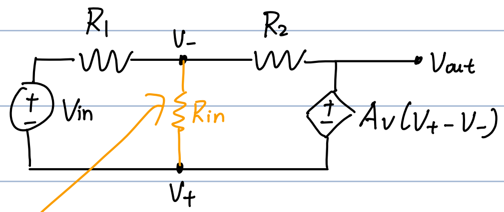
Opamp

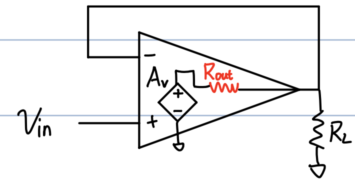
1. A_v $V_{out} = A_v (V_+ - V_-)$

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



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

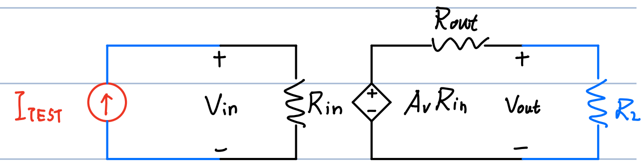


3. Input R $V_- \overset{R_{in}}{\text{—WW—}} V_+$

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

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

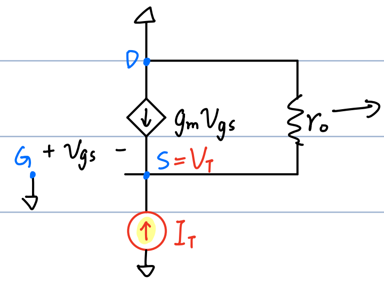
General A_v $R_{in} = \dfrac{V_{TEST}}{I_{TEST}}$, same for R_{out}

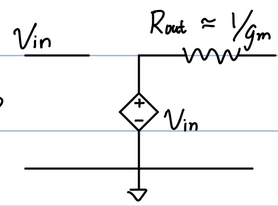


E. ss R_{out} of follower

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

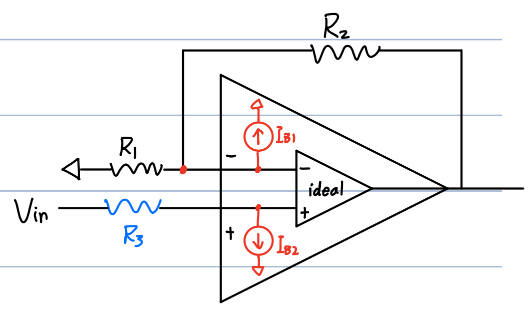
$R_{out} \overset{\cdots}{=} \dfrac{1}{g_m + 1/r_o} \approx \dfrac{1}{g_m}$





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

$\overset{\sim 50nA}{I_B} = \dfrac{I_{B1} + I_{B2}}{2}$ $\overset{\sim 5nA}{I_{OS}^{offset}} = |I_{B1} - I_{B2}|$



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

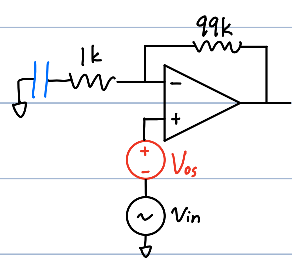
sln. add R_3 to V_+

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

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

Always have input – DC gnd path for I_B to flow

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



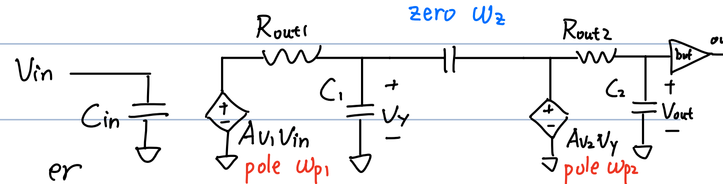
E. nia $V_{out} = 100 (V_{in} + V_{os})$

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

DC: unit 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 (para) problem, noise $1k \sim 100k$



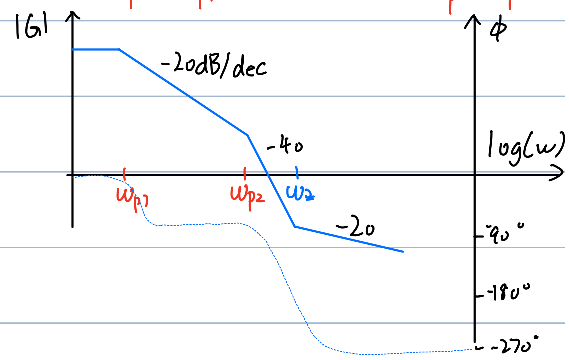
7. BW 2p1z Cin doesn't matter (Vin ideal)

$A_{V1,2}$ in form $g_m R_{out}$

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

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

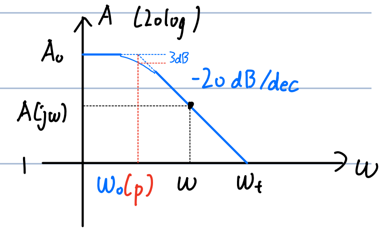
Sln. compensate to shift ω_{p2}, ω_z



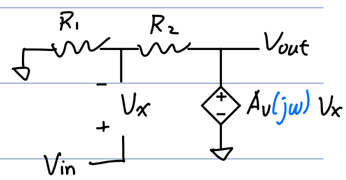
Single-pole (RC) $A_V = \dfrac{A_0}{1+j\omega/\omega_0}$, $\omega_0 = \dfrac{1}{RC}$

unity gain freq $\omega_t = \omega_0 A_0 \simeq \omega A(j\omega)$ (if $\omega >> \omega_0$)

gain-BW product: $\omega_0 A_0$



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



$$G_V(j\omega) \overset{\cdots}{=} \frac{1+R_2/R_1}{1+\frac{1+R_2/R_1}{A_V(j\omega)}} = \frac{A_V}{1+\beta A_V}, \quad \beta = \frac{R_1}{R_1+R_2}$$

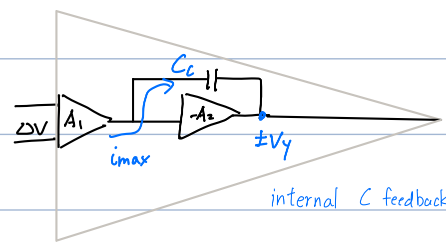
$$= \frac{1+R_2/R_1}{1+\frac{j\omega(1+R_2/R_1)}{A_0\omega_0}}, \quad A_V(j\omega) = \frac{A_0}{1+j\frac{\omega}{\omega_0}}$$

$$\equiv \frac{1+R_2/R_1}{1+j\omega/\omega_{pole}}, \quad \text{closed loop } \omega_{pole} = \omega_{3dB} = \frac{A_0\omega_0}{1+R_2/R_1} = \frac{\omega_T}{1+R_2/R_1}$$

clsd. loop curve bounded by open-loop gain, turning at ω_{3dB} (vs ω_0 at open)

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

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

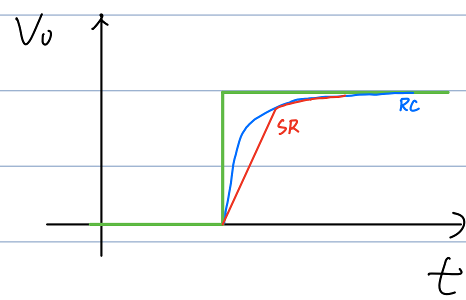


8. slew rate (non linear) limits $\dfrac{dV_{out}}{dt}$ (BW)

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

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

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



E. nia w/ step input $V_0\, u(t)$ →

RC

$v_o(t) = V_0\left(1+\frac{R_2}{R_1}\right)\left(1-e^{-t/\tau}\right)$

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

$\dot{v}(t) = \dfrac{V_0(1+R_2/R_1)}{\tau}$, if < slew rate → linear

if > → slew (straight line)

9. CM

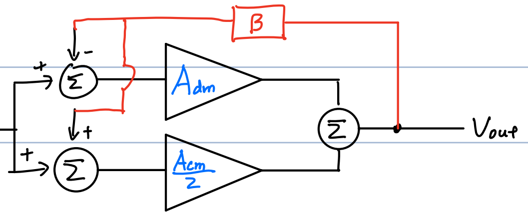
$V_{cm} = \frac{1}{2}(V_A + V_B)$ $V_{id} = V_A - V_B$

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

com mode rejection ratio

$CMRR \equiv \frac{A_{dm}}{A_{cm}}$ } open-loop (once A_{dm} closed, A_{cm} ↓↓)

E. nia



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

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

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

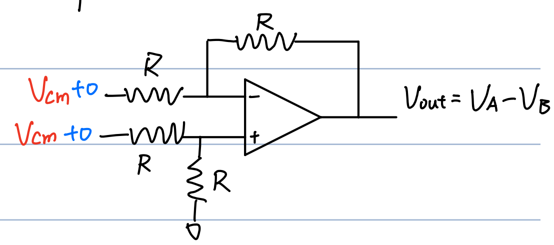
w/ opamp A_{cm}

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

$V_{out} = A^{opamp}_{dm}(V_+ - V_-) + \frac{A^{opamp}_{cm}}{2}(V_+ + V_-)$

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

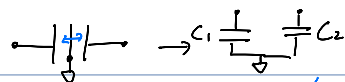
$\therefore = \frac{\frac{1}{2}A_{cm}V_{cm}}{\cancel{1} + \frac{A_{dm}}{2} - \cancel{\frac{A_{cm}}{4}}} \approx \frac{V_{cm}}{CMRR}$



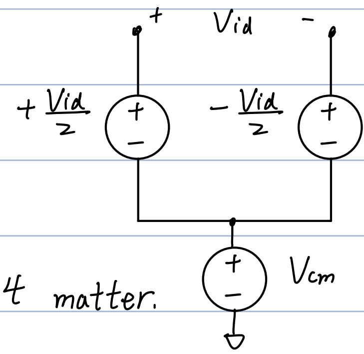
ideal opamp

E. R variation → diff amp amplifies V_{cm} !

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 (compare)
3. If plate moves further → $C_1 \downarrow$, $V_1 \uparrow$, $V_2 \downarrow$ → gets Δ, init doesn't matter.



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