EE 330
Lecture 32

- High Gain Amplifiers
- Current Source Biasing
- Current Sources and Mirrors
- The Cascode Configuration
- The Differential Amplifier
Can use these equations only when small signal circuit is EXACTLY like that shown!!

<table>
<thead>
<tr>
<th></th>
<th>Basic Amplifier Gain Table</th>
</tr>
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<tbody>
<tr>
<td>A_V</td>
<td></td>
</tr>
<tr>
<td>CE/CS</td>
<td>BJT</td>
</tr>
<tr>
<td></td>
<td>- ( g_m R_C )</td>
</tr>
<tr>
<td></td>
<td>(- \frac{I_{CQ} R_C}{V_t})</td>
</tr>
<tr>
<td>MOS</td>
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</tr>
<tr>
<td></td>
<td>(- \frac{2I_{DQ} R_D}{V_{EB}})</td>
</tr>
<tr>
<td>CC/CD</td>
<td>BJT</td>
</tr>
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<td></td>
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Can use these equations only when small signal circuit is EXACTLY like that shown!!
Basic Amplifier Characteristics Summary

**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
Example: \[ A_V = \frac{V_{out}}{V_{in}} = ? \] Express in terms of small-signal parameters
Example:

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

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

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

$$A_V \approx -g_m R_C = \frac{-I_{CQ} R_C}{V_t}$$

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!

\[ A_V \approx -g_m R_D = \frac{-2I_{DQ}R_D}{V_{EB}} \]

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

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

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?
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

\[ V_{OUT} = A_V (V_2 - V_1) \]

If \( A_V \) is large

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

\[ V_{out} = \frac{I_{EE}}{2} \]

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

\[ V_E (g_{\pi_1} + g_{\pi_1}) = g_{\pi_1} V_{IN} + g_{m_1} (V_{IN} - V_E) + g_{m_2} (-V_E) \]

\[ V_{OUT} = -R_{C_1} g_{m_1} (V_{IN} - V_E) \]

\[ V_E (g_{\pi_1} + g_{\pi_2} + g_{m_1} + g_{m_2}) = V_{IN} (g_{m_1} + g_{\pi_1}) \]

\[ V_E = \frac{(g_{m_1} + g_{\pi_1})}{(g_{\pi_1} + g_{\pi_2} + g_{m_1} + g_{m_2})} V_{IN} \]

\[ V_{OUT} = -R_{C_1} g_{m_1} V_{IN} \left[ 1 - \frac{(g_{m_1} + g_{\pi_1})}{(g_{\pi_1} + g_{\pi_2} + g_{m_1} + g_{m_2})} \right] \]

\[ V_{OUT} = -R_{C_1} g_{m_1} V_{IN} \left[ \frac{g_{\pi_1} + g_{\pi_2} + g_{m_1} + g_{m_2} - (g_{m_1} + g_{\pi_1})}{(g_{\pi_1} + g_{\pi_2} + g_{m_1} + g_{m_2})} \right] \]
Example: Determine the voltage gain of the following circuit

\[ V_{OUT} = -R_C g_m V_{IN} \left[ \frac{g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2} - (g_{m1} + g_{\pi 1})}{(g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2})} \right] \]

\[ V_{OUT} \approx -R_C g_m V_{IN} \left[ \frac{g_{m2}}{(g_{m1} + g_{m2})} \right] \]

\[ V_{OUT} \approx \left[ \frac{-R_C g_m}{2} \right] V_{IN} \]

\[ V_{OUT 2} \approx \left[ \frac{R_C g_m}{2} \right] V_{IN} \]
Differential amplifier

\[
V_{OUT1} \approx -\left[ \frac{R_{C1}g_{m1}}{2} \right] (V_{IN1} - V_{IN2})
\]

\[
V_{OUT2} \approx \left[ \frac{R_{C1}g_{m1}}{2} \right] (V_{IN1} - V_{IN2})
\]

- 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

\[ A_V \approx -8000 \]

How can we build the dc current source?

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

As a 1-port network

\[ I_1 = f(V_1) \]

\[ g_{IN} = \frac{\partial I_1}{\partial V_1} = R_{IN}^{-1} \]

"Reasonable Current Source"

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

Small-signal model of current source

want \( R_{IN} \) large
Model of Current Source

“Reasonable Current Source”

\[ I_1 \]
\[ R_S \]
\[ I_{XX} \]  \hspace{1cm} \text{Current Source} \hspace{1cm} \text{LARGE SIGNAL} \]

\[ I_{XX} \text{ independent of } V_1 \text{ and } R_S \text{ large} \]

Small-signal model of current source

\[ i_1 \]
\[ R_{IN} \]  \hspace{1cm} \text{Current Source} \hspace{1cm} \text{SMALL SIGNAL} \]

want \( R_{IN} \) large

Ideal Current Source

\[ I_1 \]
\[ I_{XX} \]  \hspace{1cm} \text{Current Source} \hspace{1cm} \text{LARGE SIGNAL} \]

\[ I_{XX} \text{ independent of } V_1 \]

\[ R_{IN=\infty} \]
Current Sources/Mirrors

\[ V_{CC} \]

\[ R \]

\[ I_0 \rightarrow I_1 \]

\[ Q_0 \rightarrow Q_1 \]

\[ A_{E0} \rightarrow A_{E1} \]

Load

\[ I_1 \]

Current Source

\[ V_{CC} \]

\[ R \]

\[ I_0 \rightarrow I_1 \]

\[ Q_0 \rightarrow Q_1 \]

\[ A_{E0} \rightarrow A_{E1} \]

Load
Current Sources/Mirrors

If the base currents are neglected

\[ I_0 \approx \frac{(V_{CC} - 0.6V)}{R} \]
Current Sources/Mirrors

If the base currents are neglected

\[ I_0 = J_S A_{E0} e^{\frac{V_{BE0}}{V_t}} \]

\[ I_1 = J_S A_{E1} e^{\frac{V_{BE1}}{V_t}} \]

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

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

Behaves as a current source!

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

Current Sink

Key Block
Current Sources/Mirrors

Multiple-Output Bipolar Current Sink

\[ I_k = \left[ \frac{A_{E_k}}{A_{E_0}} \right] I_0 \]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source

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