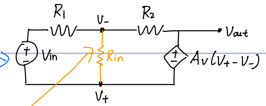
1. A_v $V_{out} = A_v(V_+ - V_-)$

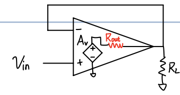
E. in. amp. $V_{out} = -A_v V_- \overset{\cdots}{=} \dfrac{-R_2/R_1}{1+\frac{1+R_2/R_1}{A_v}} V_{in}$

n.in. amp. $\overset{\cdots}{=} \dfrac{1+R_2/R_1}{1+\frac{1+R_2/R_1}{A_v}} V_{in}$



2. Output R

E. opamp buffer $V_{out} \overset{\cdots}{=} \dfrac{A_v}{(1+A_v)+\frac{R_o}{R_L}} V_{in}$



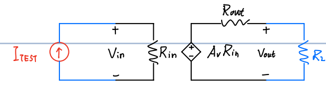
3. Input R

$V_- \overset{R_{in}}{-\!\!\!\sim\!\!\!-} V_+$

E. ia. $V_{out} = -A_v V_- \overset{\cdots}{=} -\cancel{A_v} V_{in} \dfrac{R_2/R_1}{\cancel{1+A_v+R_2/R_{in}+R_2/R_1}}$

R_{in} no effect (feedback amplifies it by A_v) (Miller)

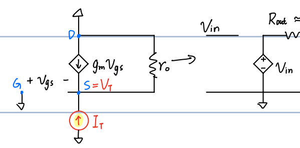
General A_v $R_{in} = \dfrac{V_{TEST}}{I_{TEST}}$, same for R_{out}



E. ss R_{out} of follower

$I_T + g_m V_{gs} + \dfrac{V_{gs}}{r_o}$, $V_T = -V_{gs}$

$R_{out} \overset{\cdots}{=} \dfrac{1}{g_m + 1/r_o} \approx \dfrac{1}{g_m}$



4. I_{bias} (for BJT base, tiny for MOS)

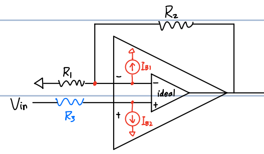
$I_B = \dfrac{I_{B1}+I_{B2}}{2}$ (~50n) $I_{OS}^{dist} = |I_{B1} - I_{B2}|$ (~5n)

E. nia. I_{B2} harmless, but $V_{out} \overset{superpos}{=} V_{in}(1+\frac{R_2}{R_1}) + I_{B1}R_2$

sln. add R_3 to V_+

When $V_{in} = 0 \xrightarrow{want} -I_{B2}R_3(1+\frac{R_2}{R_1}) + I_{B1}R_2 = 0$

if $I_{B1} = I_{B2}$, $\boxed{R_3 \overset{\cdots}{=} R_1 \| R_2}$ (DC R_{eq} seen at V_-)



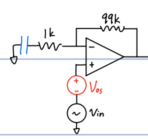
Always have input – DC gnd path for I_B to flow

5. V_{os} (any terminal)   null offset

E. nia $V_{out} = 100(V_{in} + V_{os})$

Sln. kill DC gain w/ cap $\dfrac{1}{2\pi(1k)C} << f$

DC: unity gain, AC: normal $\rightarrow$ $V_{out} = 1\,V_{os} + 100\,V_{in}$



6. I_{out} clipping, indep. of V_{DD}, V_{SS} (feedback R included)

if Large: RC (parc) problem, noise   1k ~ 100k

zero ω_z

V_{cc} & V_{EE} may not always reach

7. BW

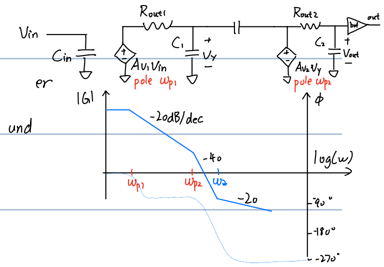
2p lz Cin doesn't matter (V_{in} ideal)

$A_{v1,2}$ in form $g_m R_{out}$

if phase shift = 180° when gain ≥ 1 → oscillate und

unity neg. feedback (neg + 180° → pos)

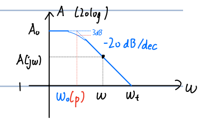
Sln. compensate to shift ω_{p2}, ω_z



Single-pole (RC) $A_v = \dfrac{A_o}{1+j\omega/\omega_o}$, $\omega_o = \dfrac{1}{RC}$

unity gain freq $\omega_t = \omega_o A_o \approx \omega A(j\omega)$ (if $\omega >> \omega_o$)

gain-BW product: $\omega_o A_o$

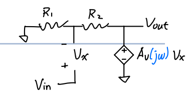


E. nia w/ $A_v(j\omega)$ limit

$G_v(j\omega) \overset{\cdots}{=} \dfrac{1+R_2/R_1}{1+\frac{1+R_2/R_1}{A_v(j\omega)}} = \dfrac{A_v}{1+\beta A_v}$, $\boxed{\beta = \frac{R_1}{R_1+R_2}}$

$= \dfrac{1+R_2/R_1}{1+\frac{j\omega(1+R_2/R_1)}{A_o\omega_o}}$, $A_v(j\omega) = \dfrac{A_o}{1+j\frac{\omega}{\omega_o}}$

$= \dfrac{1+R_2/R_1}{1+j\omega/\omega_{pole}}$, ω_{pole} (closed loop) $= \omega_{3dB} = \dfrac{A_o\omega_o}{1+R_2/R_1} = \dfrac{\omega_T}{1+R_2/R_1}$



clsd. loop curve bounded by open-loop gain, turning at ω_{3dB} (vs ω_o at open)

GBW > $G_v \cdot \omega_{max}$

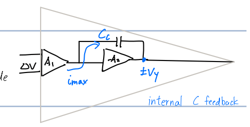
E. ia: gain $= -\dfrac{R_2}{R_1}$, but BW (ω_{-3dB}) same $\dfrac{\omega_t}{1+R_2/R_1}$

8. slew rate (nonlinear) limits $\dfrac{dV_{out}}{dt}$ (BW)

A_1 can't steer fast enough → i held on one side

if ΔV large, first stage outputs i_{max} (bias mirror)

slew rate $\equiv \dfrac{dV}{dt} = \dfrac{i_{max}}{C_c}$



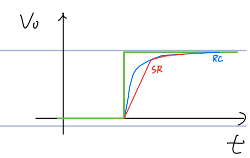
E. nia w/ step input $V_o\,u(t) \rightarrow$

$v_o(t) = V_o(1+\frac{R_2}{R_1})(1-e^{-t/\tau})$ (RC)

1st order $\tau = \dfrac{1}{\omega_{3dB}} = \dfrac{1+R_2/R_1}{\omega_t}$

$\dot{v}(t) = \dfrac{V_o(1+R_2/R_1)}{\tau}$, if < slew rate → linear

if > → slew (straight line)

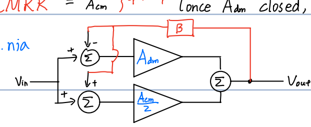


9. CM $V_{cm} = \frac{1}{2}(V_A + V_B)$ $V_{id} = V_A - V_B$

$V_{out} = A_{dm} V_{id} + A_{cm} V_{cm}$

CMRR (common mode rejection ratio) $\equiv \dfrac{A_{dm}}{A_{cm}}$ } open-loop (once A_{dm} closed, A_{cm} ↓↓)

E. nia



$V_{out} = A_{dm}(V_{in} - \beta V_{out}) + \dfrac{A_{cm}}{2}(V_{in} + \beta V_{out})$

$= V_{in} \dfrac{A_{dm} + A_{cm}/2}{1+\beta(A_{dm} - A_{cm}/2)}$

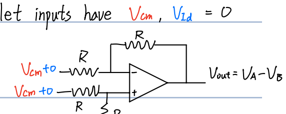
$\approx V_{in}\left(\dfrac{1}{\beta} + \dfrac{1}{2\beta\,CMRR}\right)$ $(\beta = \frac{1}{G_v})$

E. diff. amp. (w/ opamp A_{cm}) $R_1 = R_2 = R_3 = R_4$, opamp w/ nonideal CMRR, let inputs have V_{cm}, $V_{id} = 0$

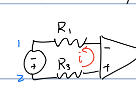
$V_{out} = A_{dm}(V_+ - V_-) + \dfrac{A_{cm}}{2}(V_+ + V_-)$

$= A_{dm}\left(\frac{V_{cm}}{2} - \left(\frac{V_{cm}}{2} + \frac{V_{out}}{2}\right)\right) + \frac{A_{cm}}{2}\left(\frac{V_{cm}}{2} + \left(\frac{V_{cm}}{2} + \frac{V_{out}}{2}\right)\right)$

$\overset{\cdots}{=} \dfrac{\frac{1}{2}A_{cm}V_{cm}}{\cancel{1}+\frac{A_{dm}}{2}-\frac{A_{cm}}{4}} \approx \dfrac{V_{cm}}{CMRR}$



$R_{Id} = \dfrac{V_{Id}}{i_I} = R_1 + R_3$



$V_+ = V_- = V_{I2}\dfrac{R_4}{R_3+R_4}$, $V_o = -\dfrac{R_2}{R_1}V_{I1} + (1+\dfrac{R_2}{R_1})V_- = \dfrac{R_2}{R_1}(V_{I2} - V_{I1})$ if =

E. R variation (ideal opamp) → diff amp amplifies V_{cm}!

Filter HPF to block DC

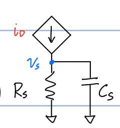
C_{in} $f_{in} = \dfrac{1}{2\pi C_{in}(R_s \| R_2)} = \dfrac{f_{min}}{10}$ → $C_1 \overset{\cdots}{=} 4.24\,\mu F$

C_s $g_m(V_g - V_s) = i_D = V_s \dfrac{1+sR_sC_s}{R_s}$ (classical approach)

$V_s \overset{\cdots}{=} V_g \dfrac{g_mR_s}{1+g_mR_s+sR_sC_s}$

corner at $1+g_mR_s = \omega R_sC_s$ $C_s \overset{\cdots}{=} 2.2\,mF$ (R_s only 180Ω)

C_s will be much smaller if R_s ↑



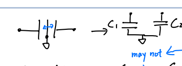
if no C_s, feedback at both AC/DC (V_{gs}↑ → i_d↑ → V_s↑ → V_{gs}↓ → ...)

$V_{out} = -(g_m V_{gs})R_D$ $V_{gs} \overset{\text{not present before}}{=} V_{in} - g_mV_{gs}R_s = \dfrac{V_{in}}{1+g_mR_s}$

$A_v = \dfrac{V_{out}}{V_{in}} \overset{\cdots}{=} \dfrac{-g_mR_D}{1+g_mR_s}$ neg. feedback, but improves distortion at same output swing

$\approx -\dfrac{R_D}{R_s}$ if $g_mR_s >> 1$

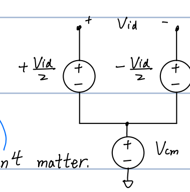
E. Accelerometer 3 parallel plates



1. middle plate can move under acceleration → $C_1 \neq C_2$ (may not)

2. Drive w/ $V_1 = V_2 = V_{ref}$. Then shut V_{ref} and hold it

3. If plate moves further → C_1↓, V_1↑, V_2↓ → gets Δ, init doesn't matter. (compare)



Single supply Can +/– all input voltages, decouple I/O

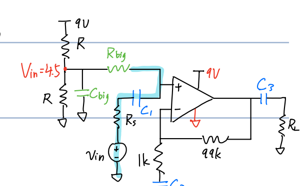
want $V_{in} = 4.5V$ (divided), no DC I

C_2 kills DC gain (=1), AC gain = 100

C_{big} filter AC noise from source

DC unity gain w/ $V_{out} = V_{in} = 4.5V$, $V_{LOAD} = 0$

AC $V_+ = V_{in}\dfrac{R_s}{R_s + \cancel{R_{big}}}$, $V_{out} = 100\,V_{in} = V_{load}$



Channel width mod: non-ideal at sat.

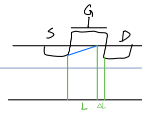
$\tilde{I}_D = \frac{1}{2} k' \frac{W}{L-\Delta L} (V_{GS}-V_T)^2$ pinchoff

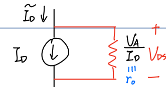
$= \frac{1}{2} k' \frac{W}{L} (V_{GS}-V_T)^2 (1+\frac{\Delta L}{L})$

$\equiv \frac{1}{2} k' \frac{W}{L} (V_{GS}-V_T)^2 (1+\lambda V_{DS})$ $\frac{1}{\lambda} \equiv V_A$ ~50V (Early voltage)

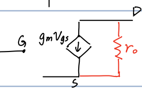
$= I_D + \frac{I_D}{V_A} V_{DS}$ → lin!

non-ideal I source (large sig)





ss $\left.\frac{\partial i_d}{\partial V_{DS}}\right|_{bias} = \frac{I_D}{V_A} \equiv \frac{1}{r_o}$ $r_o \sim 100k$ (want ∞)

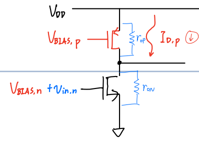


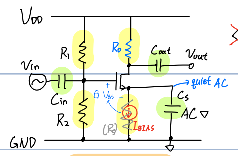
App. Current source load (more gain w/ r_o)

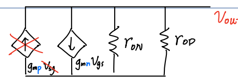
$V_{in,n}$ → contradicting Δi → flows thru r_o (huge) → huge ΔV

$A_v = -g_{mn} (r_{oN} \parallel r_{oP})$

$|A_v| = k_n' \frac{W}{L} V_{ODn} \frac{V_A}{2I_D} = \frac{V_A}{V_{OD}}$







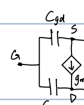
Parasitic Cap 1. gate 2. overlap 3. pn jct. cap

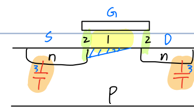
– Triode $C_{gs} = C_{sd} = \frac{1}{2} WL C_{ox}$ (cap/unit area)

(tie S, D) E. op amp compensation

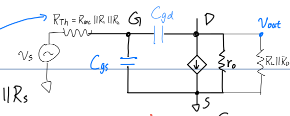
– Sat. pinched off at D side

$C_{gs} \doteq \frac{2}{3} WL C_{ox}$ (~pF) C_{gd} small, pinched (~fF)



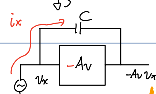


High freq. Turn bias $\xrightarrow{Th}$ $V_S = \frac{R_1 \parallel R_2}{R_{src}+R_1 \parallel R_2} V_{in}$ $R_{Th} = R_1 \parallel R_2 \parallel R_S$



Miller effect $i_x = j\omega C (1+A_v) V_x$ (cap appears $1+A_v$ larger) to gnd

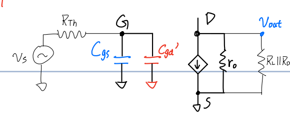
A_v can be made w/ opamp + pot ⇒ var Cap



$C_{gd}' \to C_{gd} (1+g_m R_D \parallel R_L \parallel R_D)$ to gnd

$f_{corner} = \frac{1}{2\pi RC} = \frac{1}{2\pi R_{Th} (C_{gs} + C_{gd}(1+g_m(R_L \parallel R_D)))}$ (LPF)

2p | z → lp

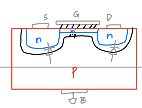


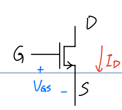
MOS Sym. device

$V_{GS} = 0$ Cutoff

$0 < V_{GS} < V_T$ Subthreshold

$V_{GS} > V_T$ Lin. small V_{DS} → R controlled by V_{GS}





$V_{DS}\uparrow$ $g \propto V_{GS} - V_t$

Triode channel pinched, R ↑, bad

Sat. $V_{DS} \geq V_{GS} - V_T$, all pinched, but $\mathcal{E}$↑, e^- drift

Sat. $i_D = \frac{1}{2} \mu C_{ox} \frac{W}{L} (V_{GS}-V_T)^2 (1+\frac{V_{DS}}{V_A})$ for nonflat sat.

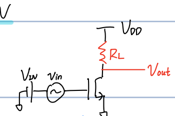
Lin. $i_D = V_{DS} [k' \frac{W}{L} (V_{GS} - V_T)]$ (1/R)

Amplifier Need V_{BIAS} for sat. (slope V_{out} vs V_{in}), $V_{GS} = V_{BIAS} + \Delta V$

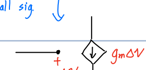
$i_D \doteq \frac{1}{2} k' \frac{W}{L} (V_{BIAS} - V_T)^2 + k' \frac{W}{L} (V_{BIAS} - V_T) \Delta V + \cancel{\cdots \Delta V^2}$ ($\equiv V_{OD}$)

$\equiv I_{BIAS}$ region setup $\equiv g_m$, for amp. $= \sqrt{2k' \frac{W}{L} I_{BIAS}}$

$= I_{BIAS} + g_m \Delta V = \frac{1}{2} k' \frac{W}{L} V_{OD}^2 + g_m \Delta V$



small sig



$V_{OUT} = V_{DD} - \frac{1}{2} k' \frac{W}{L} V_{OD}^2 R_L$ $V_{out} = -g_m V_{in} R_L$

$\equiv V_{DD} - V_{DROP}$ $\equiv -A_v V_{in}$

Design eq. $V_{OD} = \frac{2 V_{DROP}}{|A_v|}$ $(A_v = g_m R_L = k' \frac{W}{L} V_{OD})$

E. $V_T = 1V$, $k' \frac{W}{L} = 44.4 mA/V^2$, $A_v = -20$, V_{out} swing $= \pm 2V$, $V_{DD} = 10V$

Let $V_{OUT} = 5V \to V_{DROP} = 5V \to V_{OD} = \frac{2V_{DROP}}{|A_v|} = 0.5V \xrightarrow{+V_t} V_{GS} = 1.5V$ $|A_v| \doteq g_m R_L \to R_L = 900\Omega$

Diode $i_D = I_s (e^{V_D / n\phi_t} - 1)$ (I_s: f(area, T), saturation, ~10^{-14}; $1 \leq n \leq 2$)

$\phi = \frac{kT}{|q|} = \frac{1.38E\text{-}23 \text{ J/K} \cdot 300K}{1.6E\text{-}19\ C} = 25.875\ mV$

$V_D = n\phi_t \ln(\frac{i_D}{I_s} \cancel{+1})$

$V_{d1} - V_{d2} = n \frac{kT}{q} \ln \frac{I_{S2} I_{d1}}{I_{S1} I_{d2}}$

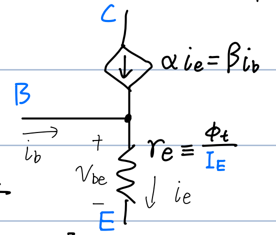
also $V_D = V_{D0} - 2m (T - T_0)$

rect $C = \frac{I_L T_p (/2)}{V_{RIP}}$

BJT $\alpha = \frac{I_C}{I_E} = \frac{\beta}{1+\beta}$ $\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$

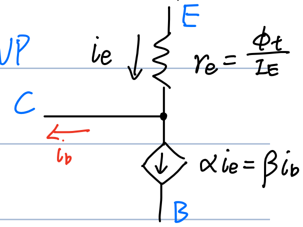
$V_{OUT} = V_{CC} - \frac{R_2}{R_1} \beta (V_{DC} - 0.75) - \frac{R_1}{R_2} \beta \Delta V$ (V_{BIAS}, ΔV_{out})

SS NPN



$r_e = \frac{\phi_t}{I_E}$

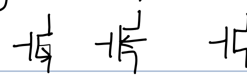
PNP $r_e = \frac{\phi_t}{I_E}$



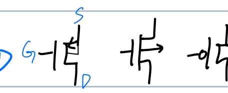
$r_e = \frac{\phi_t}{I_E}$

π $g_m = \frac{I_C}{\phi_t}$, $r_\pi = \frac{\beta}{g_m}$

MOS N



P



active $V_{GS} - V_T > 0$ $V_{SG} - |V_{T,p}| > 0$

sat $V_{DS} \geq V_{GS} - V_T$ $V_{SD} \geq V_{SG} - |V_{Tp}|$

$i_D = \frac{1}{2} k' \frac{W}{L} (V_{GS} - V_T)^2$ (A/V^2)

$g_m = \sqrt{2k' \frac{W}{L} I_{BIAS}}$

w/ load $|A_v| = g_m (R_D \parallel R_L)$

Cap open vs. gnd

inverting! amplify!

V_{OS} ±

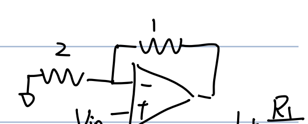
ω, f (2π)

DC path for I_{Bias}

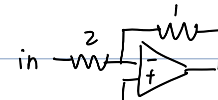
N, P (up, down?)

V_S, V_E may not be 0

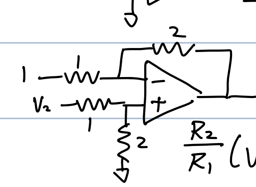
$V_p = \sqrt{2} V_{rms}$



$1 + \frac{R_1}{R_2}$



$-\frac{R_1}{R_2}$



$\frac{R_2}{R_1} (V_2 - V_1)$