EE 330
Lecture 31

Basic Amplifiers
Analysis, Operation, and Design
The three basic amplifier types for both MOS and bipolar processes

- Common Emitter
- Common Base
- Common Collector
- Common Source
- Common Gate
- Common Drain

More general models are needed to accommodate biasing, understand performance capabilities, and include effects of loading of the basic structures.

Two-port models are useful for characterizing the basic amplifier structures.

How can the two-port parameters be obtained for these or any other linear two-port networks?
Common Source/ Common Emitter Configurations

\[ R_{in} = \frac{1}{g_\pi} \quad A_{V0} = -\frac{g_m}{g_0} \quad R_0 = \frac{1}{g_0} \]

\[ R_{in} = \infty \quad A_{V0} = -\frac{g_m}{g_0} \quad R_0 = \frac{1}{g_0} \]

In terms of operating point and model parameters:

\[ R_{in} = \frac{\beta V_t}{I_{CQ}} \quad A_{V0} = -\frac{V_{AF}}{V_t} \quad R_0 = \frac{V_{AF}}{I_{CQ}} \]

\[ R_{in} = \infty \quad R_0 = \frac{1}{\lambda I_{DQ}} = \frac{V_{AF}}{I_{DQ}} \]

\[ A_{V0} = -\frac{2}{\lambda V_{EBQ}} = -2 \frac{V_{AF}}{V_{EBQ}} \]

- Input impedance is mid-range (infinite for MOS)
- Voltage Gain is Large and Inverting
- Output impedance is large
- Widely used to build voltage amplifiers
Review from Last Time

Common Source/Common Emitter Configuration

In terms of operating point and model parameters:

- **Input impedance** is mid-range (infinite for MOS)
- **Voltage Gain** is Large and Inverting
- **Output impedance** is mid-range
- Widely used as a voltage amplifier
Common Collector/Common Drain Configurations

For these CC/CD applications (not two-port models for these applications)

\[
A_V = \frac{g_m + g_{m}}{g_m + g_E + \alpha + g_\pi} \quad \text{if } g_s \gg g_e \approx 1
\]

- \( R_{\text{in}} \approx r_{\Pi} + \beta R_E \)
- \( R_0 \approx \frac{R_E}{1 + g_m R_E} \approx \frac{1}{g_m} \)

**In terms of operating point and model parameters:**

\[
A_V \approx \frac{I_{CQ} R_E}{I_{CQ} R_E + V_t} \approx 1 \quad \text{if } I_{CQ} R_s \gg V_t \quad \text{R}_0 \approx \frac{V_t}{I_{CQ}}
\]

- 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

\[
A_V = \frac{g_m}{g_m + g_s + \alpha} \approx 1
\]

- \( R_{\text{in}} = \infty \)
- \( R_0 \approx \frac{R_S}{1 + g_m R_S} \approx \frac{1}{g_m} \)

\[
A_V \approx \frac{2I_{DQ} R_S}{2I_{DQ} R_S + V_{EBO}} \quad \text{if } 2I_{DQ} R_s \gg V_{EBO} \approx 1
\]

- \( R_{\text{in}} = \infty \)
- \( R_0 \approx \frac{V_{EBO} R_S}{V_{EBO} + 2I_{DQ} R_S} \approx \frac{V_{EBO}}{2I_{DQ}} \)
Consider Common Base/Common Gate Two-port Models

Will focus on Bipolar Circuit since MOS counterpart is a special case obtained by setting $g_{\pi}=0$
Two-port model for Common Base Configuration

\[ \begin{align*}
V_{be} & \quad g_{\pi} \\
- & \quad g_{m} V_{be} \\
& \quad g_{o}
\end{align*} \]

\[ \begin{align*}
R_{oX} & \quad A_{V0} V_1 \\
B & \quad A_{V0r} V_2
\end{align*} \]

\[ \{R_{iX}, A_{V0}, A_{V0r} \text{ and } R_{oX}\} \]
Two-Port Models of Basic Amplifiers widely used for Analysis and Design of Amplifier Circuits

Methods of Obtaining Amplifier Two-Port Network

1. \( V_{\text{TEST}} : i_{\text{TEST}} \) Method

2. Write \( V_1 : V_2 \) equations in standard form

\[
V_1 = i_1 R_{\text{IN}} + A_{VR} V_2
\]

\[
V_2 = i_2 R_{O} + A_{V_0} V_1
\]

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches
Two-port model for Common Base Configuration

From KCL

\[ i_1 = v_{1g} + (v_1 - v_2) g_0 + g_m v_1 \]

\[ i_2 = (v_2 - v_1) g_0 - g_m v_1 \]

These can be rewritten as

\[ v_1 = \left( \frac{1}{g_m + g_\pi + g_0} \right) i_1 + \left( \frac{g_0}{g_m + g_\pi + g_0} \right) v_2 \]

\[ v_2 = \left( \frac{1}{g_0} \right) i_2 + \left( 1 + \frac{g_m}{g_0} \right) v_1 \]

It thus follows that:

\[ R_{ix} = \frac{1}{g_m + g_\pi + g_0} \approx \frac{1}{g_m} \]

\[ A_{VOr} = \frac{g_0}{g_m + g_\pi + g_0} \]

\[ A_{V0} = 1 + \frac{g_m}{g_0} \approx \frac{g_m}{g_0} \]

\[ R_{ox} = \frac{1}{g_0} \]
Two-port model for Common Base Configuration

\[ R_{iX} = \frac{1}{g_m + g_\pi + g_0} \approx \frac{1}{g_m} \]

\[ A_{V0r} = \frac{g_0}{g_m + g_\pi + g_0} \approx \frac{g_0}{g_m} \]

\[ A_{V0} = 1 + \frac{g_m}{g_0} \approx \frac{g_m}{g_0} \]

\[ R_{oX} = \frac{1}{g_0} \]
Consider the following CB application

(this is not asking for a two-port model for this CB application – $R_{in}$ and $A_V$ defined for no load on output, $R_o$ defined for short-circuit input)
Consider the following CB application

(this is not asking for a two-port model for this CB application – \( R_{\text{in}} \) and \( A_v \) defined for no load on output, \( R_o \) defined for short-circuit input)

Alternately, this circuit can also be analyzed directly

By KCL at the output node, obtain

\[
(g_C + g_0) V_0 = (g_m + g_0) V_{\text{in}}
\]

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

By KCL at the emitter node, obtain

\[
i_1 = (g_m + g_{\pi} + g_0) V_{\text{in}} - g_0 V_{\text{out}}
\]

\[
R_{\text{in}} = \frac{g_0 + g_C}{g_C (g_m + g_{\pi} + g_0) + g_{\pi} g_0} \approx \frac{1}{g_m}
\]

\[
R_{\text{out}} = \frac{R_C}{1 + g_0 R_C} \approx R_C
\]
Common Base Application

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

\[ A_V \approx g_m R_C \]
\[ R_{\text{in}} \approx \frac{1}{g_m} \]
\[ R_c << r_o \]
\[ R_{\text{out}} \approx R_C \]

\[ A_V \approx \frac{I_{CQ} R_C}{V_t} \]
\[ R_{\text{in}} \approx \frac{V_t}{I_{CQ}} \]
\[ R_c << r_o \]
\[ R_{\text{out}} \approx R_C \]

- 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 Base/Common Gate Application**

(These are not a two-port models)

\[ A_V \approx g_m R_C \]
\[ R_{\text{in}} \approx \frac{1}{g_m} \]
\[ R_{\text{out}} \approx R_C \]

In terms of operating point and model parameters:

\[ A_V \approx \frac{I_{\text{CQ}} R_C}{V_t} \]
\[ R_{\text{in}} \approx \frac{V_t}{I_{\text{CQ}}} \]
\[ R_{\text{out}} \approx \frac{V_{\text{EBQ}}}{2I_{\text{DQ}}} \]

- 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

\[ V_{\text{OUT}} \]

\[ V_{\text{IN}} \]

\[ v_{\text{in}} \]

\[ v_{\text{out}} \]

\[ V_{\text{DD}} \]

\[ V_{\text{BB}} \]

\[ V_{\text{in}} \]

\[ R_C \]

\[ i \]

\[ V_{\text{G}} \]

\[ V_{\text{D}} \]

\[ v_{\text{IN}} \]

\[ v_{\text{OUT}} \]

\[ v_{\text{out}} \]

\[ R_D \]

\[ R_{\text{D}} \]
Common Emitter with Emitter Resistor Configuration

By KCL at two non-grounded nodes

\[
\begin{align*}
\vec{v}_{out} (g_C + g_0) + (\vec{v}_{in} - \vec{v}_E) g_m &= g_0 \vec{v}_E \\
\vec{v}_E (g_E + g_0 + g_\pi) - (\vec{v}_{in} - \vec{v}_E) g_m &= g_0 \vec{v}_{out} + g_\pi \vec{v}_{in}
\end{align*}
\]

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

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

It can also be shown that

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

\[ R_{out} \approx R_C \]

Nearly unilateral (is unilateral if \( g_o = 0 \))
Common Emitter with Emitter Resistor Configuration

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

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

\[ R_{out} \approx R_C \]

(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>Structure</th>
<th>CE/CS</th>
<th>CC/CD</th>
<th>CB/CG</th>
<th>CEwRE/CSwRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJT</td>
<td><img src="image1" alt="BJT Circuit" /></td>
<td><img src="image2" alt="BJT Circuit" /></td>
<td><img src="image3" alt="BJT Circuit" /></td>
<td><img src="image4" alt="BJT Circuit" /></td>
</tr>
<tr>
<td>MOS</td>
<td><img src="image5" alt="MOS Circuit" /></td>
<td><img src="image6" alt="MOS Circuit" /></td>
<td><img src="image7" alt="MOS Circuit" /></td>
<td><img src="image8" alt="MOS Circuit" /></td>
</tr>
</tbody>
</table>

#### Amplifier Gain ($A_V$)
- **CE/CS**
  - $\frac{I_{CQ}R_C}{V_t}$
  - $-2 \frac{I_{DQ}R_D}{V_{EB}}$

- **CC/CD**
  - $\frac{g_m}{g_m + g_E}$
  - $\frac{I_{CQ}R_E}{I_{CQ}R_E + V_t}$
  - $\frac{2I_{DQ}R_E}{2I_{DQ}R_E + V_{EB}}$

- **CB/CG**
  - $g_m R_C$
  - $\frac{I_{CQ}R_C}{V_t}$
  - $\frac{2I_{DQ}R_C}{2I_{DQ}R_E}$

- **CEwRE/CSwRS**
  - $-\frac{R_C}{R_E}$

#### Input Resistance ($R_{in}$)
- **CE/CS**
  - $\frac{\beta V_t}{I_{CQ}}$
  - $\infty$

- **CC/CD**
  - $r_{TT} + \beta R_E$
  - $\beta \left( \frac{V_t}{I_{CQ}} + R_E \right) + \infty$

- **CB/CG**
  - $\frac{V_t}{I_{CQ}}$
  - $\frac{V_{EB}}{2I_{DQ}}$
  - $\beta \left( \frac{V_t}{I_{CQ}} + R_E \right) + \infty$

#### Output Resistance ($R_{out}$)
- **CE/CS**
  - $R_C$
  - $\frac{V_t}{I_{CQ}}$

- **CC/CD**
  - $g_m$
  - $\frac{V_{EB}}{2I_{DQ}}$

- **CB/CG**
  - $R_C$

- **CEwRE/CSwRS**
  - $R_C$

*(not two-port models for the four basic structures)*
Can use these equations only when small signal circuit is EXACTLY like that shown!!
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:CG cascade)
6. Darlington (special CC:CE or CD: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?
Why are we focusing on these basic circuits?

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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
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
Cascaded Amplifiers

Amplifier cascading widely used to enhance gain
Amplifier cascading widely used to enhance other characteristics and/or alter functionality as well

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

If \( R_o \ll R_i \quad R_S \ll R_i \quad R_o \ll R_L \)

\[ A_V \approx A_{V01} A_{V02} \]

- Amplifier cascading widely used to enhance gain
- Amplifier cascading widely used to enhance other characteristics and/or alter functionality as well
  e.g. (\( R_{iN}, \) BW, Power, \( R_O, \) Linearity, Impedance Conversion..)
Cascaded Amplifier Analysis and Operation

Adjacent Stage Coupling Only

- Systematic Methods of Analysis/Design will be Developed

One or more couplings of nonadjacent stages

- Less Common
- Analysis Generally Much More Involved, Use Basic Circuit Analysis Methods
Cascaded Amplifier Analysis and Operation

Adjacent Stage Coupling Only

Case 1: All stages Unilateral

Case 2: One or more stages are not unilateral

• Systematic Methods of Analysis/Design will be Developed
Repeat from earlier discussions on amplifiers

Cascaded Amplifier Analysis and Operation

Case 1: All stages 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

Case 2: One or more stages are not unilateral

- Standard two-port cascade

- Right-to-left nested $R_{inx}, A_{vX}$ approach

- $R_{inx}$ includes effects of all loading
- $AV_X$ is the voltage ratio from input to output of a stage
- $AV_X$’s include all loading
- Can not change any loading without recalculating everything!
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:

\[ A_{V1} = \frac{V_B}{V_A} \approx -g_{m1} \left( R_3 // R_5 // R_{in2} \right) \]

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

\[ A_{V0} = \frac{v_A}{v_{in}} \approx \frac{R_1//R_2 // R_{in1}}{R_S + R_1//R_2 // R_{in1}} \]
Thus we have

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

where

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

\[
\frac{V_B}{V_A} \approx -g_m \left( \frac{R_3//R_5//R_{\text{in2}}}{R_{\text{in1}}} \right)
\]

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

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

\[
R_{\text{in1}} \approx r_{\pi1}
\]
End of Lecture 31