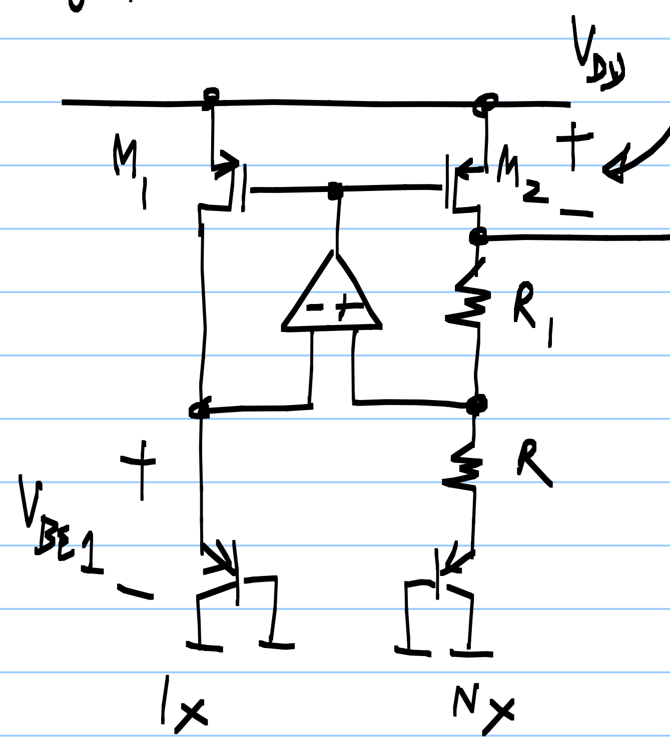
# Lecture 55

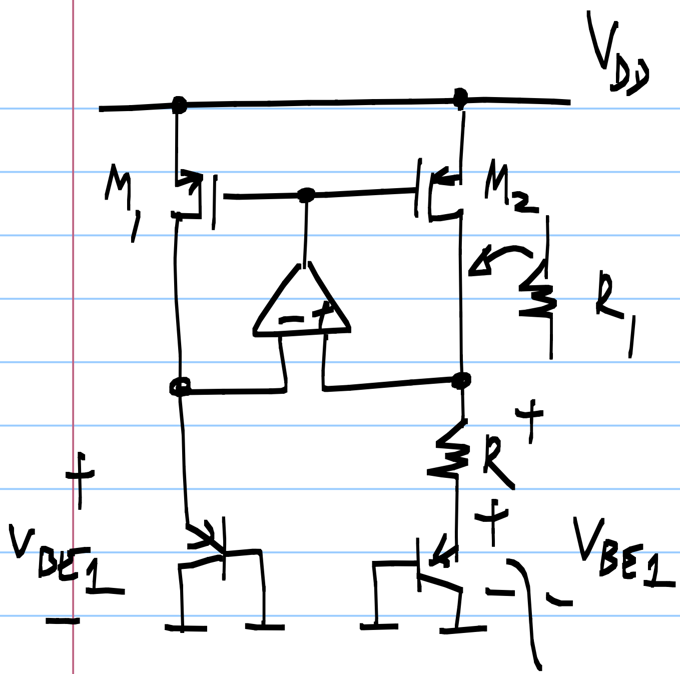
## Bandgap reference

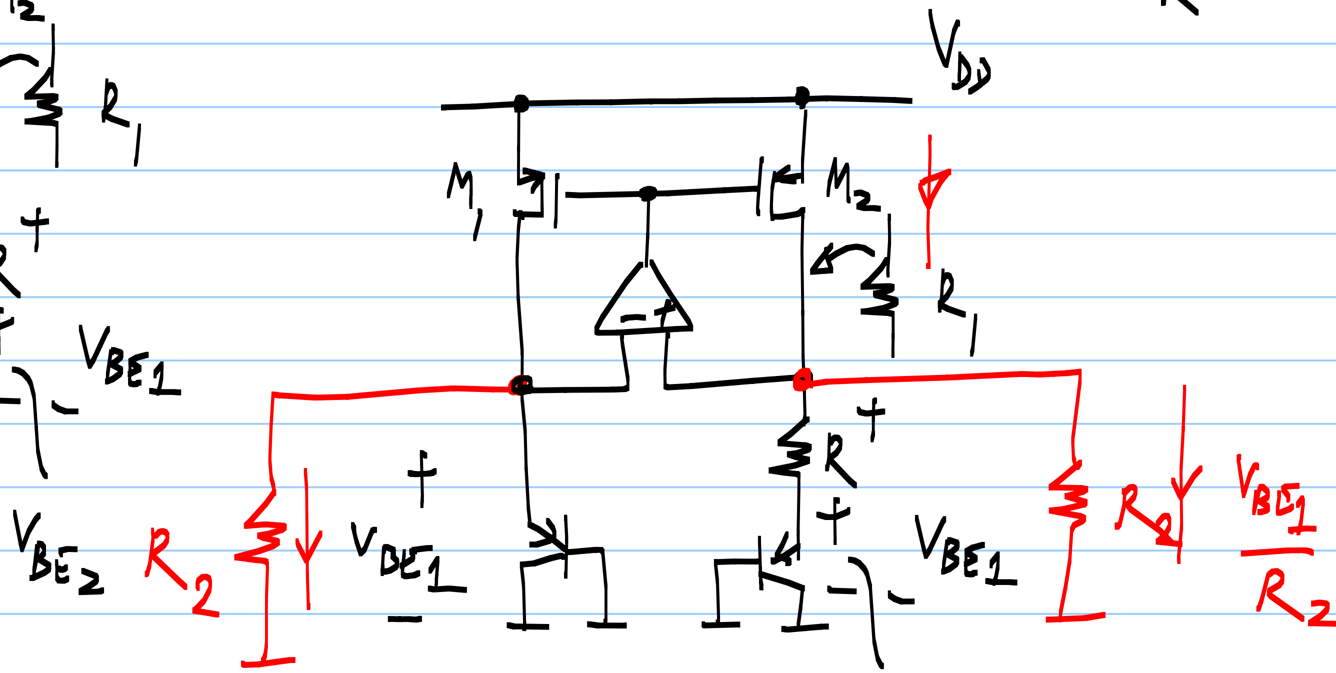



$$V_{DD,min} = V_{out} + V_{DSAT,M_2}$$
$$= 1.2V + 0.2V = 1.4V$$

$$V_{BE_1} + V_t \ln(N) \cdot \frac{R_1}{R_1} = \frac{E_{g0}}{q} \simeq 1.2V$$

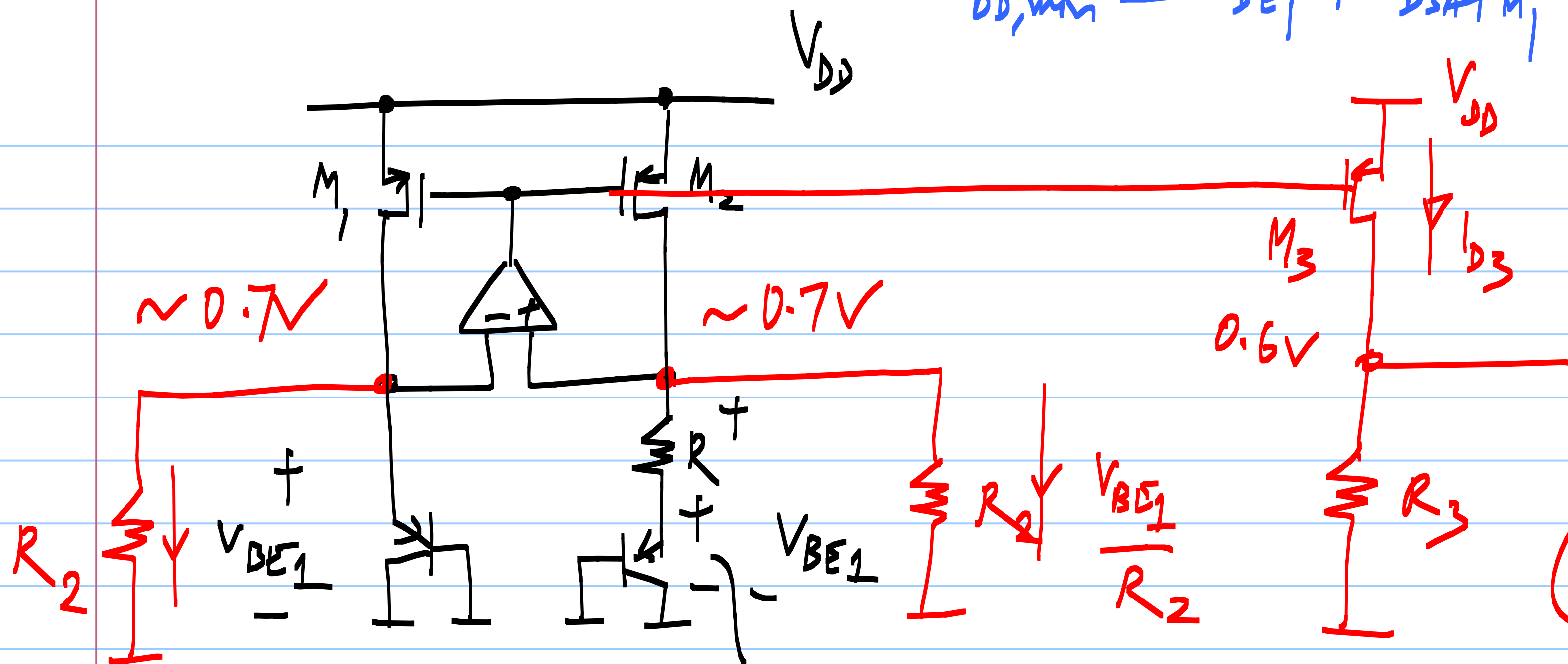
Currents in $M_{1,2}$ : PTAT $\left( V_t \frac{\ln N}{R} \right)$




Currents in $M_{1,2}$ : $\frac{V_t \ln(N)}{R} + \frac{V_{BE1}}{R_2} = \frac{\left[ V_{BE1} + V_t \ln(N) \frac{R_2}{R} \right]}{R_2}$

$$V_{DD,min} = V_{BE_1} + V_{DSAT\,M_1} \simeq 0.9V$$



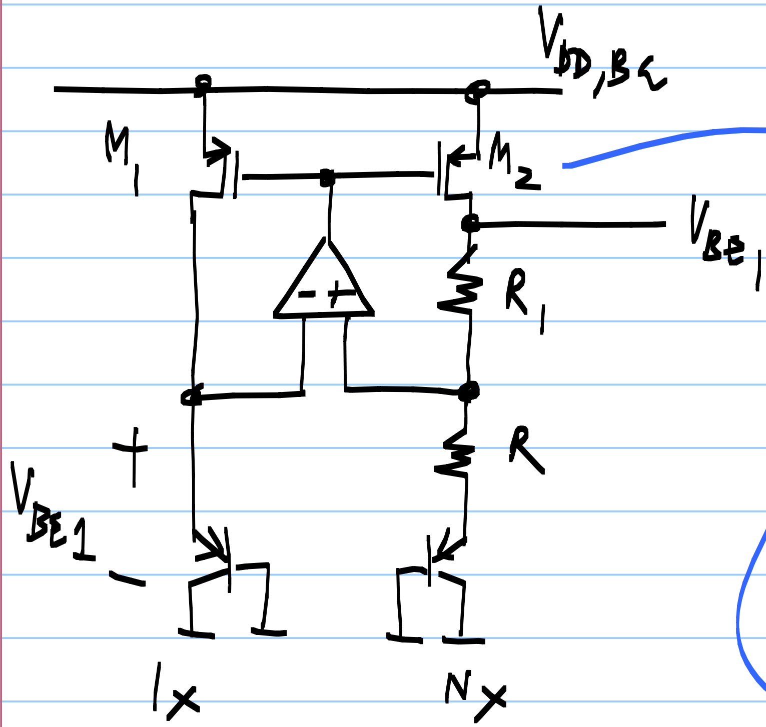

$$V_{out} = \frac{E_{g0}}{q}\cdot\frac{R_3}{R_2}$$

$$\left(\text{e.g.: } \frac{R_3}{R_2} = \frac{1}{2}\right)$$

$$I_{D3} = \frac{V_{BE_1} + V_t \ln(N)\cdot\frac{R_2}{R}}{R_2};$$

$$V_{out} = \underbrace{\left[V_{BE_1} + V_t \ln(N)\,\frac{R_2}{R}\right]}_{(E_{g0}/q)}\left(\frac{R_3}{R_2}\right)$$

## Fractional bandgap reference



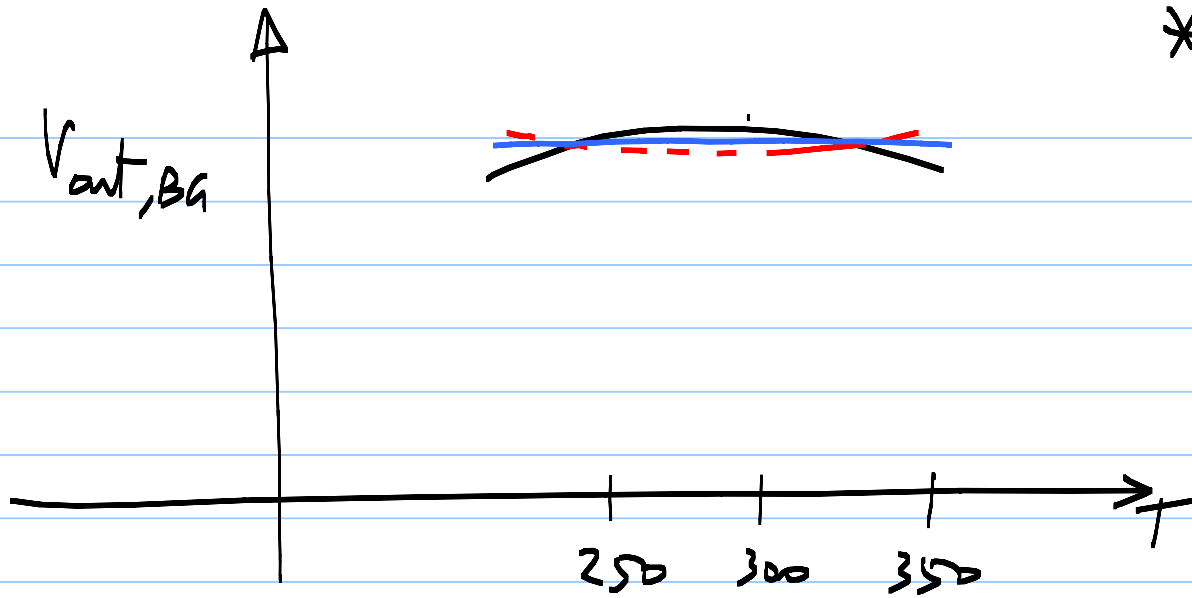

$M_{1,2}$ : different $V_{SD}$

different

* Cascode current mirror

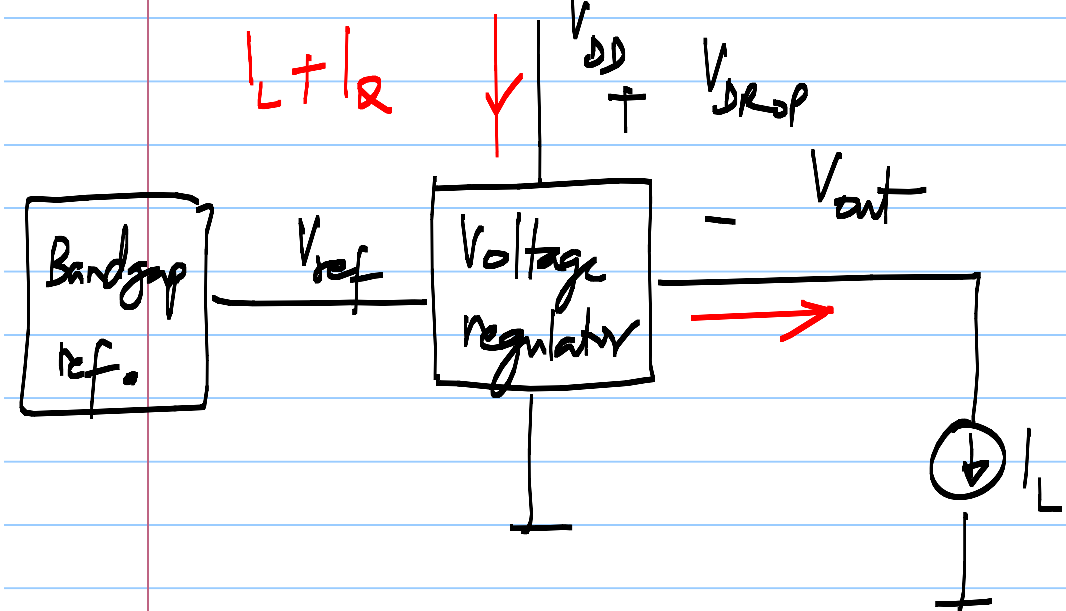
* $V_{DD,BG}$ : regulated

Reducing PS sensitivity




* For reducing variations with temperature even further, use curvature compensation

# Voltage regulators:

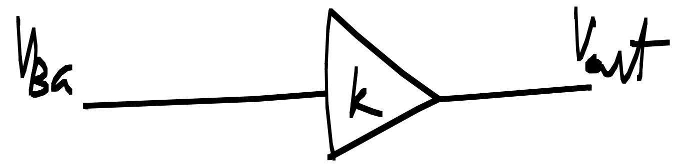



$$P_{out} = V_{out} \cdot I_L$$

$$P_{in} = V_{DD} \cdot (I_L + I_Q)$$

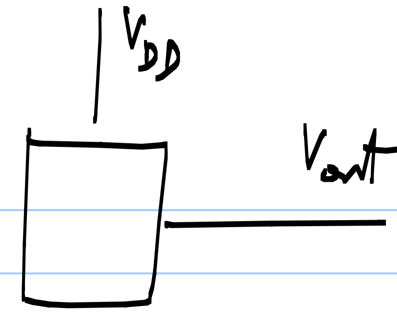
$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out}}{V_{DD}} \cdot \frac{I_L}{I_L + I_Q}$$

$$= \underbrace{\frac{V_{out}}{V_{out} + V_{DROP}}} \cdot \underbrace{\frac{I_L}{I_L + I_Q}}$$




## Voltage regulator:

* Feedback controlled voltage source with a low $R_{out}$
* Scaled version of the bandgap voltage
* "swing limit": must be close to $V_{DD}$
* only $I_L > 0$ need be supported




- * Low dropout
- * $\frac{\Delta V_{out}}{\Delta I_L} = R_{out}$ must be small (load regulation)
- * $\frac{\Delta V_{out}}{\Delta V_{DD}}$ : must be small (line regulation)
- * Output voltage must be accurately defined
- * Transient $I_L$ (step) : $\Delta V_{out}$ must be small

* $\left|\frac{V_{out}(f)}{V_{DD}(f)}\right|$ : Transfer function (small signal) from $V_{DD}$ to $V_{out}$

→ $\ll 1$

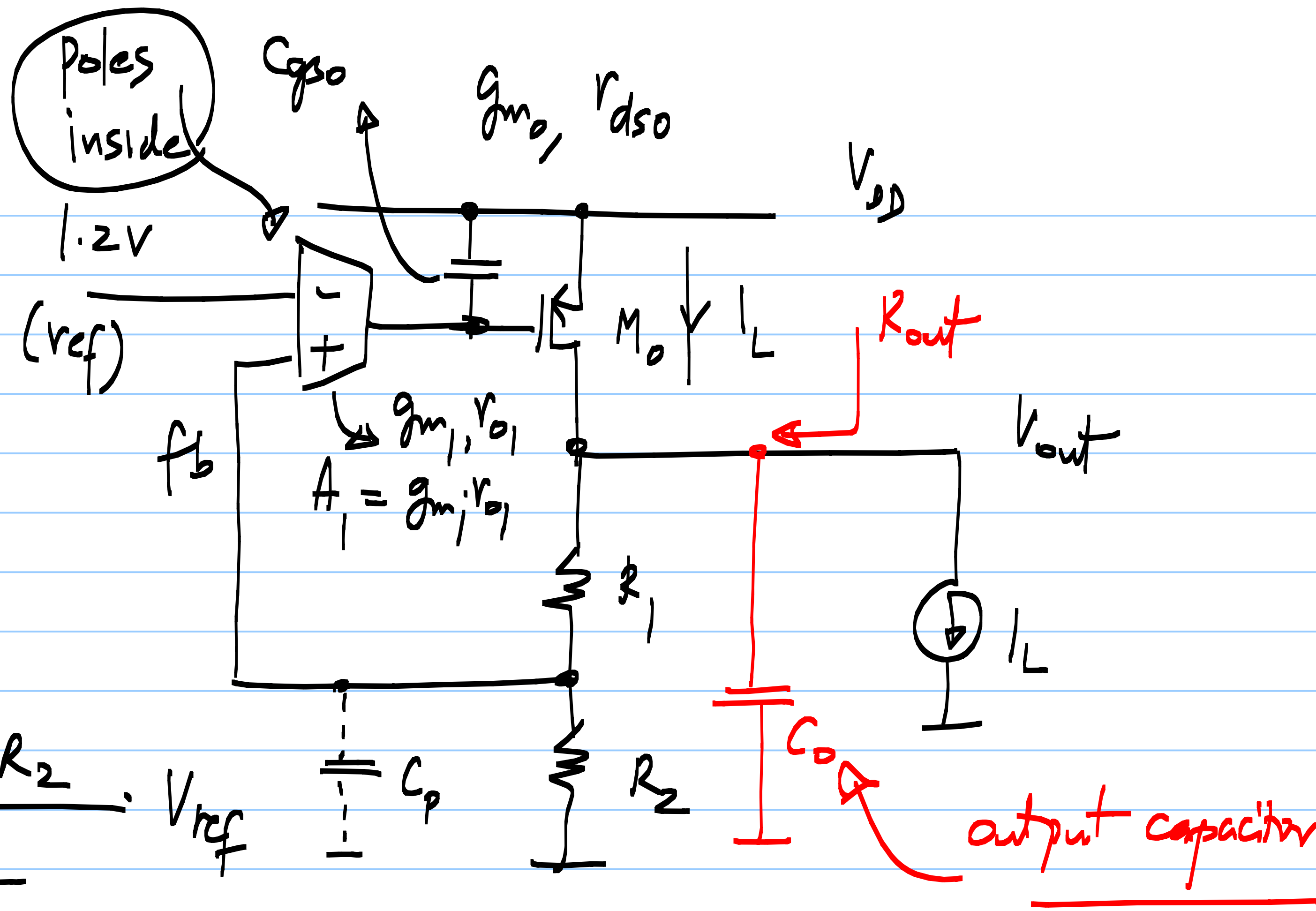
→ $\frac{1}{PSRR}$ Power supply rejection ratio

## Low dropout:

$V_{out} = 2.4V$

$V_{ref} = 1.2V$

(BG)




In steady state,

$$V_{out} = \frac{R_1 + R_2}{R_2} \cdot V_{ref}$$

$$R_{out} = \frac{r_{dso}}{1 + A_0}$$

$A_0$ : dc loop gain :

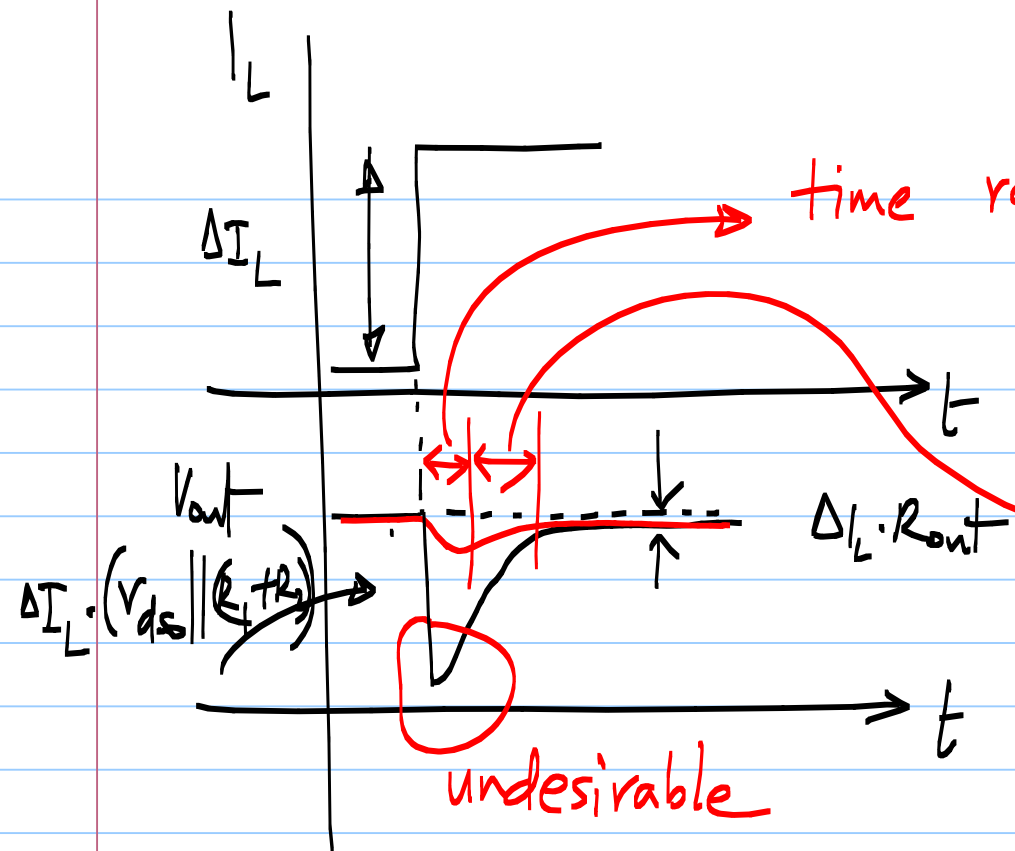
gain, transconductor: $g_{m_1} \cdot r_{o_1}$

$M_0$ : $g_{m_0}\left[r_{ds_0} \| (R_1 + R_2)\right] \simeq g_{m_0} \cdot r_{ds_0}$

$$A_0 = \underline{g_{m_1} r_{o_1} \cdot g_{m_0} \cdot r_{ds_0} \left(\frac{R_2}{R_1 + R_2}\right)}$$

$R_{out}$ small if $A_0$ is large

$I_L$ step from low to high values $\rightarrow$ large change in the output.



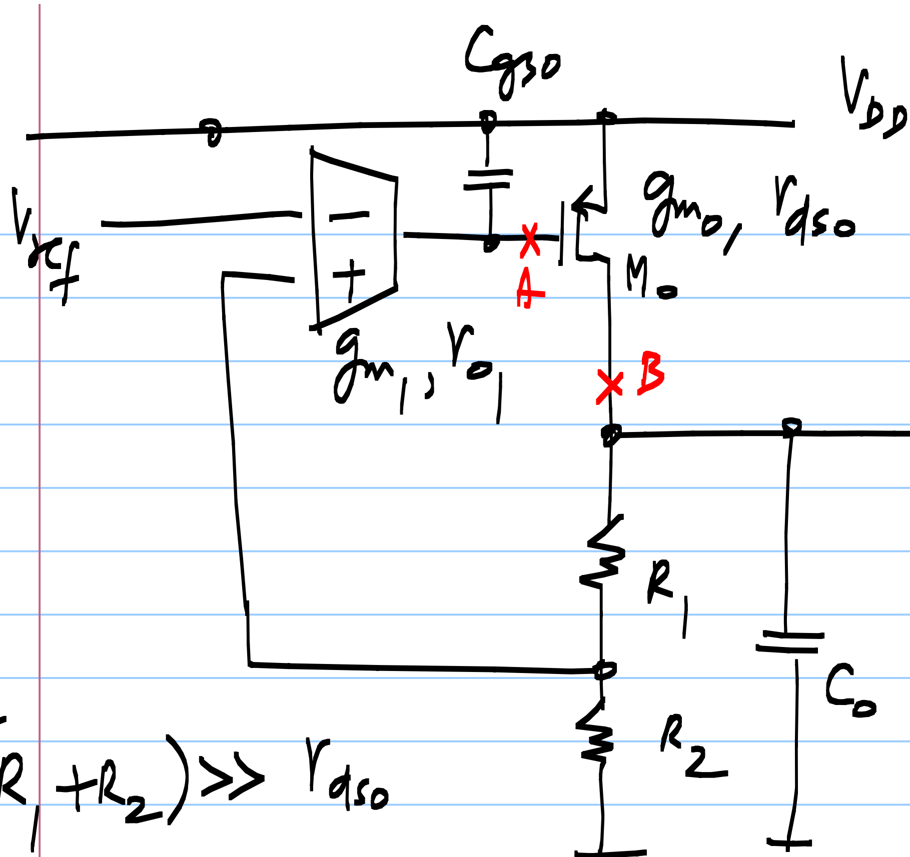

time required for feedback to come into picture $\left(\sim \frac{1}{\omega_{BW}}\right)$

settling time of the feedback loop

Poles due to (i) $C_o$

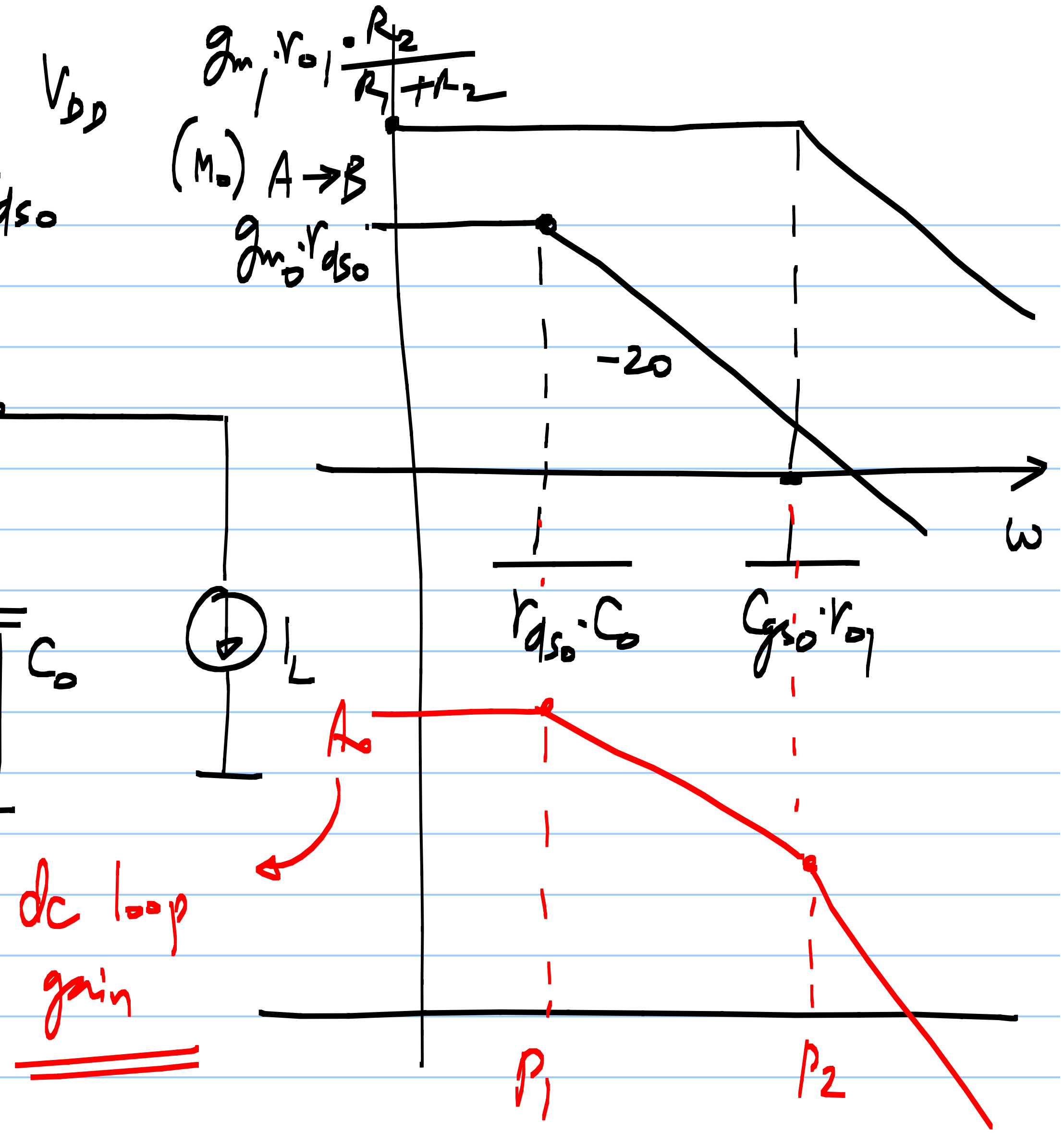
(ii) $C_{gso}$

× (iii) Poles in $g_{m1}$; feedback divider


$C_{gso}$
$V_{DD}$
$V_{ref}$
$g_{m0}, r_{dso}$
$M_0$
A
B
$g_{m1}, r_{o1}$
$R_1$
$R_2$
$C_o$
$I_L$

$(R_1 + R_2) >> r_{dso}$

A → B


$g_{m1} \cdot r_{o1} \cdot \frac{R_2}{R_1+R_2}$
$(M_0)$ A → B
$g_{m0} \cdot r_{dso}$
−20
ω
$r_{dso} \cdot C_o$
$C_{gso} \cdot r_{o1}$
$A_0$
dc loop gain
$p_1$
$p_2$

$$p_2 > \omega_{u,loop}$$

$$\left[\frac{1}{C_{gs_0} \cdot r_{o_1}} > g_{m_1} r_{o_1} \cdot g_{m_0} r_{ds_0} \left(\frac{R_2}{R_1 + R_2}\right) \cdot \frac{1}{r_{ds_0} C_0}\right]$$