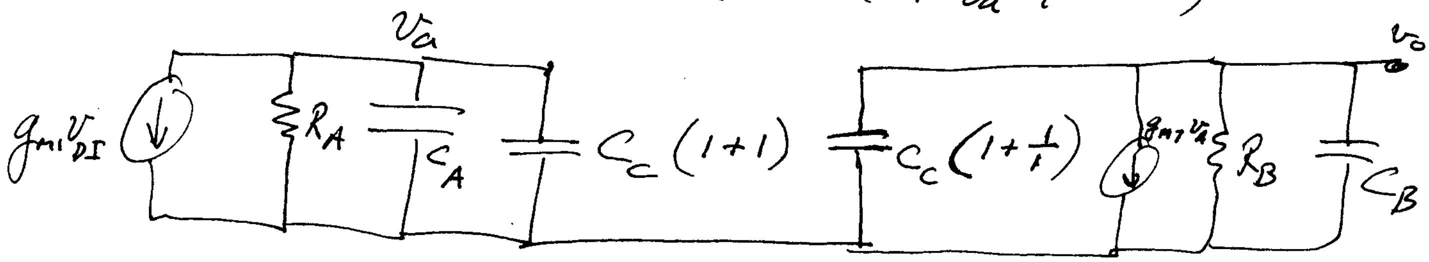
COMPENSATE W/ CAP C_c

~~At ω~~

CHOOSE C_c

At unity gain C_c act as a short so that $v_{out} = v_a$. $\left(\left| \frac{v_{out}}{v_a} \right| = 1 \right)$



$(v_o - v_A)\, j\omega C_c$

$$v_a = \frac{g_{m1} v_{DI}}{j\omega C_c (2)}$$

$$v_o = \frac{-g_{m7} v_a}{j\omega C_c (2)} = -\frac{g_{m1} g_{m7} v_{DI}}{\omega^2 C_c^2\, 4}$$

$$\left| \frac{v_o}{v_{DI}} \right| = 1 = \frac{g_{m1} g_{m7}}{4 \omega_u^2 C_c^2} \qquad (g_{m1} \cong g_{m7})$$

$$\frac{g_{m1}}{2 \omega_u C_c} = 1$$

$$\frac{g_{m1}}{4\pi f_u} = C_c$$

book uses 2

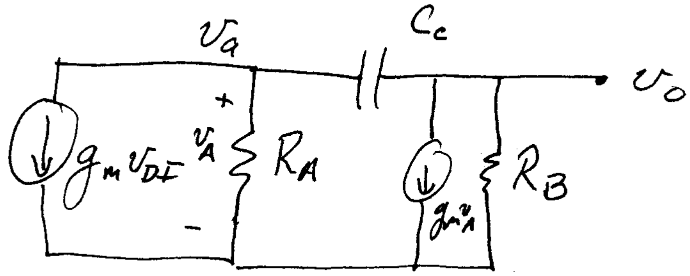
Choose f_u to give $\geq 45°$ phase margin.

Setting $f_u = 1$ MHz

$$C_c = \frac{55\,\mu A/V^2}{2\pi\, 10^6 (\frac{1}{s})} = 8.75\, pF$$

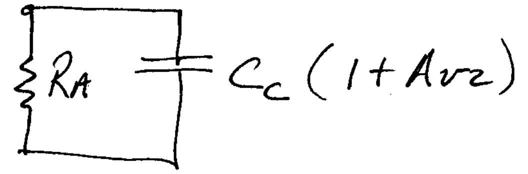
$$f_{-3dB} =$$

W7



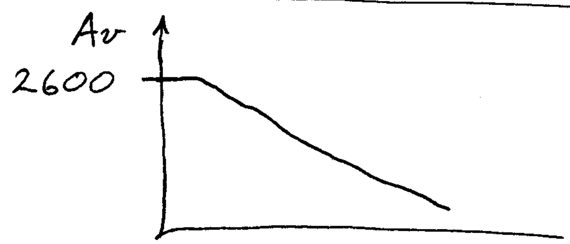
$$(v_o - v_A)\,j\omega C_c = g_m v_{DI} + \frac{v_A}{R_A}$$

$I_A =$



$$8.75\,pF\,(58.5)\,833\,k\Omega = 0.043\ s$$

$$\boxed{f_{-3dB} = 23\ Hz}$$



Zero

$$g_m v_{DI} + \frac{v_a}{R_A} = \underline{v_o - v_a}\,(j\omega C_c)$$

$$g_m v_a + \frac{v_o}{R_B} + (v_o - v_a)\,j\omega C_c = 0$$

$$(g_m - j\omega C_c)\,v_a + v_o\left(\frac{1}{R_B} + j\omega C_c\right) = 0$$

$$v_a = v_o\left(\frac{\frac{1}{R_B} + j\omega C_c}{j\omega C_c - g_m}\right)$$

$$\cancel{g_m v_{DI} + v_o\left(\frac{\frac{1}{R_B} + j\omega C_c}{j\omega C_c - g_m}\right)\frac{1}{R_A} = v_o\left[1 - \frac{\frac{1}{R_B} + j\omega C_c}{j\omega C_c - g_m}\right]}$$

$$g_{m1} v_{DI} = v_o j\omega C_c - v_a \left(\frac{1}{R_A} + j\omega C_c\right)$$

$$g_{m1} v_{DI} = v_o j\omega C_c - v_o \frac{\frac{1}{R_B} + j\omega C_c}{j\omega C_c - g_m} \left(\frac{1}{R_A} + j\omega C_c\right)$$

$$g_{m1} v_{DI} = v_o \left[s C_c - \frac{1}{R_B g_{m7}} \frac{1 + s C_c R_B}{(-1 + s C_c/g_{m7})} \frac{1}{R_A} (1 + s R_A C_c) \right]$$

$$= v_o \left[\frac{+1}{R_A R_B g_{m7}}\right] \left[s C_c R_A R_B g_{m7} + \frac{(1 + s R_B C_c)(1 + s R_A C_c)}{(1 - s C_c/g_{m7})} \right]$$

$$= \frac{v_o}{R_A R_B g_{m7}} \left[\frac{s C_c R_A R_B g_{m7} - s^2 C_c^2 R_A R_B + (1 + s R_B C_c)(1 + s R_A C_c)}{1 - s C_c/g_{m7}} \right]$$

$$\frac{v_o}{v_{DI}} = \frac{g_{m1} g_{m7} R_A R_B (1 - s C_c/g_{m7})}{(1 + s R_B C_c)(1 + s R_A C_c) + s C_c R_A R_B g_{m7} - s^2 C_c^2 R_A R_B}$$

in RHP:

$$\text{zero} = z = \frac{g_{m7}}{C_c} = s, \quad \text{or} \quad f_z = \frac{g_{m7}}{2\pi C_c}$$

Recall $f_u \cong \dfrac{g_{m1}}{2\pi C_c}$

Zero adds phase & reduces roll-off.

$\Rightarrow$ reduces phase margin.

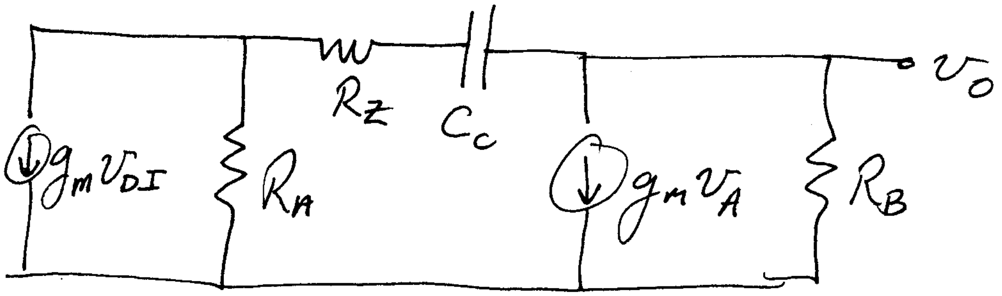
~~Intuitively,~~

~~C_c shorts v_a to v_o~~

~~$\Rightarrow v_o = -g_m v_{DI} \dfrac{R_A}{1 + j\omega R_A C_c} \approx \dfrac{+g_{m1} v_{DI}}{\omega} (j)$~~

~~$= -\dfrac{A_{VDO}}{j\omega R_A C_c} =$~~

MOVE ZERO by adding R_Z



$$\Rightarrow \frac{1}{sC_c} \rightarrow \frac{1}{sC_c} + R_Z$$

or $$sC_c \rightarrow \frac{sC_c}{1 + sR_ZC_c}$$

$$1 - \frac{sC_c}{g_m} \rightarrow 1 - \frac{sC_c}{g_m(1+sR_ZC_c)}$$

$$\frac{1}{g_m(1+sR_ZC_c)}\left[g_m + sg_mR_ZC_c - sC_c\right]$$

$$g_m\left[1 + s\left(R_ZC_c - \frac{C_c}{g_m}\right)\right]$$

$$\left[1 + sC_c\left(R_Z - \frac{1}{g_m}\right)\right]$$

$$\left[1 - sC_c\left(\frac{1}{g_m} - R_Z\right)\right]$$

$$Z = \frac{1}{C_c\left(\frac{1}{g_{m7}} - R_Z\right)}$$

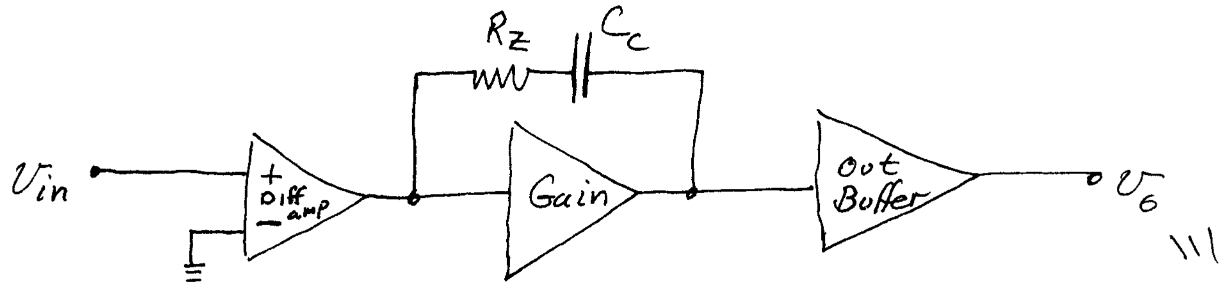
FOR $R_Z > \frac{1}{g_{m7}}$ $\quad Z \rightarrow$ LHP

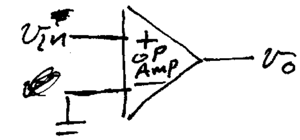
& Z adds to phase margin (Good)

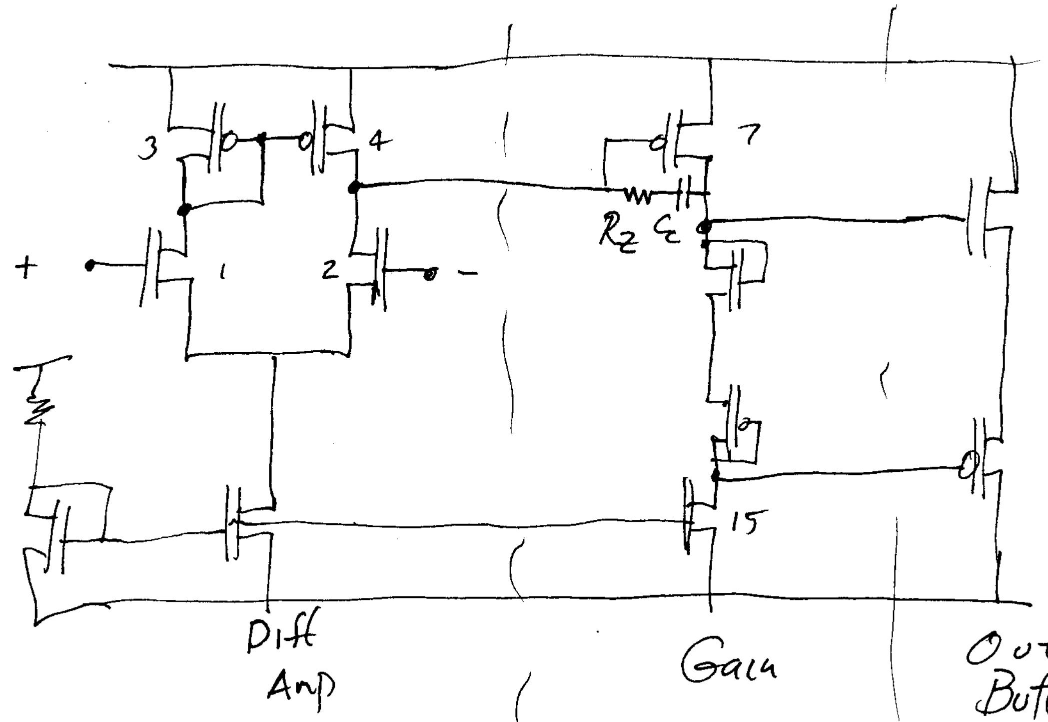
$R_Z = \frac{1}{g_{m7}}$ zero gone.

→ W8 p.0.1

W8





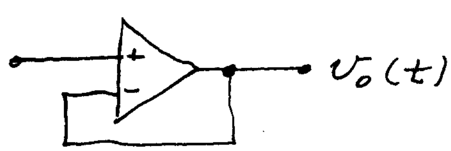


→ 0.1 R_K

BASIC TOPOLOGY of OP AMP → 0.1

- So far discussed small signal f-response.
- What about <u>SLEW RATE</u>?
  - Consider op-amp in unity gain (voltage follower) configuration w/

$v_I(t) = 2\,u(t)$



- Assume response dominated by a single pole:

$$\frac{v_O}{v_I}(s) = \frac{A=1}{1+s\tau}$$

$$v_o(s) = \frac{2}{s} \; \frac{1}{1+s\tau} = \frac{2}{s} - \frac{2}{s+1/\tau}$$

$$v_o(t) = 2\left(1 - e^{-t/\tau}\right) u(t) \quad \text{(WRONG)}$$

ACTUALLY response is linear

- $v_o(t)$ is determined by how fast you can charge C_c.

$$v_o(t) = \frac{I_{SS}}{C_c}\, t$$

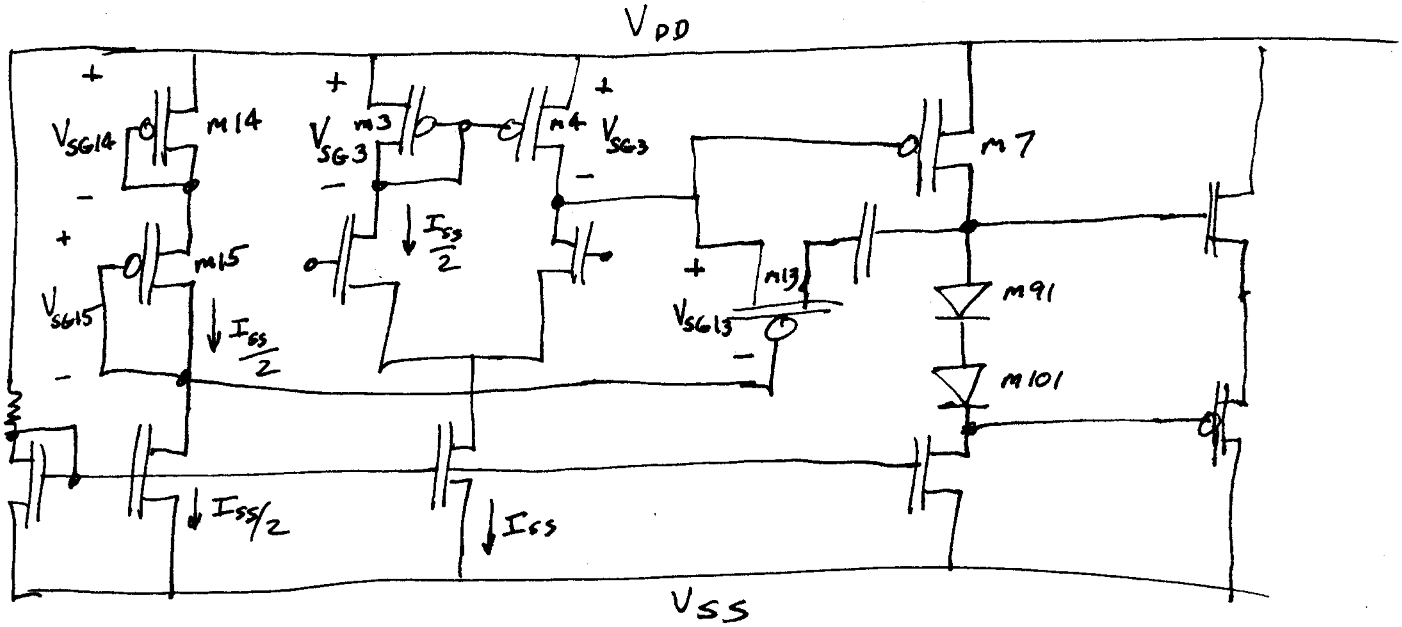
Only I_{SS} from diff-amp is available to charge C_c.

⟶ p. Q2W8

IMPLEMENTING R_Z w/ transistor

$\Longrightarrow$ R_Z can track $\frac{1}{g_{m7}}$ over Temp. & process variations

(To get rid of zero, want $R_Z = 1/g_{m7}$)



DC BIASING of M13

$$V_{SG13} = \overbrace{\cancel{V_{DD}} - \cancel{V_{SG3}}}^{V_{S13}} - (\cancel{V_{DD}} - \overset{V_{SG3}}{\cancel{V_{SG14}}} - \overset{V_{SG3}}{V_{SG15}})$$

$$= V_{SG3} \quad (W14 = W15 = W3 = W4)$$

- $V_{SG3} > V_{THP} \Longrightarrow$ not cutoff
- $I_{SD13} = 0 \Longrightarrow V_{SD13} = 0$

$\Big\} \Rightarrow$ triode w/ $V_{SD} = 0$

$$I_{SD13} = \beta_{13}\left[(V_{SG3} - V_{THP})V_{SD13} - \frac{V_{SD13}^2}{2}\right]$$

$$\left.\frac{\partial I_{D13}}{\partial V_{SD13}}\right|_{V_{SD13}=0} = \underbrace{\beta_{13}\,(V_{SG3} - V_{THP})}_{g_{m7}} = \frac{1}{R_Z}$$

~~W8 P.10~~

- $V_{SG7} = V_{SG3}$

$$g_{m7} = \beta_7 \left(V_{SG3} - V_{THP} \right)$$

FOR $\beta_7 = \beta_{13}$, $R_Z = \dfrac{1}{g_{m7}} \Rightarrow$ zero removed.

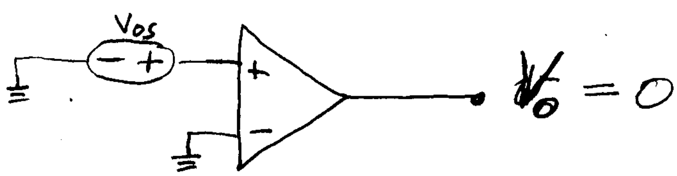
Want $R_Z > \dfrac{1}{g_{m7}}$, choose $W13 < W7$.

$$R_Z = \frac{L_{13}}{W_{13}\, u_p C_{ox} \left(V_{SG3} - V_{THP} \right)}$$

→ P. 0

FIGURES of MERIT of OP-AMP

1) Input offset voltage

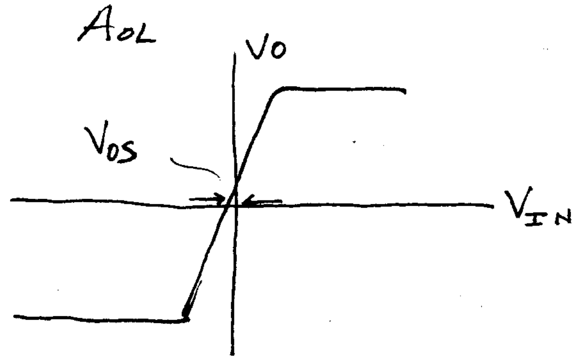


$V_{OS} = V_{IN}$ required to drive $V_o = 0$.

WORST CASE:

$$V_{OS} = \frac{V_{DD}}{A_{OL}} \quad \text{or} \quad \frac{V_{SS}}{A_{OL}}$$

$$\frac{V_{SS}}{A_{OL}} \leq V_{OS} \leq \frac{V_{DD}}{A_{OL}}$$



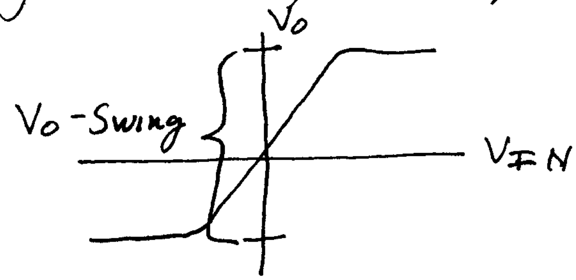
2) OUTPUT V-SWING (Determined by class A/B OUT Buffer)

$$\left[V_{DD} - |V_{GSMAX}|\right] - \left[V_{SS} + |V_{GSMAX}|\right]$$

$$= V_{DD} - V_{SS} - 2|V_{GSMAX}| \qquad (\text{MAX VALUE})$$

(ACTUALLY LESS)

- Determined by linear part of V_o vs. V_{IN} curve (SPICE)



3) Common Mode Rejection Ratio (CMRR)

$$CMRR = 20\log_{10}\left(\frac{A_{OL}}{A_C A_2}\right)$$

A_{OL}: Open Loop Gain

A_C: Common Mode Gain of Diff Amp

A_2: Gain of gain stage

$$= 20\log_{10}\left(\frac{A_1 \cancel{A_2}}{A_C \cancel{A_2}}\right) = 20\log_{10}\frac{A_1}{A_C}$$

$$= \text{CMRR of Diff-Amp.}$$

NB: The diff amp ONLY discriminates bet^n differential V_{IN} & common V_{IN}.

4) Power Dissipation

$$\underbrace{(V_{DD} - V_{SS})}_{5V}\ (\text{TOTAL DC CURRENT})$$

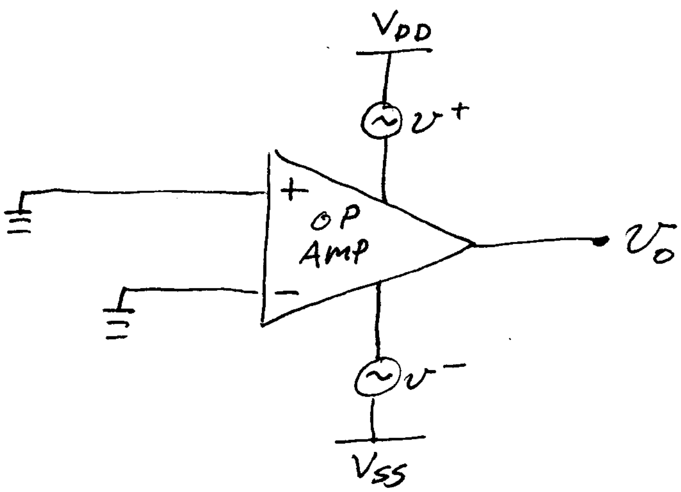
$$(I_{D5} + I_{D6} + I_{D8} + I_{D10})$$

$$\frac{I_{SS}}{2} \quad I_{SS} \quad \frac{I_{SS}}{2} \quad \frac{I_{SS}}{2}(10) =$$

$$I_{SS}\left(\tfrac{1}{2} + 1 + \tfrac{1}{2} + 5\right) = 0.14\ mA$$

$$= 5V(0.00014\ A) = \underline{0.7\ mW}$$

5) Power Supply Rejection Ratio



$$PSRR^+ = \frac{A_{OL}}{\underbrace{v_o/v^+}_{A_p}} \qquad PSSR^- = \frac{A_{OL}}{v_o/v^-}$$

6) Slew rate

← p.0