Announcements:

- Make up lecture this evening, at 7 p.m., in 247 Cory
- HW#6 due Wednesday at 6:00 p.m.
- New HW#3 solutions, this time using OCTC analysis
- If you want a regrade of HW#3 to get credit for having used OCTC analysis, turn in your HW#3 to the EE 140 box Thursday by 6 p.m.
- Lab#2 will be stretched to be due the week after Spring Break

Today:

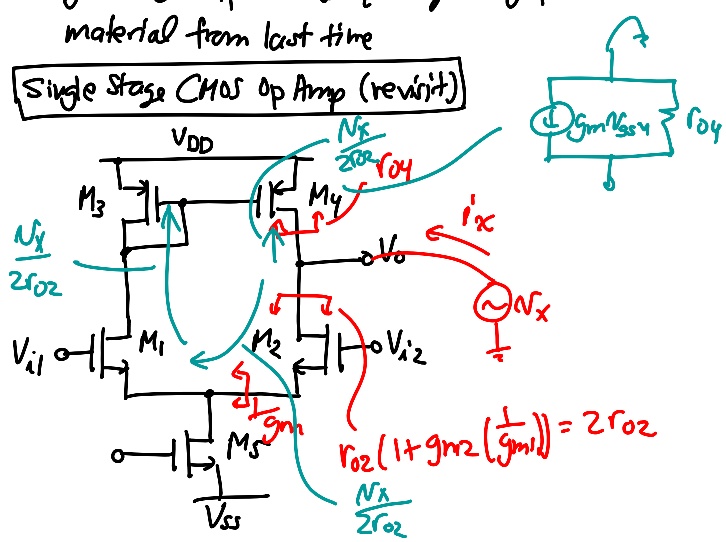
- Finite Gain & Bandwidth in Op Amps
- Higher Gain Op Amps

Last Time –

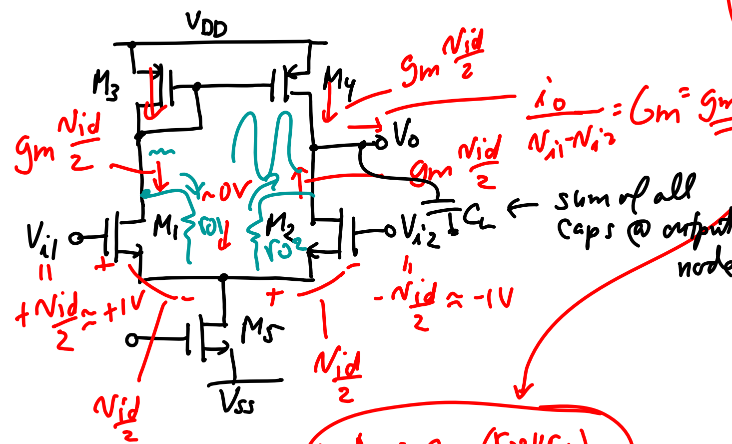
⇒ go through MOS V_{os} notes from last lecture

⇒ go through bipolar V_{os} quickly using pre-made material from last time

$\boxed{\text{Single Stage CMOS Op Amp (revisit)}}$



$$i_x = \frac{v_x}{r_{o4}} + \frac{v_x}{2r_{o2}} + \frac{v_x}{2r_{o2}} \rightarrow R_o = \frac{v_x}{i_x} = \frac{1}{\frac{1}{r_{o2}} + \frac{1}{r_{o4}}} = (r_{o2} \| r_{o4})$$



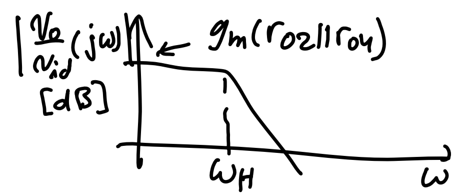
$$\therefore A_v = g_m(r_{o2} \| r_{o4})$$

Problem: This is not a lot of gain! (for many applications)

But note that this is still usable for many apps.

Frequency Response:

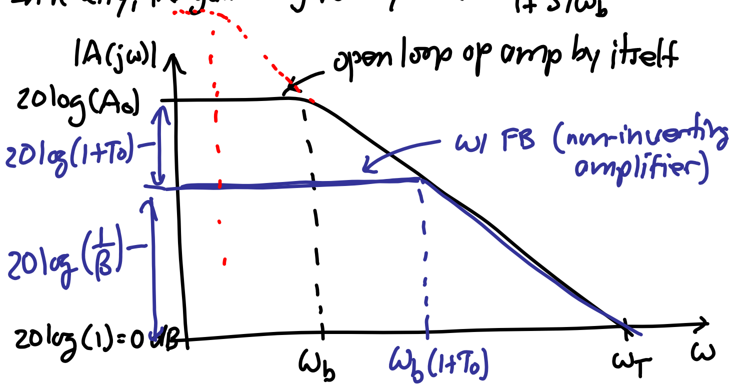
$$\omega_H = \frac{1}{(r_{o4} \| r_{o2})C_L} \quad \leftarrow \text{dominant pole}$$



Finite Op Amp Gain & Bandwidth

For an ideal op amp, $A = \infty$.

In reality, the gain is given by: $A(s) = \dfrac{A_o}{1 + s/\omega_b}$



$\omega_T \triangleq$ unity gain frequency = freq. @ which $|A(j\omega)| = 1$ $(= 0\,dB)$

At ω_T:

$$|A(j\omega_T)| = 1 = \frac{A_o}{\sqrt{1 + \left(\frac{\omega_T}{\omega_b}\right)^2}}$$

$[\omega_T \gg \omega_b] \Rightarrow \dfrac{A_o}{\frac{\omega_T}{\omega_b}} = 1 \rightarrow \underbrace{\boxed{\omega_T = A_o \omega_b}}_{\text{Gain-Bandwidth Product}}$

For $\omega \gg \omega_b$:

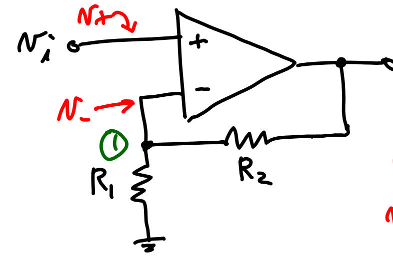
$$A(s) \approx \frac{A_o}{\frac{s}{\omega_b}} = \frac{A_o \omega_b}{s} = \frac{\omega_T}{s} = \frac{f_T}{f}$$

[Integrator w/ time constant $\tau = \frac{1}{\omega_T}$]

The unity gain bandwidth f_T is usually specified on op amp data sheets. Knowing f_T, one can easily determine the op amp gain at a given frequency f.

Frequency Response of Closed Loop Amplifiers

Example. Non-Inverting Amplifier



$N_o = A(s)(N_+ - N_-)$

$N_- = N_+ - \dfrac{N_o}{A(s)}$

$N_- = N_i - \dfrac{N_o}{A(s)}$

Find an expression for the gain as a function of frequency.

① Brute force derivation:

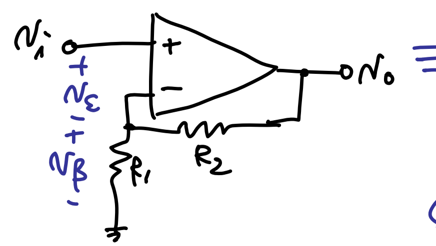
KCL @ ①: $\dfrac{N_o - N_-}{R_2} = \dfrac{N_-}{R_1} \rightarrow \dfrac{N_o}{R_2} = N_-\left(\dfrac{1}{R_1} + \dfrac{1}{R_2}\right)$

$$\frac{N_o}{R_2} = \left(N_i - \frac{N_o}{A(s)}\right)\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \longrightarrow \frac{N_o}{N_i}(s) = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{1}{A(s)}\left(1 + \frac{R_2}{R_1}\right)}$$

$\left[A(s) = \dfrac{A_o}{1 + \frac{s}{\omega_b}}\right] \Rightarrow \boxed{\dfrac{N_o}{N_i}(s) = \left(1 + \dfrac{R_2}{R_1}\right)\dfrac{1}{1 + \dfrac{s}{A_o \omega_b\left(\frac{R_1}{R_1 + R_2}\right)}}}$

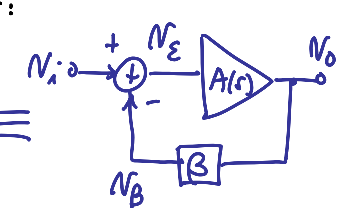
(after a lot of algebraic rearrangement)

② More insightful way to do this:



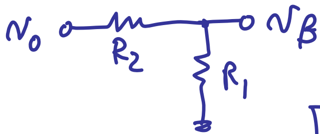
$\equiv$

Neg. FB Block Diagram



$N_\varepsilon = N_i - N_\beta$

$N_i = N_\varepsilon + N_\beta$



$$v_\beta = \left(\frac{R_1}{R_1+R_2}\right) v_o$$

$$\boxed{\beta = \frac{v_\beta}{v_o} = \frac{R_1}{R_1+R_2}}$$

Recall from our previous FB analysis:

$$\frac{v_o}{v_i}(s) = \frac{A(s)}{1+\beta A(s)}$$

$$\left[A(s) = \frac{A_o}{1+\frac{s}{\omega_b}}\right] \rightarrow \frac{v_o}{v_i}(s) = \frac{\frac{A_o}{1+s/\omega_b}}{1+\beta\left(\frac{A_o}{1+s/\omega_b}\right)}$$

$$\frac{v_o}{v_i}(s) = \underbrace{\frac{A_o}{1+\beta A_o}}_{\text{closed loop dc gain term}} \underbrace{\frac{1}{1+\frac{s}{\omega_b(1+\beta A_o)}}}_{\text{frequency shaping term}}$$

$\beta A_o >> 1$ $\downarrow$ $\frac{A_o}{1+\beta A_o} \approx \frac{1}{\beta}$

$T_o = \beta A_o \triangleq$ "loop gain" at $\omega = 0$ (i.e., at dc)

Plug in β:

$$\frac{v_o}{v_i}(s) \cong \frac{1}{\beta}\frac{1}{1+\frac{s}{\omega_b \beta A_o}} = \left(1+\frac{R_2}{R_1}\right)\frac{1}{1+\frac{s}{\omega_b A_o\left(\frac{R_1}{R_1+R_2}\right)}} = \frac{v_o}{v_i}(s)$$

What if $A_o \neq$ large?
↳ can't say $\frac{A_o}{1+\beta A_o} \not\approx \frac{1}{\beta}$
↳ Need to increase the gain of our op amp!

Observations:

① Closed loop DC gain $= \frac{A_o}{1+\beta A_o} = \frac{A_o}{1+T_o} \approx \frac{A_o}{T_o}$ $[T_o >> 1]$

i.e., the closed loop gain is reduced from the open loop gain by $1+T_o$ → show this on graph

② Alternatively, closed loop DC gain $\approx \frac{A_o}{\beta A_o} = \frac{1}{\beta}$ $[T_o >> 1]$

③ ω_{-3dB} has increased from $\omega_b \rightarrow \omega_b(1+A_o\beta) = \omega_b(1+T_o)$

↳ To draw the Bode plot, just find the dc gain, draw a horizontal line across, then follow the open loop response after running into it!

④ Gain-BW Product $= \frac{A_o}{1+\beta A_o}\omega_b(1+\beta A_o) = A_o\omega_b = \omega_T$

∴ the Gain-BW product remains the same for the open & closed loop FB cases!