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

Review from Last Time

Characteristics:

- Input impedance is mid-range (infinite for MOS)
- Voltage Gain is Large and Inverting
- Output impedance is large
- Unilateral
- Widely used to build voltage amplifiers
Common Source/Common Emitter Configuration

Review from Last Time

Characteristics:
- 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
- Unilateral
Review from Last Time

Two-port model for Common Collector Configuration

\[ R_{ix} = r_{\pi} \]
\[ A_{V0r} = 1 \]

\[ R_{0X} = \left( \frac{1}{g_m + g_{\pi} + g_o} \right) \approx \frac{1}{g_m} \]
\[ A_{V0} = \left( \frac{g_m + g_{\pi}}{g_m + g_{\pi} + g_o} \right) \approx 1 \]
Common Collector/Common Drain Configurations

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

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

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

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

In terms of operating point and model parameters:

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

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

- Output impedance is low
- \( A_{V0} \) is positive and near 1
- Input impedance is very large

\[ A_V \approx \frac{g_m}{g_m + g_s + g_0} \approx 1 \]

\[ R_{in} = \infty \]

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

\[ R_{in} = \infty \]

- Widely used as a buffer
- Not completely unilateral but output-input transconductance is small
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

\[ V_{be} \]

\[ g_m V_{be} \]

\[ g_{\pi} \]

\[ V_{be} \]

\[ g_m \]

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\[ g_m \]

\[ V_{be} \]

\[ g_{\pi} \]

\[ V_{be} \]
Two-Port Models of Basic Amplifiers widely used for Analysis and Design of Amplifier Circuits

Methods of Obtaining Amplifier Two-Port Network

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

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

\[
V_1 = i_1 R_{IN} + A_{VR} V_2 \\
V_2 = i_2 R_O + A_{V0} V_1
\]

3. Thevenin-Norton Transformations

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

From KCL

\[ i_1 = v_1 g_{\pi} + (v_1 - v_2) g_0 + g_m v_1 \]

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

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:

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

\[ A_{V0R} = \frac{g_0}{g_m + g_{\pi} + g_0} \]

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

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

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

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

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

\[ R_{oX} = \frac{1}{g_0} \]
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 )
Common Base Configuration

Consider the following CB application

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

Alternately, this circuit can also be analyzed directly

By KCL at the output node, obtain

$$(g_C + g_0)v_0 = (g_m + g_0)v_{\text{in}}$$

$A_{\text{V}} = \frac{g_m + g_0}{g_C + g_0} \approx g_m R_C$

By KCL at the emitter node, obtain

$$i_1 = (g_m + g_\pi + g_0)v_{\text{in}} - g_0v_{\text{out}}$$

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

$R_{\text{out}} = R_C / r_0$

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

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

\[ A_V \approx g_m R_C \]

\[ R_{in} \approx \frac{1}{g_m} \]

\[ R_{out} \approx R_C \]

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

\[ R_{in} \approx \frac{V_t}{I_{CQ}} \]

\[ R_{out} \approx R_C \]

Characteristics:

- 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
Characteristics:

- 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

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

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

It can also be shown that

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

It can also be shown that

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

\[ R_{\text{out}} \approx R_C \]

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

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

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

\[ R_{out} \approx R_C \]

(this is not a two-port model)

Characteristics:
- 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></th>
<th>CE/CS</th>
<th>CC/CD</th>
<th>CB/CG</th>
<th>CEwRE/CSwRS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BJT</td>
<td>MOS</td>
<td>BJT</td>
<td>MOS</td>
</tr>
<tr>
<td>$A_V$</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>
</tr>
<tr>
<td>$R_{in}$</td>
<td>$r_{TT}$</td>
<td>$r_{TT} + \beta R_E$</td>
<td>$\frac{g_m}{\beta \left( \frac{V_t}{I_{CQ}} + R_E \right)}$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$R_{out}$</td>
<td>$R_C$</td>
<td>$g_m$</td>
<td>$R_C$</td>
<td>$R_C$</td>
</tr>
</tbody>
</table>

(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?

1. So that we can develop analytical skills
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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
  
  e.g. (R_{iN}, BW, Power, R_O, Linearity, Impedance Conversion,..)

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

If \( R_o << R_i \) \hspace{1 cm} \( R_S << R_i \) \hspace{1 cm} \( R_o << R_L \)

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

- 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
Cascaded Amplifier Analysis and Operation

Case 1: All stages Unilateral

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

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

Case 2: One or more stages are not unilateral

- Standard two-port cascade

Analysis by creating new two-port of entire amplifier quite tedious because of the reverse-gain elements

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

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

Determine the voltage gain of the following circuit in terms of the small-signal parameters of the transistors. Assume Q₁ and Q₂ are operating in the Forward Active region and C₁…C₄ 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:

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

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

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

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

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

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

\[ R_{in1} \approx r_{\pi1} \]
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:

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

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

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

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

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

\[
R_{in1} \approx r_{\pi 1}
\]
End of Lecture 32