EE 330
Lecture 32

• High Gain Amplifiers
• Current Source Biasing
• Current Sources and Mirrors
Can use these equations only when small signal circuit is EXACTLY like that shown!!
Basic Amplifier Characteristics Summary

**Review from Last Lecture**

**CE/CS**

- Large inverting gain
- Moderate input impedance
- Moderate (or high) output impedance
- Widely used as the basic high gain inverting amplifier

**CC/CD**

- Gain very close to +1 (little less)
- High input impedance for BJT (high for MOS)
- Low output impedance
- Widely used as a buffer

**CB/CG**

- Large noninverting gain
- Low input impedance
- Moderate (or high) output impedance
- Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode

**CEwRE/CSwRS**

- Reasonably accurate but somewhat small gain (resistor ratio)
- High input impedance
- Moderate output impedance
- Used when more accurate gain is required
Will calculate $A_V$ by determining the three ratios (not voltage gains of dependent source):

$$A_V = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_B} \frac{V_B}{V_A} \frac{V_A}{V_{in}} = A_{V2} A_{V1} A_{V0}$$
Review from Last Lecture

Example:

\[ A_{V2} = \frac{v_{\text{out}}}{v_B} \approx -\frac{R_6//R_8}{R_7} \]

\[ R_{\text{in2}} \approx \beta R_7 \]
Review from Last Lecture

Example:

Thus we have

\[ A_V = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_B} \frac{V_B}{V_A} \]

where

\[ \frac{V_{out}}{V_B} \approx R_6 // R_8 R_7 \]

\[ \frac{V_B}{V_A} \approx -g_{m1}(R_3 // R_5 // R_{in2}) \]

\[ \frac{V_A}{V_{in}} \approx \frac{R_1 // R_2 // R_{in2}}{R_S + R_1 // R_2 // R_{in1}} \]

\[ R_{in2} \approx \beta R_7 \]

\[ R_{in1} \approx r_{π1} \]
Formalization of cascade circuit analysis working from load to input: \(\text{(when stages are unilateral or not unilateral)}\)

\[ \frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{V_1}{V_{\text{IN}}} \cdot \frac{V_2}{V_{\text{IN}}} \cdot \frac{V_3}{V_{\text{OUT}}} \]

\(R_{\text{in}}\) includes effects of all loading
Must recalculate if any change in loading
Analysis systematic and rather simple

This was the approach used in analyzing the previous cascaded amplifier
Example:

Observation: By working from the output back to the input we were able to create a sequence of steps where the circuit at each step looked EXACTLY like one of the four basic amplifiers. Engineers often follow a design approach that uses a cascade of the basic amplifiers and that is why it is often possible to follow this approach to analysis.

Two other methods could have been used to analyze this circuit

What are they?
Two other methods could have been used to analyze this circuit

1. Create a two-port model of the two stages
   (for this example, since the first-stage is unilateral, it can be shown that)

\[ A_V = \frac{V_{out}}{V_{in}} = \frac{V_A}{V_{in}} \cdot \frac{V_B}{V_{out}} \]
Example:

Two other methods could have been used to analyze this circuit

2. Put in small-signal model for Q₁ and Q₂ and solve resultant circuit
   (not too difficult for this specific example but time consuming)
Example: \[ A_V = \frac{V_{out}}{V_{in}} = ? \] Express in terms of small-signal parameters
Example:

\[
A_v = \frac{V_{out}}{V_2} \frac{V_2}{V_1} \frac{V_1}{V_{in}} \cong \left[-g_{m4} \left(\frac{R_D}{R_L}\right)\right][1] \left[\frac{-g_{m1}}{g_{m2} + \left(\beta_3 \left(\frac{R_{B1}}{R_{B2}}\right)\right)^{-1}}\right]
\]

Note: Even though the second stage has a resistor in the collector, the gain expressions developed for the common collector amplifier still apply.
High-gain BJT amplifier

\[ A_V = \frac{-g_m}{g_0 + G_C} \approx -g_mR_C \]

To make the gain large, it appears that all one needs to do is make \( R_C \) large!

\[ A_V \approx -g_mR_C = \frac{-I_{CQ}R_C}{V_t} \]

But \( V_t \) is fixed at approx 25mV and for good signal swing, \( I_{CQ}R_C < (V_{DD} - V_{EE})/2 \)

\[ |A_V| < \frac{V_{DD} - V_{EE}}{2V_t} \]

If \( V_{DD} - V_{EE} = 5V \),

\[ |A_V| < \frac{5V}{2 \cdot 25mV} = 100 \]

- Gain is practically limited with this supply voltage to around 100
- And in extreme case, limited to 200 with this supply voltage with very small signal swing
High-gain MOS amplifier

$$A_V = \frac{-g_m}{g_0 + G_D} \approx -g_m R_D$$

To make the gain large, it appears that all one needs to do is make $R_D$ large!

$$A_V \approx -g_m R_D = \frac{-2I_D Q R_D}{V_{EB}}$$

But $V_{EB}$ is practically limited to around 100mV and for good signal swing, $I_{DQ} R_D < (V_{DD} - V_{SS})/2$

$$|A_V| < \frac{V_{DD} - V_{SS}}{V_{EB}}$$

If $V_{DD} - V_{SS} = 5V$ and $V_{EB} = 100mV$,

$$|A_V| < \frac{5V}{100mV} = 50$$

Gain is practically limited with this supply voltage to around 50

Are these fundamental limits on the gain of the BJT and MOS Amplifiers?
High-gain amplifier

This gain is very large!

Too good to be true!

Need better model of MOS device!
High-gain amplifier

This gain is very large (but realistic)!
And no design parameters affect the gain
But how can we make a current source?
High-gain amplifier

\[ A_V \approx -8000 \]

How can we build the ideal current source?

What is the small-signal model of an actual current source?
Before addressing the issue of how a current source is designed, will consider another circuit that uses current source biasing.

The Basic Differential Amplifier

If $A_V$ is large

Operational Amplifier (Op Amp)
Example: Determine the voltage gain of the following circuit

Since symmetric when $v_{in}=0$

\[
I_{C1} = I_{C2} = \frac{I_{EE}}{2}
\]

\[
g_{m1} = g_{m2} = \frac{I_{EE}}{2V_t}
\]
Example: Determine the voltage gain of the following circuit

\[
\begin{align*}
\mathbf{v}_E &= (g_{\pi 1} + g_{\pi 1}) = g_{\pi 1} \mathbf{v}_{IN} + g_{m1} (\mathbf{v}_{IN} - \mathbf{v}_E) + g_{m2} (-\mathbf{v}_E) \\
\mathbf{v}_{OUT} &= -R_{C1} g_{m1} (\mathbf{v}_{IN} - \mathbf{v}_E)
\end{align*}
\]

\[
\begin{align*}
\mathbf{v}_E &= (g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2}) = \mathbf{v}_{IN} (g_{m1} + g_{\pi 1}) \\
\mathbf{v}_E &= \frac{(g_{m1} + g_{\pi 1})}{(g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2})} \mathbf{v}_{IN} \\
\mathbf{v}_{OUT} &= -R_{C1} g_{m1} \mathbf{v}_{IN} \left[ 1 - \frac{(g_{m1} + g_{\pi 1})}{(g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2})} \right] \\
\mathbf{v}_{OUT} &= -R_{C1} g_{m1} \mathbf{v}_{IN} \left[ \frac{g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2} - (g_{m1} + g_{\pi 1})}{(g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2})} \right]
\end{align*}
\]
Example: Determine the voltage gain of the following circuit

\[
V_{\text{OUT}} = -R_{C1} g_{m1} V_{\text{IN}} \left[ \frac{g_{\pi1} + g_{\pi2} + g_{m1} + g_{m2} - (g_{m1} + g_{\pi1})}{(g_{\pi1} + g_{\pi2} + g_{m1} + g_{m2})} \right]
\]

\[
V_{\text{OUT}} \approx -R_{C1} g_{m1} V_{\text{IN}} \left[ \frac{g_{m2}}{(g_{m1} + g_{m2})} \right]
\]

\[
V_{\text{OUT}} \approx \left[ \frac{-R_{C1} g_{m1}}{2} \right] V_{\text{IN}}
\]

\[
V_{\text{OUT2}} \approx \left[ \frac{R_{C1} g_{m1}}{2} \right] V_{\text{IN}}
\]
Differential amplifier

\[ V_{OUT1} \approx -\left[ \frac{R_C g_{m1}}{2} \right] (V_{IN1} - V_{IN2}) \]

\[ V_{OUT2} \approx \left[ \frac{R_C g_{m1}}{2} \right] (V_{IN1} - V_{IN2}) \]

- Very useful circuit
- This is a basic Op Amp
- Uses a current source and \( V_{DD} \) for biasing (no biasing resistors or caps!)
- But – needs a dc current source !!!!
High-gain amplifier

How can we build the dc current source?

What is the small-signal model of an actual current source?
Model of dc Current Source

“Reasonable dc Current Source”

\[ I_1 \]
\[
\begin{array}{c}
+ \\
V_1 \\
- \\
\end{array}
\]

Current Source

\[ R_S \]
\[ I_{XX} \]

LARGE SIGNAL

\[ I_{XX} \] independent of \( V_1 \) and \( t \), \( R_S \) large

Small-signal model of dc current source

\[ i_1 \]
\[
\begin{array}{c}
+ \\
V_1 \\
- \\
\end{array}
\]

Current Source

\[ R_{IN} \]

SMALL SIGNAL

want \( R_{IN} \) large

Ideal dc Current Source

\[ I_1 \]
\[
\begin{array}{c}
+ \\
V_1 \\
- \\
\end{array}
\]

Current Source

\[ I_{XX} \]

LARGE SIGNAL

\[ I_{XX} \] independent of \( V_1 \) and \( t \)

R_{IN}=\infty
Current Sources/Mirrors

Will show circuit in red behaves as a current source
If the base currents are neglected, the current $I_0$ can be expressed as:

$$I_0 = \frac{(V_{CC} - 0.6V)}{R}$$
Current Sources/Mirrors

\[ I_0 = \left( \frac{V_{CC} - 0.6V}{R} \right) \]

If the base currents are neglected

\[
\begin{align*}
I_0 &= J_S A_{E0} e^{\frac{V_{BE0}}{V_t}} \\
I_t &= J_S A_{E1} e^{\frac{V_{BE1}}{V_t}}
\end{align*}
\]

since \( V_{BE1} = V_{BE2} \)

\[ I_1 \approx \left( \frac{A_{E1}}{A_{E0}} \right) I_0 = \left( \frac{A_{E1}}{A_{E0}} \right) \frac{V_{CC} - 0.6V}{R} \]

Note \( I_1 \) is not a function of \( V_1 \)

Behaves as a current source! So is ideal with this model!!

Actually termed a “sink” current since coming out of load

And does not require an additional dc voltage source !!!
Current Sources/Mirrors

- Multiple Outputs Possible
- Can be built for sourcing or sinking currents
- Also useful as a current amplifier
- MOS counterparts work very well and are not plagued by base current
Current Sources/Mirrors

Biasing Circuit

Key Block

Current Sink
Current Sources/Mirrors

\[ I_k = \left[ \frac{A_{E_k}}{A_{E_0}} \right] I_0 \]

Multiple-Output Bipolar Current Sink
Current Sources/Mirrors

Multiple-Output Bipolar Current Source

\[
I_k = \left[ \frac{A_{E_k}}{A_{E0}} \right] I_0
\]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source and Sink

\[ I_{nk} = ? \quad I_{pk} = ? \]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source and Sink

\[ I_{nk} = \left[ \frac{A_{Enk}}{A_{E0}} \right] I_0 \]

\[ I_{pk} = \left[ \frac{A_{En1}}{A_{E0}} \right] \left[ \frac{A_{Epk}}{A_{Ep0}} \right] I_0 \]
End of Lecture 32