2 stage wrap
poles & zeros
common mode gain

slew rate

current mirror op-amp

uncompensated

ω_{p1}

ω_{p2}

ω_{pm} $\frac{g_{m2}}{2C_{gs2}}$

ω_{zm} $2\omega_{pm}$

ω_{zc} $\left(\frac{G_{m2}}{C_{gs4}}\right)$ RH

compensated w/ C_c

$\omega_{p1c} = \frac{1}{G_{m2}R_{o1}R_{o2}C_c}$

$\omega_{p2c} = \frac{G_{m2}}{C_1+C_2+\frac{C_1C_2}{C_c}}$

"

"

$\frac{G_{m2}}{C_c}$ if present

$\omega_{uc} = \frac{G_{m2}}{C_c}$
iff so designed

feedback

2 stage, uncomp.

oscillates

ok if f<<1

$\underbrace{\text{2 stage, comp}}_{\text{looks like}}$ or single pole

$A_{CL} \approx \frac{1}{f}$

error $\cong \frac{-1}{Af}$

$\omega_{p,CL} = f\,\omega_{u,c}$

$= \frac{\omega_{u,c}}{A_{CL}}$

$\omega_{u,CL} = \omega_{u,c}$

≈ single pole

PM ≈ 90

unity gain
stable

but low gain, output swing issues

so, add 2nd stage: gain↑ swing↑

but stability a pain.

Some options: current mirror op-amp.

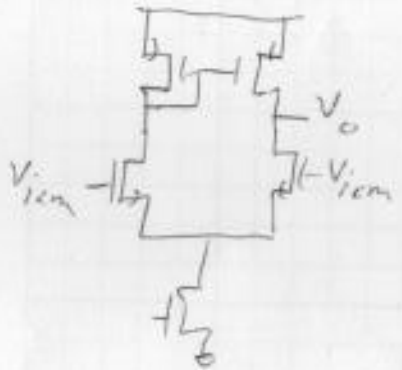
good swing
low gain

telescopic cascode
good gain, terrible swing

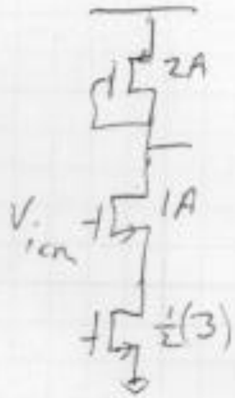
cascode current mirror

folded cascode

Common mode



$\frac{1}{2}$ circuit



$R_o \cong \frac{1}{g_{m2A}}$

$G_m \cong \frac{1}{R_s}$

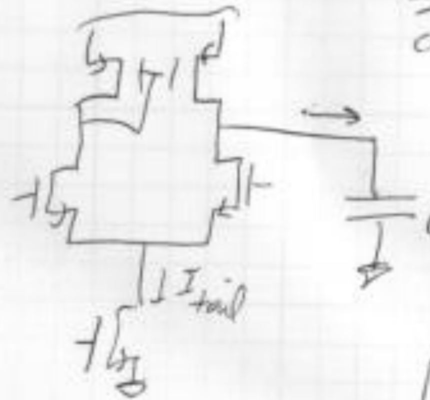
$= \frac{1}{r_{o(\frac{1}{2}3)}}$

$= \frac{\cancel{1}}{2r_{o3}}$

$A_{v_{cm}} = -G_m R_o = \frac{-\cancel{1}}{2g_{m2A}r_{o3}}$

$CMRR = \frac{A_{vdm}}{A_{vcm}}$

slew rate



$\frac{dV_o}{dt} = \frac{i_c}{C_o}$

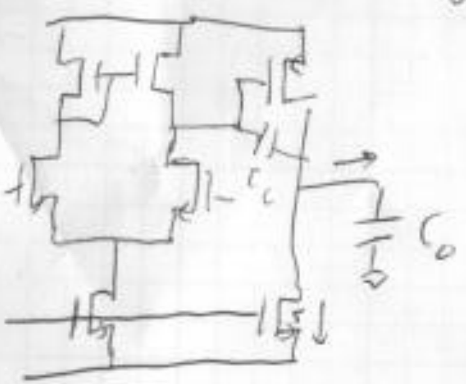
$\frac{max}{min} \frac{dV_o}{dt}$ is called <u>slew</u> <u>rate</u>

$i_c \max = I_{tail}$!

$i_c \min = -I_{tail}$

Nonlinear behavior
$H(s)$ no longer applies

2 stage



$\left.\frac{dV_o}{dt}\right|_{min} = \frac{-I_{D5}}{C_o}$

$\left.\frac{dV_o}{dt}\right|_{max} = \frac{\gg I_{D5}}{C_o}$

right?

what about C_c?

$v_{o2} = v_{o1} + v_{C_c}$

$\frac{dv_{o2}}{dt} = \frac{dv_{o1}}{dt} + \frac{dv_{cc}}{dt}$

$v_{o2} = A_{v2} v_{o1}$

$\frac{dv_{o1}}{dt} = \frac{1}{A_{v2}} \frac{dv_{o2}}{dt}$

$\frac{dv_{o2}}{dt}\left(1 - \frac{1}{A_{v2}}\right) = \frac{dv_{cc}}{dt} = \frac{i_c}{C_c}$

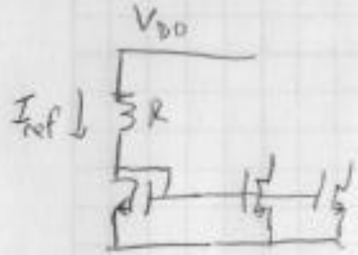
need to check both caps C_{o2} and C_c

and their currents

slew rate low $= \min\left(\frac{-I_{tail}}{C_c}, \frac{-I_{D5}}{C_{o2}}\right)$

slew rate high $= \frac{I_{tail}}{C_c}$

PVT-independent biasing
and temp sensing and voltage reference



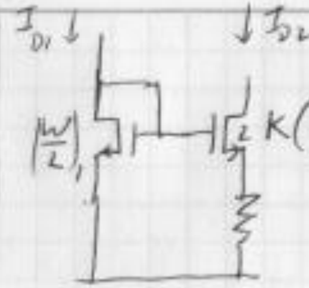
$$I_{ref} = \frac{V_{DD} - (V_{tn} + V_{OV})}{R}$$

would like a stable reference
over changes in

Process $V_{tn}, \mu_n C_{ox}, \lambda, \ldots$

Voltage $V_{DD} = 0.8 - 1.6V$

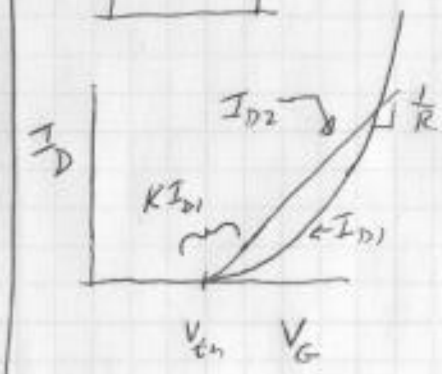
$V_{tn} = V_{tn0} - 2\frac{mV}{K}\Delta T$ T industrial $-40 - +85C$, consumer $0 - 70C$, mil auto $-55 + 125C$



$$I_{D1} = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)_1 (V_{OV1})^2$$

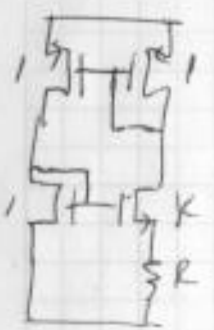
$$I_{D2} = K\left(\frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)_1\right)(V_{OV1} - I_{D2}R)^2$$

K is an integer. K=4 common



← looks like a source follower at some point

Enforce that $I_{D2} = I_{D1}$



$$K(V_{OV1} - I_{D2}R)^2 = V_{OV1}^2$$

$$V_{OV1} = \sqrt{K}(V_{OV1} - I_{D2}R)$$

$$\frac{V_{OV1}}{\sqrt{K}} - V_{OV1} = -I_{D2}R$$

$$I_{D2}R = \left(1 - \frac{1}{\sqrt{K}}\right)V_{OV1}$$

pick K=4 $\quad I_{D2}R = \frac{1}{2}V_{OV1}$

$$V_{OV2} = V_{OV1} - \frac{1}{2}V_{OV1} = \frac{1}{2}V_{OV1}$$

if quadratic $\left(\frac{V_{OV}}{L} < \frac{1V}{\mu m}\right)$

$$g_{m1} = \frac{2I_{D1}}{V_{OV1}} = \frac{2I_{D1}}{2I_{D1}R} = \frac{1}{R} \; !$$

$V_{OV1} = 2I_{D2}R$

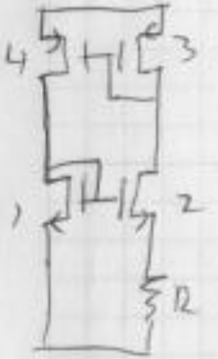
$I_{D1} = I_{D2}$

indep of V_{DD}, V_{tn}, T

"const g_m bias"

but we ignored λ - use long channels

ignored $I_{D1} = I_{D2} = 0$

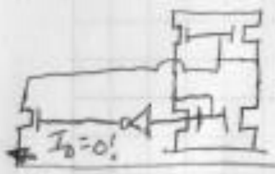


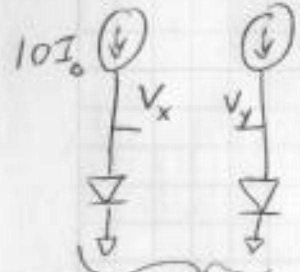
$$\frac{\partial I_{D2}}{\partial V_{DD}} = \frac{i_o}{v_{dd}} \approx \frac{1}{r_{o4}(2K-1)}$$

(much ugly algebra)

so use long-channel, or cascode or both.

startup - what if $I_{D1} = I_{D2} = 0$ $\quad V_{GS1} \approx 0$





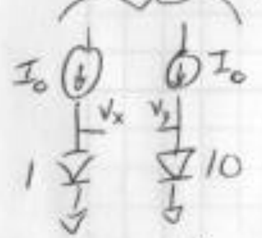
$$V_x = V_{TN} \ln \frac{10 I_o}{I_s}$$

$$V_y = V_{TN} \ln \frac{I_o}{I_s}$$

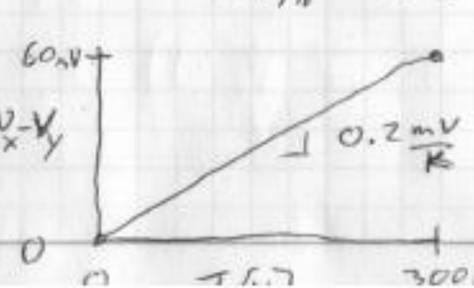
$$V_x - V_y = V_{TH}\left(\ln \frac{10 I_o}{I_s} - \ln \frac{I_o}{I_s}\right)$$

$$= V_{TN} \ln(10)$$

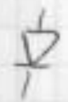
Same result



true even if T changes w/



More fun: Bandgap reference, PTAT



$$I_D = I_s\left(e^{V_D/V_{TH}} - 1\right) \approx I_s e^{V_D/V_{TH}}$$

$$V_D = V_{TH} \ln \frac{I_D}{I_s} \qquad 60 \frac{mV}{decade} \text{ @R.T. } 300K$$

$$V_{TN} = \frac{K_D}{q} T$$

V_{TH} is Proportional To Absolute Temperature

$$V_D = V_{TN} \ln \frac{I_{fixed}}{I_s}$$

temp response?

$V_{TN} = \frac{K_B}{q} T$ contributes positive coeff.

factor of ≈ 2 over automotive temp.

I_s increases by 10^5 from -40 to +85 C

result: at const current, V_D has a negative temp coeff $\approx -2 \frac{mV}{K}$