EE 330
Lecture 30

• Basic Amplifier Analysis
• High-Gain Amplifiers
• Current Source Biasing
  – (just introduction)
## Basic Amplifier Gain Table

<table>
<thead>
<tr>
<th></th>
<th>MOS</th>
<th>BJT</th>
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<th>BJT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AV</strong></td>
<td>$-g_mR_C$</td>
<td>$\frac{g_m}{g_m+g_E}$</td>
<td>$g_mR_C$</td>
<td>$-\frac{R_C}{R_E}$</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>$\frac{2I_{DQ}R_C}{V_{EB}}$</td>
<td>$\frac{2I_{DQ}R_E}{2I_{DQ}R_E+V_{EB}}$</td>
<td>$\frac{2I_{DQ}R_C}{V_{EB}}$</td>
<td>$\frac{I_{CQ}R_C}{V_{t}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>R_{in}</strong></td>
<td>$\infty$</td>
<td>$\frac{\beta V_t}{I_{CQ}}$</td>
<td>$\infty$</td>
<td>$\beta \left( \frac{V_t}{I_{CQ}} + R_E \right)$</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>R_{out}</strong></td>
<td>$R_C$</td>
<td>$g_m^{-1}$</td>
<td>$R_C$</td>
<td>$R_C$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\frac{2I_{DQ}}{V_{EB}}$</td>
<td>$\frac{I_{CQ}}{V_t}$</td>
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</tr>
</tbody>
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# Basic Amplifier Gain Table

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<thead>
<tr>
<th>Circuit Type</th>
<th>MOS</th>
<th>BJT</th>
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<th>BJT</th>
<th>MOS</th>
<th>BJT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$A_V$</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CE/CS</td>
<td>$-g_mR_C$</td>
<td>$\frac{g_m}{g_m+g_E}$</td>
<td>$g_mR_C$</td>
<td>$-\frac{R_C}{R_E}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC/CD</td>
<td>$-\frac{2I_{DQ}R_C}{V_{EB}} - \frac{I_{CQ}R_C}{V_t}$</td>
<td>$\frac{2I_{DQ}R_E}{2I_{DQ}R_E+V_{EB}}$</td>
<td>$\frac{I_{CQ}R_E}{I_{CQ}R_E+V_t}$</td>
<td>$\frac{2I_{DQ}R_C}{V_{EB}}$</td>
<td>$\frac{I_{CQ}R_C}{V_t}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB/CG</td>
<td>$\infty$</td>
<td>$\beta \left( \frac{V_t}{I_{CQ}} + R_E \right)$</td>
<td>$\infty$</td>
<td>$\frac{2I_{DQ}}{V_{EB}}$</td>
<td>$\frac{I_{CQ}}{V_t}$</td>
<td>$\infty$</td>
<td>$\beta \left( \frac{V_t}{I_{CQ}} + R_E \right)$</td>
<td></td>
</tr>
<tr>
<td>CEwRE/CSwRS</td>
<td>$R_C$</td>
<td>$g_m^{-1}$</td>
<td>$R_C$</td>
<td>$R_C$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Can use these equations only when circuit is EXACTLY like that shown above!!
Why are we focusing on these basic circuits?

1. So that we can develop analytical skills
2. So that we can design a circuit
3. So that we can get the insight needed to design a circuit

Which is the most important?
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Which is the most important?

1. So that we can get the insight needed to design a circuit
2. So that we can design a circuit
3. So that we can develop analytical skills
Properties/Use of Basic Amplifiers

CE and CS

- More practical biasing circuits usually used
- \( R_C \) or \( R_D \) may (or may not) be load
Properties/Use of Basic Amplifiers

CE and CS

- Large inverting gain
- Moderate input impedance for BJT (high for MOS)
- Moderate output impedance
- Most widely used amplifier structure
Properties/Use of Basic Amplifiers

CC and CD
(emitter follower or source follower)

- More practical biasing circuits usually used
- $R_E$ or $R_S$ may (or may not) be load
Properties/Use of Basic Amplifiers

CC and CD
(emitter follower or source follower)

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

CB and CG

- More practical biasing circuits usually used
- $R_C$ or $R_D$ may (or may not) be load
Properties/Use of Basic Amplifiers

CB and 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
Properties/Use of Basic Amplifiers

CEwRE or CSwRS

• More practical biasing circuits usually used
• $R_C$ or $R_D$ may (or may not) be load
Properties/Use of Basic Amplifiers

CEwRE or CSwRS

- Reasonably accurate but somewhat small gain (resistor ratio)
- High input impedance
- Moderate output impedance
- Used when more accurate gain is required
Repeat from earlier discussions on amplifiers

Cascaded Amplifier Analysis and Operation

\[ A_V = \frac{V_{\text{out}}}{V_{\text{in}}} = \left( \frac{R_{iX1}}{R_{iX1} + R_S} \right) A_{V01} \left( \frac{R_{L1}/R_{iX2}}{R_{L1}/R_{iX2} + R_{0X1}} \right) A_{V02} \left( \frac{R_L}{R_L + R_{0X2}} \right) \]

Accounts for all loading between stages!
Example:

Determine the voltage gain of the following circuit in terms of the small-signal parameters of the transistors. Assume $Q_1$ and $Q_2$ are operating in the Forward Active region and $C_1$...$C_4$ are large.

In this form, does not look “EXACTLY” like any of the basic amplifiers!
Will calculate $A_V$ by determining the three ratios:

$$A_V = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_B} \frac{V_B}{V_A} \frac{V_A}{V_{in}} = A_{V2}A_{V1}A_{V0}$$
Example:

\[ A_{V_2} = \frac{V_{\text{out}}}{V_B} \approx -\frac{R_6//R_8}{R_7} \]

\[ R_{\text{in2}} \approx \beta R_7 \]
Example:

\[ \mathcal{V}_{\text{out}} \]

\[ R_7 \]

\[ R_6//R_8 \]

\[ Q_2 \]

\[ R_{\text{in}2} \]

\[ R_{\text{in}2} \approx \beta R_7 \]
Example:

\[ A_{v2} = \frac{v_{out}}{v_B} \approx -\frac{R_6/\!\!//R_8}{R_7} \]

\[ R_{in2} \approx \beta R_7 \]
**Example:**

\[ A_{V1} = \frac{v_B}{v_A} \approx -g_{m1} \quad R_3//R_5//R_{in2} \]

\[ R_{in1} \approx r_{\pi 1} \]
Example:
Example:

\[
A_{V_0} = \frac{V_A}{V_{in}} = \frac{R_1//R_2 // R_{in1}}{R_S + R_1//R_2 // R_{in1}}
\]
Thus we have

$$A_V = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{V_{\text{out}}}{V_B} \cdot \frac{V_B}{V_A} \cdot \frac{V_A}{V_{\text{in}}}$$

where

$$\frac{V_{\text{out}}}{V_B} \approx -\frac{R_6//R_8}{R_7}$$

$$\frac{V_B}{V_A} \approx -g_{m1} \cdot \frac{R_3//R_5//R_{\text{in}2}}{}$$

$$\frac{V_A}{V_{\text{in}}} \approx \frac{R_1//R_2//R_{\text{in}1}}{R_S + R_1//R_2//R_{\text{in}1}}$$

$$R_{\text{in}2} \approx \beta R_7$$

$$R_{\text{in}1} \approx r_{\pi 1}$$
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.

Will formalize what we have done (consider 3-stage cascade)
Formalization of cascade circuit analysis working from load to input:

\[
\frac{V_{OUT}}{V_{IN}} = \frac{V_1}{V_{IN}} \cdot \frac{V_2}{V_1} \cdot \frac{V_3}{V_2} \cdot \frac{V_{OUT}}{V_3}
\]
Formalization of cascade circuit analysis working from load to input:

Starting at output stage obtain:

\[
\frac{V_{OUT}}{V_{IN}} = \frac{V_1}{V_{IN}} \frac{V_2}{V_1} \frac{V_3}{V_2} \frac{V_{OUT}}{V_3}
\]
Formalization of cascade circuit analysis working from load to input:

Replace Stage 3 with $R_{IN3}$

Analyze Stage 2:

$$\frac{V_{OUT}}{V_{IN}} = \frac{V_1}{V_{IN}} \frac{V_2}{V_1} \frac{V_3}{V_2} \frac{V_{OUT}}{V_3}$$
Formalization of cascade circuit analysis working from load to input:

Replace Stage 2 with $R_{IN2}$

Analyze Stage 1:

$$\frac{V_{OUT}}{V_{IN}} = \frac{V_1}{V_{IN}} \frac{V_2}{V_1} \frac{V_3}{V_2} \frac{V_{OUT}}{V_3}$$
Formalization of cascade circuit analysis working from load to input:

Replace Stage 1 with $R_{IN1}$

Analyze Stage 0:

$$\frac{V_{OUT}}{V_{IN}} = \frac{V_1}{V_{IN}} \frac{V_2}{V_1} \frac{V_3}{V_2} \frac{V_{OUT}}{V_3}$$
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?
Example:

Two other methods could have been used to analyze this circuit:

1. Create a two-port model of the two stages

\[ A_V = \frac{v_{out}}{v_{in}} = \left( \frac{R_{iX1}}{R_{iX1}+R_S} \right) A_{V01} \left( \frac{R_{L1}/R_{iX2}}{R_{L1}/R_{iX2}+R_{0X1}} \right) A_{V02} \left( \frac{R_L}{R_L+R_{0X2}} \right) \]

\( A_{V01} \) and \( A_{V02} \) are open-loop two-port gain and are different than what used above.

2. Small signal model could have been put in for \( Q_1 \) and \( Q_2 \)
Example: \[ A_V = \frac{v_{out}}{v_{in}} = ? \] Express in terms of small-signal parameters
Note: Even though the second stage has a resistor in the collector, the gain expressions developed for the common collector amplifier still apply

\[
A_v = \frac{v_{out}}{v_2} \frac{v_2}{v_1} \frac{v_1}{v_{in}} \approx \left[-g_{m4} \ \frac{R_D}{R_L} \right] \left[\frac{-g_{m1}}{g_{m2} + \beta_3 \ \frac{R_{B1}}{R_{B2}}}\right]^{-1}
\]
High-gain BJT amplifier

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

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
High-gain MOS amplifier

$$\begin{align*}
A_V &= \frac{-g_m}{g_0 + G_D} \\ &\approx -g_m R_D
\end{align*}$$

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, $I_{DQ} R_D < (V_{DD} - V_{SS})/2$

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

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 100

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!
This gain is very large (but realistic)!

But how can we make a current source?