Announcements:
- As has been mentioned numerous times in lecture, your Lab#2 reports are individual reports; not group reports
- Evening lecture next week, Tuesday, 7 p.m., in TBD

Today:
- Finish Output Stages
- Start Stability & Compensation

Two Cases:
Case 1: \( R_c: \text{large} \rightarrow I_o \ll I_Q \)
- \( I_o \) not big enough to drive \( I_C \) fully
- For \( V_i: \text{large and } (\text{10}) \): \( Q_1 \) must sink \( I_o + I_Q \)
  
  \[ I_Q = \frac{V_{CC} - V_{CEO}}{R_c} \]
  \[ V_o = V_i - V_{BE1} \]
  \[ \text{at same point } Q_1 \text{ will saturate as } V_o \]
  \[ V_{on} = V_{CC} - V_{CEO} \]
  \[ V_o = V_{CC} - V_{CEO} + V_{BE1} \]

Case 2: \( R_c: \text{small} \rightarrow \text{this, } I_o \text{ can be large!} \)
- For \( V_i: \text{(8)} \) and large \( Q_1 \) can source as much current as needed until it saturates (\( n \) until it triodes)
  
  \[ I_Q = \text{cur. of } Q_1 \]
  \[ V_o = I_o R_c \rightarrow \text{min } V_o = -I_Q R_c \]
  
  \[ \Rightarrow Q_1 \text{ cut off } (I_C = 0) \]
  
  \[ \Rightarrow V_o \text{ clamps at } -I_Q R_c \]
  
  \[ \Rightarrow \text{furth decrease in } V_i \rightarrow \text{no } I_o \text{ in } V_o! \]

Need \( I_o \) large to avoid this problem!

Problems: too much power consumption

\[ P_o = (V_{CC} - V_{BE}) I_o \]

DC power consumption:
- If want large output swing, \( V_{CC} = C \) must consume power!
Solutions: Class B Output Stage
DC

\[ V_o \rightarrow 0 \text{ by choosing } V_o = 0 \]

DC bias

Operation:

1. \( V_o < V_{BE(on)} \rightarrow I_{E1} = 0 \)
2. \( V_{CC} > V_o \rightarrow V_o = V_i - V_{BE(on)} \)
3. \( V_{max} = V_{CC} - V_{BE(adj)} \), \( V_{min} = V_{EE} + V_{CE2(sat)} \)

Stability & Compensation

\[ V_o = A_1 A_2 \left( V_i - V_o \right) \]

Used \( C_c \) to set BW:

Why is \( C_c \) needed?

Stability & Compensation in Op Amps

In general, op amps are used in neg Fb loops.

Reason:

1. Feedback sets the biasing—no large coupling or bypass caps needed.
2. FB increases BW.
3. FB increases linearity or input range.
4. FB gain determined by external FB components—more accurate than op amp gain.
5. FB sets \( R_i \) and \( R_o \).
6. FB can improve temperature stability.
Ee 140: Analog Integrated Circuits
Lecture 19: Output Stages & Compensation

Theorem: any FB loop can become unstable under certain conditions: must compensate to suppress instability!

Ex. Non-inverting Amplifier

\[ V_0 = a_c V_E \]
\[ V_E = V_i - V_f \]
\[ V_f = fV_0 \]

\[ A(s) = \frac{V_0}{V_i} = \frac{a_c}{1 + a_c s} = \frac{a(s)}{1 + T(s)} \]

Closed loop Op amp gain

\[ T(s) = a(s) f \]

Instability occurs when \( A(s) \to \infty \).

\[ A(s) = \frac{a(s)}{1 + a(s) f} \to A(s) = \frac{a(s)}{f} \text{ will also go unstable if down in (\(\to\))} \]

In General:

\[ a(s) f = -1 \]

If \(|a(s)f| \geq 1 \text{ and } a(s)f = -180^\circ \} \Rightarrow \text{Instability} \]

This is a simplified form of the Nyquist Criterion.

Stability of FB Ctl. Using a Single Pole Op Amp

For a single pole op amp:

\[ a(s) = \frac{a_0}{1 - \frac{s}{\omega_p}} \]

Then:

\[ A(s) = \frac{a(s)}{1 + a(s) s} = \frac{a_0}{1 - \frac{s}{\omega_p}} \]

\[ \omega_p \text{ high } \tan \theta \text{ low} \]

\[ A_0 = \text{closed loop dc gain} = (1 + a(s)f) \approx a_0 \times \text{ small } \epsilon < \text{ than } a_0 \]

\[ T_0 = a_0 f = \text{loop gain (defined at dc)} \]

\[ T(s) = a(s) f = \text{loop transmission (defined for general frequencies)} \]

Bode Plot: \( \Rightarrow \text{ use to determine} \)

\[ \begin{align*}
20 \log (a_0) & \text{ open loop ac} \\
20 \log (A_0) & \\
\end{align*} \]

\[ \delta \]

Closed loop w/ closed loop gain \( A_0 \)

\[ \begin{align*}
\log (a(s)) & \\
\log (s) & \\
\end{align*} \]

\[ \begin{align*}
\text{angle} & = \text{angle} \times \omega_0 \times \text{at } \text{ stable!} \\
\end{align*} \]
Remarks:

1. For the case of a single pole op amp, \( \phi \) can never reach \( \angle \hat{T}(j\omega) = -180^\circ \).

2. Thus, an op amp \( H(j\omega) \) with \( \omega_0 \) very near and using a single-pole op amp is always stable.
   
   But add a few non-dominant poles -- then instability is possible!

\[ \text{Since } \Im\{ \angle \hat{T}(j\omega) \} \text{ can reach } -180^\circ \]