EE 330
Lecture 33

- Basic Amplifier Analysis
- High-Gain Amplifiers
- Current Source Biasing
  - (just introduction)
Common Emitter Configuration

Consider the following CE application

(this is also a two-port model for this CE application)

\[
\begin{align*}
A_v & \quad g_o << g_c \\
& \approx -g_m R_C \\
R_{out} & = \frac{1}{g_0 + g_C} \quad g_o << g_c \\
& \approx R_C \\
R_{in} & = r_\pi \\
A_v & \quad g_o << g_c \\
& \approx -\frac{I_{CQ} R_C}{V_t} \\
R_{out} & \approx R_C \\
R_{in} & = \frac{\beta V_t}{I_{CQ}}
\end{align*}
\]

- Input impedance is mid-range
- Voltage Gain is Large and Inverting
- Output impedance is mid-range
- Widely used as a voltage amplifier
Common Collector Configuration

Review from Last Time

For this CC application

(this is not a two-port model for this CC application)

\[ A_V = \frac{g_{\pi} + g_m}{g_m + g_E + g_0 + g_{\pi}} \]

\[ R_{in} \approx r_\pi + \beta R_E \]

\[ R_0 \approx \frac{R_E}{1 + g_m R_E} \]

\[ A_V \approx \frac{l_{CQ} R_E}{l_{CQ} R_E + V_t} \]

\[ R_{in} \approx \beta R_E \]

\[ R_0 \approx \frac{g_m R_E \gg \! > > 1}{l_{CQ}} \]

\[ \frac{1}{l_{CQ}} \approx \frac{V_t}{I_{CQ}} \]

- Output impedance is low
- \( A_{V0} \) is positive and near 1
- Input impedance is very large
- Widely used as a buffer
- Not completely unilateral but output-input transconductance is small
Two-port model for Common Base Configuration

This is not a two-port model for this CB application.

\[ A_V \approx g_m R_C \]
\[ R_{in} \approx \frac{1}{g_m} \]
\[ R_c \ll r_0 \]
\[ R_{out} \approx R_C \]

\[ A_V \approx \frac{I_{CQ} R_C}{V_t} \]
\[ R_{in} \approx \frac{V_t}{I_{CQ}} \]
\[ R_c \ll r_0 \]
\[ R_{out} \approx R_C \]

- Output impedance is mid-range
- \[ A_{V0} \] is large and positive (equal in mag to that to CE)
- Input impedance is very low
- Not completely unilateral but output-input transconductance is small
Common Emitter with Emitter Resistor Configuration

By KCL at two non-grounded nodes

\[
\begin{align*}
\nu_{out} (g_C + g_0) + (\nu_{in} - \nu_E) g_m &= g_0 \nu_E \\
\nu_E (g_E + g_0 + g_\pi) - (\nu_{in} - \nu_E) g_m &= g_0 \nu_{out} + g_\pi \nu_{in}
\end{align*}
\]

\[
A_v = \frac{\nu_{out}}{\nu_{in}} = \frac{-g_m g_E + g_0 g_\pi}{g_C g_m + g_C (g_0 + g_\pi + g_E) + g_0 (g_\pi + g_E)} \approx -\frac{R_C}{R_E}
\]
Common Emitter with Emitter Resistor Configuration

\[ A_V \approx -\frac{R_C}{R_E} \]

It can also be shown that

\[ R_{in} \approx r_\pi + \beta R_E \]

\[ R_{out} \approx R_C \]
Common Emitter with Emitter Resistor Configuration

\[ A_V \approx -\frac{R_C}{R_E} \]
\[ R_{in} \approx r_T + \beta R_E \]
\[ R_{out} \approx R_C \]

(this is not a two-port model)

- Analysis would simplify if \( g_0 \) were set to 0 in model
- Gain can be accurately controlled with resistor ratios
- Useful for reasonably accurate low gains
- Input impedance is high
## Basic Amplifier Gain Table

<table>
<thead>
<tr>
<th>Type</th>
<th>MOS</th>
<th>BJT</th>
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<th>BJT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AV</strong></td>
<td>$-g_m R_C$</td>
<td>$-2I_{DQ} R_C / V_{EB}$</td>
<td>$g_m R_C$</td>
<td>$\frac{g_m}{g_m + g_E}$</td>
<td>$\frac{2I_{DQ} R_E}{V_{EB}}$</td>
<td>$\frac{I_{CQ} R_E}{V_{EB}}$</td>
<td>$\frac{2I_{DQ} R_C}{V_{EB}}$</td>
<td>$\frac{I_{CQ} R_C}{V_{EB}}$</td>
</tr>
<tr>
<td><strong>R_{in}</strong></td>
<td>$r_{tT}$</td>
<td>$\infty$</td>
<td>$r_{tT} + \beta R_E$</td>
<td>$\infty$</td>
<td>$\beta \left( \frac{V_t}{I_{CQ}} + R_E \right)$</td>
<td>$\infty$</td>
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<td></td>
</tr>
<tr>
<td><strong>R_{out}</strong></td>
<td>$R_C$</td>
<td>$g_m^{-1}$</td>
<td>$R_C$</td>
<td>$\frac{2I_{DQ}}{V_{EB}}$</td>
<td>$\frac{I_{CQ}}{V_{t}}$</td>
<td>$R_C$</td>
<td>$R_C$</td>
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</tbody>
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**CE/CS**

**CC/CD**

**CB/CG**

**CEwRE/CSwRS**
# Basic Amplifier Gain Table

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<tr>
<td>$R_{in}$</td>
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<td>$\frac{\beta V_t}{I_{CQ}}$</td>
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Can use these equations only when circuit is EXACTLY like that shown above!!
Basic Amplifier Structures

1. Common Emitter/Common Source
2. Common Collector/Common Drain
3. Common Base/Common Gate
4. Common Emitter with $R_E$/ Common Source with $R_S$
5. Cascode (actually CE:CB or CS:CD cascade)
6. Darlington (special CE:CE or CS:CS cascade)

The first 4 are most popular
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
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
Basic Amplifier Characteristics Summary

**CE/CS**
- 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

**CC/CD**
- Gain very close to +1 (little less)
- High input impedance for BJT (high for MOS)
- Low output impedance
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**CB/CG**
- Large noninverting gain
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**CEwRE/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

(applicable when all stages are unilateral)

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

Accounts for all loading between stages!
Cascaded Amplifier Analysis and Operation

(when stages are not unilateral)

- Standard two-port cascade

- Right-to-left nested \( R_{\text{inx}}, A_{\text{vX}} \) approach

\[ R_{\text{inx}} \text{ includes effects of all loading} \]
\[ A_{\text{vX}}'s \text{ include all loading} \]
\[ \text{Can not change any loading} \]
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 $C_1\ldots C_4$ are large.

In this form, does not look “EXACTLY” like any of the basic amplifiers!
Example:

Will calculate $A_V$ by determining the three ratios (not voltage gains of dependent source):

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

\[ A_{V2} = \frac{V_{out}}{V_B} \approx -\frac{R_6//R_8}{R_7} \]

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

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

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

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

\[ A_{V1} = \frac{v_B}{v_A} \approx -g_m (R_3//R_5//R_{in2}) \]

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

\[ A_{V0} = \frac{V_A}{V_{in}} \approx \frac{R_{1//R_2 // R_{in1}}}{R_S + R_{1//R_2 // R_{in1}}} \]
Example:

![Circuit Diagram]

Thus we have

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

where

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

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

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

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

\[
R_{in1} \approx r_{\pi1}
\]
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 even though stages were not unilateral. 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 unilateral cascade)
Formalization of cascade circuit analysis working from load to input: (consider 3-stage unilateral cascade)
Formalization of cascade circuit analysis working from load to input: (consider 3-stage unilateral cascade)

Starting at output stage obtain:

\[ \frac{V_{OUT}}{V_{IN}} = \frac{V_1}{V_{IN}} \frac{V_2}{V_1} \frac{V_3}{V_2} \]
Formalization of cascade circuit analysis working from load to input: (consider 3-stage unilateral cascade)

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: (consider 3-stage unilateral cascade)

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

Replace Stage 2 with \( R_{\text{IN}2} \)

Analyze Stage 1:
Formalization of cascade circuit analysis working from load to input: (consider 3-stage unilateral cascade)

Replace Stage 1 with $R_{IN1}$

Analyze Stage 0:

\[
\frac{V_{OUT}}{V_{IN}} = \frac{V_1}{V_{IN}} \frac{V_2}{V_1} \frac{V_3}{V_2} V_{OUT}
\]
Formalization of cascade circuit analysis working from load to input:  
(when stages are not unilateral)

\[ \frac{v_{\text{OUT}}}{v_{\text{IN}}} = \frac{v_1}{v_{\text{IN}}} \cdot \frac{v_2}{v_1} \cdot \frac{v_3}{v_2} \cdot \frac{v_{\text{OUT}}}{v_3} = \frac{v_1}{v_{\text{IN}}} A_{V1X} A_{V2X} A_{V3X} \]

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

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 )

   \[
   A_V = \frac{v_{out}}{v_{in}} = \left( \frac{R_{i\text{X}1}}{R_{i\text{X}1} + R_S} \right) A_{V01} \left( \frac{R_{L1}/R_{i\text{X}2}}{R_{L1}/R_{i\text{X}2} + R_{0\text{X}1}} \right) A_{V02} \left( \frac{R_L}{R_L + R_{0\text{X}2}} \right)
   \]

   $A_{V01}$ and $A_{V02}$ are open-loop two-port gain and are different than what used above

1. Small signal model could have been put in for $Q_1$ and $Q_2$
Example: \[ A_V = \frac{\nu_{out}}{\nu_{in}} = ? \] 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.

\[ A_v = \frac{v_{out}}{v_{2}} \frac{v_{2}}{v_{1}} \frac{v_{1}}{v_{in}} \approx \left[ -g_{m4} \left( R_D // R_L \right) \right][1] \left[ -\frac{g_{m1}}{g_{m2} + \left( \beta_3 \left( R_{B1} // R_{B2} \right) \right)} \right]^{-1} \]
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!

\[ A_V \approx -g_m R_C = \frac{-I_C Q R_C}{V_t} \]

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

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

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

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

Gain is practically limited with this supply voltage to around 100
High-gain MOS amplifier

\[ A_V = -g_m \frac{1}{g_0 + G_D} \approx -g_m R_D \]

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

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

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!
High-gain amplifier

This gain is very large (but realistic)!

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?