Announcements:

- HW#3 online and due Friday via Gradescope
- Lab#1 prelab due before lab session
- Lab#1 (experimental part) online

- Most of you have your lab kits, so should start Lab#1 this week
- You would normally turn in Lab#1 at the next lab session, but we will give two lab sessions due to variability in arrival of lab kits

- Lab#2 online
  - Lab#2 prelab due before lab next week
  - Lab#2 (experimental part) due in two lab sessions from the date the prelab is due

- Friday, 9/18, lecture will again be at 12 noon rather than our usual 2-3 p.m.
  - This is one of the days when I have a committee meeting that coincides
  - I will be recording this lecture, so you should be okay if you cannot make this time

Lecture Topics:

- Closed Loop Amplifier Freq. Response
  - Inverting Amplifier
  - Limiting
  - Finite Input & Output Resistance
  - Slew Rate

Last Time:

- Covering finite gain-BW op amp circuits
- Now, continue with this …
Plug in $\beta$:

\[
\frac{\alpha_0}{\alpha_0(s)} \approx \frac{1}{\beta} \frac{1}{1 + \frac{s}{\omega_0 A_0}}
\]

\[
\frac{\alpha_0}{\alpha_0(s)} \approx \frac{1}{\beta} \cdot \left(1 + \frac{s}{\omega_a A_0 (R_1 + R_2)}\right)
\]

Observations:

1. Closed loop DC gain $= \frac{A_0}{1 + \beta A_0} = \frac{A_0}{T_0}$
   
   i.e., the closed loop gain is reduced from the open loop gain by $1 + T_0$ [as seen on graph]

2. Alternatively, closed loop DC gain $\approx \frac{A_0}{\beta A_0} = \frac{1}{\beta}$ [as seen on graph]

3. $\omega_{3dB}$ has increased from $\omega_b$ to $\omega_b (1 + A_0 \beta) : \omega_b (1 + T_0)$

   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 $= \frac{A_0}{1 + \beta A_0} \omega_b (1 + A_0 \beta) = A_0 \omega_b = \omega_T$

   \[\therefore\text{the Gain BW product remains the same for the open \& closed loop FB cases!}\]

Example: Inverting Amplifier

\[
\frac{V_o}{V_i}(s) = \frac{R_2}{R_1 + R_2}
\]

Signal from $V_0 \& V_T$ sum here

\[\Rightarrow \text{current sum} \Rightarrow \text{how much of each appears depends on } \alpha \& \beta\]

Determine $\alpha$:

1. Ground the output to break the loop
2. Feed $V_o$ forward to get the TF.

Determine $\beta$:

1. Ground input, open loop
2. Feedback $V_o$ to get the TF.
Now, get the TF for the system block diagram:

\[ \begin{align*}
    N_o &= A(s)N_e \\
    N_e &= \alpha A(s)N_e - \beta A(s)N_v \\
    N_v &= \alpha N_e + \beta N_o \\
    N_v(s) &= \alpha A(s)N_e(s) - \beta A(s)N_v(s)
\end{align*} \]

\[ \frac{N_o(s)}{N_e(s)} = -\frac{\alpha A(s)}{1 + \beta A(s)} \]

\[ \frac{N_o(s)}{N_e(s)} = -\frac{\alpha A_0}{1 + \beta A_0} \frac{1}{1 + \frac{s}{\omega_b(1+\beta A_0)}} \]

Remarks.

1. Closed loop DC gain now modified by \( \alpha \).
2. BW still \( \omega_b(1+\beta A_0) \) same as for non-inverting case.
3. \( \omega_T \) or Gain-BW product now smaller than that of open-loop amplifier:
   \[ \text{gain-BW} = \alpha \omega_T \]

[rememr, \( \alpha \leq 1 \)]
Finite Input & Output Resistance

\[ A_w(j\omega) = \frac{1}{R_o C_o} \omega_b \]

Unity Gain Follower:

\[ V_o(s) = \frac{1}{1 + \frac{s}{\omega_T}} \]

Step Response:

\[ V_o(t) = V_0 + \frac{V_0}{\tau} \left(1 - e^{-t/\tau}\right) \]

\[ \tau = \frac{1}{\omega_T} \]

Slew Rate:

Linear increase caused by internal limitations that limit the maximum output current the op amp can source! Slew rate!
The max. rate of change of output voltage is defined as the Slew Rate (SR): \( SR = \frac{dv_o}{dt} \)\(_{\text{max}}\) [V/\mu s].

Example: Output a sinusoid, but...

The long slope of the sinusoid is greater than the Slew Rate, transforming the sinusoid into a triangle wave.