EE 330
Lecture 29

Basic amplifier architectures
Review from Last Time

How does \( g_m \) vary with \( I_{DQ} \)?

\[
g_m = \sqrt{\frac{2 \mu C_{OX} W}{L}} \sqrt{I_{DQ}}
\]

Varies with the square root of \( I_{DQ} \)

\[
g_m = \frac{2I_{DQ}}{V_{GSQ} - V_T} = \frac{2I_{DQ}}{V_{EBQ}}
\]

Varies linearly with \( I_{DQ} \)

\[
g_m = \frac{\mu C_{OX} W}{L} (V_{GSQ} - V_T)
\]

Doesn't vary with \( I_{DQ} \)
Amplifier input impedance, output impedance and gain are usually of interest. Why?

Amplifiers can be modeled as a two-port.

Amplifier usually unilateral and thevenin equivalent output port often more standard.
Several different biasing circuits can be used.
Determine the SS voltage gain

\[ V_{OUT} = -g_m V_{BE} R_1 \]

\[ V_{IN} = V_{BE} \]

\[ A_V = -R_1 g_m \]

\[ A_V \approx -\frac{I_{CQ} R_1}{V_t} \]

This basic amplifier structure is widely used and repeated analysis serves no useful purpose.

Have seen this circuit before but will repeat for review purposes.
Determine SS voltage gain

\[ V_{OUT} = -g_m V_{BE} R_2 \]

\[ V_{IN} = V_{BE} + R_1 (V_{BE} [g_\pi + g_m]) \]

\[ A_V = \frac{-R_2 g_m V_{BE}}{V_{BE} + R_1 (V_{BE} [g_\pi + g_m])} = \frac{-R_2 g_m}{1 + R_1 ([g_\pi + g_m])} \]

\[ A_V \approx -\frac{R_2 g_m}{R_1 g_m} = -\frac{R_2}{R_1} \]

Note: This voltage gain is nearly independent of the characteristics of the nonlinear BJT!
Basic Amplifier Structures

- MOS and Bipolar Transistors Both have 3 primary terminals
- MOS transistor has a fourth terminal that is generally considered a parasitic terminal

Transistors as 3-terminal Devices

Small Signal Transistor Models as 3-terminal Devices
Basic Amplifier Structures

Observation:

These circuits considered previously have a terminal (emitter or source) common to the input and output in the small-signal equivalent circuit.
Basic Amplifier Structures

Amplifiers using these devices generally have one terminal common and use remaining terminals as input and output.

Since devices are unilateral, designation of input and output terminals is uniquely determined.

Three different ways to designate the common terminal:

- Source or Emitter termed Common Source or Common Emitter
- Gate or Base termed Common Gate or Common Base
- Drain or Collector termed Common Drain or Common Collector
Basic Amplifier Structures

Can analyze the BJT structures and then obtain the characteristics of The MOS structure by setting $g_{m}=0$
Basic Amplifier Structures

[Diagrams of MOS and BJT transistors with labels: G, S, D, E, B, C]

Common Source or Common Emitter
Common Gate or Common Base
Common Drain or Common Collector

MOS
Common Input Output
S G D
G S D
D G S

BJT
Common Input Output
E B C
B E C
C B E
Characterization of Basic Amplifier Structures

- Observe that the small-signal equivalent of any 3-terminal network is a two-port.
- Thus to characterize any of the 3 basic amplifier structures, it suffices to determine the two-port equivalent network.

How should the two-port characterization be done?

Why is the two-port characterization useful?
Two-Port Characterization of 3-terminal devices

\[ i_1 = y_{11}v_1 + y_{12}v_2 \]
\[ i_2 = y_{21}v_1 + y_{22}v_2 \]

- If unilateral, \( y_{12} = 0 \)
- \( y \)-parameters not widely used

Small Signal Transistor Models as 3-terminal Devices
Unilateral Properties of Basic Amplifier Structures

Both the MOS transistor and the Bipolar transistor are unilateral devices and have a two-port characterization with $y_{12}=0$

Embedding a unilateral device, however, into a circuit does not necessarily guarantee that the resultant circuit is unilateral

Example: The circuit shown in blue is unilateral. It can be shown that the following circuit is characterized by the two-equations given and is thus not unilateral.

\[
\begin{align*}
i_1 &= \left( \frac{g_{11}(g_1+g_2)}{g_1+g_2+g_{11}+g_{21}} \right) v_1 - \left( \frac{g_{11}g_2}{g_1+g_2+g_{11}+g_{21}} \right) v_2 \\
i_2 &= \left( \frac{g_{21}g_1-g_{11}g_2}{g_1+g_2+g_{11}+g_{21}} \right) v_1 + \left( \frac{g_2(g_1+g_{11})}{g_1+g_2+g_{11}+g_{21}} \right) v_2
\end{align*}
\]
Two-Port characterization of unilateral 3-terminal devices

By doing a Norton-Thevenin Transformation of Right-Side Obtain

For notational consistency with prior work, rename parameters in this model
Two-Port characterization of unilateral 3-terminal devices

Widely used characterization strategy

Model parameters are \{R_{iX}, A_{V0} and R_{0X}\}
Example: Use of two-port unilateral model

\[
A_V = \frac{V_{out}}{V_{in}} = \left( \frac{R_{iX}}{R_{iX} + R_S} \right) A_{V0} \left( \frac{R_L}{R_L + R_{OX}} \right)
\]
Example: Use of two-port unilateral models

\[ A_V = \frac{V_{out}}{V_{in}} = \left( \frac{R_{iX1}}{R_{iX1} + R_S} \right) A_{V01} \left( \frac{R_{L1}/R_{iX2}}{R_{L1}/R_{iX2} + R_{0X1}} \right) A_{V02} \left( \frac{R_L}{R_L + R_{0X2}} \right) \]
The three basic amplifier types for both MOS and bipolar processes

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

How can the two-port parameters be obtained for these or any other linear two-port networks?
Determination of two-port unilateral model parameters

A method of obtaining $R_{in}$

\[ i_1 = v_1 \left( \frac{1}{R_{in}} \right) \]
\[ i_2 = v_1 \left( -\frac{A_{v0}}{R_0} \right) + v_2 \left( \frac{1}{R_0} \right) \]

Terminate the output in an open-circuit

\[ R_{in} = \frac{v_{test}}{i_{test}} \]
Determination of two-port unilateral model parameters

A method of obtaining $A_{V0}$

Terminate the output in an open-circuit

$$i_1 = v_1 \left( \frac{1}{R_{in}} \right)$$

$$i_2 = v_1 \left( -\frac{A_{V0}}{R_0} \right) + v_2 \left( \frac{1}{R_0} \right)$$

$$A_{V0} = \frac{v_{out-test}}{v_{test}}$$
Determination of two-port unilateral model parameters

A method of obtaining $R_0$

Terminate the input in a short-circuit

\[
\begin{align*}
    i_1 &= v_1 \left( \frac{1}{R_{\text{in}}} \right) \\
    i_2 &= v_1 \left( -\frac{A_{v_0}}{R_0} \right) + v_2 \left( \frac{1}{R_0} \right)
\end{align*}
\]

\[
R_0 = \frac{v_{\text{test}}}{i_{\text{test}}}
\]
Two-port model for Common Emitter Configuration

It can be readily shown that the common-emitter configuration is unilateral

Thus is is characterized by the parameters \( R_{in}, A_{v0} \) and \( R_0 \)
Two-port model for Common Emitter Configuration

\[ \begin{align*}
&v_{be} \\
&- g_m v_{be} \\
&g_o \\
\end{align*} \]

\[ \{R_{ix}, A_{v0} \text{ and } R_{0x}\} \]
Two-port model for Common Emitter Configuration

To obtain $R_{in}$

\[ R_{iX} = \frac{U_{test}}{i_{test}} \]

\[ R_{iX} = \frac{1}{g_{\pi}} \]

$\{R_{inX}, A_{V0} \text{ and } R_{0X}\}$
Two-port model for Common Emitter Configuration

To obtain $A_{V0}$

\[ A_{V0} = \frac{v_{out-test}}{v_{test}} \]

\[ v_{out-test} = v_{test} \left( -\frac{g_m}{g_0} \right) \]

\[ A_{V0} = -\frac{g_m}{g_0} \]

\{R_{inx}, A_{V0} and R_{0X}\}
Two-port model for Common Emitter Configuration

To obtain $g_0$,

$$R_{0X} = \frac{v_{test}}{i_{test}}$$

$$v_{test} = i_{test} (g_0)$$

$$R_{0X} = \frac{1}{g_0}$$

$\{R_{inX}, A_{V0} and R_{0X}\}$
Two-port model for Common Emitter Configuration

\[ i_1 \]
\[ V_1 \]
\[ R_{\text{in}} \]
\[ A_{V0} V_1 \]
\[ R_0 \]
\[ i_2 \]
\[ V_2 \]

Input impedance is mid-range
Voltage Gain is Large and Inverting
Output impedance is large
Widely used to build voltage amplifiers

\[ R_{iX} = \frac{1}{g_{\pi}} \quad A_{V0} = -\frac{g_m}{g_0} \quad R_{0X} = \frac{1}{g_0} \]

In terms of operating point and model parameters:

\[ R_{iX} = \frac{\beta V_t}{I_{CQ}} \quad A_{V0} = -\beta \quad R_{0X} = \frac{V_{AF}}{I_{CQ}} \]
Consider the following CE application

\[ V_{out} (g_C + g_0) = g_0 A_{V0} V_{in} \]

\[ A_V = \frac{V_{out}}{V_{in}} = \frac{g_0 A_{V0}}{g_0 + g_C} = \frac{-g_m}{g_0 + g_C} \approx -g_m R_C \]

\[ R_{in} = R_{ix} = r_{\pi} \]

\[ R_{out} = R_{ox} // R_C \]

\[ R_{out} = R_{ox} // R_C = \frac{1}{g_0 + g_C} \approx R_C \]
Common Emitter Configuration

Consider the following CE application

This circuit can also be analyzed directly without using 2-port model for CE configuration

\[ V_{out} = -g_m V_{in} \left( \frac{1}{g_0 + g_C} \right) \]

\[ A_v = \frac{V_{out}}{V_{in}} = -\left( \frac{g_m}{g_0 + g_C} \right) \]

\[ g_e \ll g_C \implies A_v \approx -g_m R_C \]

\[ R_{in} = r_{\pi} \]

\[ R_{out} = \frac{1}{g_0 + g_C} \]

\[ g_e \ll g_C \implies R_{out} \approx R_C \]
Common Emitter Configuration

Consider the following CE application

\[ A_v \approx -g_m R_C \]

\[ R_{out} = \frac{1}{g_0 + g_C} \approx R_C \]

\[ R_{in} = r_\pi \]

\[ A_v \approx -\frac{I_{CQ} R_C}{V_t} \]

\[ R_{out} \approx R_C \]

\[ R_{in} = \frac{\beta V_t}{I_{CQ}} \]

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

It can be readily shown that the common-collector and the common base configurations are not unilateral.

Thus a 4-parameter two-port model is needed to characterize these structures.

Or, equivalently
Two-port model for Common Collector Configuration

\[ \{R_{ix}, A_{V0}, A_{V0r} \text{ and } R_{ox}\} \]
Two-port model for Common Collector Configuration

Applying KCL at the input and output node, obtain

\[ i_1 = (v_1 - v_2)g_\pi \]
\[ i_2 = (g_m + g_\pi + g_o)v_1 - (g_m + g_\pi)v_2 \]

These can be rewritten as

\[ v_1 = i_1r_\pi + v_2 \]
\[ v_2 = \left( \frac{1}{g_m + g_\pi + g_o} \right) i_2 + \left( \frac{g_m + g_\pi}{g_m + g_\pi + g_o} \right) v_1 \]

It thus follows that

\[ R_{ix} = r_\pi \]
\[ A_{VOR} = 1 \]
\[ R_{0x} = \left( \frac{1}{g_m + g_\pi + g_o} \right) \]
\[ A_{V0} = \left( \frac{g_m + g_\pi}{g_m + g_\pi + g_o} \right) \]
Two-port model for Common Collector Configuration

\[ \begin{align*}
R_{ix} &= r_\pi \\
A_{vor} &= 1
\end{align*} \]

\[ \begin{align*}
R_{0x} &= \frac{1}{g_m + g_\pi + g_o} \\
A_{v0} &= \frac{g_m + g_\pi}{g_m + g_\pi + g_o}
\end{align*} \]
Consider the following CC application

$$A_V = \frac{g_m + g_\pi}{g_m + g_\pi + g_o} \left( \frac{g_m + g_\pi + g_o}{g_m + g_\pi + g_o + g_E} \right) = \frac{g_m + g_\pi}{g_m + g_\pi + g_o + g_E} \approx \frac{g_m}{g_m + g_E}$$

$$R_{in} = \frac{r_\pi}{1 - \frac{g_o + g_E}{g_m + g_\pi + g_o + g_E}} = r_\pi \frac{g_m + g_\pi + g_o + g_E}{g_o + g_E} \approx r_\pi + \beta R_E$$

$$R_0 \approx \frac{1}{g_m + g_E + g_o + g_\pi} = \frac{1}{g_m + g_E} = \frac{R_E}{1 + g_m R_E} \approx \frac{1}{g_m}$$
Consider the following CC application

Alternately, this circuit can also be analyzed directly

\[
\begin{align*}
\textbf{v}_{\text{out}} (g_E + g_0 + g_\pi) &= \textbf{v}_{\text{in}} g_\pi + g_m \textbf{v}_1 \\
\textbf{v}_{\text{in}} &= \textbf{v}_1 + \textbf{v}_{\text{out}} \\
i_{\text{in}} &= g_\pi (\textbf{v}_{\text{in}} - \textbf{v}_{\text{out}}) \\
\textbf{v}_{\text{out}} (g_m + g_E + g_0 + g_\pi) &= \textbf{v}_{\text{in}} (g_\pi + g_m)
\end{align*}
\]

\[
A_V = \frac{\textbf{v}_{\text{out}} (g_m + g_E + g_0 + g_\pi)}{g_m + g_E + g_0 + g_\pi} = \frac{g_m}{g_m + g_E} \\
\approx \frac{g_m}{g_m + g_E} = \frac{I_{CQ} R_E}{I_{CQ} R_E + V_t} \\
i_{\text{in}} (g_m + g_\pi + g_E + g_0) = g_\pi \textbf{v}_{\text{in}} (g_E + g_0) \\
R_{\text{in}} = r_\pi \frac{g_m + g_\pi + g_0 + g_E}{g_0 + g_E} \approx r_\pi + \beta R_E
\]
Consider the following CC application

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

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

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

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

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

\[ R_0 \approx \frac{V_t}{I_{CQ}} \]

- 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
Two-port model for Common Base Configuration

\[ \begin{align*}
V_{be} & \quad g_{m} V_{be} \\
\frac{1}{R_{iX}} & \quad \frac{1}{R_{0X}} \\
A_{V0} V_{2} & \quad A_{V0} V_{1} \\
\end{align*} \]

\{R_{iX}, A_{V0}, A_{V0r} and R_{0X}\}
Two-port model for Common Base Configuration

From KCL

\[
\begin{align*}
    i_1 &= v_1 g_\pi + (v_1 - v_2) g_0 + g_m v_1 \\
    i_2 &= (v_2 - v_1) g_0 - g_m v_1
\end{align*}
\]

These can be rewritten as

\[
\begin{align*}
    v_1 &= \left( \frac{1}{g_m + g_\pi + g_0} \right) i_1 + \left( \frac{g_0}{g_m + g_\pi + g_0} \right) v_2 \\
    v_2 &= \left( \frac{1}{g_0} \right) i_2 + \left( 1 + \frac{g_m}{g_0} \right) v_1
\end{align*}
\]

It thus follows that:

\[
\begin{align*}
    R_{iX} &= \frac{1}{g_m + g_\pi + g_0} \approx \frac{1}{g_m} \\
    A_{VOR} &= \frac{g_0}{g_m + g_\pi + g_0} \\
    A_{V0} &= 1 + \frac{g_m}{g_0} \approx \frac{g_m}{g_0} \\
    R_{oX} &= \frac{1}{g_0}
\end{align*}
\]
Two-port model for Common Base Configuration

![Diagram of a two-port model for a Common Base configuration](image)

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

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

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

\[
R_{0X} = \frac{1}{g_0}
\]
Consider the following CB application

\[
A_V = A_{V0} \frac{R_C}{R_C + R_{0X}} = \left( \frac{g_m + g_0}{g_0} \right) \left( \frac{g_0}{g_C + g_0} \right) = \frac{g_m + g_0}{g_C + g_0} \approx g_m R_C
\]

\[
R_{in} = \frac{v_{in}}{i_1} = i_1 R_{iX} + A_{V0r} v_{out} \quad \Rightarrow \quad R_{in} = \frac{R_{iX}}{1-A_{V0r} A_V} = \frac{g_0 + g_C}{g_C \left( g_m + g_\pi + g_0 \right) + g_\pi g_0} \approx \frac{1}{g_m}
\]

\[
R_{out} = R_C // R_{0X} \quad \Rightarrow \quad R_{out} = \frac{R_C}{1 + g_0 R_C}
\]
Common Base Configuration

Consider the following CB application

Alternately, this circuit can also be analyzed directly

By KCL at the output node, obtain
\[(g_C + g_0) V_0 = (g_m + g_0) V_{in}\]
\[A_V = \frac{g_m + g_0}{g_C + g_0} \approx g_m R_C\]

By KCL at the emitter node, obtain
\[i_1 = (g_m + g_\pi + g_0) V_{in} - g_0 V_{out}\]
\[R_{in} = \frac{g_0 + g_C}{g_C (g_m + g_\pi + g_0) + g_\pi g_0} \approx \frac{1}{g_m}\]

\[R_{out} = R_C // r_0\]

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

\[ A_V \approx g_m R_C \]
\[ R_{in} \approx \frac{1}{g_m} \]
\[ R_{out} \approx R_C \]
\[ A_V \approx \frac{I_{CQ} R_C}{V_t} \]
\[ R_{in} \approx \frac{V_t}{I_{CQ}} \]
\[ R_{out} \approx R_C \]

- 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