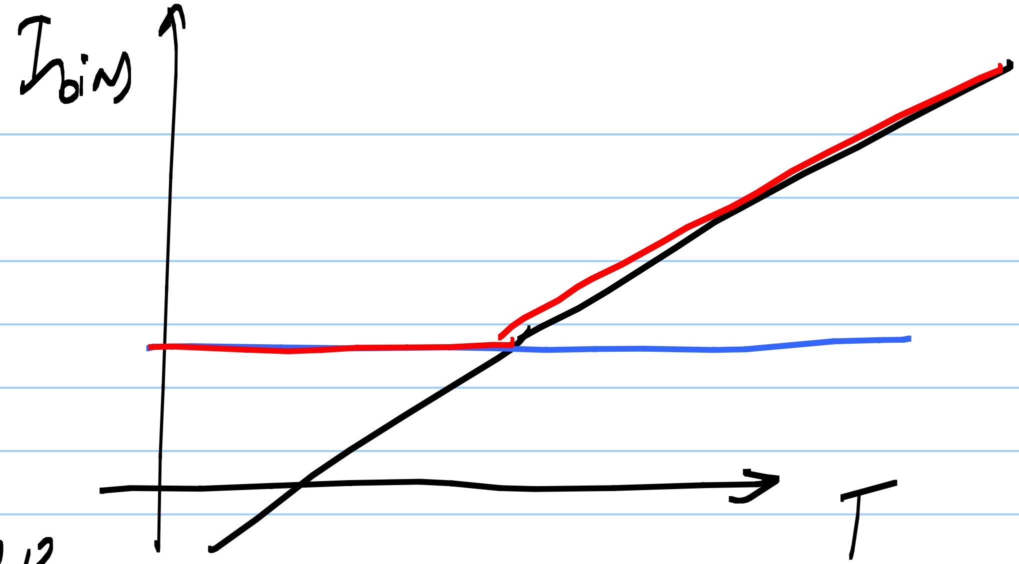


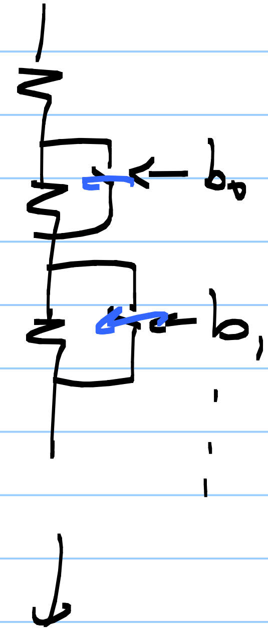
VDD
Vref
+
-
Sat.
Vmin.
Vout



$I_2 = PTAT \ (\propto T)$

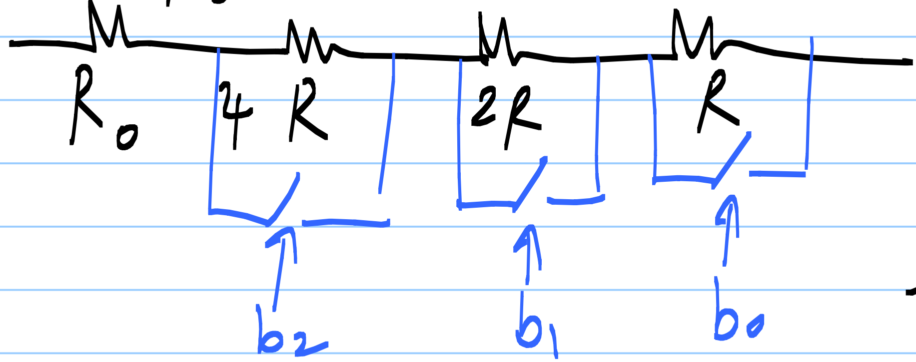
$V_R \propto kT/q$





$R_{max} = R_0 + 7R$

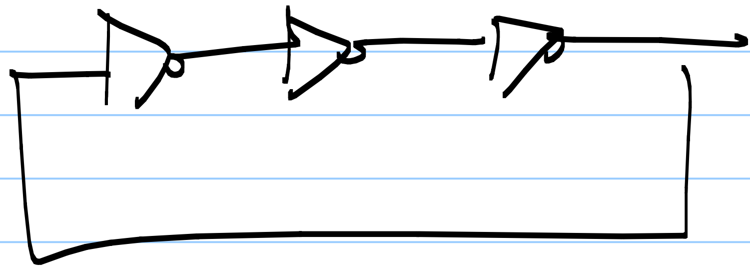
$R_{min} = R_0$

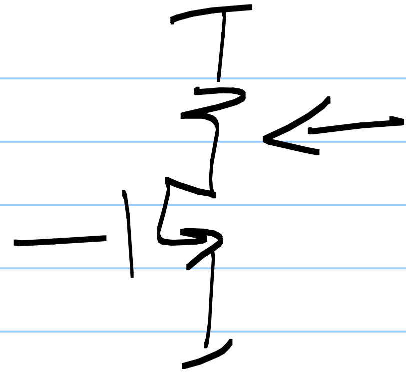


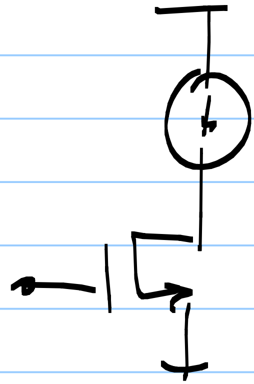
$b_{n-1} \cdots b_0$

$1\ 0\ 0 \cdots 0$

$= 011 \quad R_{nom} = R_0 + 4R$

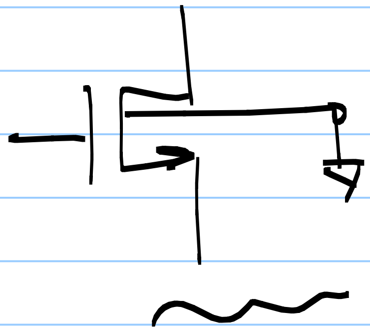


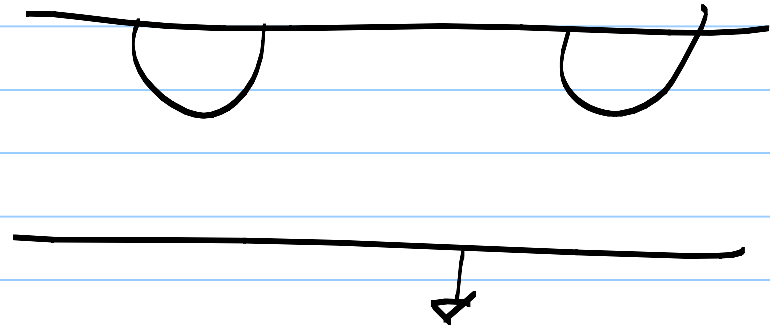




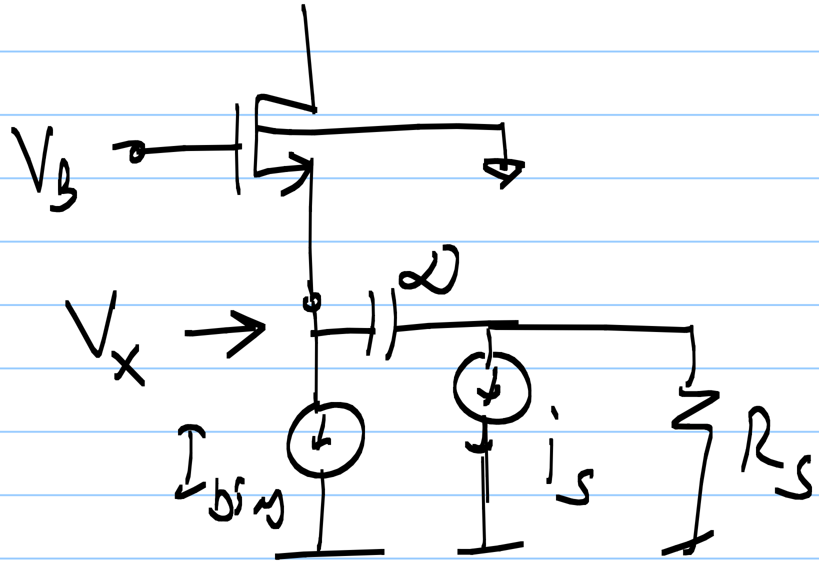
2) <u>g_{mb}</u>

$$V_T = V_{To} + \gamma\left[\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right]$$



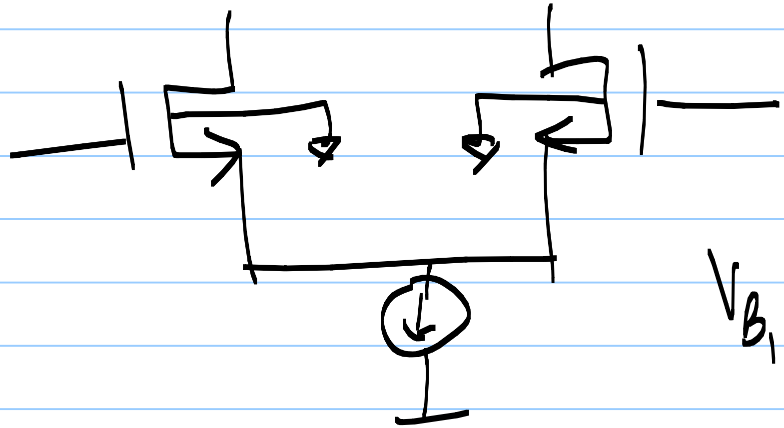


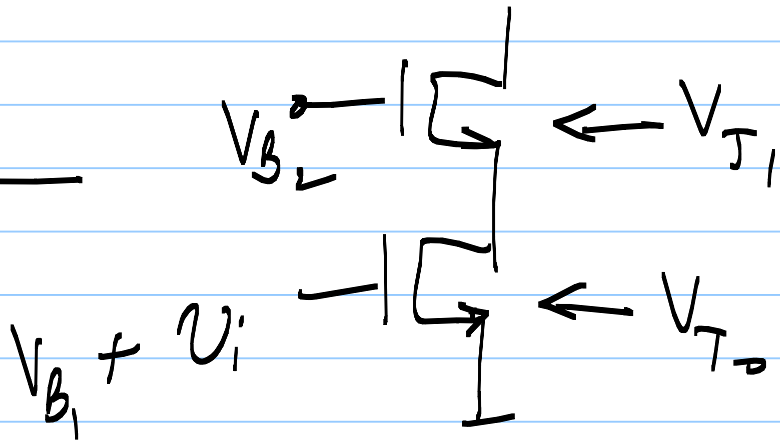
$$V_{SB} > 0 \Rightarrow V_T > V_{To}$$

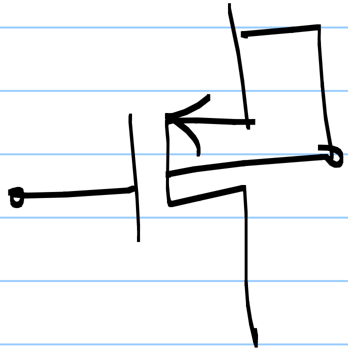


$$V_{SB} = V_x$$

$$V_T > V_{T0}$$

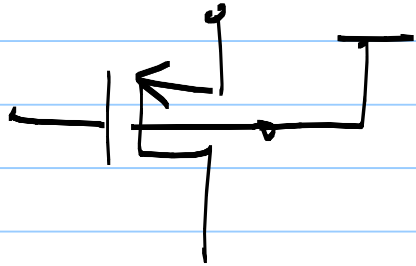


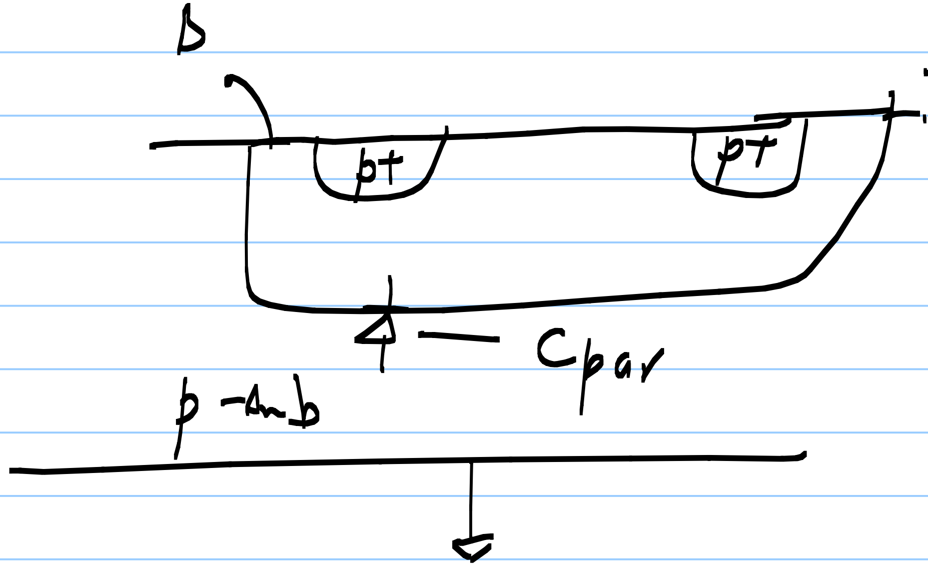


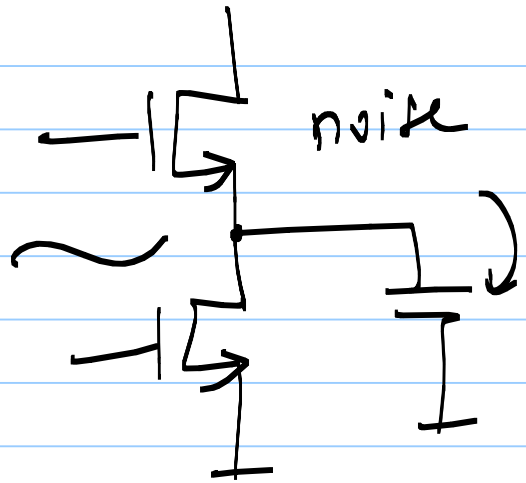


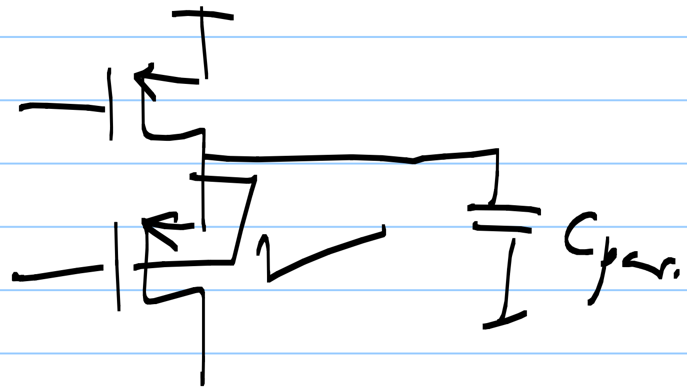
DC biasing circuits

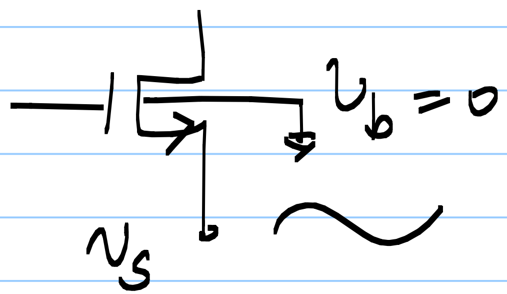
or low-freq. ckts







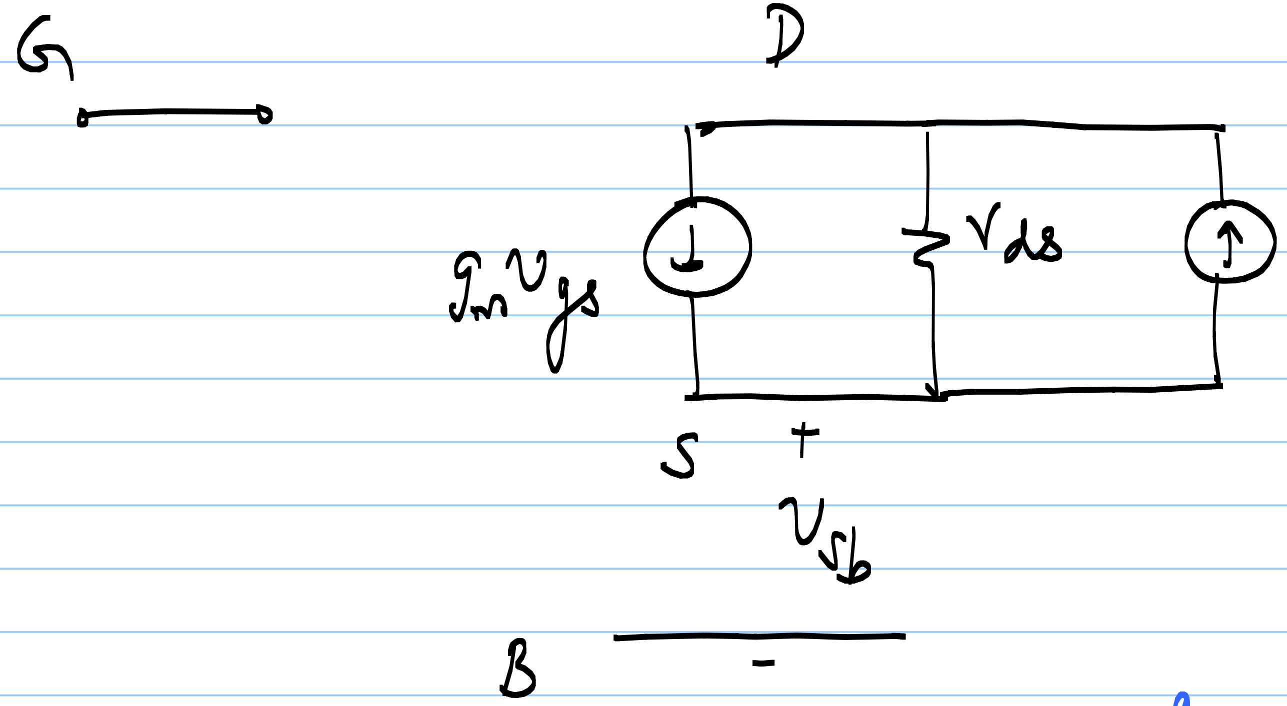




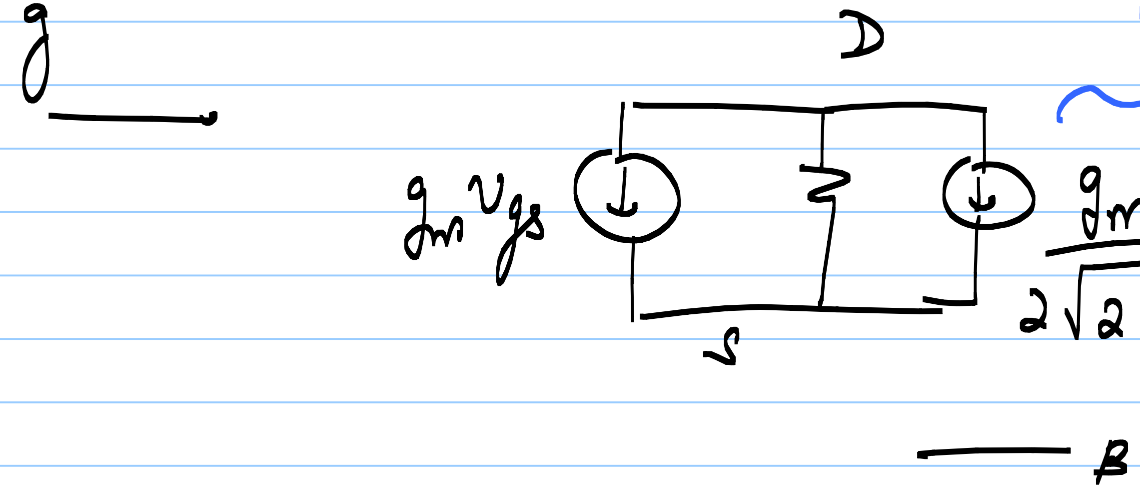
$$\frac{\partial V_T}{\partial V_{SB}} = \frac{\gamma}{2\sqrt{V_{SB}+2\phi_F}}$$

$$\frac{\partial I_D}{\partial V_{SB}} = \frac{\partial I_D}{\partial V_T} \cdot \frac{\partial V_T}{\partial V_{SB}} = \frac{-g_m \cdot \gamma}{2\sqrt{V_{SB}+2\phi_F}}$$

$$i_d = \frac{\partial I_D}{\partial V_{SB}} \cdot v_{sb}$$



$$\frac{g_m \cdot \gamma}{2\sqrt{2\phi_f + V_{SB}}} \cdot v_{sb}$$



$$\overbrace{\frac{g_m \gamma}{2\sqrt{2\phi_f V_{SB}}}}^{g_{mbs}} \cdot v_{bs}$$

$< 10\%$ of g_m

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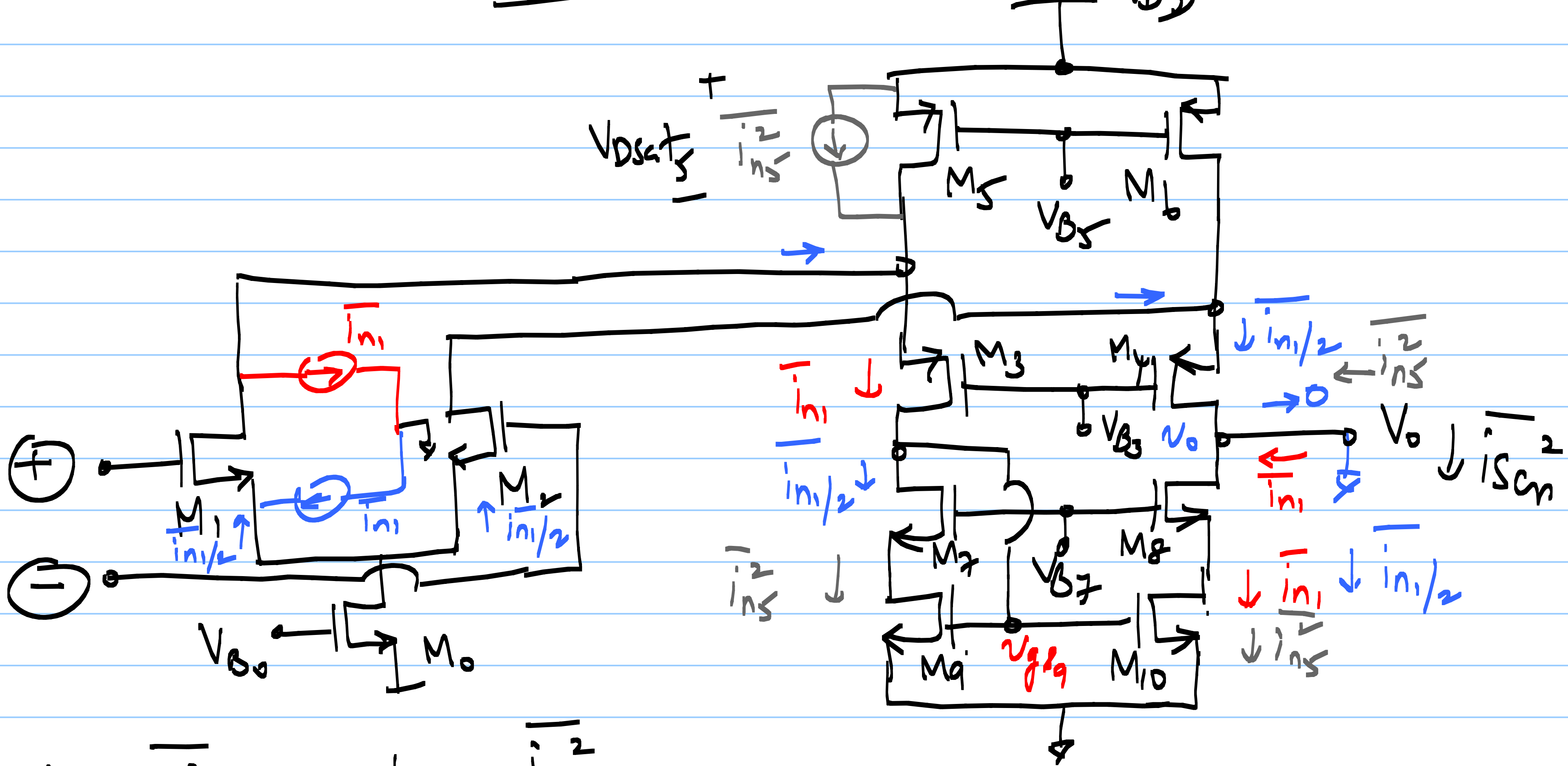
Lec 16



7) $$\overline{e_n^2} = \frac{1}{g_{m1}^2} \cdot \overline{i_{scn}^2}$$

$$= \frac{1}{g_{m1}^2}\left[\overline{i_{n1}^2} + \overline{i_{n2}^2} + \overline{i_{n5}^2} + \overline{i_{n6}^2} + \overline{i_{n9}^2} + \overline{i_{n10}^2}\right]$$

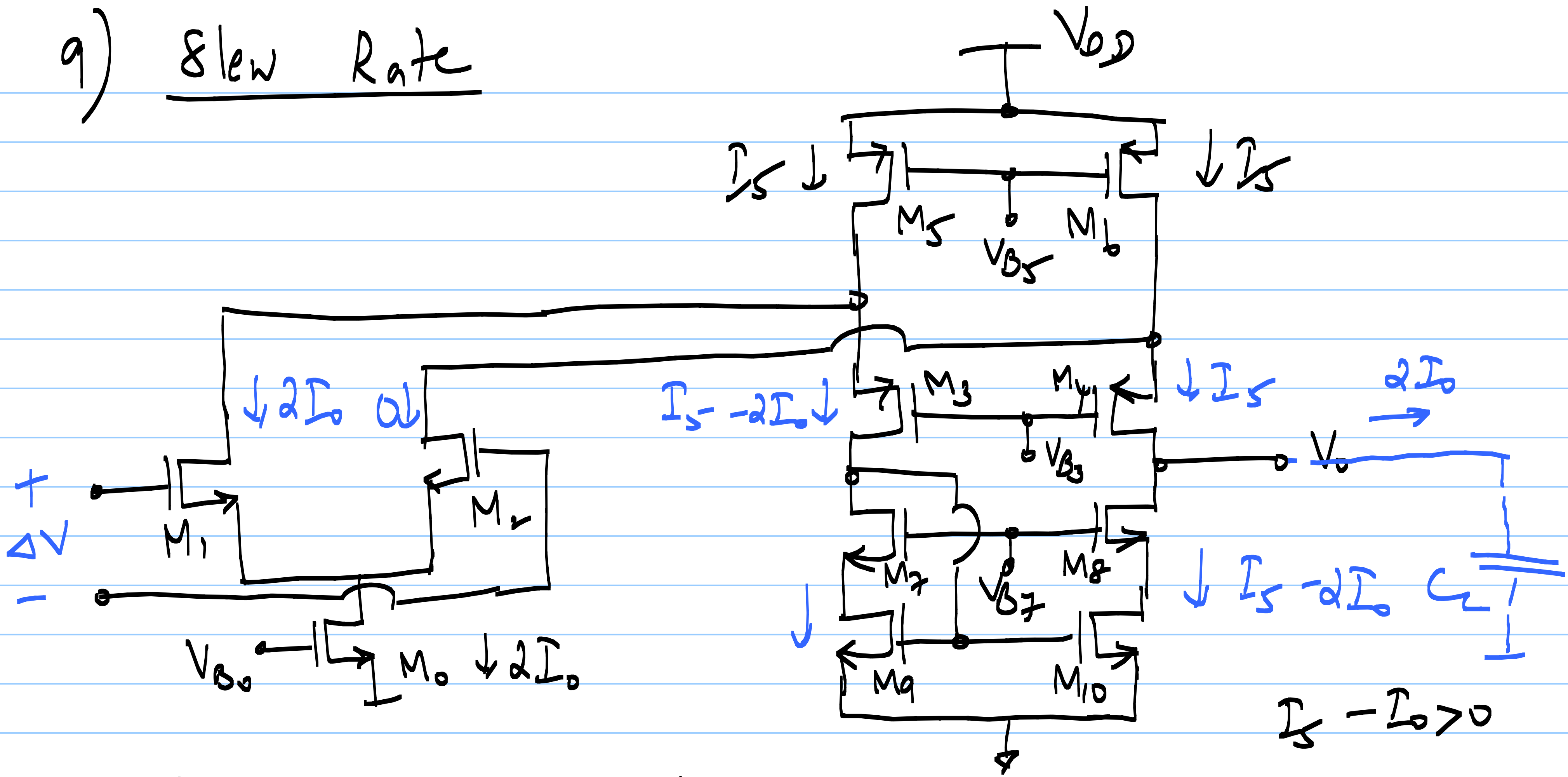
$$\frac{\overline{e_n^2}}{\Delta f} = \frac{16kT}{3g_{m_1}} + \frac{16kT\, g_{m_5}}{3\, g_{m_1}^2} + \frac{16kT\, g_{m_9}}{3\, g_{m_1}^2}$$

noise of folded cascode is worse than 1-stage or telescopic opamps

8) $$\sigma_{os}^2 = \sigma_{V_{T_{1/2}}}^2 + \sigma_{V_{T_{5,6}}}^2 \cdot \frac{g_{m_5}^2}{g_{m_1}^2} + \sigma_{9,10}^2 \cdot \frac{g_{m_9}^2}{g_{m_1}^2}$$

offset is worse

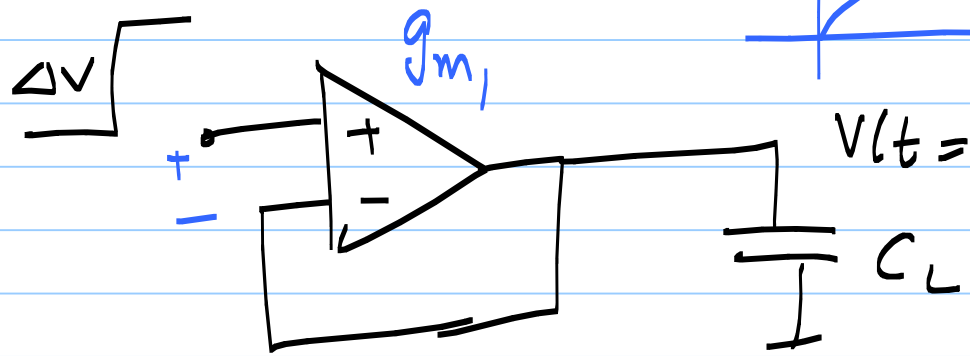
9) Slew Rate



$I_5 - I_0 > 0$

Case 1 : $SR = \pm 2I_0 / C_L$ if $I_5 > 2I_0$

Case 2 : If $I_5 < 2I_0$?



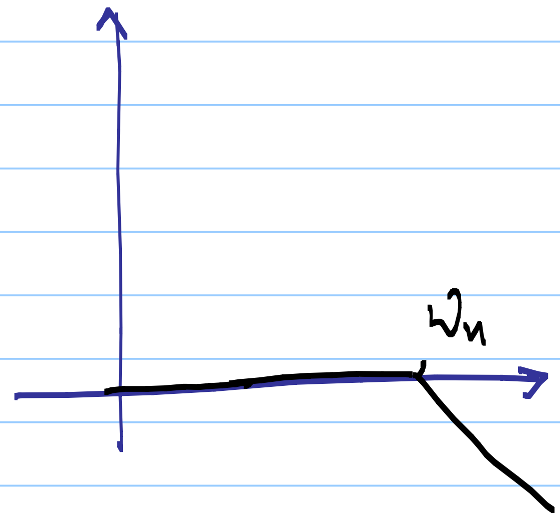
$$\tau = \frac{1}{\omega_u}$$

$$V(t=0^-) = V(t=0^+)$$

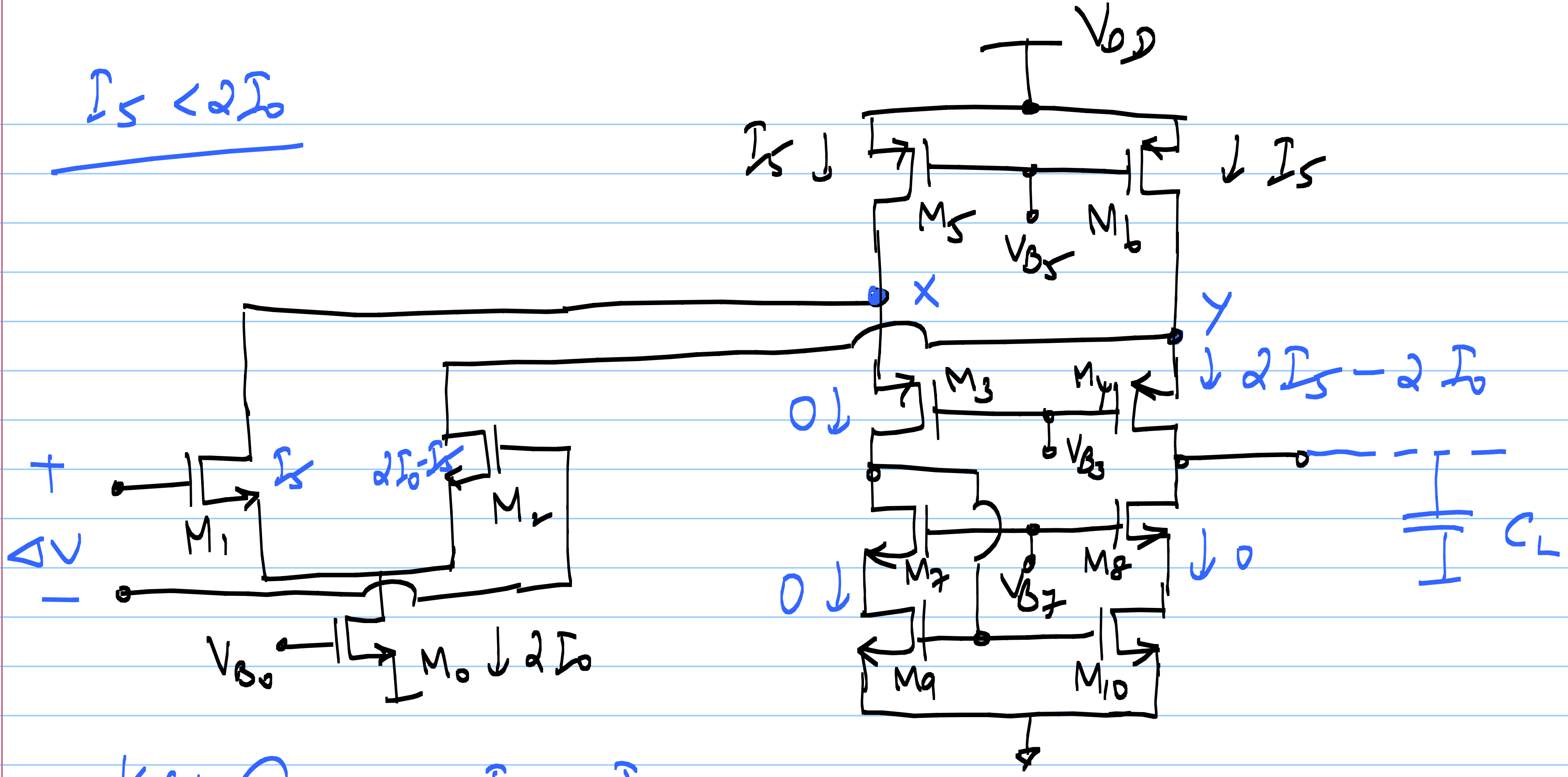
$$(V_+ - V_-)(t=0^+) = \Delta V$$

$$|LG| = |A|$$

$|CLG|$



$I_5 < 2I_0$



KCL @ X : $I_{D_1} = I_5$; $I_{D_2} = 2I_0 - I_5$

KCL @ Y : $I_{s_4} = I_5 - (2I_0 - I_5) = 2I_5 - 2I_0$

$$SR = \pm \frac{2I_5 - 2I_0}{C_L}$$

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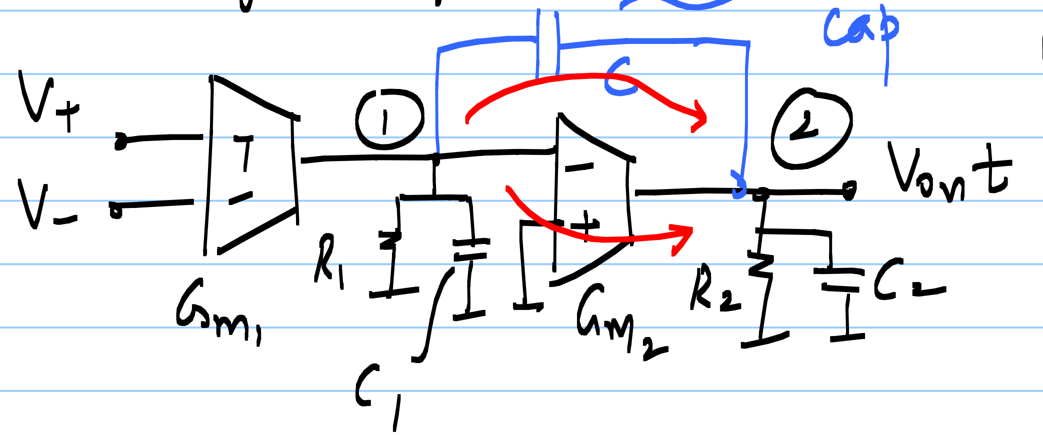
2-stage opamps

Miller cap



$$\text{gain} = G_{m_1} R_1 G_{m_2} R_2$$

If you drive R_L

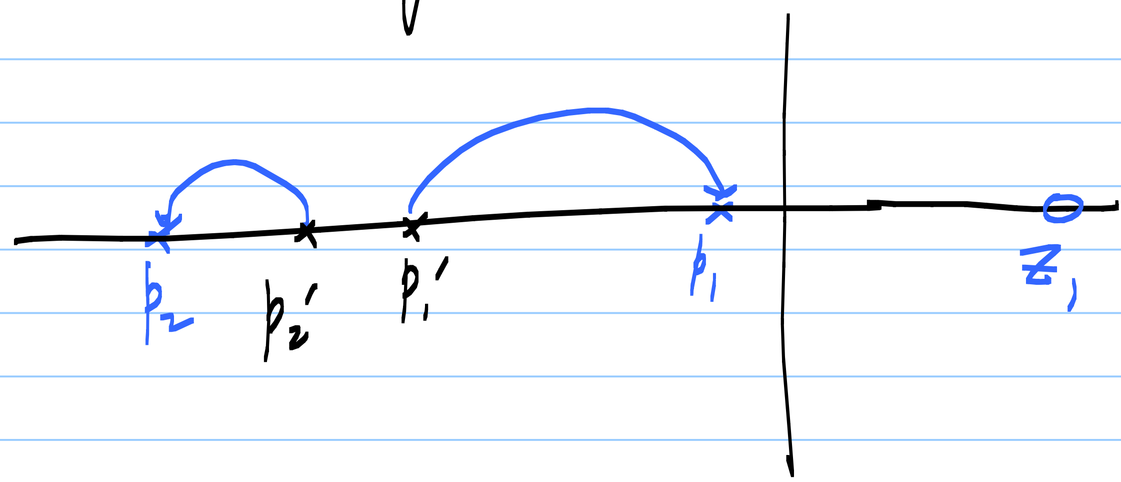
$$\text{gain} = G_{m_1} R_1 G_{m_2} (R_L \| R_2)$$

2 pole

LHP

$$p_1' = \frac{-1}{R_1 C_1}$$

$$p_2' = \frac{-1}{R_2 C_2}$$



phase margin

gain margin

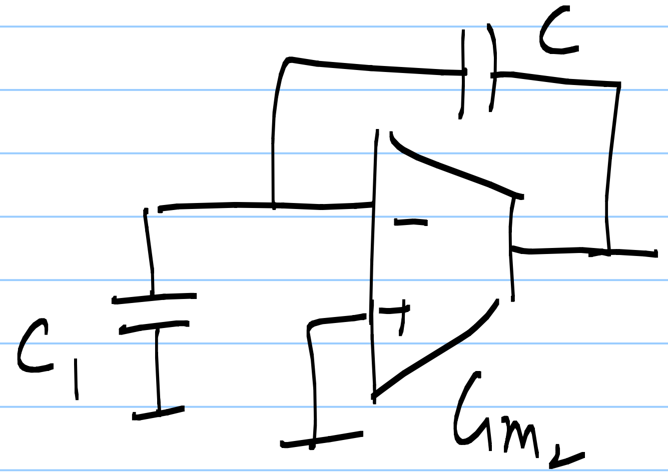
pole splitting improves PM

$$C \text{ @ Node } 1 = C_1 + G_{m_2} R_2 C \approx G_{m_2} R_2 C$$

$$R \text{ @ node } 1 = R_1$$

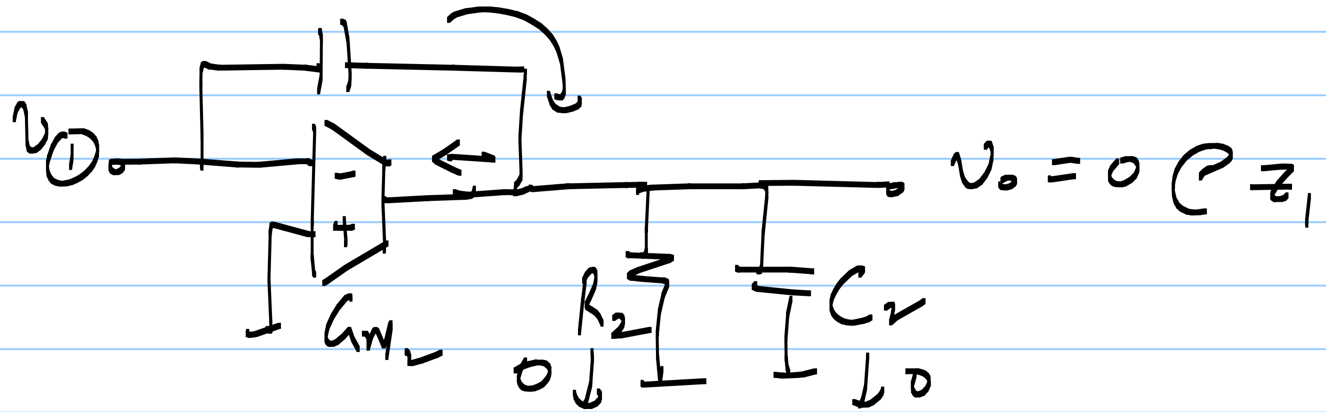
$$p_1' \longrightarrow \text{moves to } p_1 = \frac{-1}{R_1 G_{m_2} R_2 C}$$

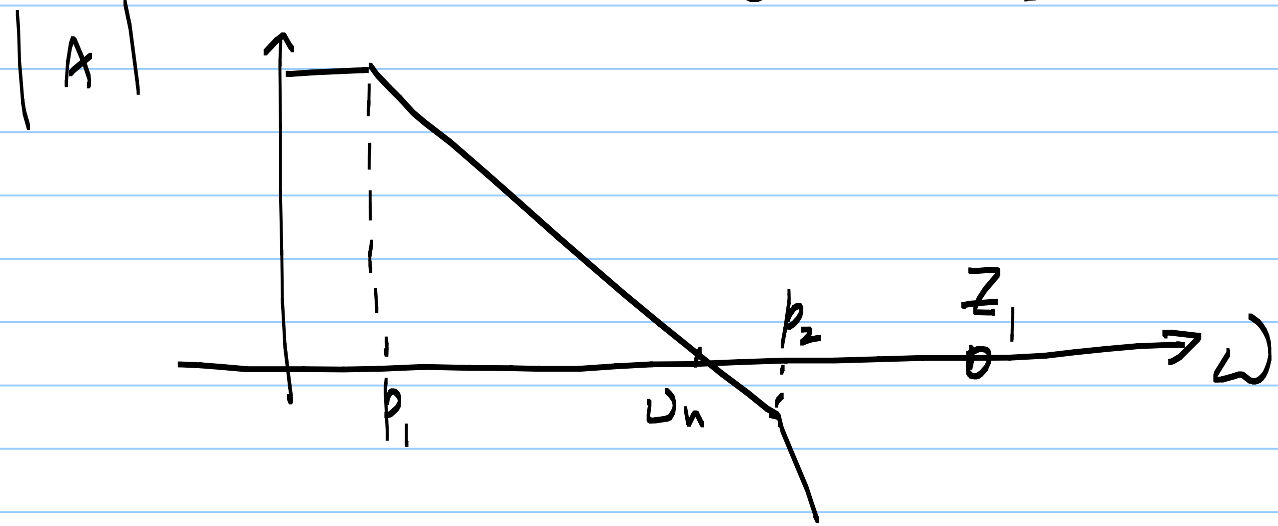
$$p_2' \longrightarrow \text{moves to } p_2 = \frac{-1}{\left[R_2 \,\|\, \frac{1}{G_{m_2}} \cdot \frac{C_1+C}{C}\right]\left[C_2 + \frac{C C_1}{C+C_1}\right]}$$



$$\leftarrow R_{out} = \left(\frac{C_1+C}{C}\right)\frac{1}{G_{m_2}}$$

Zero Z_1 @ $+\frac{G_{m2}}{C}$



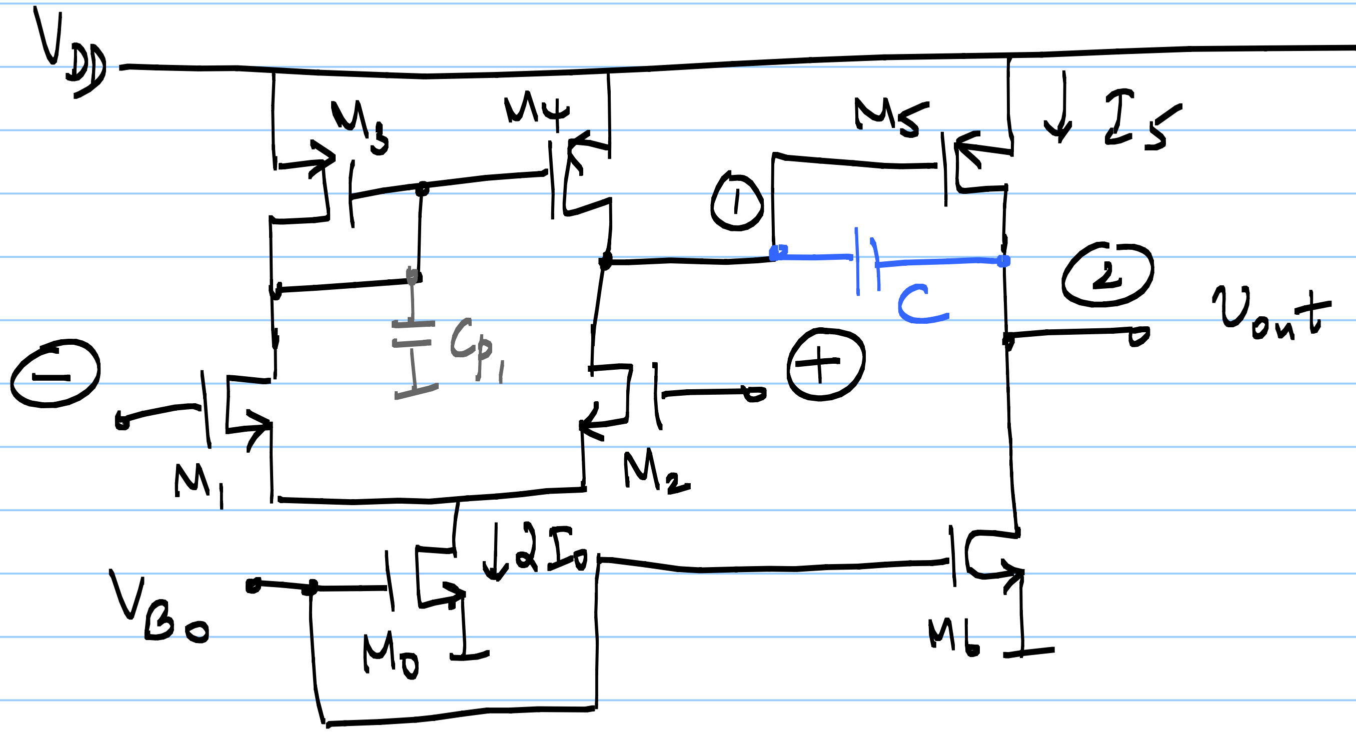


$Z_1 \gg \omega_u$

$$\omega_u = A_0 \cdot \omega_d = G_{m1}R_1 G_{m2}R_2 \cdot \frac{1}{R_1 G_{m2} R_2 C}$$

$$\omega_u = \frac{G_{m1}}{C}$$

$$Z_1 >> \omega_u \Rightarrow G_{m2} >> G_{m1}$$



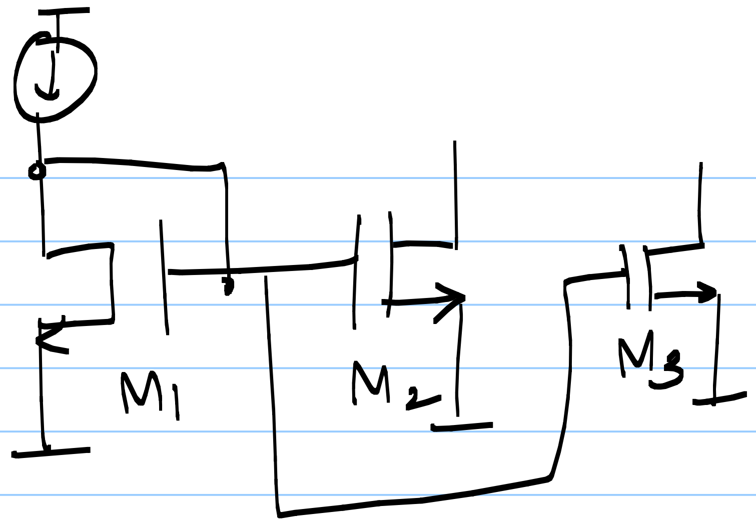
1) $$V_{GS_0}\Big|_{2I_0} = V_{GS_6}\Big|_{I_5}$$

$$L_0 = L_6$$

$$\frac{2I_0}{(W/L)_0} = \frac{I_5}{(W/L)_6}$$

2) $$V_{DD} - V_{SG_3}\Big|_{I_0} = V_{DD} - V_{SG_5}\Big|_{I_5}$$

$$\frac{I_0}{(W/L)_3} = \frac{I_5}{(W/L)_5}$$



$L_1 = L_2 = L_3$

2-stage opamp datasheet

1) $$G_m = G_{m_1} R_1 \cdot G_{m_2} = g_m (r_{ds_2} || r_{ds_4}) \cdot g_{m_5}$$

$$G_{m_1} = g_{m_1} \;;\; G_{m_2} = g_{m_5}$$

$$R_1 = r_{ds_2} || r_{ds_4} \;;\; R_2 = r_{ds_5} || r_{ds_6}$$

(A_0) DC gain $= G_{m_1} R_1 \, G_{m_2} R_2$

$$= g_{m_1} (r_{ds_2} || r_{ds_4}) \cdot g_{m_5} (r_{ds_5} || r_{ds_6})$$

2) $$\omega_u = \frac{G_{m_1}}{C} = \frac{g_{m_1}}{C}$$

3) $$\omega_d = \frac{1}{G_{m_2} R_2 R_1 C} = \frac{-1}{(r_{ds_2} || r_{ds_4})(g_{m_5}(r_{ds_5} || r_{ds_6}))C}$$

(p_1)

4) Non dominant poles & zeroes:

$$p_2 = \frac{-1}{\left[R_2 \,||\, \frac{1}{G_{m_2}} \cdot \frac{C_1 + C}{C}\right]\left[C_2 + \frac{C C_1}{C + C_1}\right]} \quad ; \; z_1 = + \frac{G_{m_2}}{C}$$

Mirror M_3, M_4
$$\begin{cases} p_3 = -g_{m_3}/C_{p_1} \\ z_2 = -2g_{m_3}/C_{p_1} \end{cases}$$

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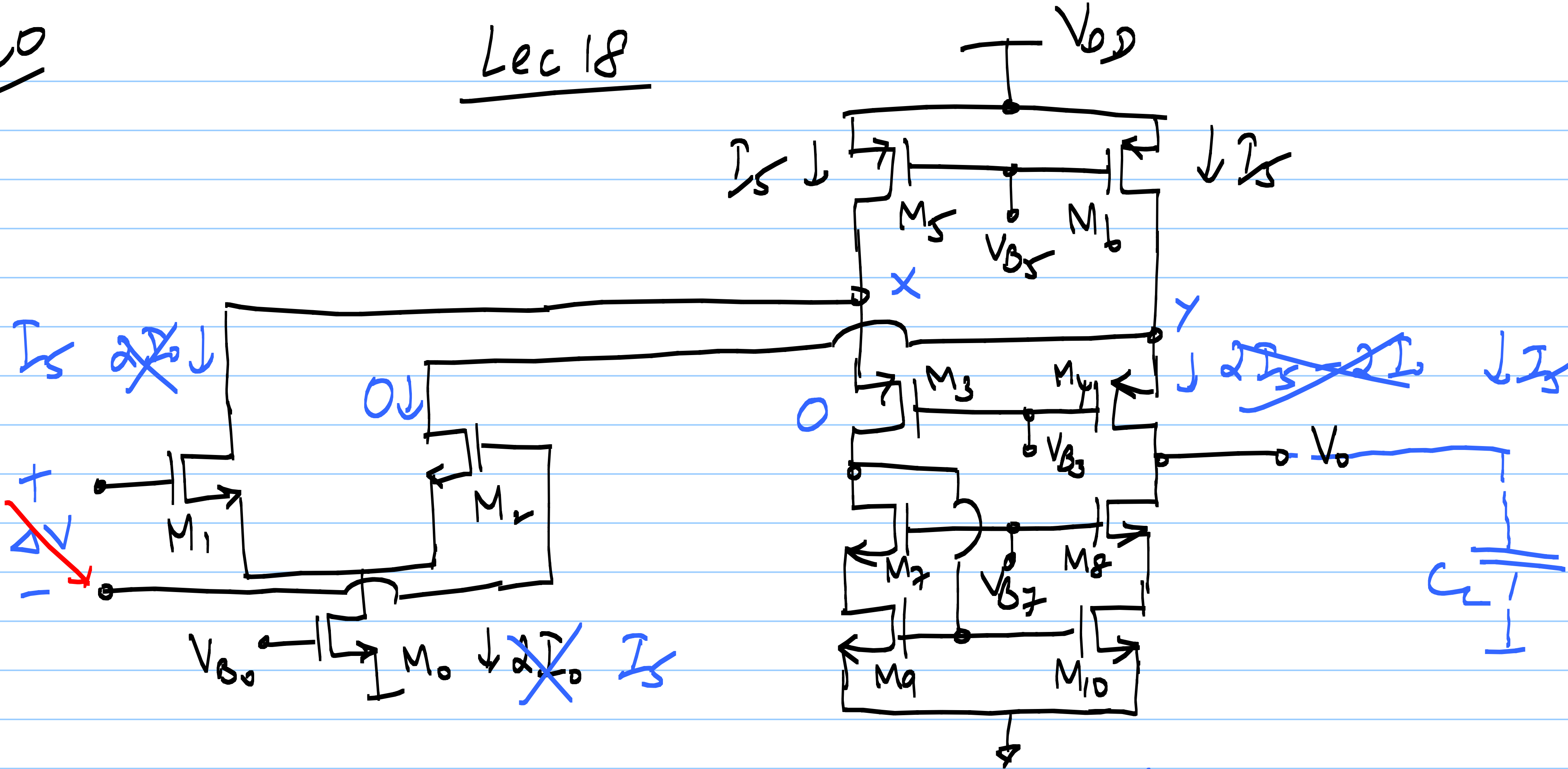
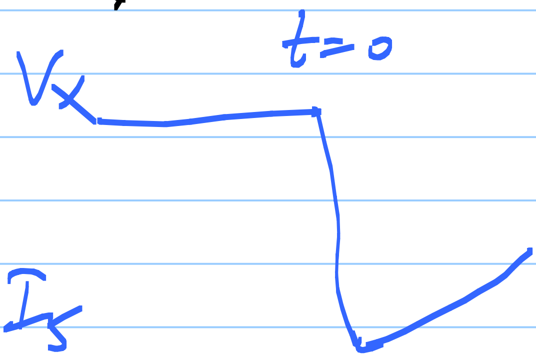


case 2 : If $I_5 < 2I_0$ ✓

$I_5 + I_5 - 2I_0 < I_5$



2-stage opamp datasheet

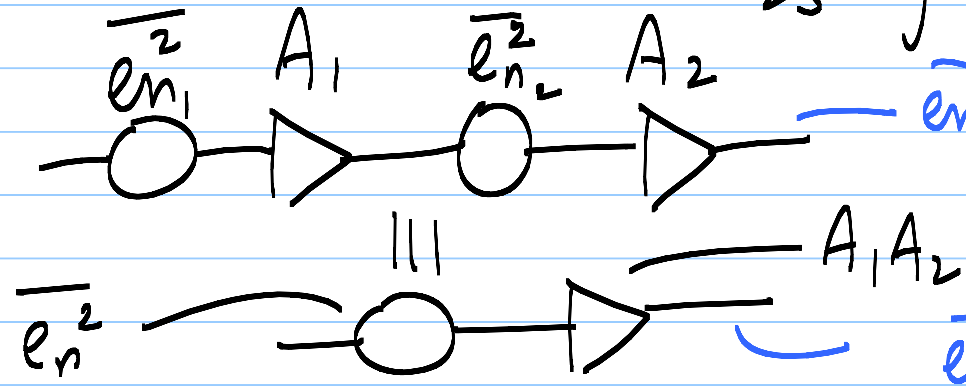
5) **ICMR** :

$$V_{CM,in} \in \left\{ V_{Dsat0}\Big|_{2I_0} + V_{GS1}\Big|_{I_0} \,,\; V_{DD} - V_{SG3}\Big|_{I_0} + V_{T1} \right\}$$

6) **OCMR** :

$$V_{CM,out} = \left\{ V_{B0} - V_{T6} \,,\; V_{DD} - V_{SDsat5}\Big|_{I_5} \right\}$$

7) $\overline{e_n^2} = ?$



$$\overline{e_{n1}^2}(A_1A_2)^2 + \overline{e_{n2}^2}\cdot A_2^2$$

$$\|$$

$$\overline{e_n^2}\cdot(A_1A_2)^2$$

$$\overline{e_n^2} = \overline{e_{n_1}^2} + \frac{1}{A_1^2} \cdot \overline{e_{n_2}^2}$$

$$A_1 = g_{m_1}(r_{out_1}) \quad ; \quad A_2 = g_{m_5}(r_{out_2})$$

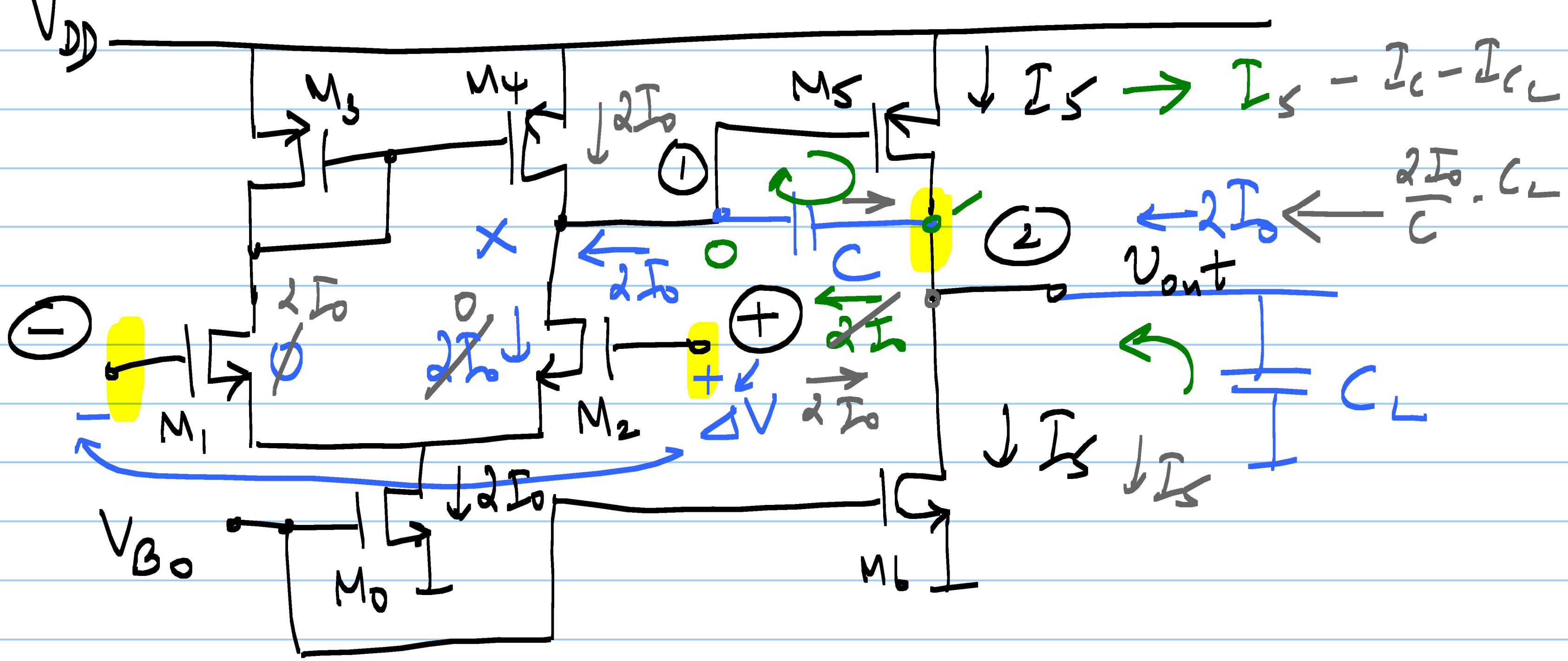
$$\overline{e_{n_1}^2} = \frac{16kT}{3g_{m_1}^2}\left[g_{m_1} + g_{m_3}\right]$$

$$\overline{e_{n_2}^2} = \frac{8kT}{3g_{m_5}^2}\left[g_{m_5} + g_{m_6}\right]$$

$$\overline{e_n^2} = \frac{16kT}{3g_{m_1}^2}\left[g_{m_1} + g_{m_3}\right] + \left(\frac{1}{g_{m_1} r_{out_1}}\right)^2 \cdot \frac{8kT}{3g_{m_5}^2}\left[g_{m_5} + g_{m_6}\right]$$

8) $\sigma_{os}^2 = \sigma_{V_{T_{1-2}}}^2 + \frac{g_{m_3}^2}{g_{m_1}^2} \cdot \sigma_{V_{T_{3-4}}}^2 + (\quad)$

9) <u>Slew rate</u>



@ $t = 0^+$, $V_x(t=0^+) = V_x(t=0^-)$

$\Rightarrow I_L(t=0^+) = 2I_0$

@ $t = 0^+$, $SR = -\dfrac{2I_0}{C_L}$

$$\downarrow$$

$$-\frac{2I_0}{C}$$

$$\frac{I_{C_L}}{C_L} = \frac{2I_0}{C} \Rightarrow I_{CL} = \frac{2I_0 \cdot C_L}{C}$$

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Design Example

Specs : $A_o \gg 80\,dB$; $f_u \geq 5MHz$; $V_{o\,p\text{-}p} = 4V$;

$SR \geq 10V/\mu s$; $PM = 60°$ for unity gain ;

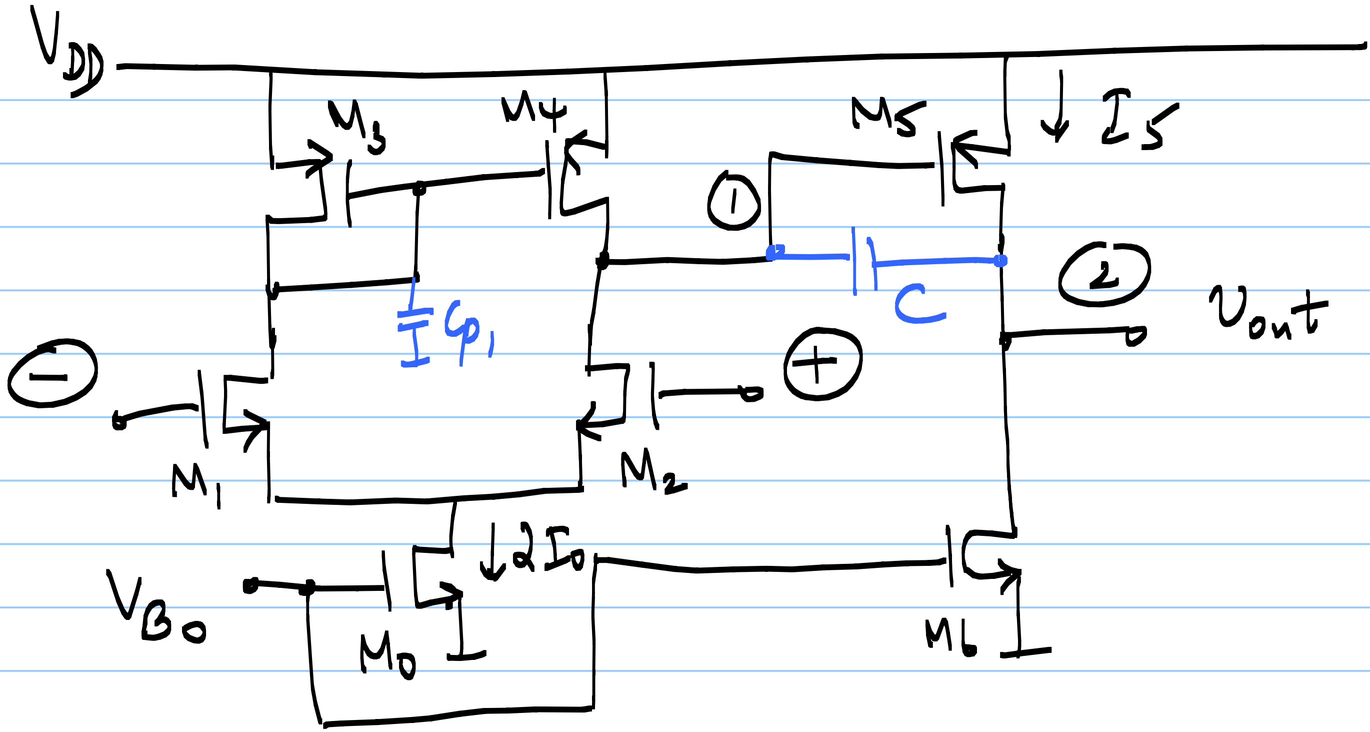
Design parameters

$V_{DD} = 5V$; $C_L = 10pF$; $\mu_n C_{ox} = 50\,\mu A/V^2$

$\mu_p C_{ox} = 25\,\mu A/V^2$; $V_{Tn} = V_{Tp} = 1V$;

$L_{min} = 2\mu m$; $C_{ox} = 1.5\,fF/\mu m^2$;

$(\lambda L)_n = 0.04\,\mu m/V$; $(\lambda L)_p = 0.1\,\mu m/V$



1) Set all $L = L_{min.} = 2\mu m$

2) $$\frac{2I_0}{C} = SR$$

3) $$\frac{g_{m1}}{C} = 2\pi f_u$$

4) $g_{m5} = 10\, g_{m1}$

5) $PM = 60^\circ \Rightarrow$ $p_2 = \sqrt{3}\,\omega_u$

$= -54.4\ Mrad/s$

6) $p_2 \approx \dfrac{-G_{m2}}{C_L} = \dfrac{-g_{m5}}{C_L}$

$g_{m5} = 544\ \mu S$

$g_{m1} = 54.4\ \mu S$

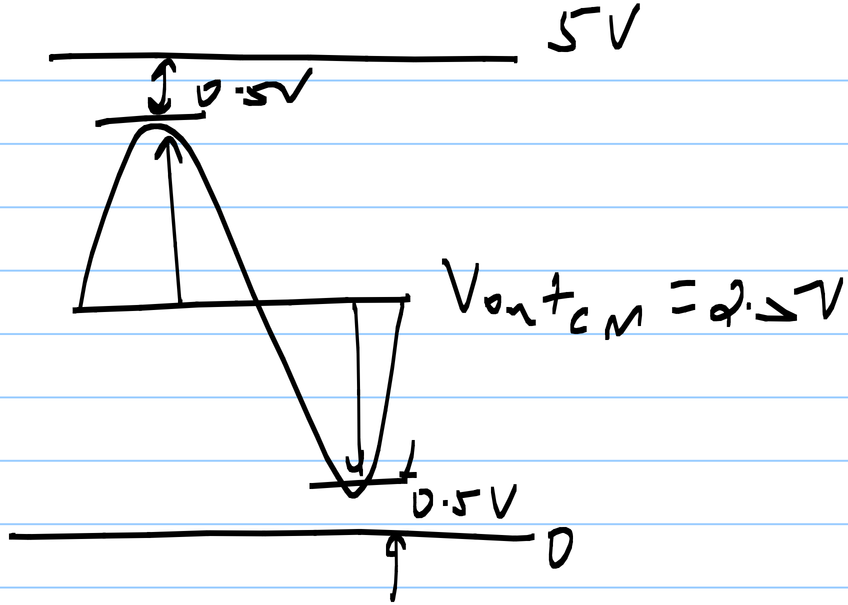
$\dfrac{g_{m1}}{C} = 2\pi f_u \Rightarrow$ $C = 1.73\ pF$

$\dfrac{2 I_o}{C} = SR \Rightarrow$ $2 I_o = 17.32\ \mu A$

$I_o = 8.66\ \mu A$

$$\left(\frac{W}{L}\right)_1 = 3.4$$

7) $V_{op\text{-}p} = 4V$



$V_{Dsat_5} = V_{Dsat_6} = 0.5V$

$$g_{m5} = \frac{2I_5}{V_{Dsat_5}} \Rightarrow I_5 = 136\mu A$$

$$\Rightarrow (W/L)_5 = 43.5$$

$$(W/L)_6 = 21.7 \Rightarrow (W/L)_0 = 2.8$$

$$(W/L)_{3,4} = \frac{I_0}{I_5}(W/L)_5 = 2.8$$

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$\lambda_n = 0.02 V^{-1}$

$\lambda_p = 0.05\ V^{-1}$

$I_o = 8.66\,\mu A$

$r_{ds_2} = 5.75\ M\Omega$

$r_{ds_4} = 2.3\ M\Omega$

$\Big\}\ r_{out_1} = 1.64\, M\Omega$

$I_5 = 136\,\mu A$

$r_{ds_5} = 0.15\ M\Omega$

$r_{ds_6} = 0.36\ M\Omega$

$\Big\}\ r_{out_2} = 0.11\, M\Omega$

$g_{m_1} = 54.4\,\mu S$, $g_{m_2} = 544\,\mu S$

$A_1 = g_{m_1} r_{out_1} = 89.2\ V/V$ $\qquad A_1 A_2 = 5334\ V/V$

$A_2 = g_{m_2} r_{out_2} = 59.8\ V/V$

$$C_{gs} = \frac{2}{3} WL C_{ox}$$

A_i needs to $\uparrow$ by α

$\uparrow L$ by α ($r_{out} \uparrow$ by α)

$\uparrow W$ by α

g_m stays same

$C_{gs} \uparrow$ by α^2

$\uparrow W$ by α^2

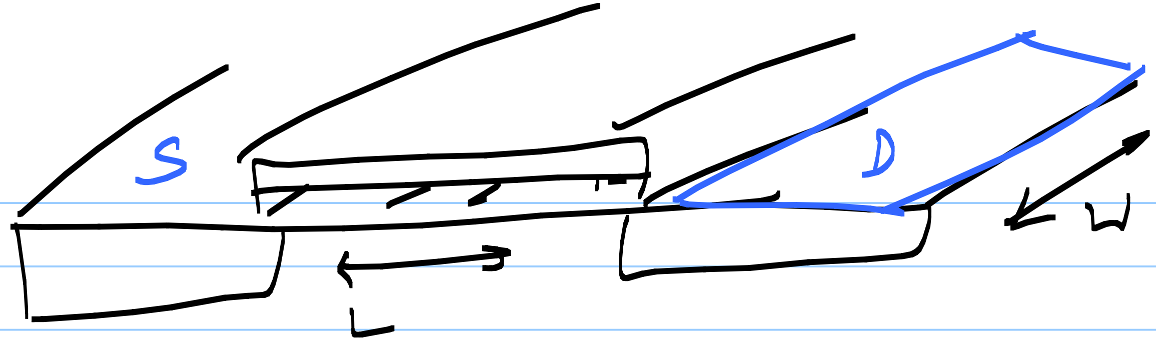
keep L same

$g_m \uparrow$ by α

$C_{gs} \uparrow$ by α^2

as $I \uparrow$ by x, $g_m \uparrow$ by $\sqrt{x}$

$r_{ds} \downarrow$ by x



Instead, equalize r_{up} & r_{dn} @ outputs of 1^{st} & 2^{nd} stages.

Set $L_{3,4,5} = \left(\frac{\lambda_p}{\lambda_n}\right) \cdot L_{min} = 5\,\mu m$

Set $W_{3,4,4}$ so that $(W/L)_{3,4,5}$ stays the same

$$r_{out_1} = 2.88\,M\Omega$$

$$r_{out_2} = 0.18\,M\Omega$$

$A_1 = 156.6\ V/V$; $A_2 = 97.9\ V/V$

$A_o = 15334$ V/V ≈ 84 dB

<u>Check</u>:

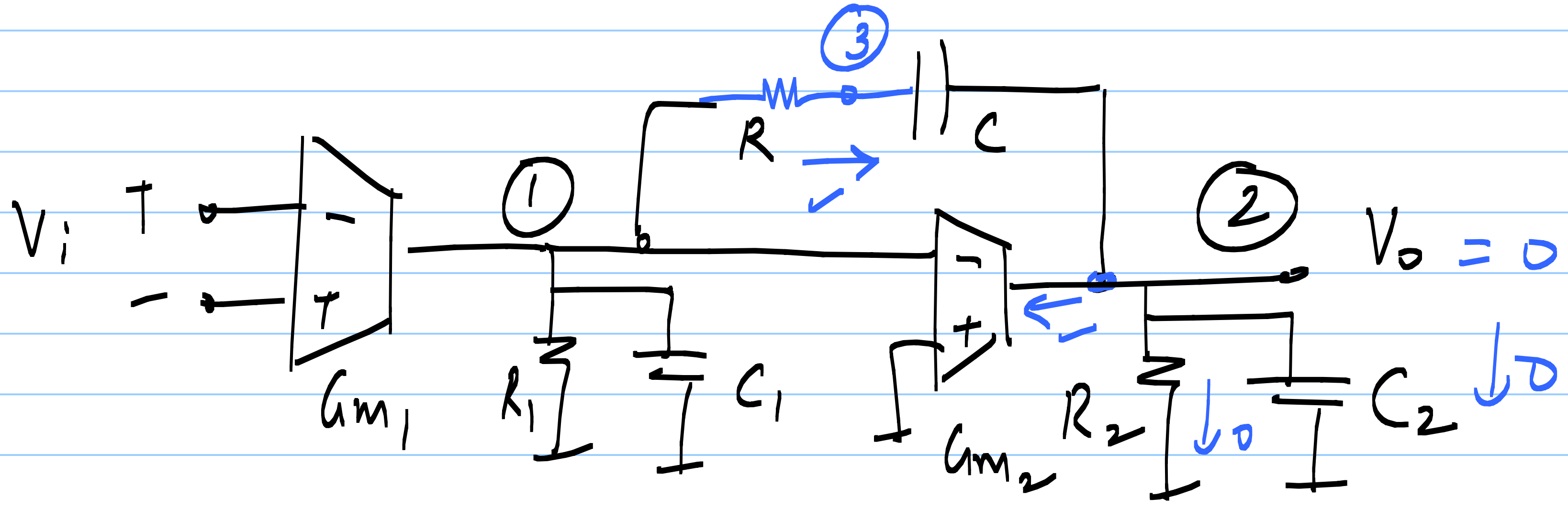
1) Mirror pole $= \dfrac{g_{m_3}}{C_{p_1}} \gg p_2$

Mirror zero $= \dfrac{2 g_{m_3}}{C_{p_1}} \gg p_2$

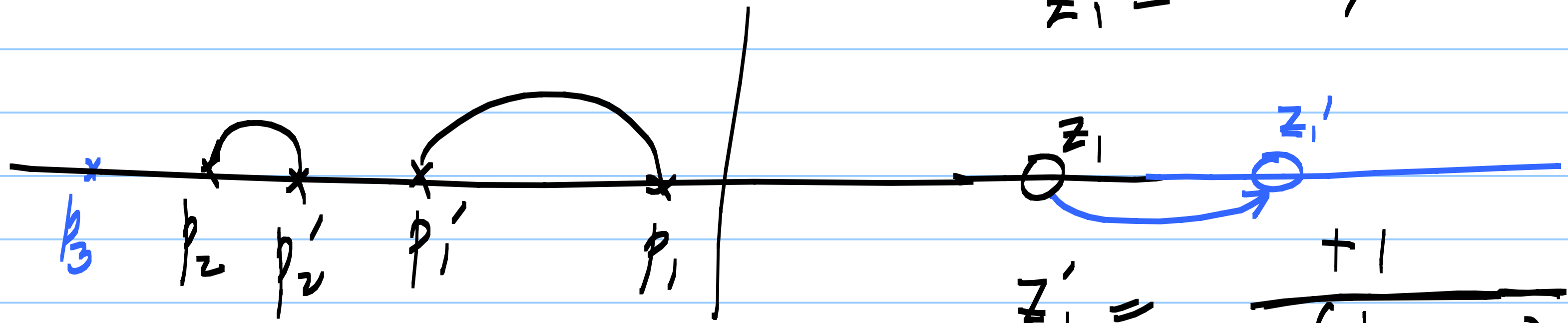
2) $g_{m_5} r_{out_2} \cdot C \gg C_{gs_5}$

3) $C_{gd} \ll$ all $C_{par.}$

Pole-zero cancellation compensation



$$z_1 = +G_{m_2}/C$$



$$z_1' = \frac{+1}{C\left(\frac{1}{G_{m_2}} - R\right)}$$

$$p_3 \approx \frac{-1}{R \cdot C_1}$$

1) Case 1: Set $z_1' = \infty$ (very large)

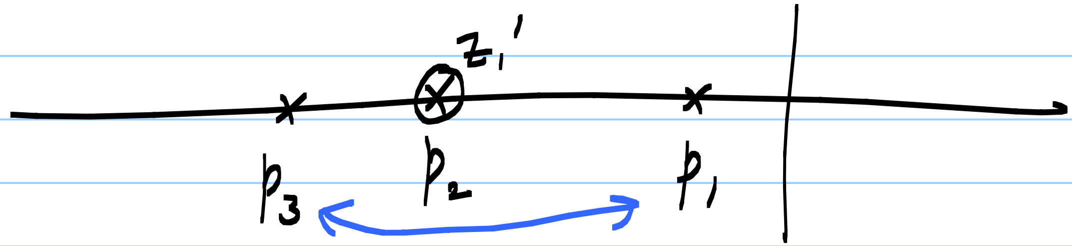
$$\Rightarrow \quad R = \frac{1}{G_{m_2}}$$

$$p_3 \approx -\frac{G_{m_2}}{C_1}$$

2) Choose $R > \frac{1}{G_{m_2}}$ $\Rightarrow$ zero moves into LHP (from $-\infty$ side)

Set z_1' to cancel p_2

$\Rightarrow$ larger PM or larger BW



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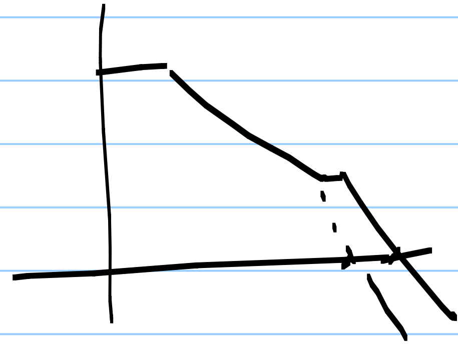
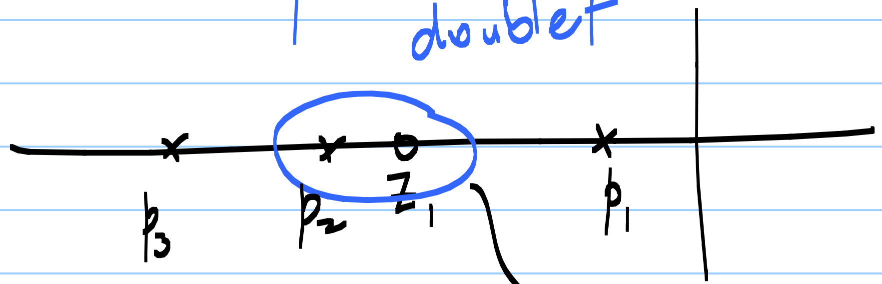
2) $p_2 = \dfrac{1}{(\ )\, G_{m_2} \cdot (\ )}$



still need $R \propto \dfrac{1}{G_{m_2}}$

pole zero doublet



slow settling component

We want $p_2 - z_1$ on top of each other

& track each other (due to process variations
temp.)

We want R to track $\frac{1}{G_{m_2}}$

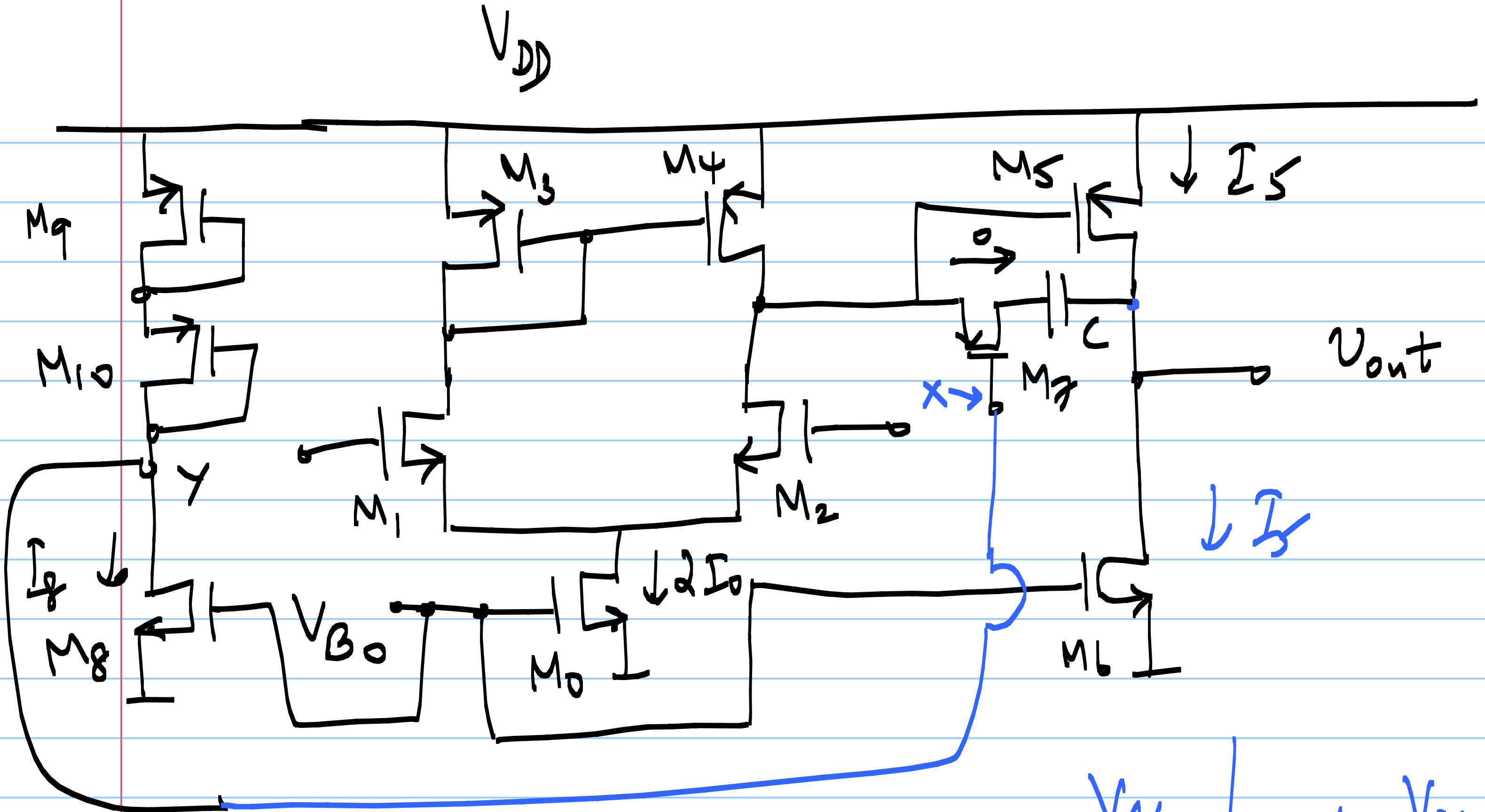
Technique 1) Use MOSFET in linear region to realize R

$$I_D = \mu C_{ox} \left(\frac{W}{L}\right) \left\{ (V_{GS} - V_T)(V_{DS}) - \frac{V_{DS}^2}{2} \right\}$$

$$g_{ds} = \frac{\partial I_D}{\partial V_{DS}} = \mu C_{ox} \left(\frac{W}{L}\right) (V_{GS} - V_T - V_{DS})$$

$$r_{ds}\Big|_{V_{DS}=0} = \frac{1}{g_{ds}} = 1 \Big/ \left(\mu C_{ox} \left(\frac{W}{L}\right) (V_{GS} - V_T) \right)$$

$$g_{ds}\Big|_{V_{DS}=0} = g_m\Big|_{sat}$$



$$V_x = V_{DD} - V_{SG_5} - V_{SG_7}$$

$$V_y = V_{DD} - V_{SG_9} - V_{SG_{10}}$$

$$V_{SG_5}\Big|_{I_5} + V_{SG_7} = V_{SG_9}\Big|_{I_8} + V_{SG_{10}}\Big|_{I_8}$$

e.g. set $V_{SG_5}\Big|_{I_5} = V_{SG_9}\Big|_{I_8} \Rightarrow \dfrac{I_5}{(W/L)_5} = \dfrac{I_8}{(W/L)_9}$

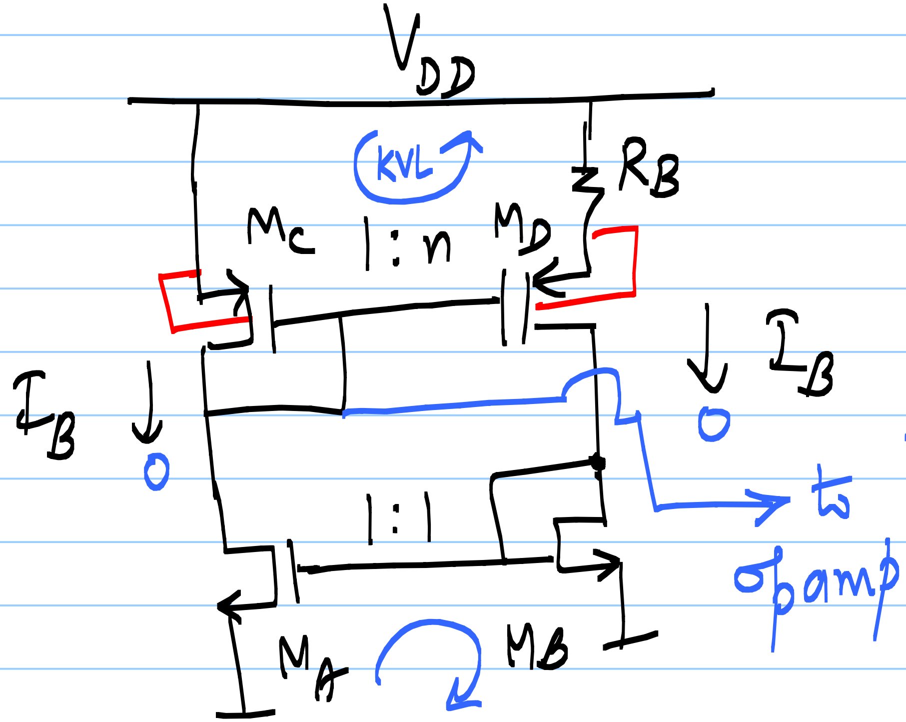
$$V_{SG_7} = V_{SG_{10}}\Big|_{I_8}$$

$T\uparrow \Rightarrow g_{m5}\downarrow \Rightarrow r_{ds_7}\uparrow \Rightarrow V_{SG}\downarrow$

$$V_{sg_7} = \underset{\Delta V_9}{V_{sg_9}} + \underset{\Delta V_{10}}{V_{sg_{10}}} - \underset{\Delta V_5}{V_{sg_5}} = + \Delta V_7$$

$$g_{ds} = \mu_p C_{ox} \left(\frac{W}{L}\right)\left(V_{sg_{7_{orig}}} + \Delta V_7 - V_{T_7}\right)$$

Technique 2) Use passive resistor R, force g_{m5} to track $1/R$



$$V_{GS_C} = V_{GS_D} + I_B R_B$$

$$\cancel{V_{T_C}} + V_{Dsat_C} = \cancel{V_{T_D}} + V_{Dsat_D} + I_B R_B$$

$$\frac{2I_B}{g_{m_C}} = V_{Dsat_C}$$

$$\frac{2I_B}{g_{m_D}} = V_{Dsat_D}$$

$$g_{m_D} = \sqrt{n}\, g_{m_C}$$

$$\frac{2I_B}{g_{m_C}} = \frac{2I_B}{g_{m_D}} + I_B R_B$$

* $I_B = 0$ is a valid state of the circuit

$\Rightarrow$ need a startup circuit

* If $I_B \neq 0$,

$$\frac{2}{g_{mc}} = \frac{2}{g_{mD}} + R_B$$

$$\frac{2}{g_{mc}} = \frac{2}{g_{mc}\sqrt{n}} + R_B$$

$$\frac{1}{g_{mc}}\left[2 - \frac{2}{\sqrt{n}}\right] = R_B$$

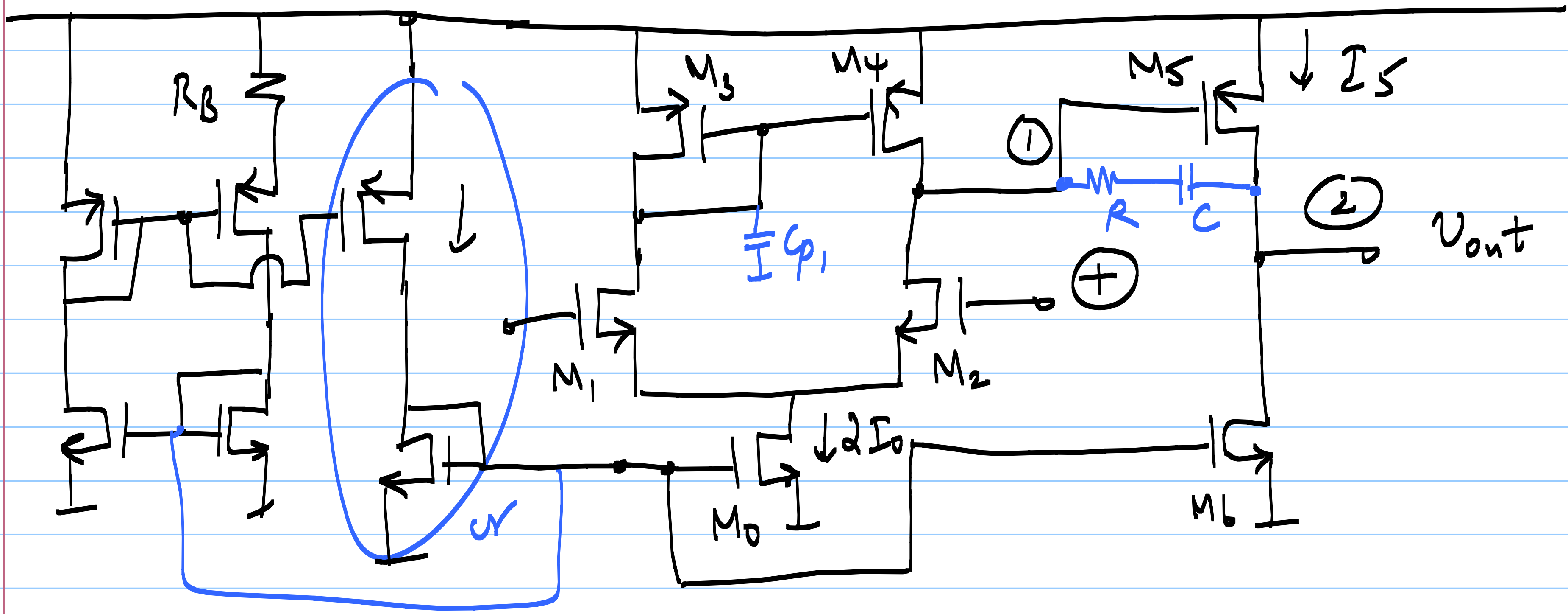
$$\frac{1}{g_{mc}} \propto R_B$$

choose same type of resistor so that R_B tracks R

$$I_B \propto \frac{1}{R_B^2}$$

We want $I_5 \propto \frac{1}{R_B^2} \propto \frac{1}{R^2}$

$$g_{m_5} \propto \frac{1}{R}$$



R_B
M_3
M_4
M_5
I_5
C_{p1}
①
②
R
C
v_{out}
M_1
M_2
M_0
M_6
$2I_0$
+

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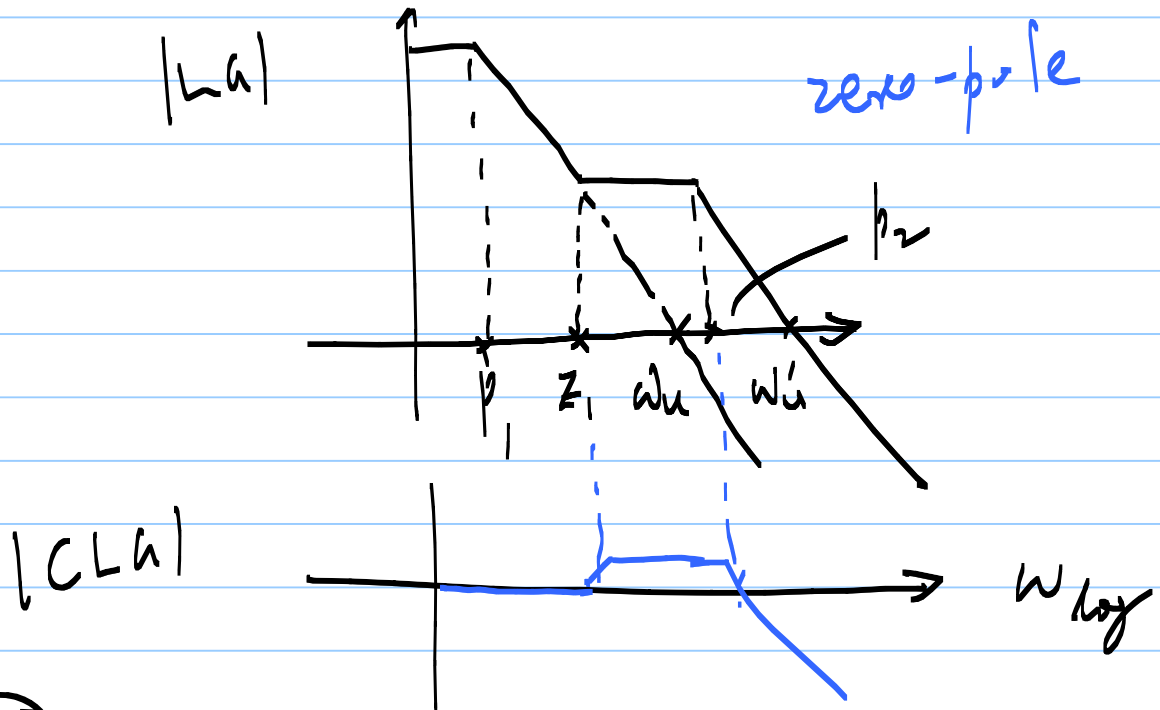
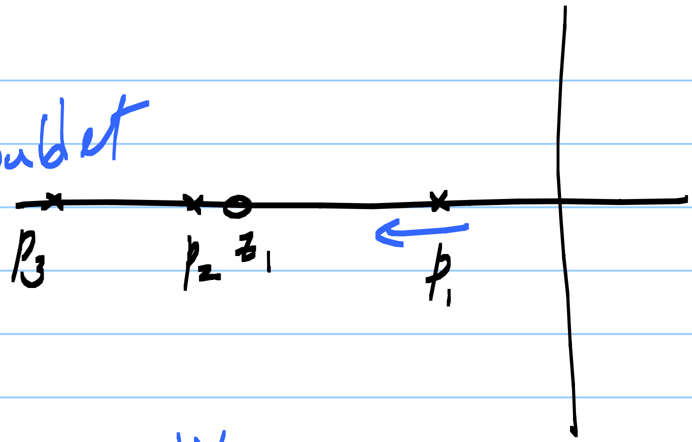
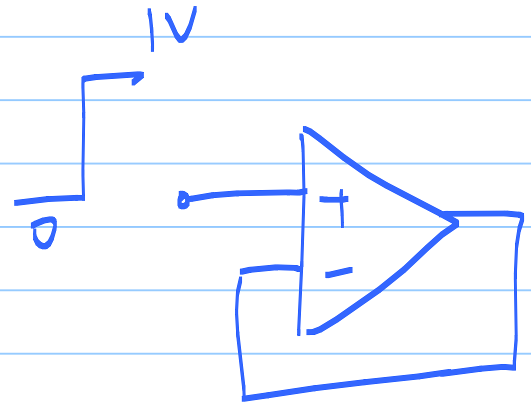
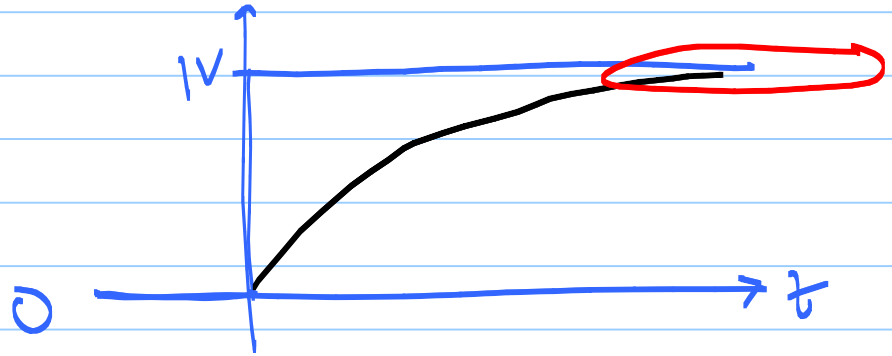


zero-pole doublet





Hw



$$(\ )\left(e^{-\omega_u' t}\right) + (\ )\, e^{(-z_1 t)}$$

large

small

Example :

$A_0 = 80\,\text{dB} = 10^4\ \text{V/V}$

$A_1 = 156\ \text{V/V}\quad A_2 = 98\ \text{V/V}$

$g_{m2} = 0.5\,\text{mS}$

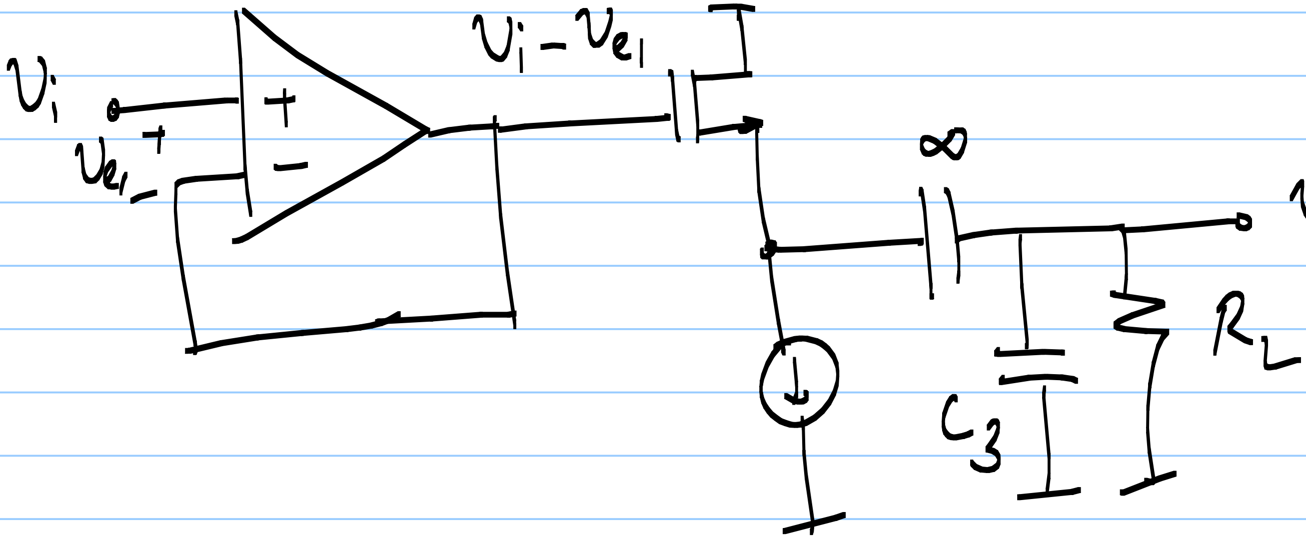
resistive load $R_L \downarrow$:

$$A_2 = g_{m5}\left(r_{out2} \| R_L \downarrow\right) \approx g_{m5} R_L$$

e.g. if $R_L = 2\,k\Omega \Rightarrow A_2 = 1\ \text{V/V}$

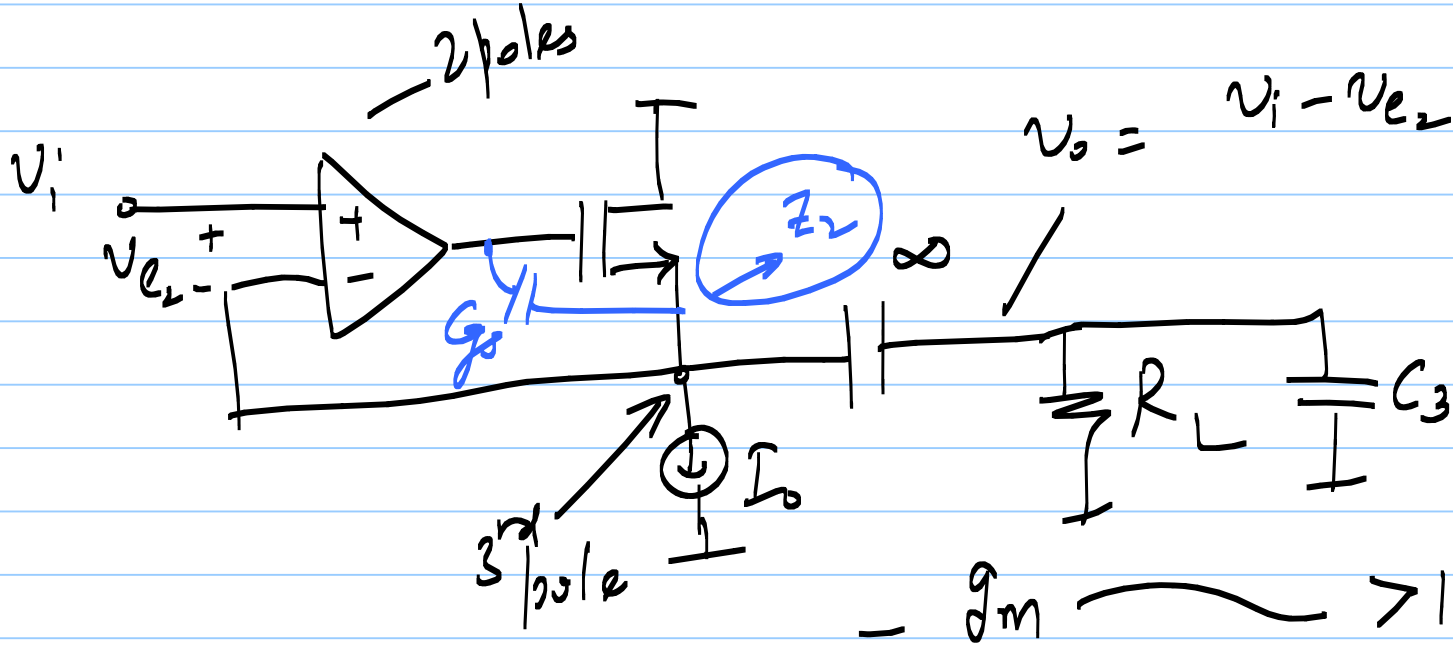
$A_1 = 156 = A_0$

We want to drive $R_L < 2\,k\Omega$



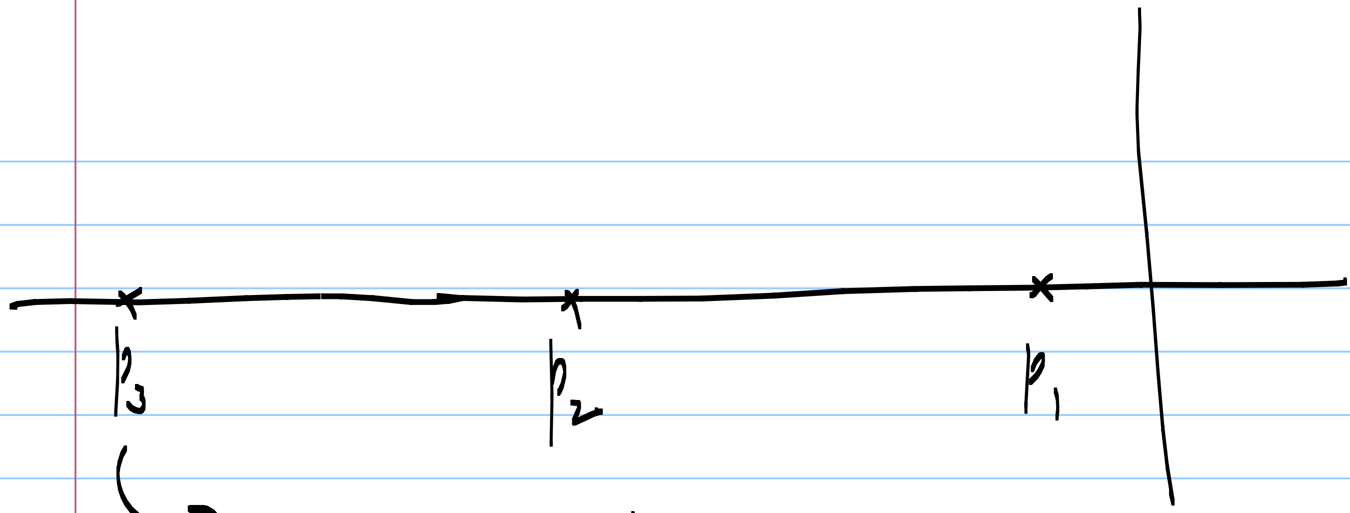
$$v_o = \frac{g_m R_L}{1 + g_m R_L} \cdot (v_i - v_{e_1})$$

$$g_m \gg \frac{1}{R_L}$$

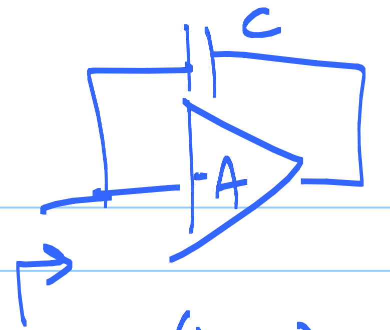


$$v_o = v_i - v_{e_2}$$

$$p_3 = -\frac{g_m}{C_3} \qquad > 10\,\frac{1}{R_L}$$

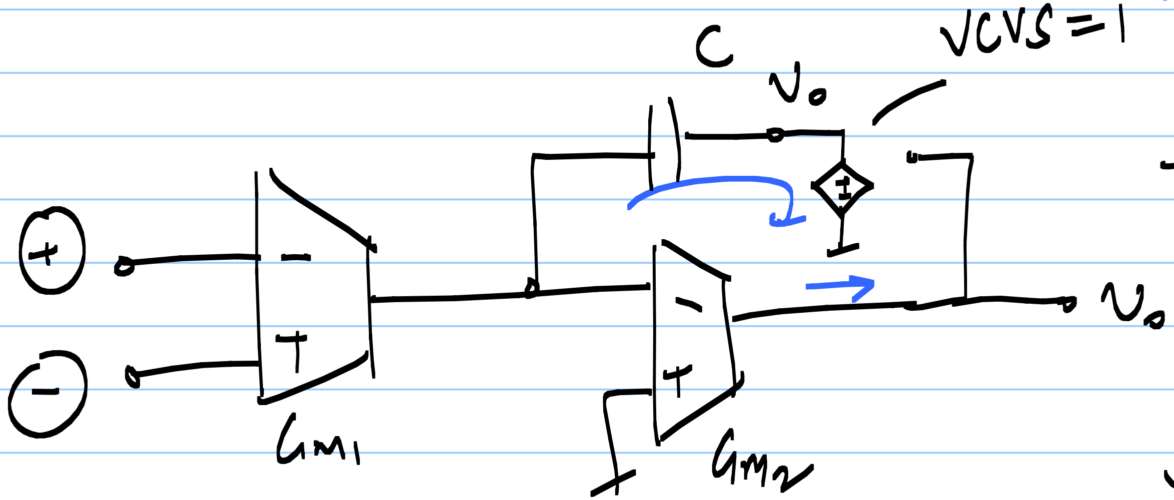


$\approx 100 \times p_2$



$C_{in} = (1+A)\,C$

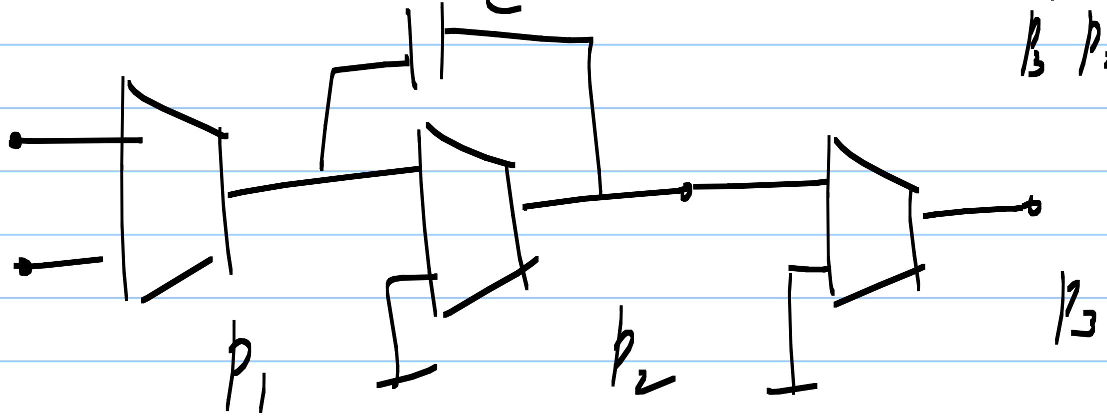
VCVS = 1 → Source follower

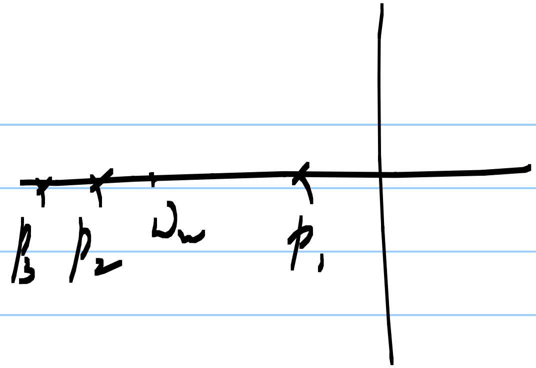


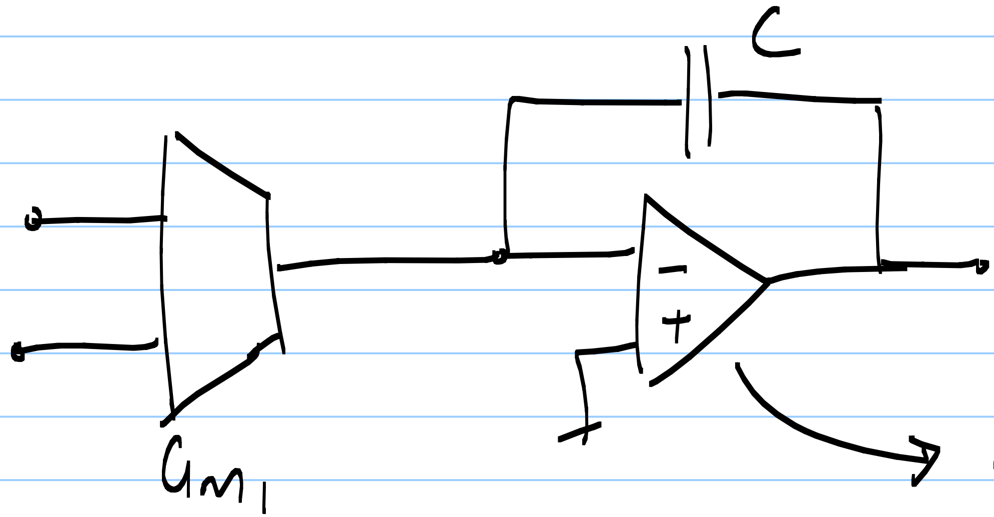
→ p_1, p_2, $\cancel{Z_1}$

stays the same

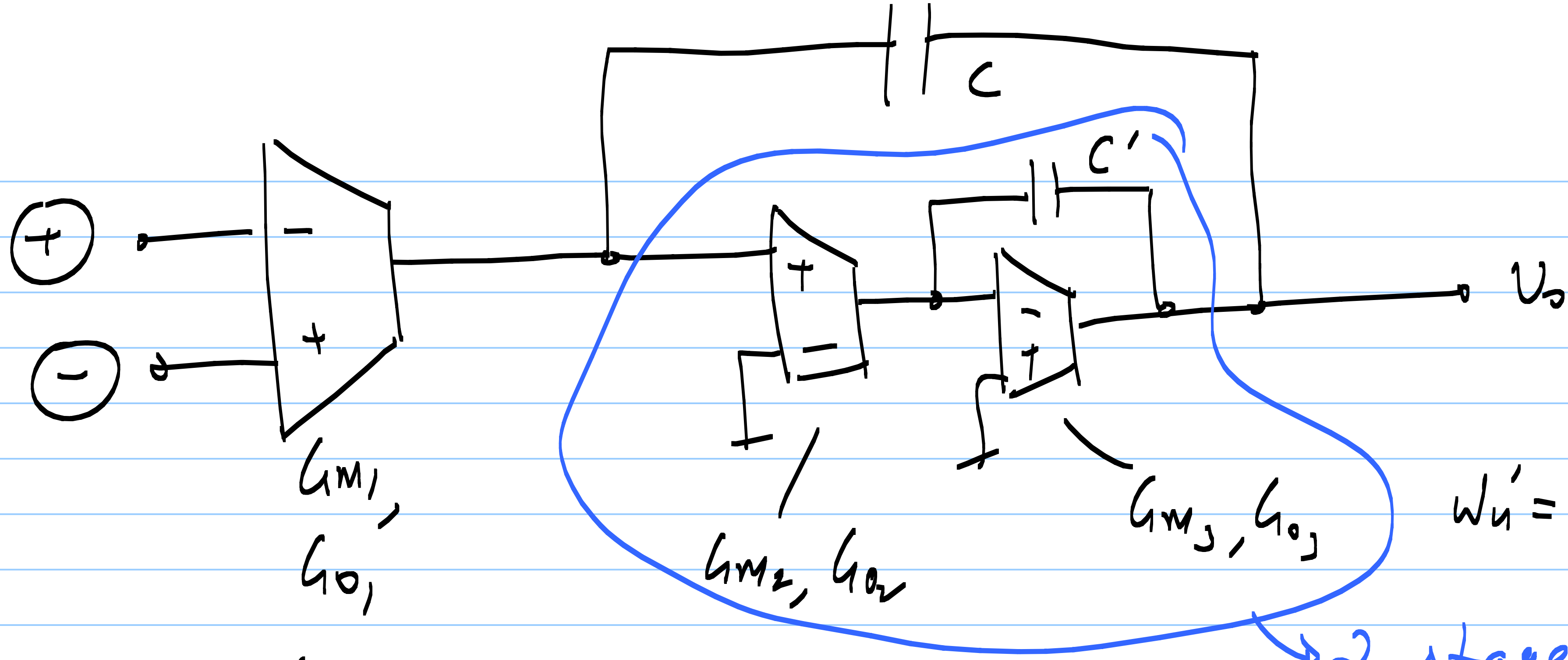
3- stage opamp







2-stage opamp



$$\omega_u' = \frac{G_{m_2}}{C'}$$

→ 2 stage opamp

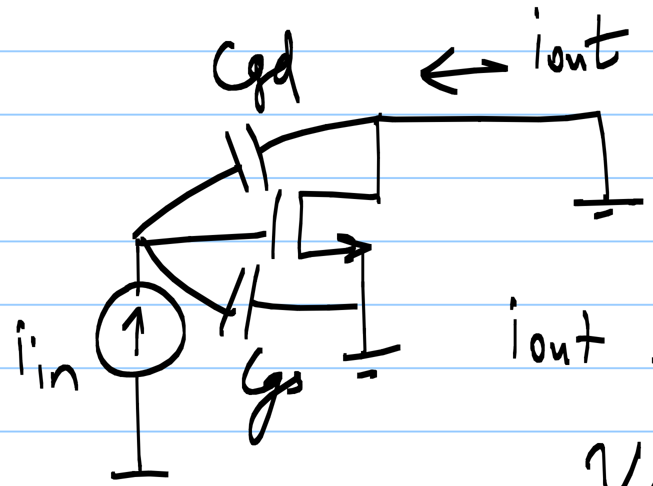
$$\omega_u = \frac{G_{m_1}}{C}$$

$$\omega_u' \gg \omega_u$$

"Nested Miller" Configuration

25/2/20

Lec 23

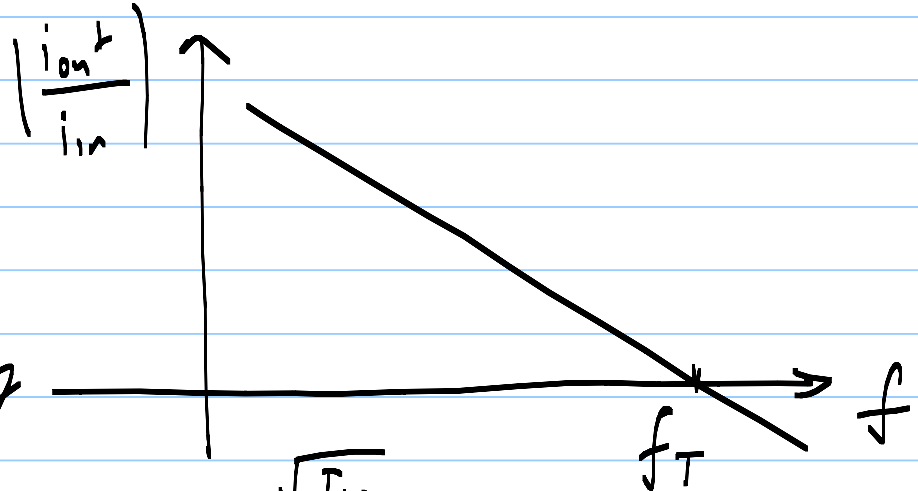


plot $\left|\frac{i_{out}}{i_{in}}\right|$ vs. f

$$i_{out} = g_m v_{gs}$$

$$v_{gs} = \frac{i_{in}}{s(C_{gs}+C_{gd})}$$

$$\frac{i_{out}}{i_{in}} = \frac{g_m}{s(C_{gs}+C_{gd})}$$



f_T = transition frequency

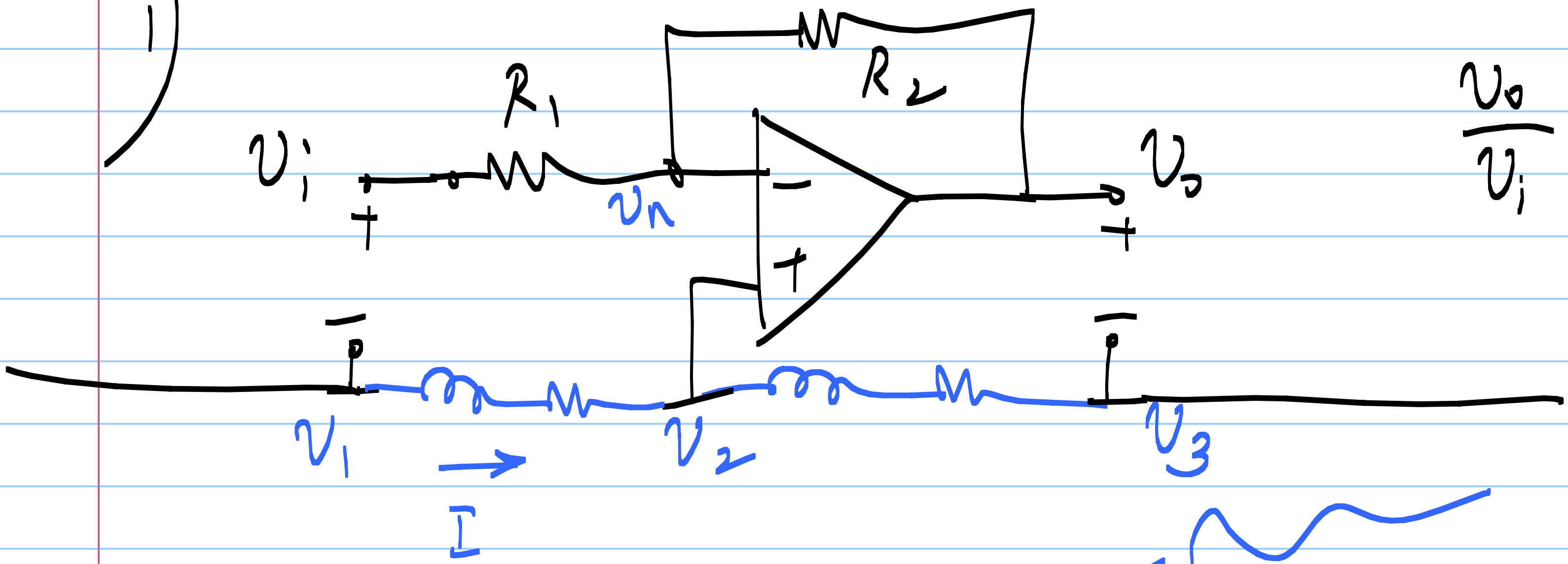
$$2\pi f_T = \frac{g_m}{C_{gs}+C_{gd}} \approx \frac{g_m}{C_{gs}} \propto \frac{\sqrt{I_{bias}}}{\sqrt{W}\, L^{3/2}}$$

26/2/20

Lec 24

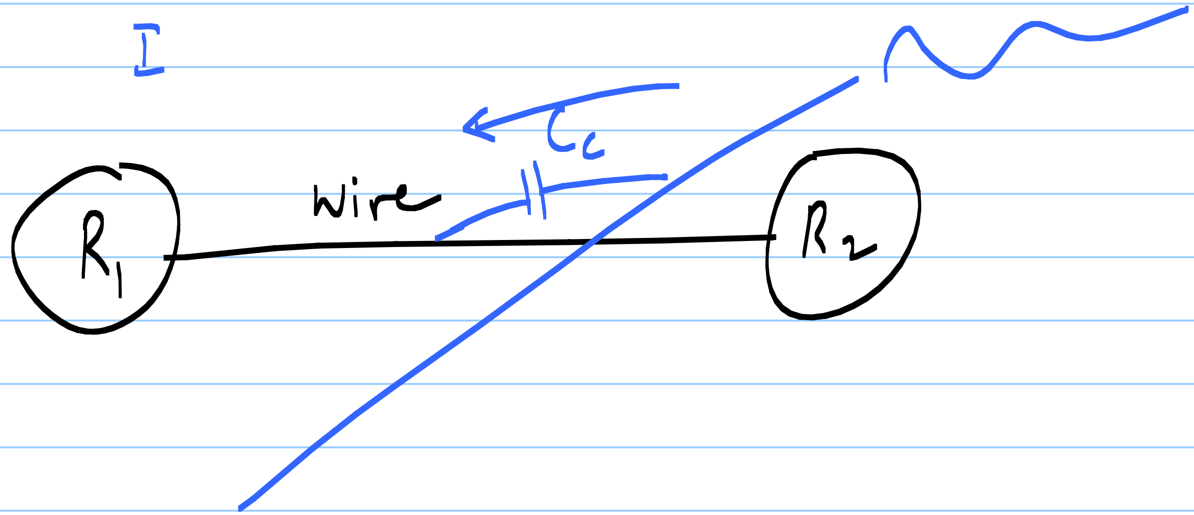
Fully Differential Opamps

1)

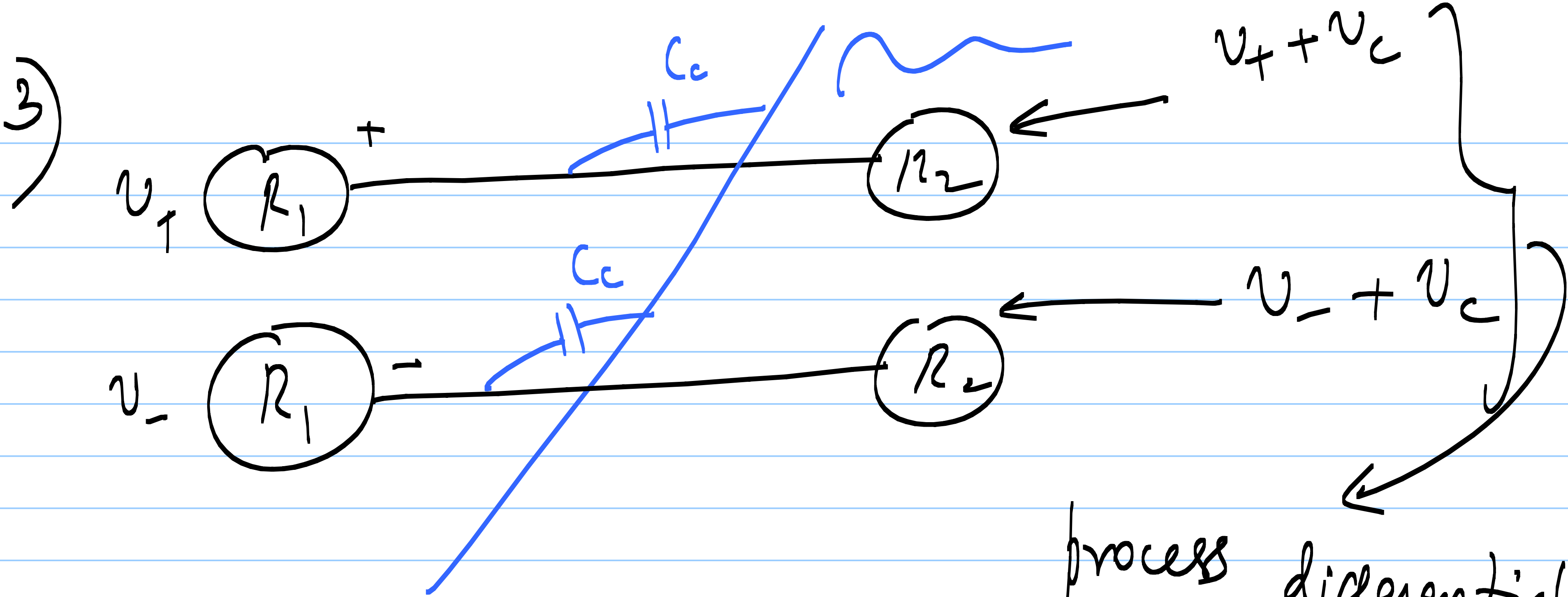


$$\frac{v_o}{v_i} = -\frac{R_2}{R_1}$$

2)



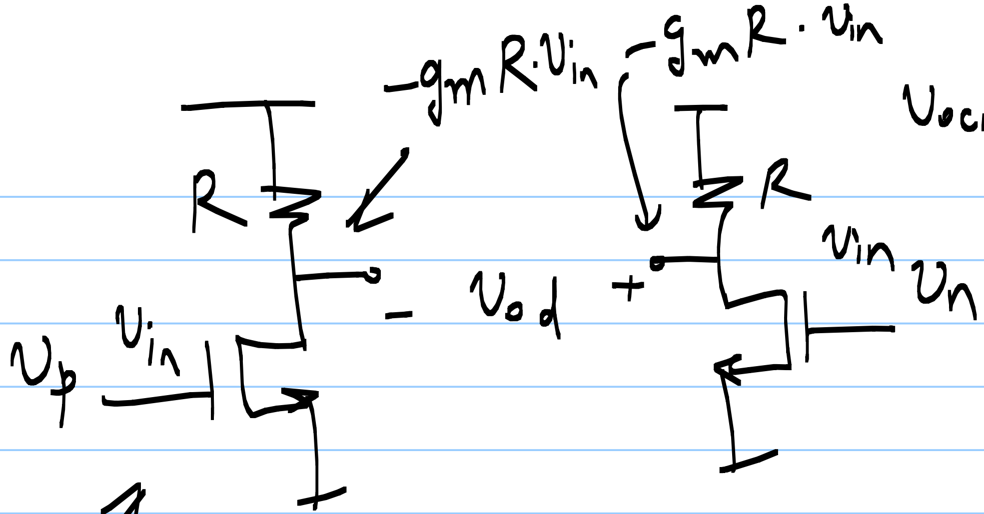
3)

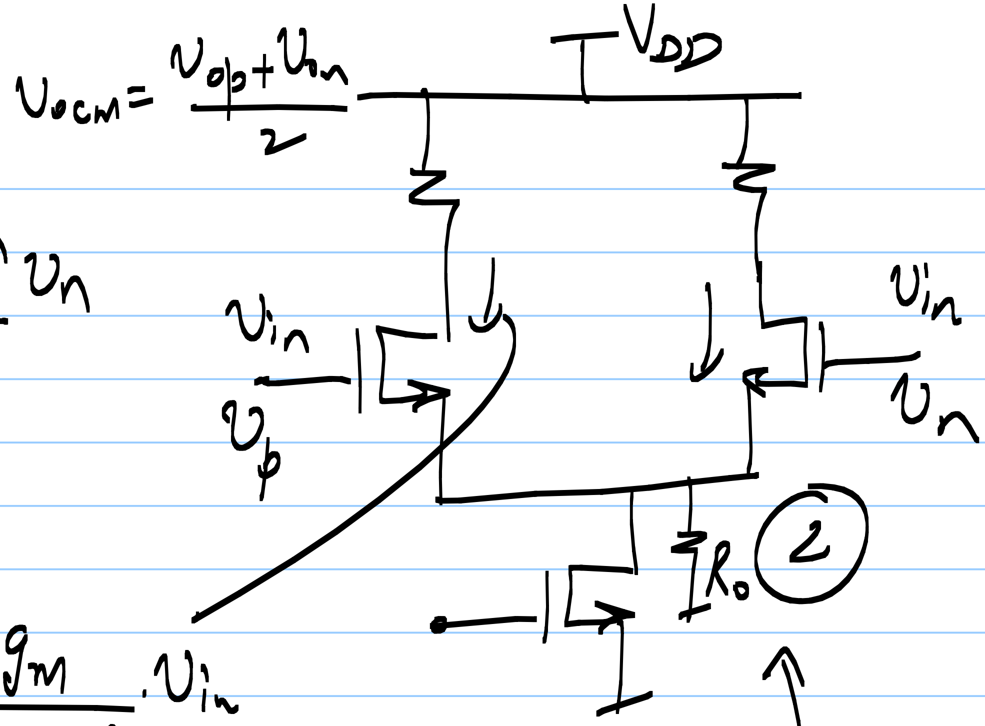


process differentially

$\Rightarrow$ process $v_p - v_n$ $\leftarrow$ differential mode

reject $\frac{v_p + v_n}{2}$ $\leftarrow$ common mode





$\frac{g_m}{1+2g_mR_o}\cdot v_{in}$

1

has no CMRR

$A_{dm_1} = A_{dm_2}$

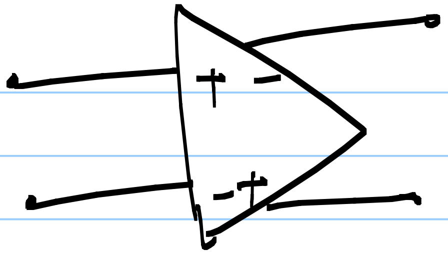
$A_{cm_1} = A_{dm_1}$

"pseudo differential" amplifier

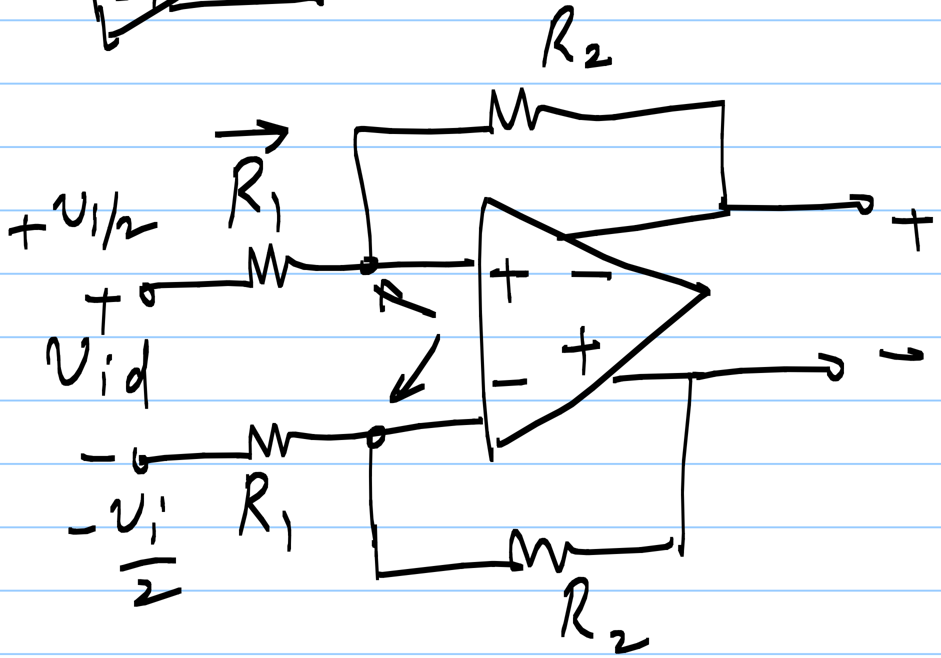
$A_{cm_2} \approx 0$

has large CMRR

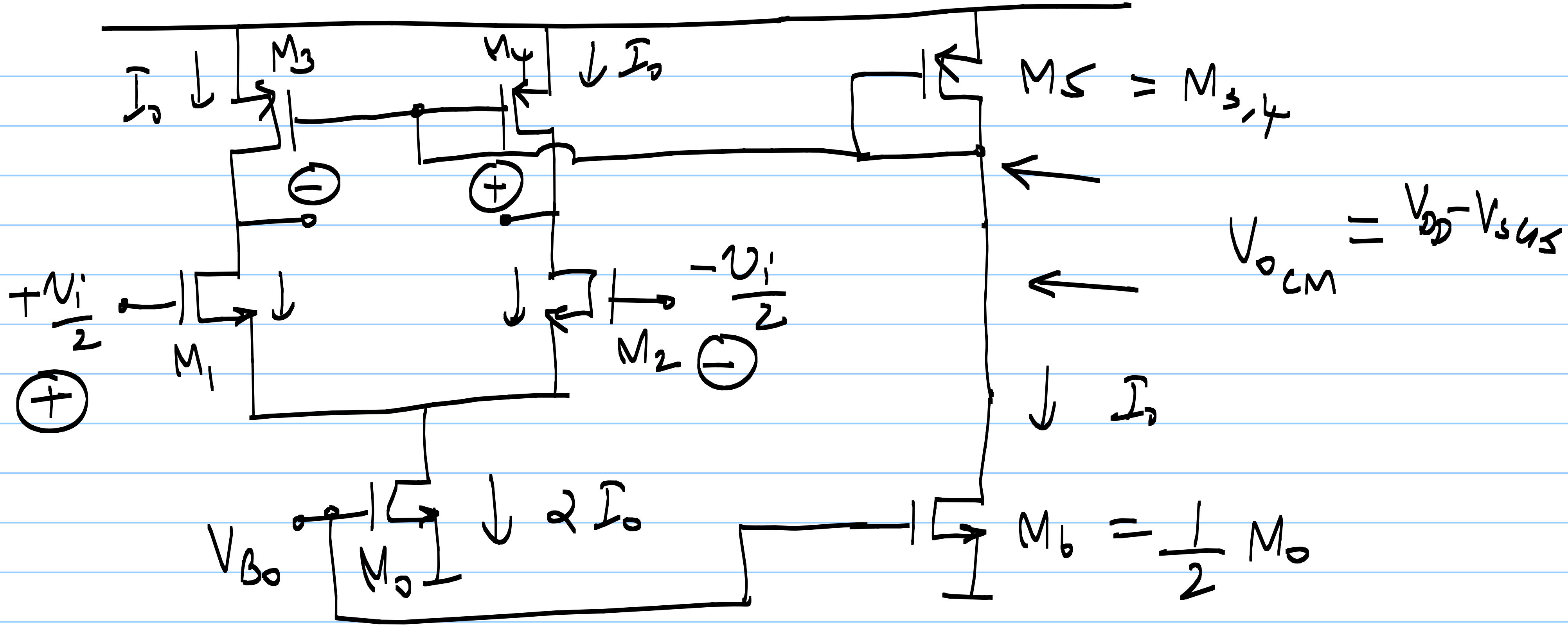
"Differential" amplifier



← fully differential opamp



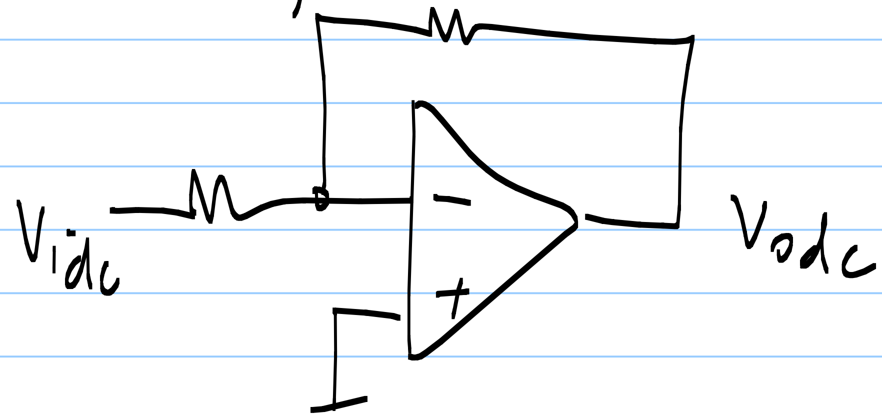
$$v_{od} = \left(-\frac{R_2}{R_1}\right) \cdot v_{id}$$

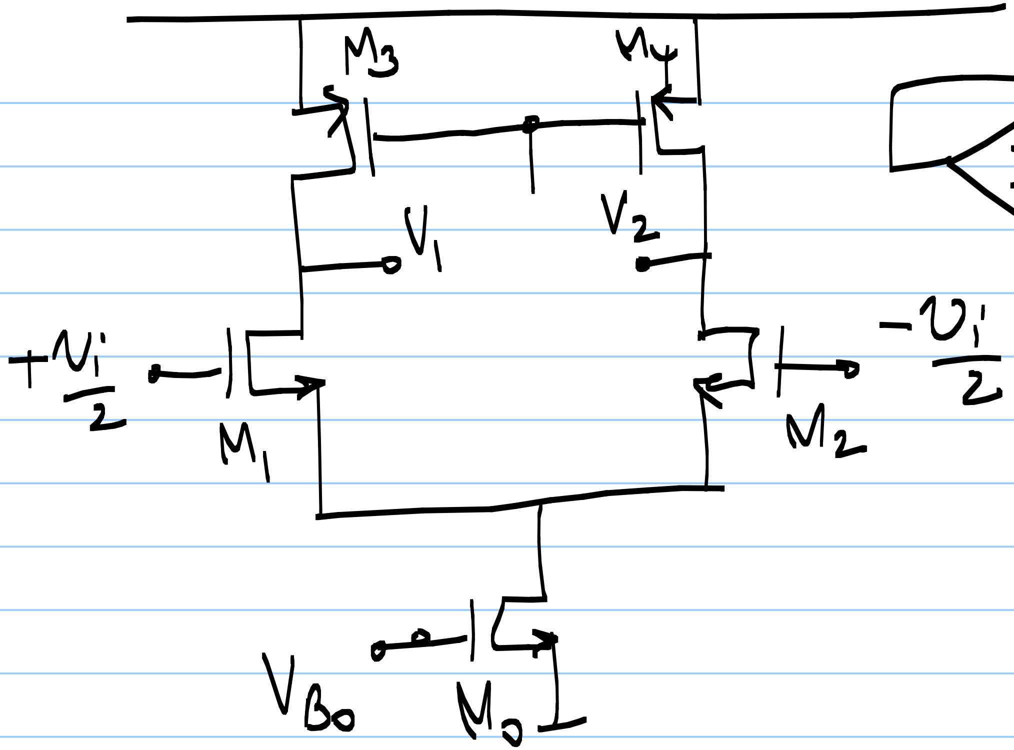


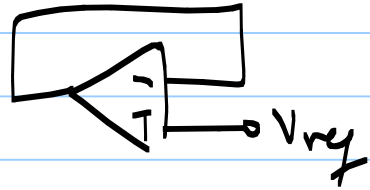
M3
M4
I_0
I_0
M5 = M3,4
$+\frac{v_i}{2}$
$-\frac{v_i}{2}$
M1
M2
$V_{ocm} = V_{DD} - V_{SG5}$
I_0
$2I_0$
V_{B0}
M0
M6 = $\frac{1}{2}$ M0

* Ill biased because output DC is not set properly

* Need common mode feedback (CMFB) to set output Commn mode properly

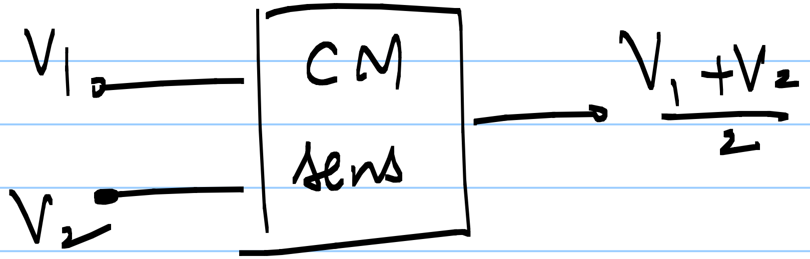


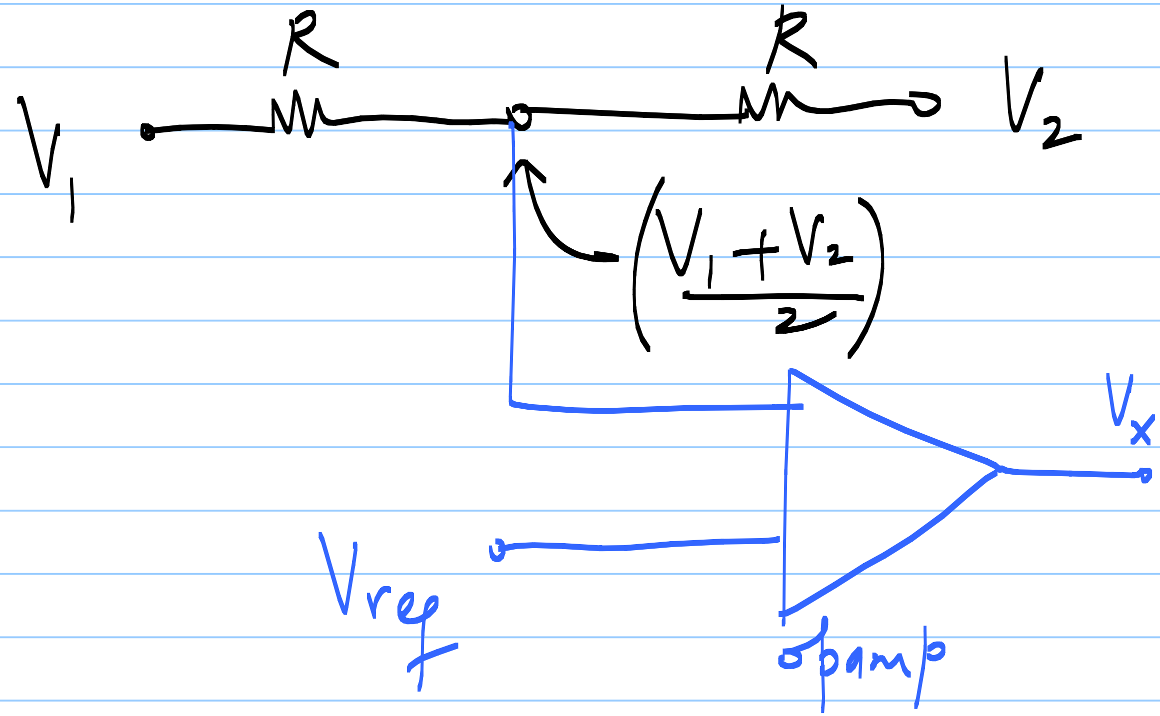




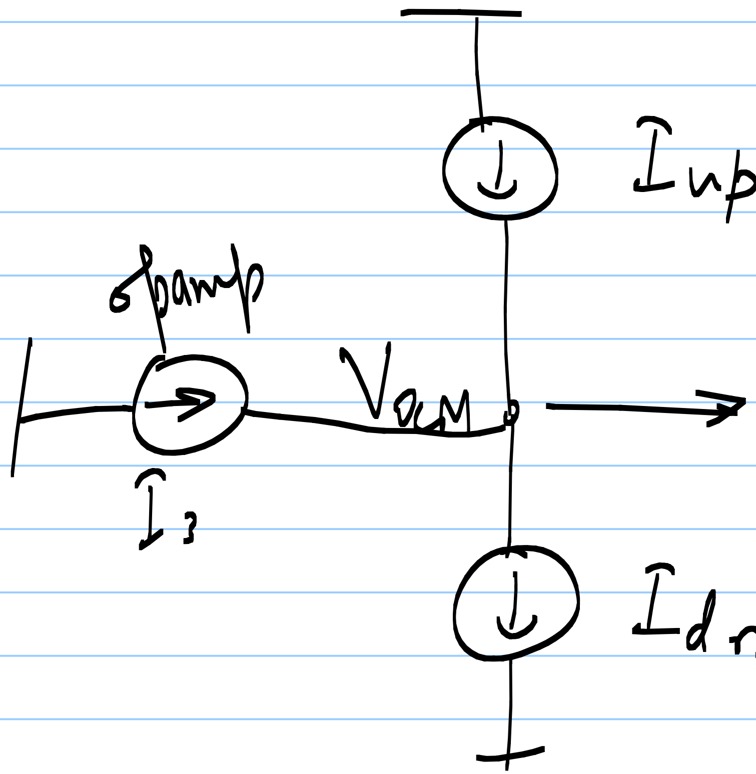
Need

* CM sensing n/w
* Compare V_{OCM} with desired value V_{ref}
* Apply negative fb to drive V_{OCM} to V_{ref}





$V_x \leftarrow$ connect V_x to a node on the ckt that changes V_{ocm}



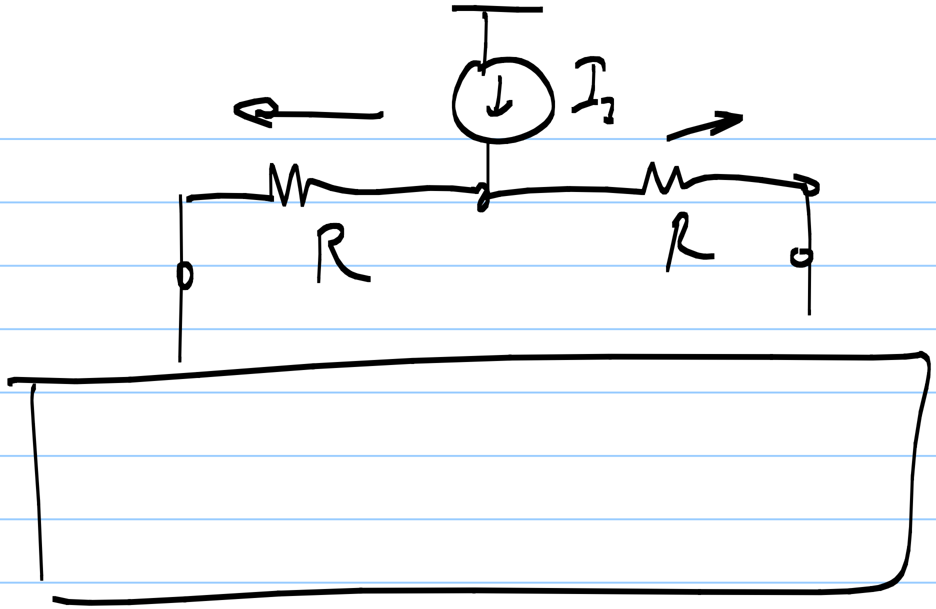
I_{up} (M_3, M_4)

I_{dn} (M_1, M_2)

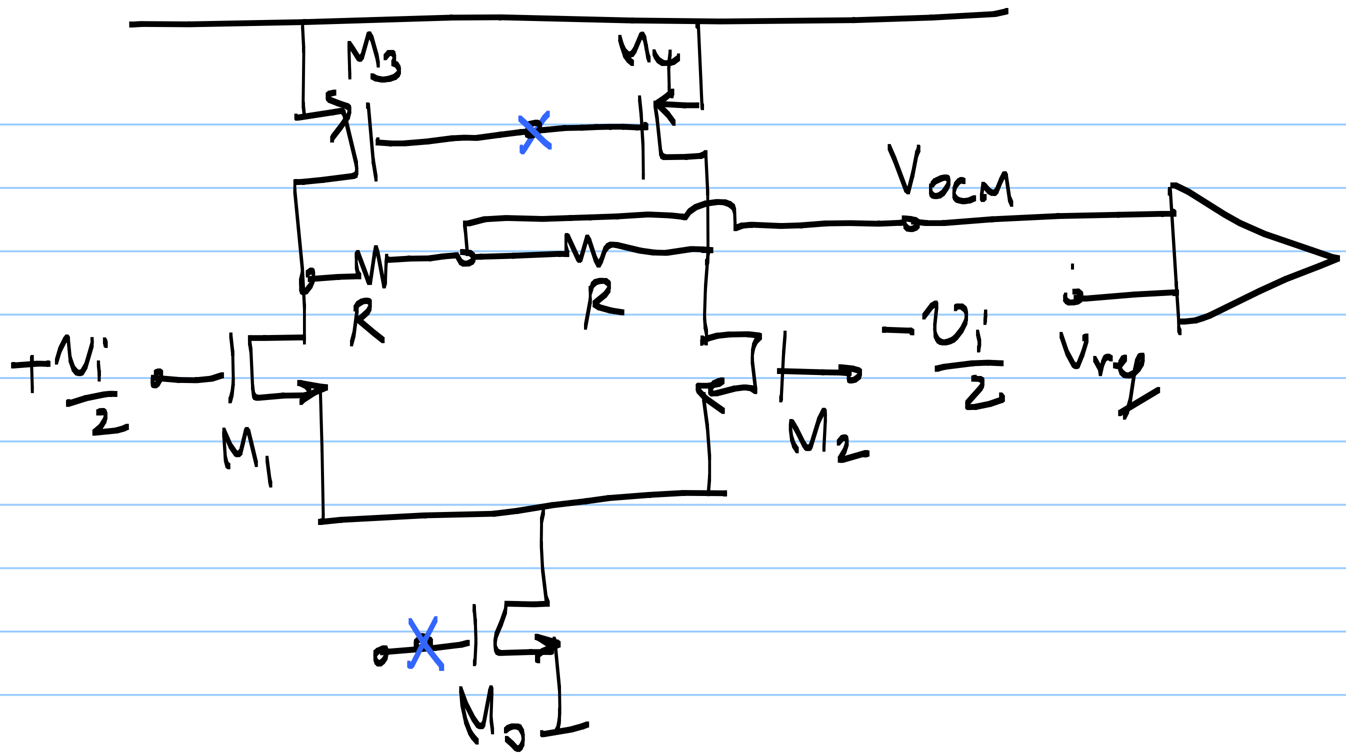
If $I_{up} > I_{dn}$, $V_{ocm} \uparrow$

$I_{up} < I_{dn}$, $V_{ocm} \downarrow$

In steady state, $I_{up} = I_{dn}$



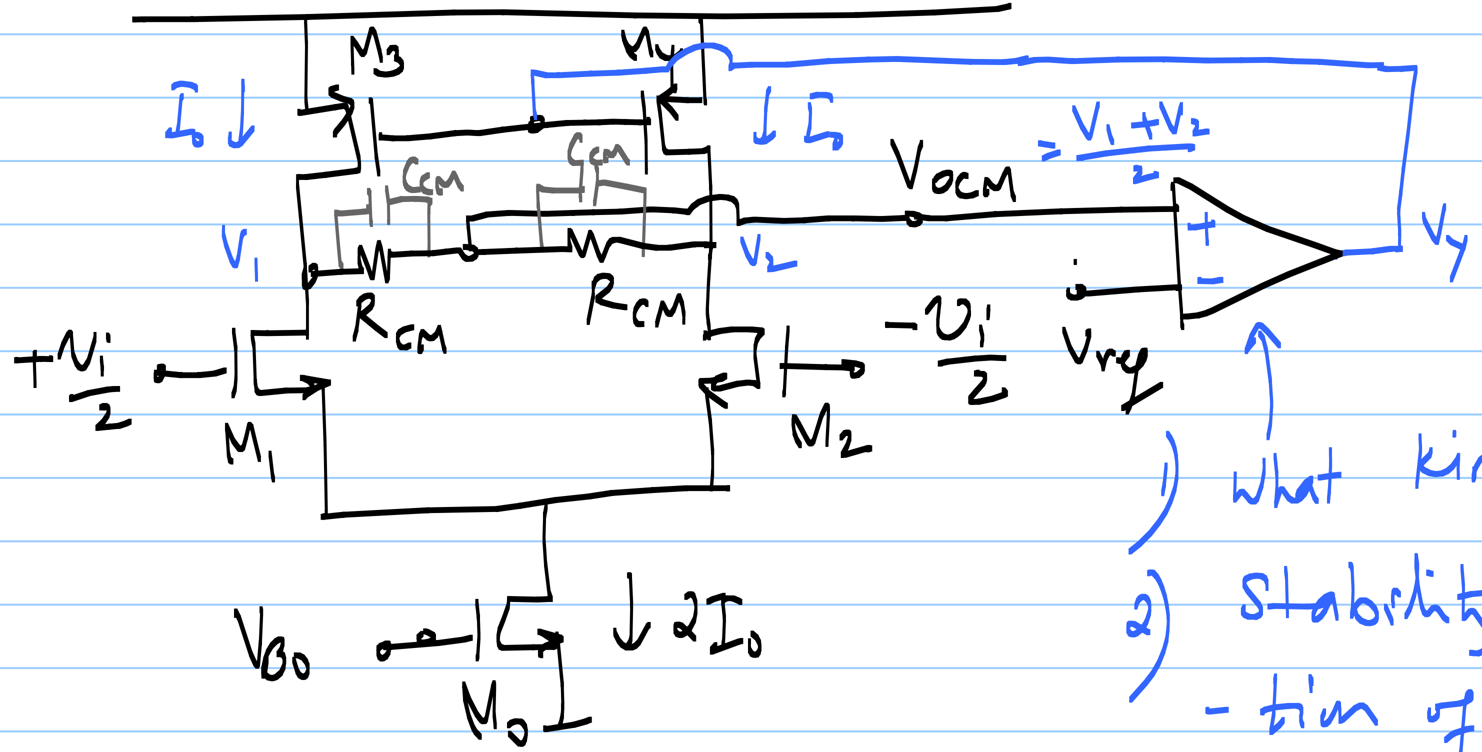
I_7
R
R

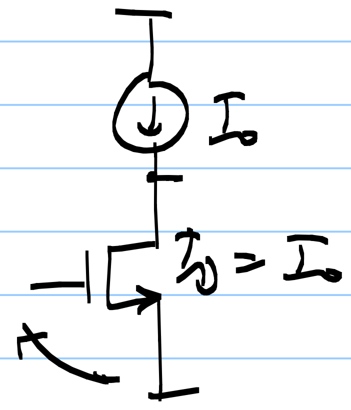


M_3
M_4
V_{OCM}
R
R
$+\frac{v_i}{2}$
$-\frac{v_i}{2}$
V_{ref}
M_1
M_2
M_0

28|2|20

Lec 25



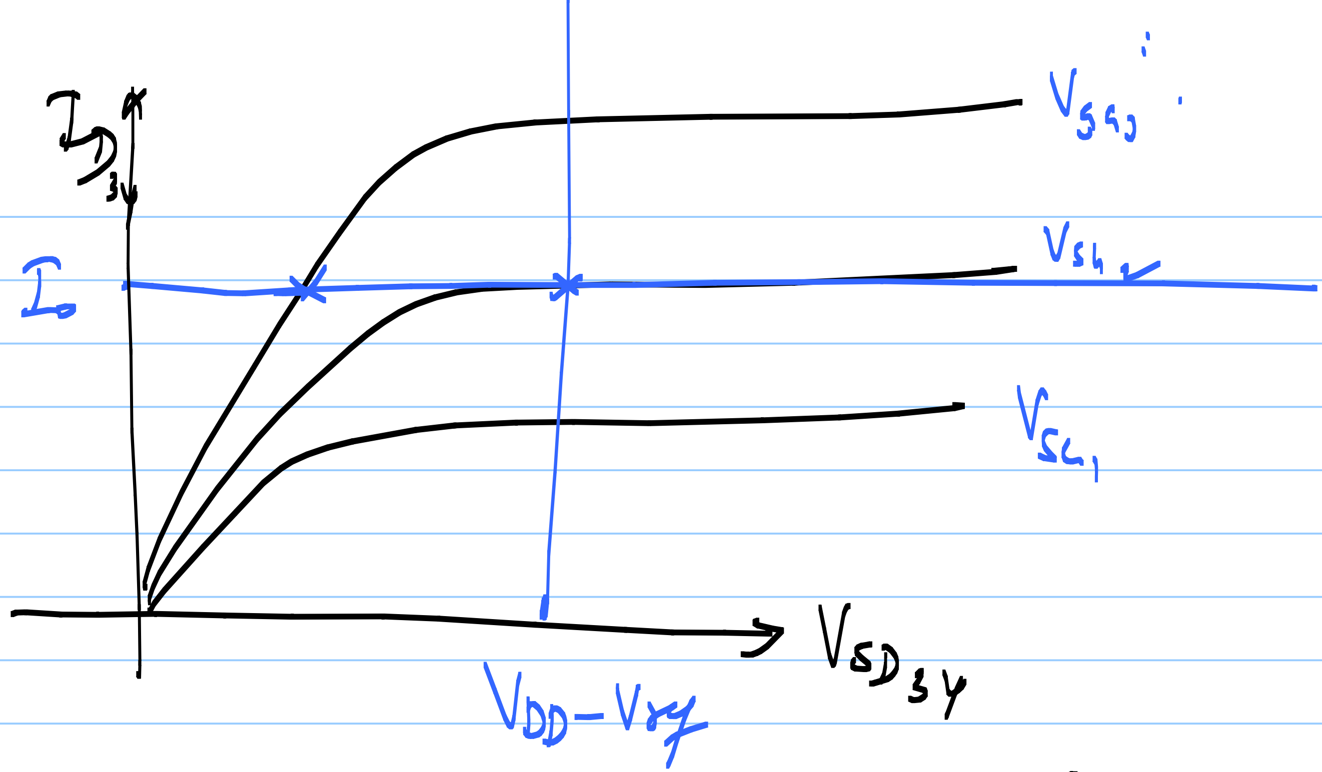


1) What kind of opamp?

2) Stability & compensation of CMFB

3) Does CMFB affect diff. operation?

4) Use other types of CM sensors?



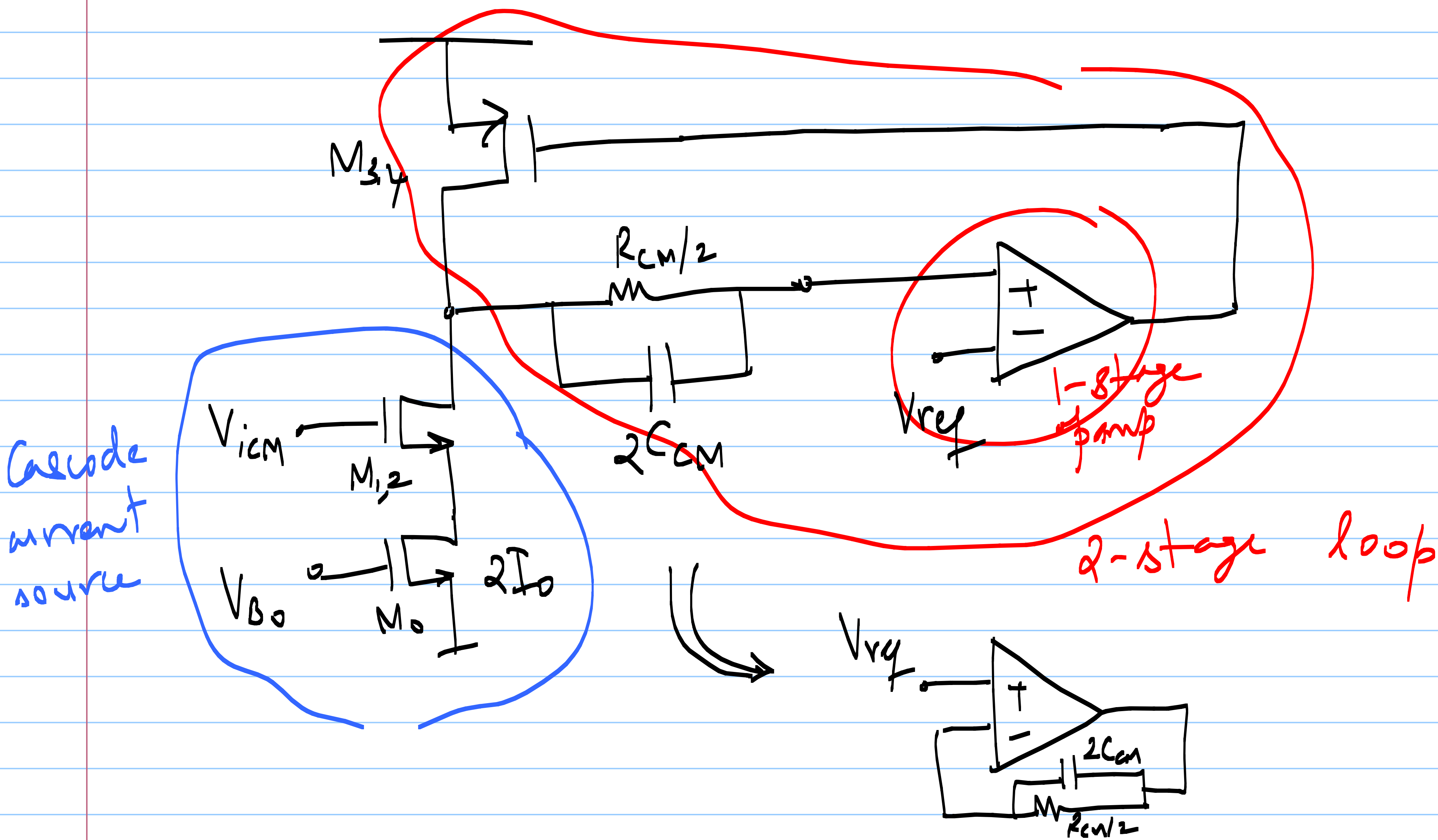
4) CM sensor: → passive (linear) – use this for 1-stage FD opamp.
→ active

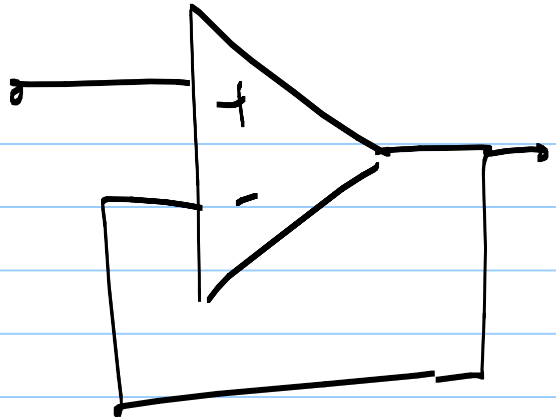
3) Diff'l. operation: $\frac{v_{od}}{v_{id}} = g_{m_1}(r_{ds_2} \| r_{ds_4} \| R_{cm})$

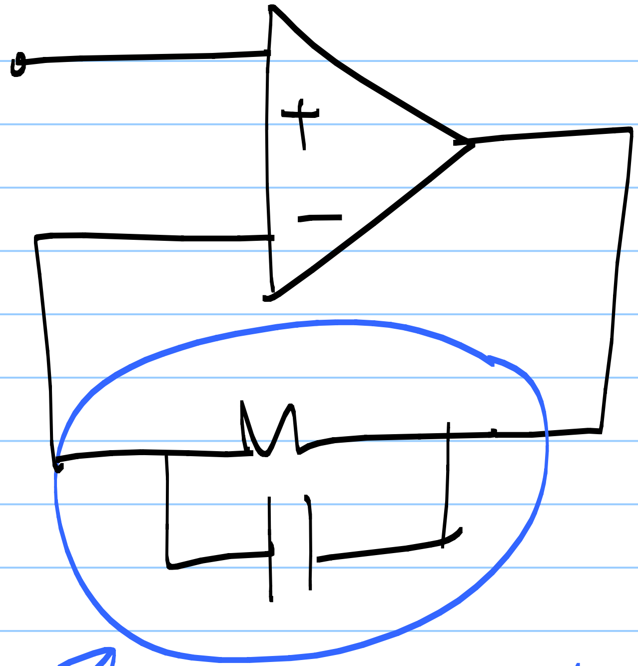
$R_{cM} \gg r_{ds_2}, r_{ds_4}$ $\sim M\Omega$
comes with parasitic cap C_{cM}

1) choose 1-stage opamp for simplicity

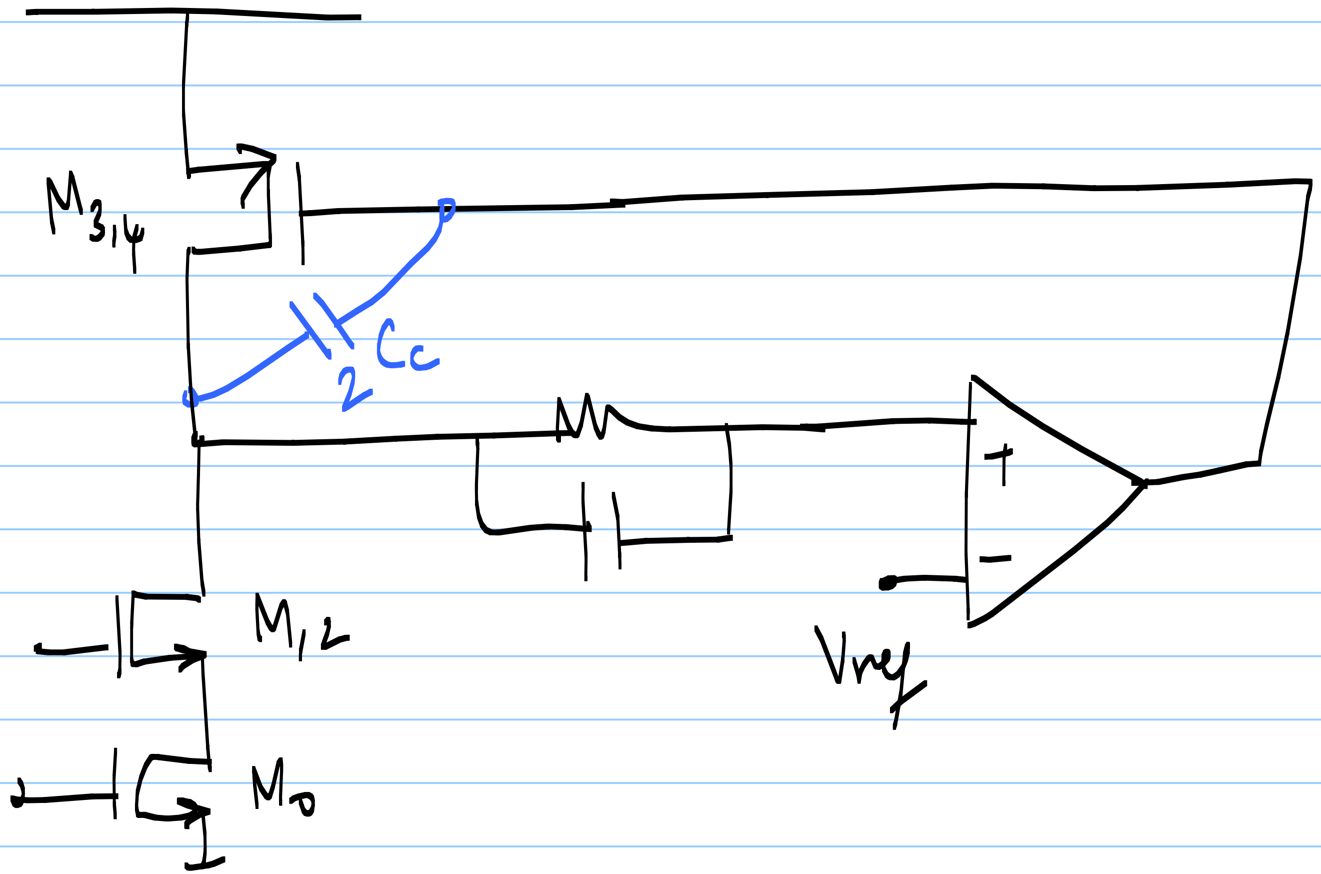
2) <u>stability</u>

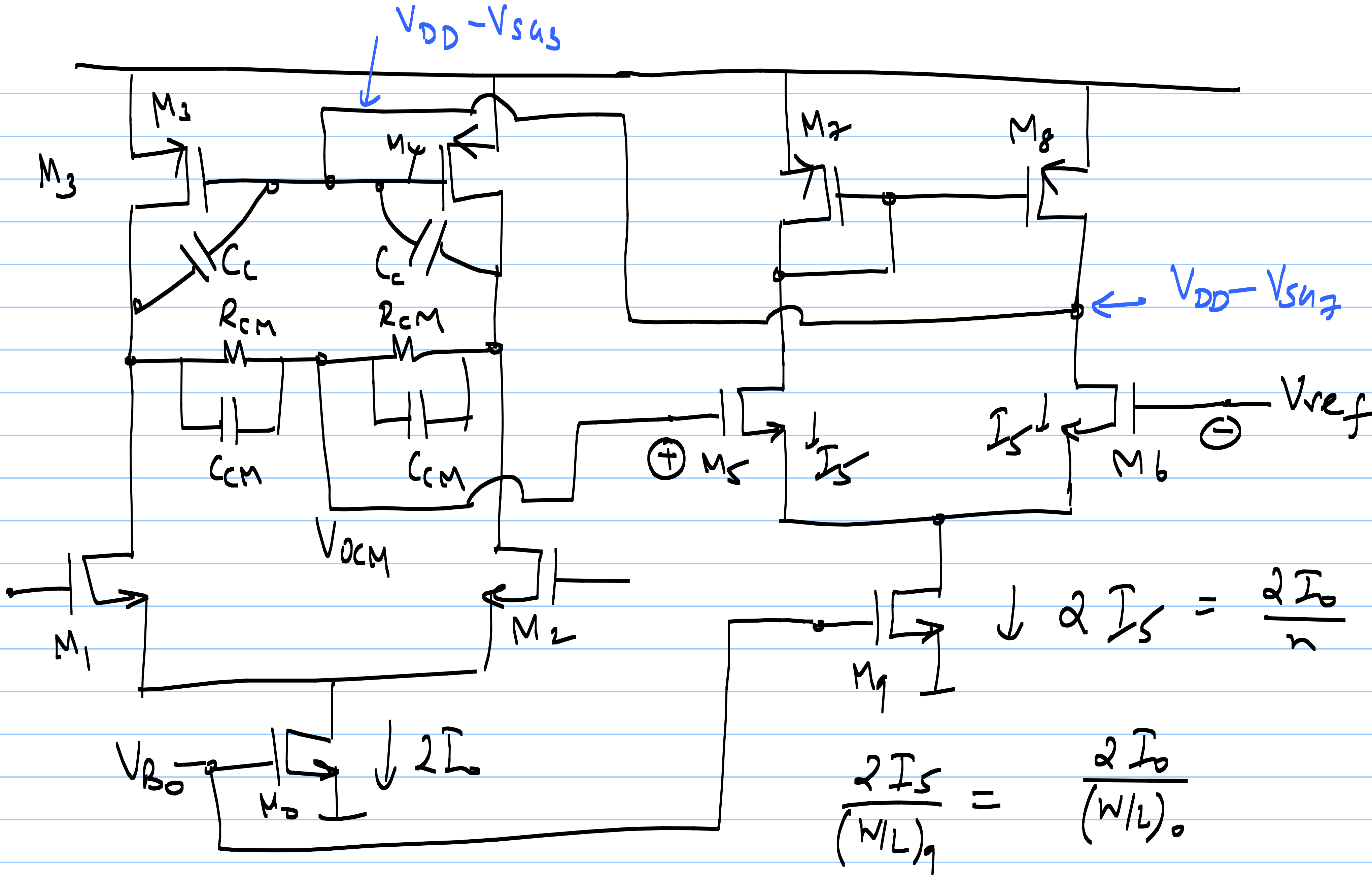






adds/subtract phase shift } changes PM


M3,4
Cc
2
M1,2
M0
+
−
Vref



$$\downarrow 2I_5 = \frac{2I_0}{n}$$

$$\frac{2I_5}{(W/L)_9} = \frac{2I_0}{(W/L)_0}$$

Set $V_{DD} - V_{SG_3}\Big|_{I_0} = V_{DD} - V_{SG_7}\Big|_{I_5}$

$V_{OCM} = V_{ref}$ in absence of mismatches

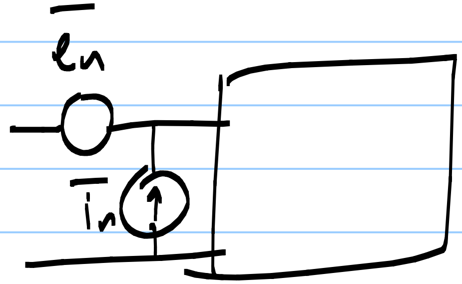
2/3/20

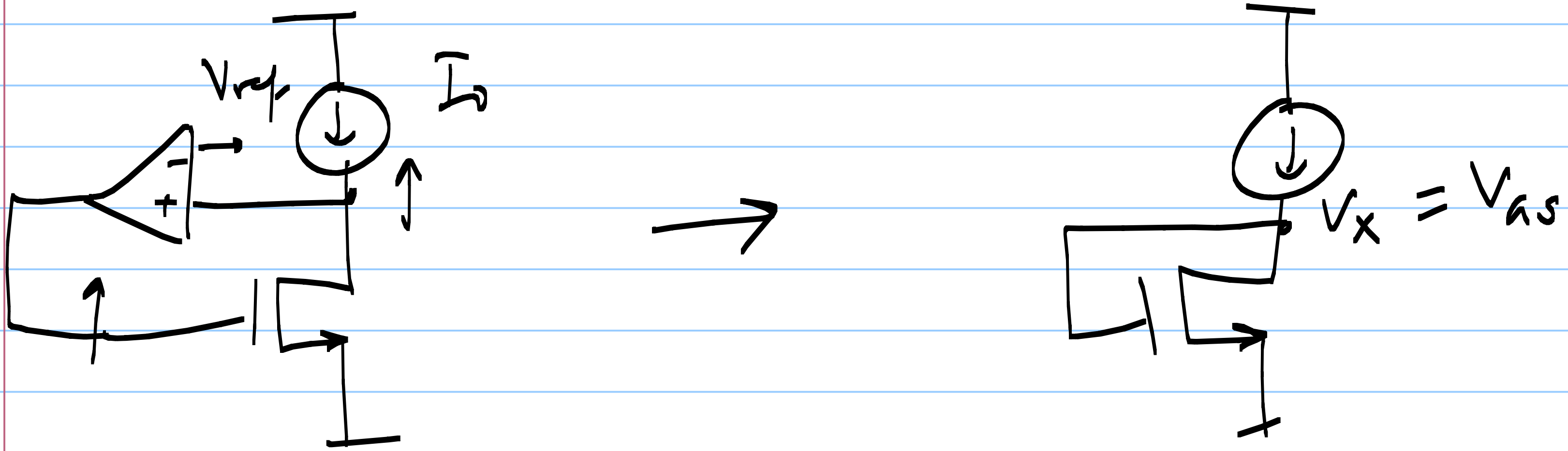
Lec 26

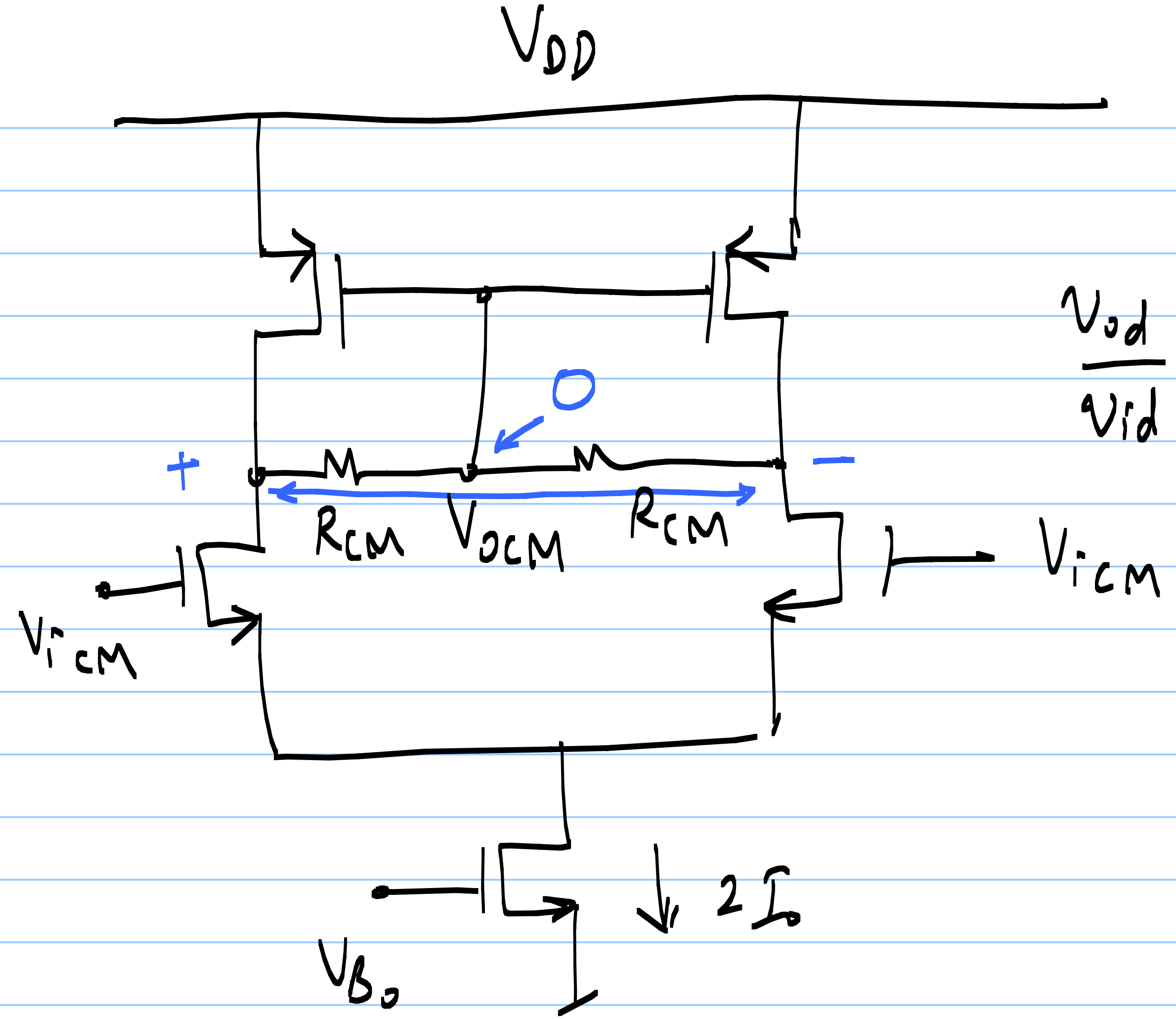
Asg 3

1) $V_{ov.}$ - cannot be kept constant?

2) Input step mg.

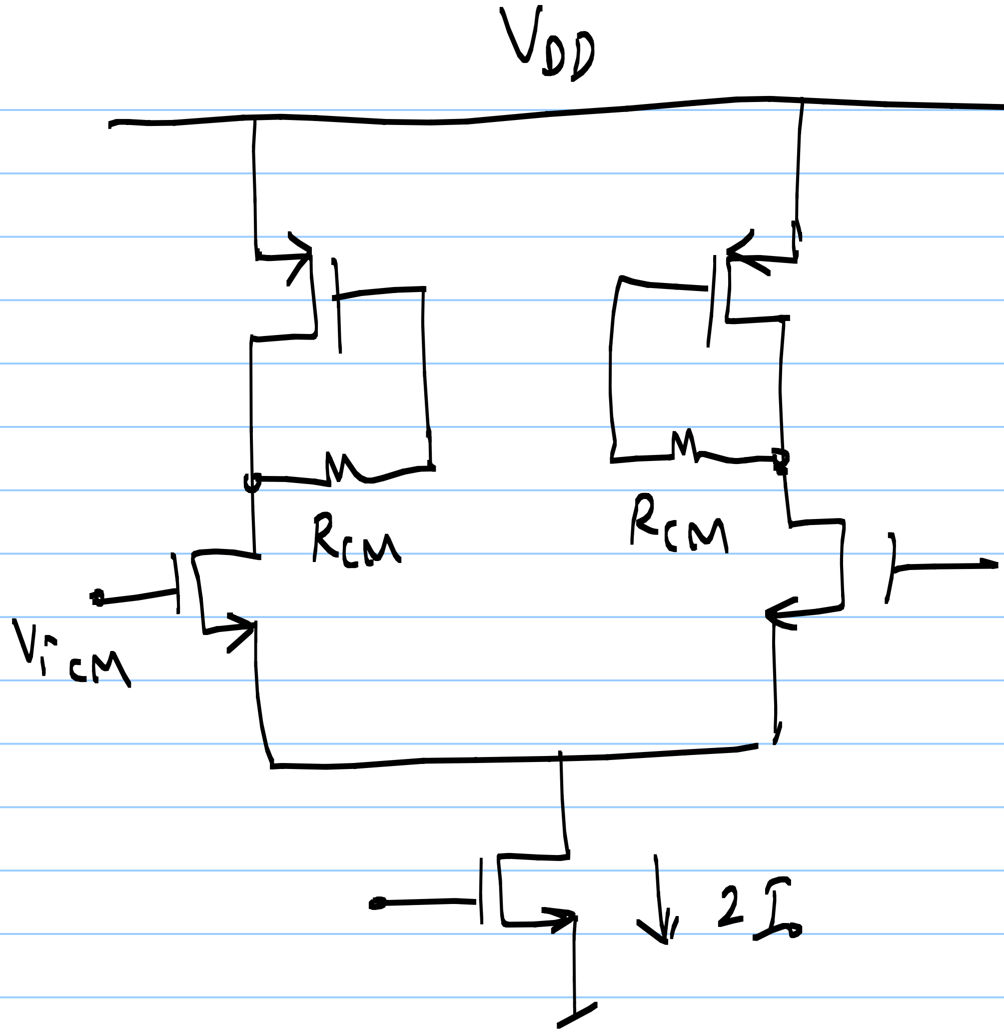






$$V_{OCM} = V_{DD} - V_{SG_{3,4}}$$

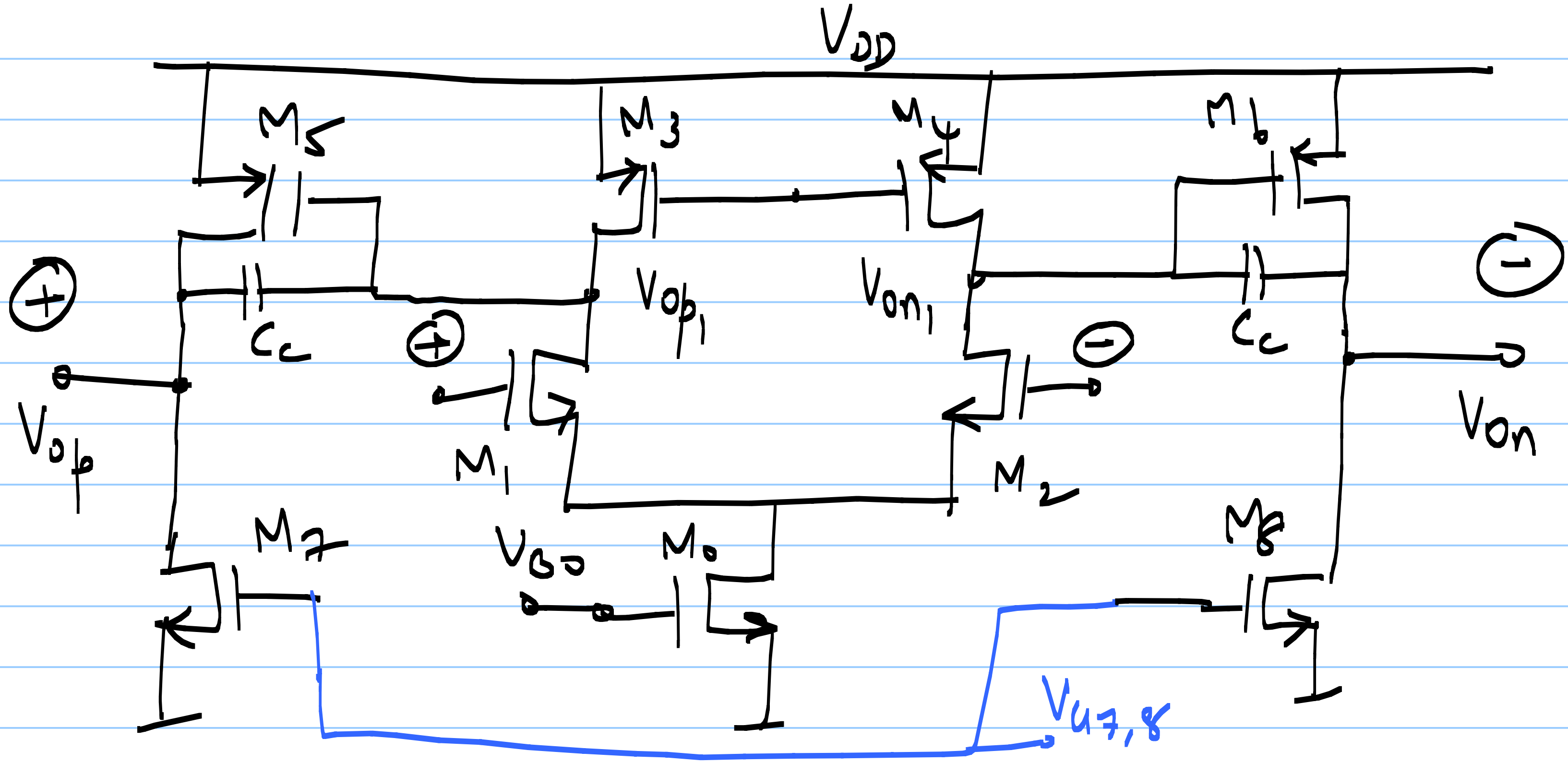
$$\frac{v_{od}}{v_{id}} = g_{m_1}\left(r_{ds_2} \| r_{ds_4} \| R_{CM}\right)$$



$$V_{ocm} = V_{DD} - V_{SG34}$$

$$\frac{v_{od}}{v_{id}} \approx \frac{g_{m_1}}{g_{m_3} + g_{ds_2} + g_{ds_4}}$$

Two-stage fully differential opamps



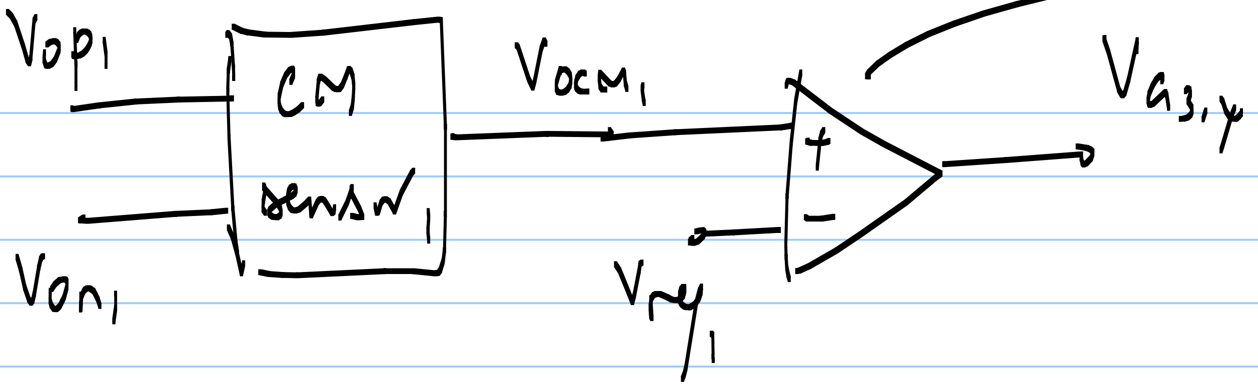
need to set $V_{ocM_1} = \frac{V_{op_1} + V_{on_1}}{2}$

and $V_{ocM} = \frac{V_{op} + V_{on}}{2}$

* $M_5 - M_6$ stage is a pseudo-differential amplifier — has CM gain
* changing $V_{a3,4}$ → changes V_{OCM_1} → changes V_{OCM}

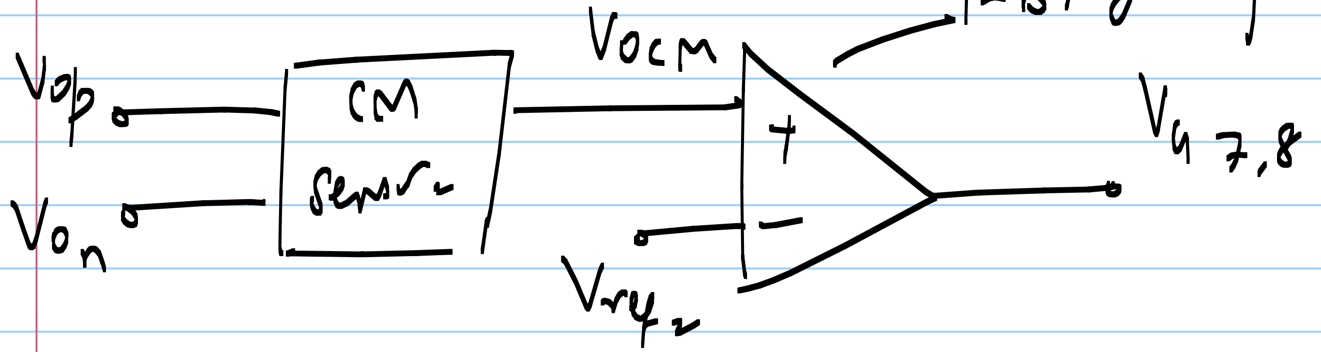
1) Sense V_{OCM} — feedback to $V_{a3,4}$
   → sets both V_{OCM_1} & V_{OCM} with a single CMFB
   → may end up with a 3-stage loop
   → stabilizing may be tricky.

2) Have 2 CMFB, one around each stage



onestage opamp

1) nmos input pair
2) pmos CM load
3) same current density in pmos as M_{34}

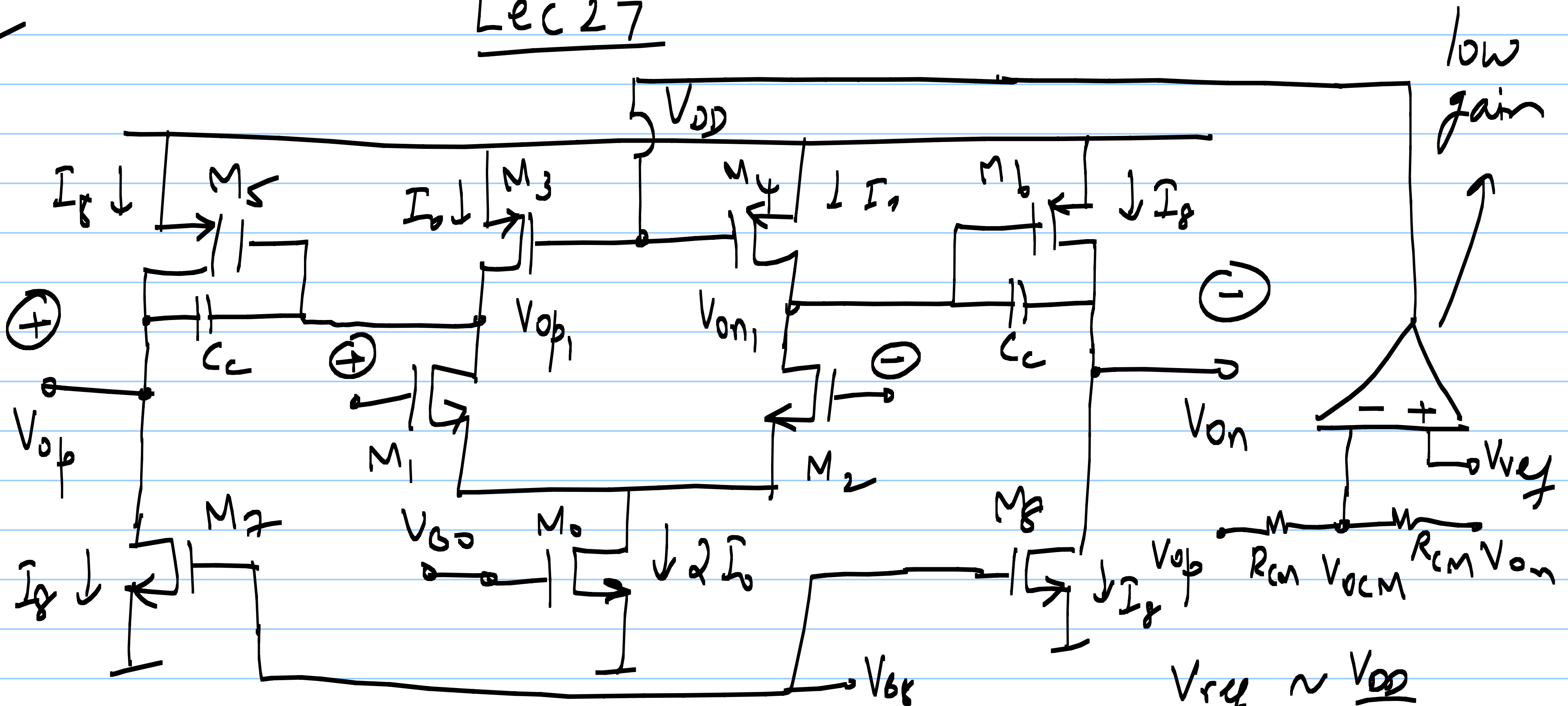


1-stage opamp

1) pmos input pair
2) nmos CM load
3) same current density in nmos CM as M_{78}

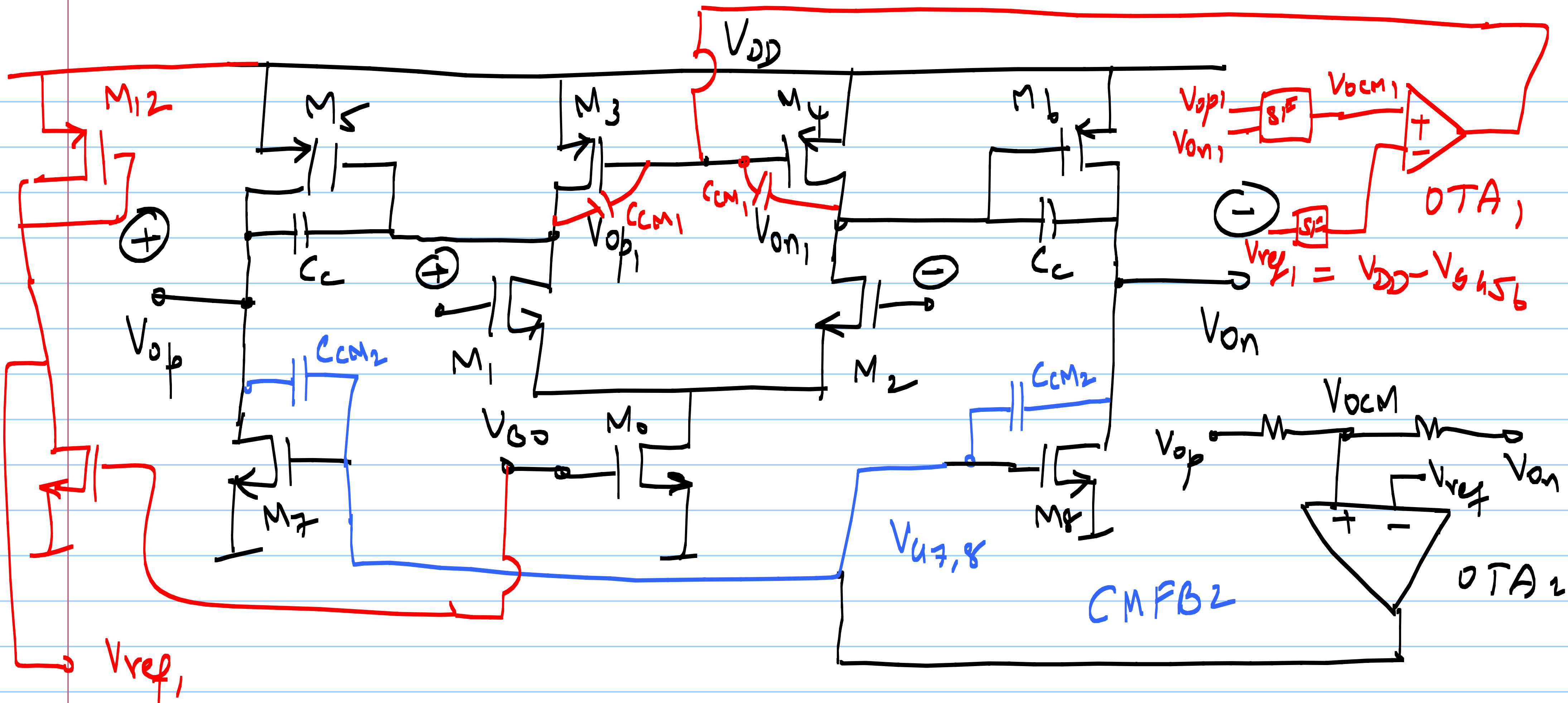
3|3|20

Lec 27



$V_{ref} \sim \frac{V_{DD}}{2}$

C_c – can compensate for CMFB also (in certain cases)

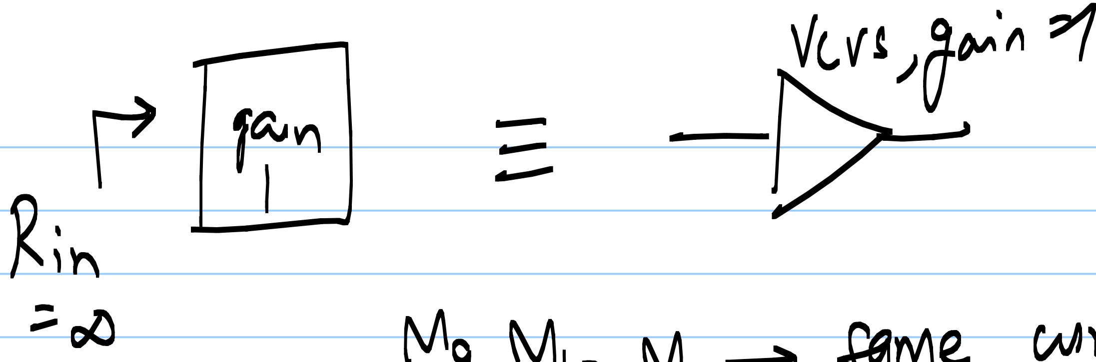


OTA 2 − pmos input pair + $\underbrace{\text{nmos CM load}}$

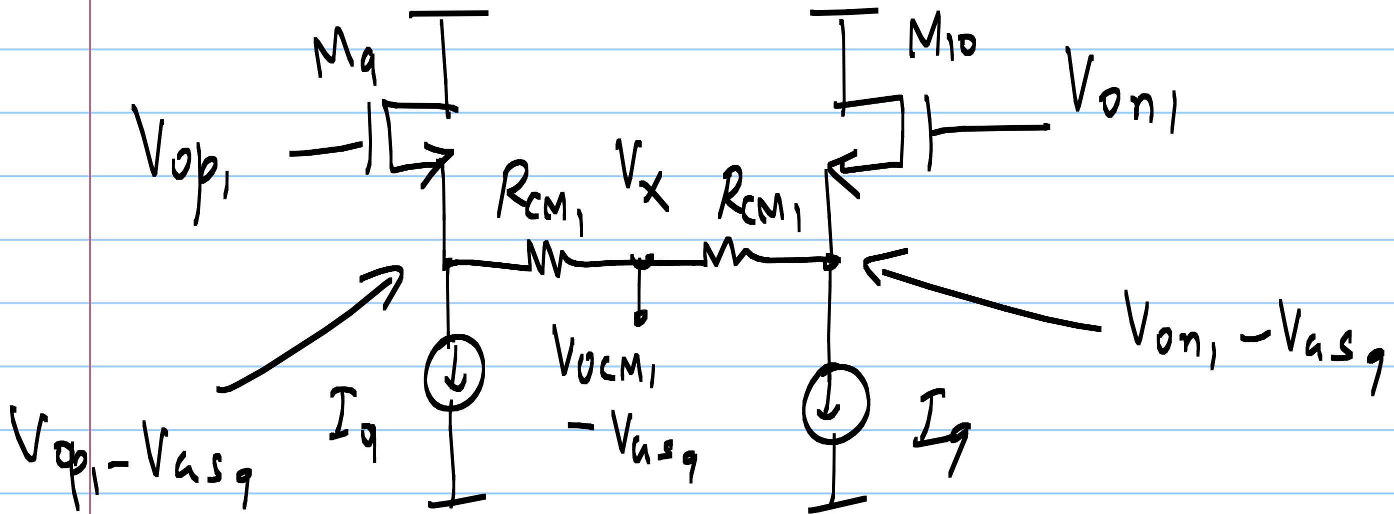
same current density as M_7 − 8

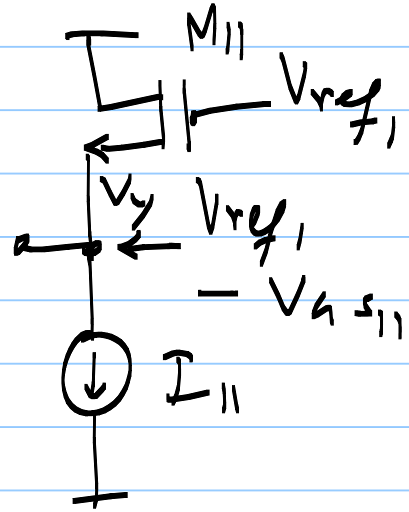
M_{12} & M_5 - M_6 need to have same current density

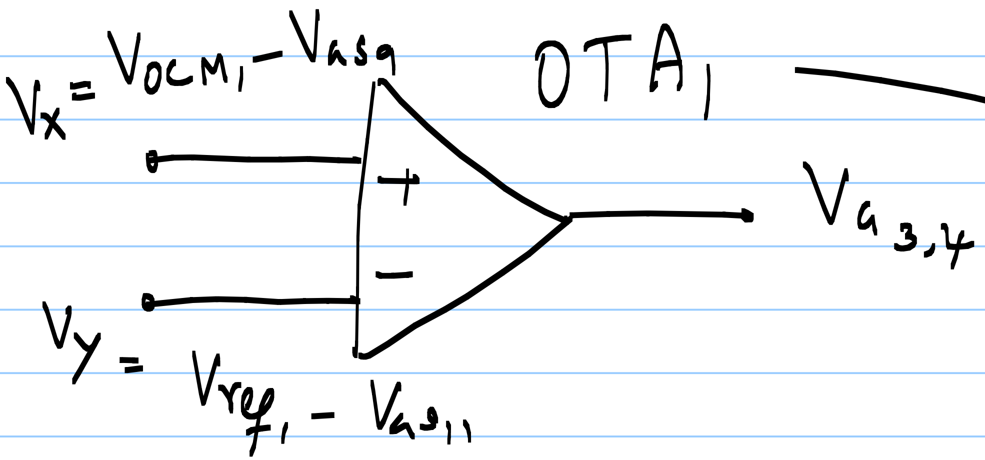
$$V_{OCM_1} = \frac{V_{op_1} + V_{on_1}}{2}$$



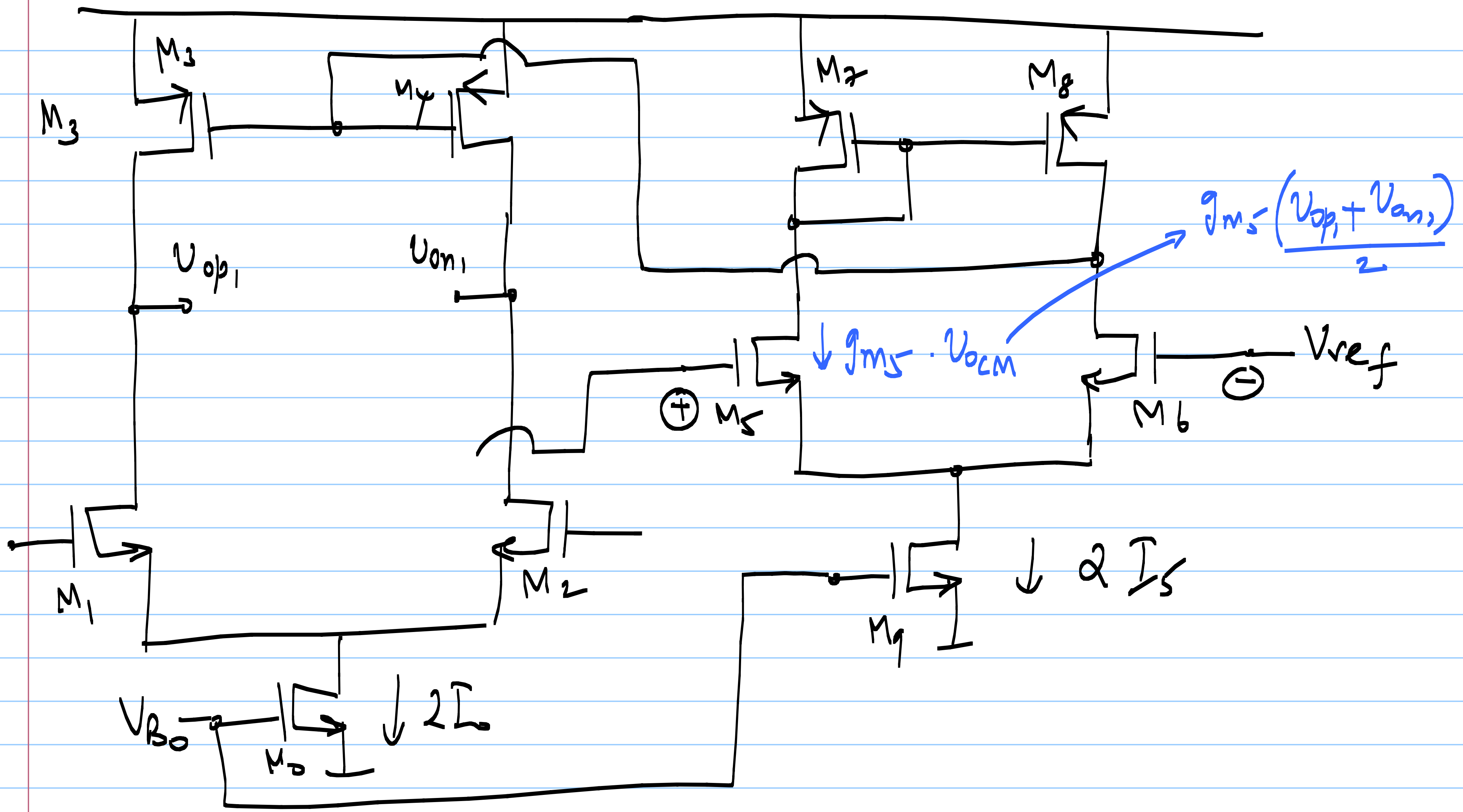
$M_9, M_{10}, M_1 \rightarrow$ same current densities





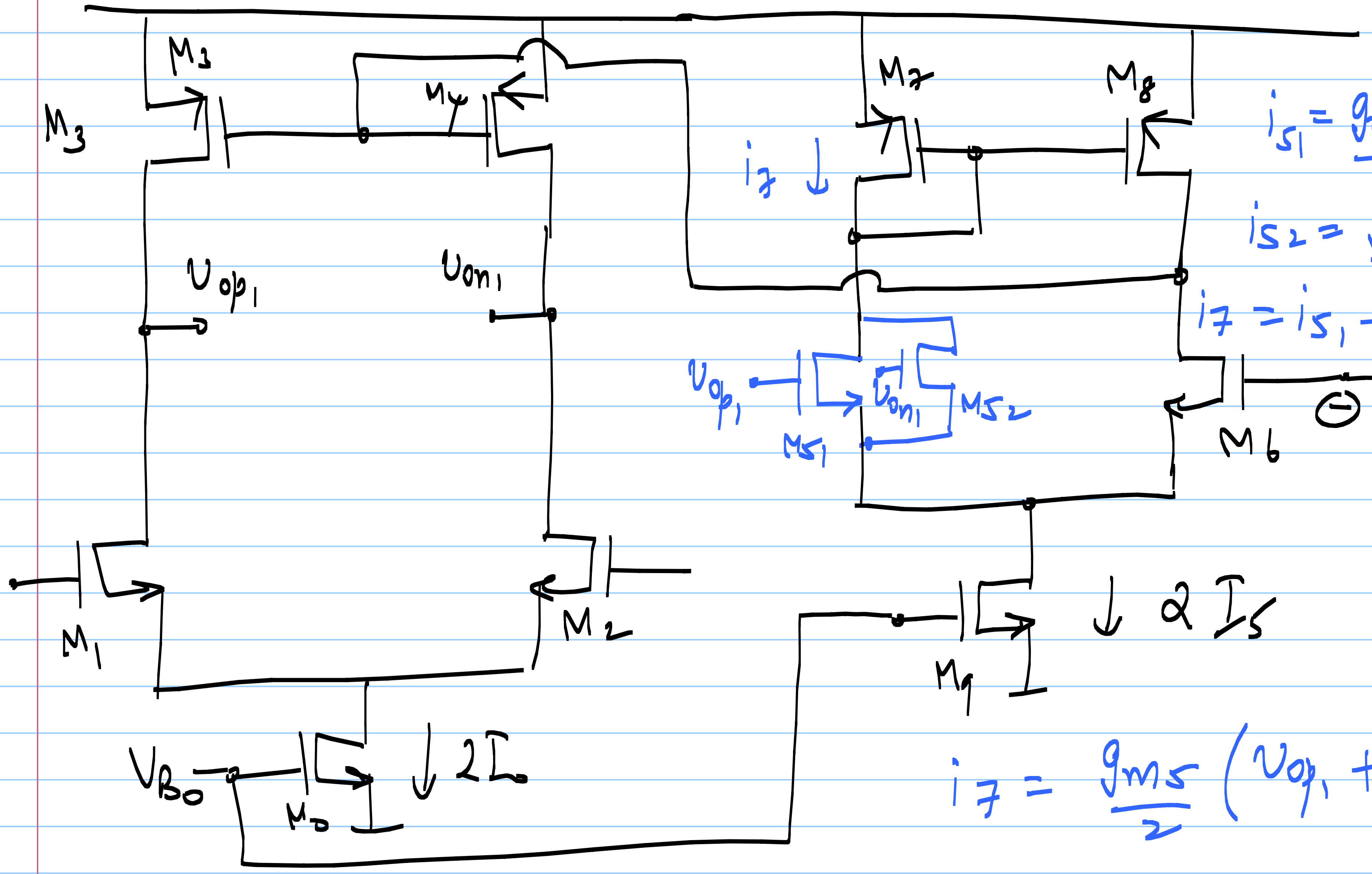


$\rightarrow$ nmos input pair + pmos CM load (same I density as $M_{3,4}$)



M3
M3
M4
M7
M8
V_{op_1}
V_{on_1}
$g_{m5}\frac{(V_{op_1}+V_{on_1})}{2}$
$g_{m5}\cdot V_{ocm}$
+
M5
M6
−
Vref
M1
M2
M9
2 I_5
V_{B0}
M0
2 I_0

$M_{5_1} = M_{5_2} = \frac{M_5}{2}$ $\qquad g_{m5_1} = g_{m5_2} = \frac{g_{m5}}{2}$



$i_{s_1} = \frac{g_{m5}}{2} \cdot v_{op_1}$

$i_{s_2} = \frac{g_{m5}}{2} \cdot v_{on_1}$

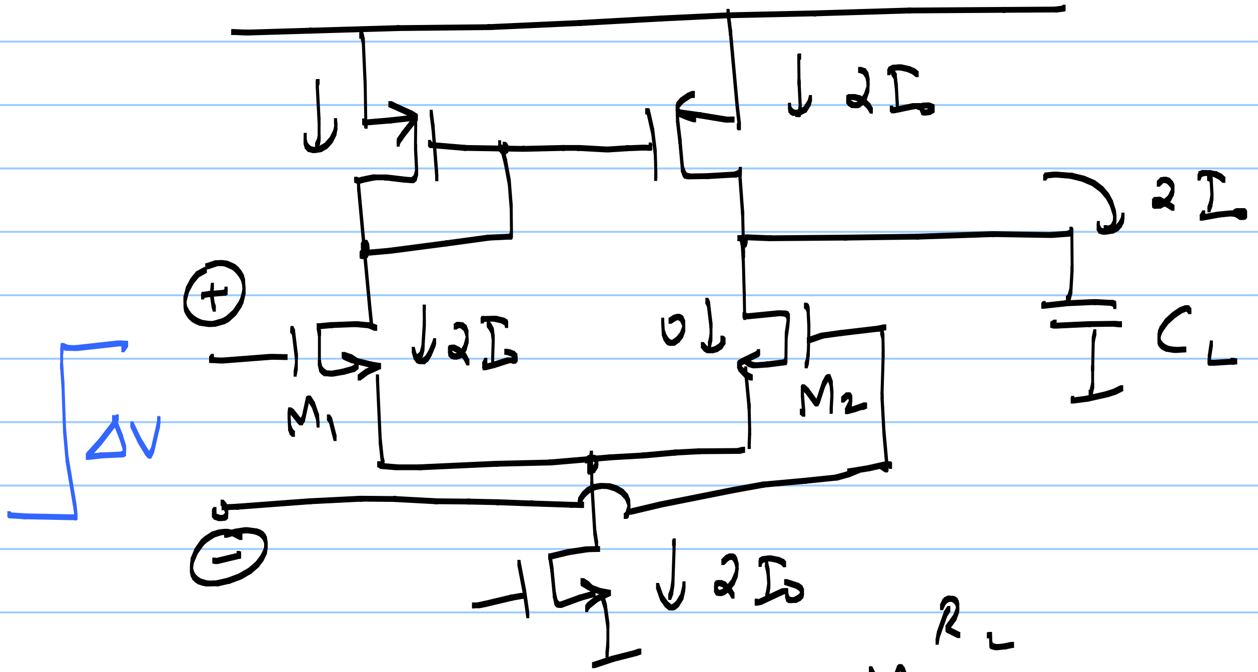
$i_7 = i_{s_1} + i_{s_2}$

$i_7 = \frac{g_{m5}}{2}(v_{op_1} + v_{on_1})$

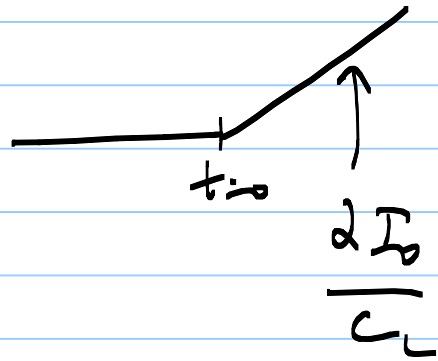
6/3/20

Lec 28

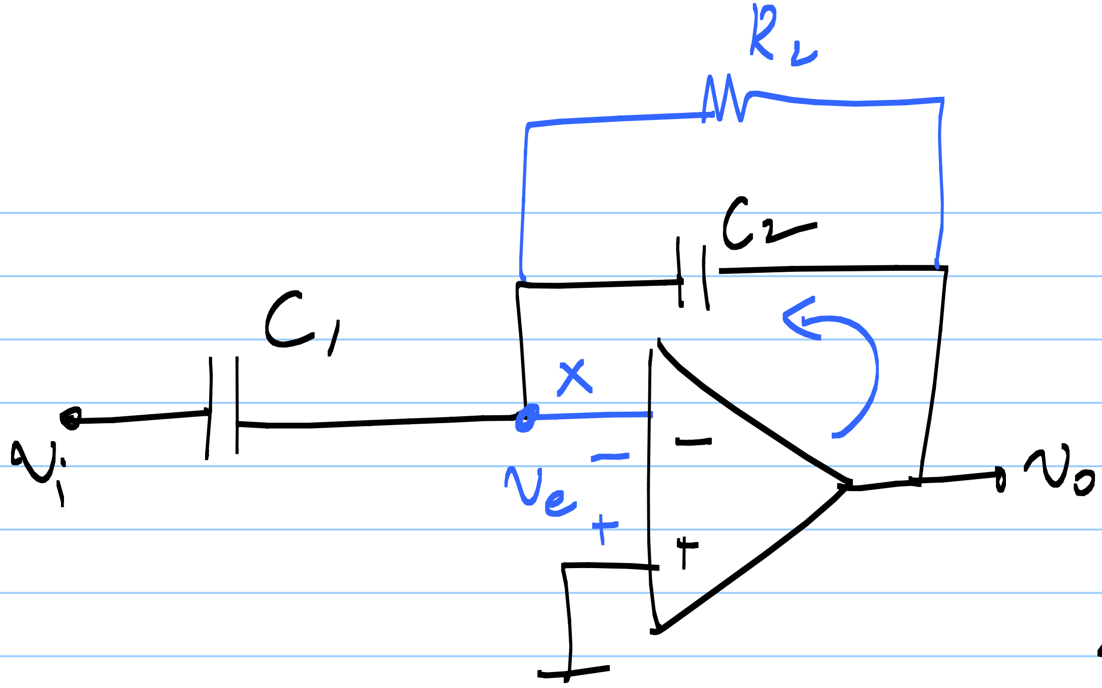
Review Class



Slew rate



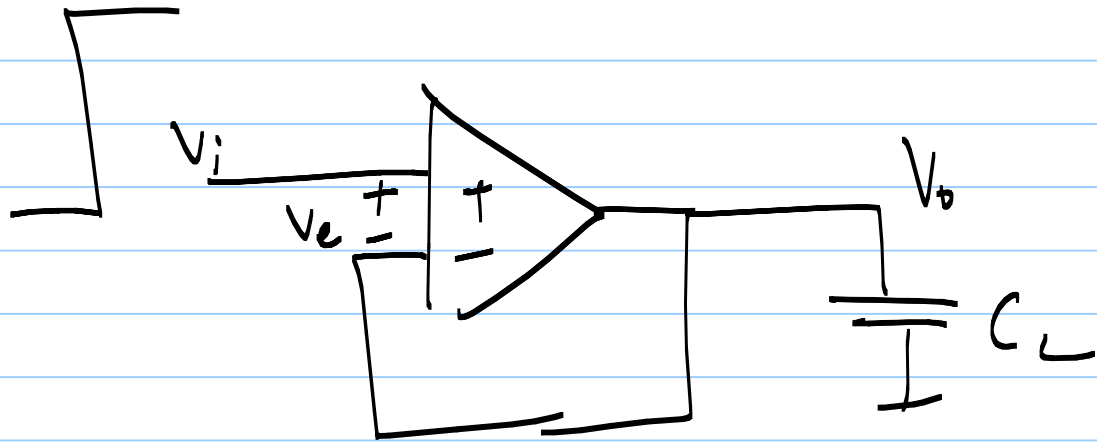
$$\frac{V_o}{V_i} = -\frac{R_2}{R_1}$$

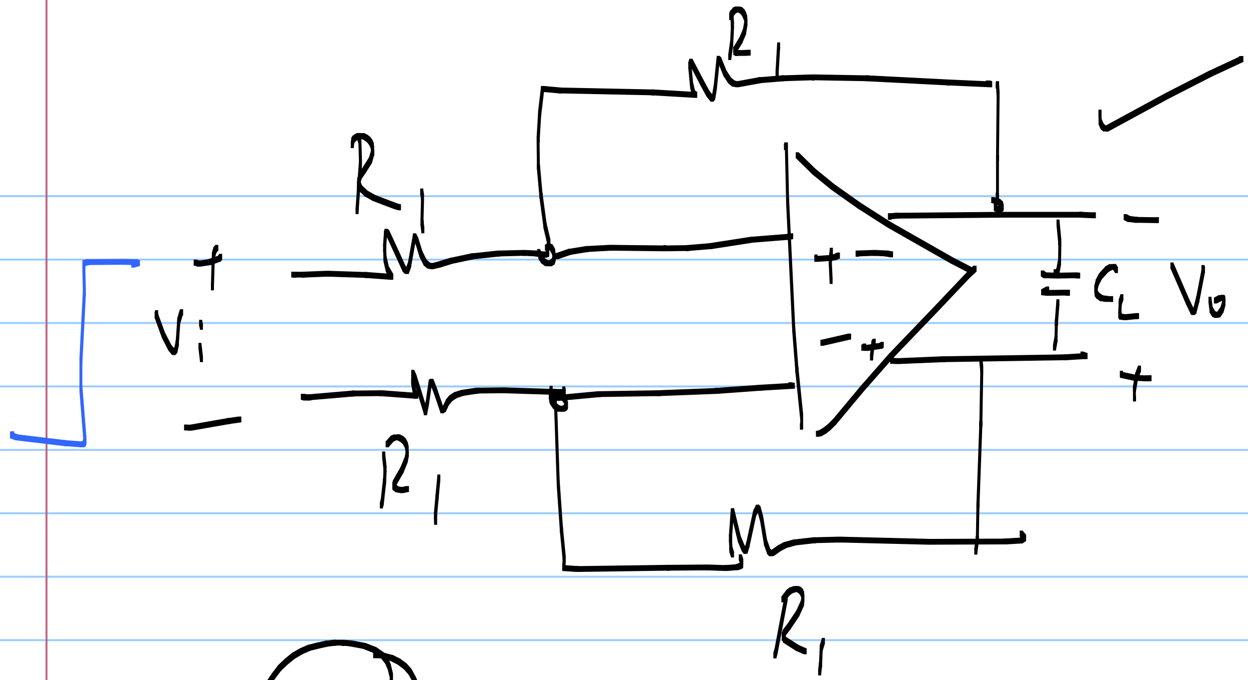


$$\frac{v_o}{v_i} = -\frac{C_1}{C_2}$$

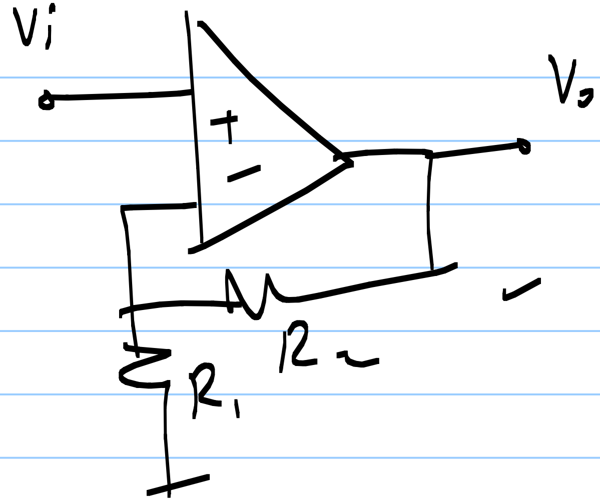
$$R_2 \gg \frac{1}{sC_2}$$

If $\omega \gg \frac{1}{R_2 C_2}$

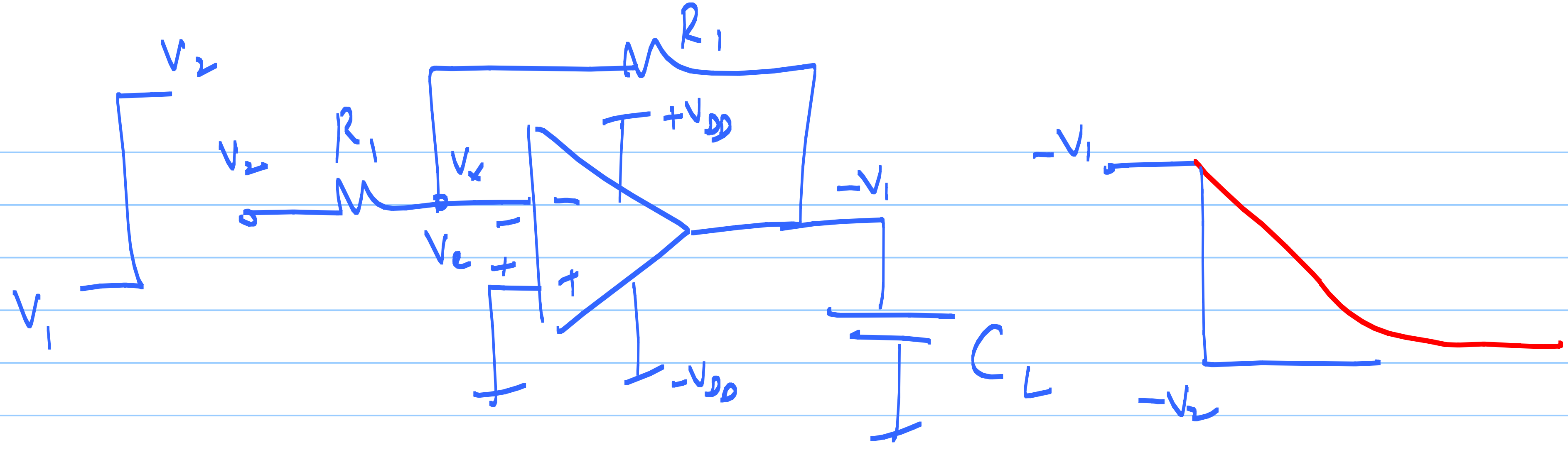




Hw



$$\frac{V_o}{V_i} = 1 + \frac{R_2}{\cancel{R_1} \to \infty}$$



$$V_x = V_2 - \left(\frac{V_2+V_1}{2R_1}\right) R_1 = \frac{V_2 - V_1}{2} = -V_e$$

$$V_e = \frac{V_1 - V_2}{2}$$