Chapter 5    Bipolar Amplifiers

- 5.1 General Considerations
- 5.2 Operating Point Analysis and Design
- 5.3 Bipolar Amplifier Topologies
- 5.4 Summary and Additional Examples
In an ideal voltage amplifier, the input impedance is infinite and the output impedance zero.

But in reality, input or output impedances depart from their ideal values.
Input/Output Impedances

\[ R_x = \frac{V_x}{i_x} \]

- The figure above shows the techniques of measuring input and output impedances.

Input Impedance Example I

- When calculating input/output impedance, small-signal analysis is assumed.
When calculating I/O impedances at a port, we usually ground one terminal while applying the test source to the other terminal of interest.

With Early effect, the impedance seen at the collector is equal to the intrinsic output impedance of the transistor (if emitter is grounded).
The impedance seen at the emitter of a transistor is approximately equal to one over its transconductance (if the base is grounded).

Three Master Rules of Transistor Impedances

- Rule #1: looking into the base, the impedance is $r_\pi$ if emitter is (ac) grounded.
- Rule #2: looking into the collector, the impedance is $r_o$ if emitter is (ac) grounded.
- Rule #3: looking into the emitter, the impedance is $1/g_m$ if base is (ac) grounded and Early effect is neglected.
Transistors and circuits must be biased because (1) transistors must operate in the active region, (2) their small-signal parameters depend on the bias conditions.

First, DC analysis is performed to determine operating point and obtain small-signal parameters. Second, sources are set to zero and small-signal model is used.
Notation Simplification

Hereafter, the battery that supplies power to the circuit is replaced by a horizontal bar labeled Vcc, and input signal is simplified as one node called Vin.

Example of Bad Biasing

The microphone is connected to the amplifier in an attempt to amplify the small output signal of the microphone. Unfortunately, there’s no DC bias current running thru the transistor to set the transconductance.
Another Example of Bad Biasing

- The base of the amplifier is connected to Vcc, trying to establish a DC bias.
- Unfortunately, the output signal produced by the microphone is shorted to the power supply.

Biasing with Base Resistor

- Assuing a constant value for VBE, one can solve for both IB and IC and determine the terminal voltages of the transistor.
- However, bias point is sensitive to β variations.
Using resistor divider to set VBE, it is possible to produce an IC that is relatively independent of $\beta$ if base current is small.

\[ V_x = \frac{R_2}{R_1 + R_2} V_{CC} \]

\[ I_c = I_s \exp\left(\frac{R_2}{R_1 + R_2} \frac{V_{CC}}{V_T}\right) \]

With proper ratio of $R_1$ and $R_2$, $I_c$ can be insensitive to $\beta$; however, its exponential dependence on resistor deviations makes it less useful.
Emitter Degeneration Biasing

The presence of $R_E$ helps to absorb the error in $V_X$ so $V_{BE}$ stays relatively constant.

This bias technique is less sensitive to $\beta$ ($I_1 \gg I_B$) and $V_{BE}$ variations.

Design Procedure

- Choose an $I_C$ to provide the necessary small signal parameters, $g_m$, $r_{\pi}$, etc.
- Considering the variations of $R_1$, $R_2$, and $V_{BE}$, choose a value for $V_{RE}$.
- With $V_{RE}$ chosen, and $V_{BE}$ calculated, $V_x$ can be determined.
- Select $R_1$ and $R_2$ to provide $V_x$. 
This bias technique utilizes the collector voltage to provide the necessary $V_x$ and $I_B$.

One important characteristic of this technique is that the collector has a higher potential than the base, thus guaranteeing active operation of the transistor.

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**Self-Biasing Design Guidelines**

1. $R_C >> \frac{R_B}{\beta}$
2. $\Delta V_{BE} << V_{CC} - V_{BE}$

- (1) provides insensitivity to $\beta$.
- (2) provides insensitivity to variation in $V_{BE}$.
Summary of Biasing Techniques

PNP Biasing Techniques

- Same principles that apply to NPN biasing also apply to PNP biasing with only polarity modifications.
**Possible Bipolar Amplifier Topologies**

- Three possible ways to apply an input to an amplifier and three possible ways to sense its output.
- However, in reality only three of six input/output combinations are useful.

**Study of Common-Emitter Topology**

- Analysis of CE Core
  - Inclusion of Early Effect
- Emitter Degeneration
  - Inclusion of Early Effect
- CE Stage with Biasing
Common-Emitter Topology

\[ V_{cc} \]
\[ R_c \]
\[ V_{out} \]
\[ Q_1 \]
Output Sensed at Collector

Input Applied to Base

Small Signal of CE Amplifier

\[ V_{in} \]
\[ r_{\pi} \]
\[ v_{\pi} \]
\[ g_m v_{\pi} \]
\[ R_c \]
\[ V_{out} \]

\[ A_v = \frac{v_{out}}{v_{in}} \]
\[ -\frac{v_{out}}{R_c} = g_m v_{\pi} = g_m v_{in} \]
\[ A_v = -g_m R_c \]
Limitation on CE Voltage Gain

Since \( g_m \) can be written as \( I_C/V_T \), the CE voltage gain can be written as the ratio of \( V_{RC} \) and \( V_T \).

\[ |A| = \frac{I_C R_C}{V_T}, \quad |A| = \frac{V_{RC}}{V_T}, \quad |A| < \frac{V_{CC} - V_{BE}}{V_T} \]

- \( V_{RC} \) is the potential difference between \( V_{CC} \) and \( V_{CE} \), and
- \( V_{CE} \) cannot go below \( V_{BE} \) in order for the transistor to be in active region.

Tradeoff between Voltage Gain and Headroom

- \( |A| = \frac{I_C R_C}{V_T} \)
- \( |A| = \frac{V_{RC}}{V_T} \)
- \( |A| < \frac{V_{CC} - V_{BE}}{V_T} \)

- \( \triangle \) Since \( g_m \) can be written as \( I_C/V_T \), the CE voltage gain can be written as the ratio of \( V_{RC} \) and \( V_T \).
- \( V_{RC} \) is the potential difference between \( V_{CC} \) and \( V_{CE} \), and
- \( V_{CE} \) cannot go below \( V_{BE} \) in order for the transistor to be in active region.
When measuring output impedance, the input port has to be grounded so that $V_{in} = 0$. 

\[
R_{in} = \frac{V_X}{i_X} = r_{\pi} \\
R_{out} = \frac{V_X}{i_X} = R_C
\]
Inclusion of Early Effect

Early effect will lower the gain of the CE amplifier, as it appears in parallel with $R_C$. 

\[ A_v = -g_m \left( R_c \parallel r_o \right) \]
\[ R_{\text{out}} = R_c \parallel r_o \]

Intrinsic Gain

As $R_c$ goes to infinity, the voltage gain reaches the product of $g_m$ and $r_o$, which represents the maximum voltage gain the amplifier can have.

The intrinsic gain is independent of the bias current.
Another parameter of the amplifier is the current gain, which is defined as the ratio of current delivered to the load to the current flowing into the input.

For a CE stage, it is equal to $\beta$.

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By inserting a resistor in series with the emitter, we "degenerate" the CE stage.

This topology will decrease the gain of the amplifier but improve other aspects, such as linearity, and input impedance.
Interestingly, this gain is equal to the total load resistance to ground divided by \(1/g_m\) plus the total resistance placed in series with the emitter.

$$A_v = -\frac{g_m R_C}{1 + g_m R_E}$$

$$A_v = -\frac{R_C}{1/g_m + R_E}$$

Emitter Degeneration Example I

The input impedance of \(Q_2\) can be combined in parallel with \(R_E\) to yield an equivalent impedance that degenerates \(Q_1\).
Emitter Degeneration Example II

In this example, the input impedance of $Q_2$ can be combined in parallel with $R_C$ to yield an equivalent collector impedance to ground.

$$A_v = -\frac{R_C \parallel r_{\pi 2}}{\frac{1}{g_{m1}} + R_E}$$

Input Impedance of Degenerated CE Stage

With emitter degeneration, the input impedance is increased from $r_\pi$ to $r_\pi + (\beta+1)R_E$; a desirable effect.
Emitter degeneration does not alter the output impedance in this case. (More on this later.)

At DC the capacitor is open and the current source biases the amplifier.

For ac signals, the capacitor is short and the amplifier is degenerated by $R_E$. 
Example: Design CE Stage with Degeneration as a Black Box

If $g_m R_E$ is much greater than unity, $G_m$ is more linear.

Degenerated CE Stage with Base Resistance
Input/Output Impedances

- $R_{in1}$ is more important in practice as $R_B$ is often the output impedance of the previous stage.

\[ V_A = \infty \]
\[ R_{in1} = r_x + (\beta + 1)R_E \]
\[ R_{in2} = R_B + r_x + (\beta + 1)R_E \]
\[ R_{out} = R_C \]

Emitter Degeneration Example III

\[ A_v = \frac{-(R_c \| R_i)}{1 + R_2 + \frac{R_B}{g_m} \beta + 1} \]
\[ R_{in} = r_x + (\beta + 1)R_2 \]
\[ R_{out} = R_C \| R_1 \]
Emitter degeneration boosts the output impedance by a factor of $1 + g_m (R_E \parallel r_\pi)$. This improves the gain of the amplifier and makes the circuit a better current source.

Two Special Cases

1) $R_E >> r_\pi$

\[
R_{out} \approx r_O (1 + g_m r_\pi) \approx \beta r_O
\]

2) $R_E << r_\pi$

\[
R_{out} \approx (1 + g_m R_E) r_O
\]
This seemingly complicated circuit can be greatly simplified by first recognizing that the capacitor creates an AC short to ground, and gradually transforming the circuit to a known topology.

\[
R_{\text{out}} = R_1 \parallel R_{\text{out1}} \quad \Rightarrow \quad R_{\text{out}} = [1 + g_m (R_2 \parallel r_x)] r_o \quad \Rightarrow \quad R_{\text{out}} = [1 + g_m (R_2 \parallel r_x)] r_o \parallel R_1
\]

Example: Degeneration by Another Transistor

\[
R_{\text{out}} = [1 + g_m (r_{o2} \parallel r_{x1})] r_{o1}
\]

Called a “cascode”, the circuit offers many advantages that are described later in the book.
Study of Common-Emitter Topology

- Analysis of CE Core
  Inclusion of Early Effect
- Emitter Degeneration
  Inclusion of Early Effect
- CE Stage with Biasing

Bad Input Connection

Since the microphone has a very low resistance that connects from the base of \( Q_1 \) to ground, it attenuates the base voltage and renders \( Q_1 \) without a bias current.
Use of Coupling Capacitor

- Capacitor isolates the bias network from the microphone at DC but shorts the microphone to the amplifier at higher frequencies.

DC and AC Analysis

- Coupling capacitor is open for DC calculations and shorted for AC calculations.

\[ A_i = -g_m (R_C \parallel r_D) \]
\[ R_{in} = r_e \parallel R_B \]
\[ R_{out} = R_C \parallel r_D \]
Bad Output Connection

Since the speaker has an inductor, connecting it directly to the amplifier would short the collector at DC and therefore push the transistor into deep saturation.

Still No Gain!!!

In this example, the AC coupling indeed allows correct biasing. However, due to the speaker’s small input impedance, the overall gain drops considerably.
CE Stage with Biasing

\[ A_v = -g_m (R_E \parallel r_o) \]
\[ R_{in} = r_x \parallel R_1 \parallel R_2 \]
\[ R_{out} = R_C \parallel r_o \]

CE Stage with Robust Biasing

\[ A_v = -\frac{R_c}{\frac{1}{g_m} + R_E} \]
\[ R_{in} = [r_x + (\beta+1)R_E] \parallel R_1 \parallel R_2 \]
\[ R_{out} = R_C \]
Removal of Degeneration for Signals at AC

- Capacitor shorts out $R_E$ at higher frequencies and removes degeneration.

Complete CE Stage

Thevenin model of the input:

$$R_{Thv} = R_C \parallel R_L$$

Gain equation:

$$A_v = \frac{-g_m R_C}{\frac{1}{\beta + 1} + R_g + R_C \parallel R_F \parallel R_L \parallel R_E + R_F + R}$$
Common Base (CB) Amplifier

In common base topology, where the base terminal is biased with a fixed voltage, emitter is fed with a signal, and collector is the output.
**CB Core**

The voltage gain of CB stage is $g_m R_C$, which is identical to that of CE stage in magnitude and opposite in phase.

**Tradeoff between Gain and Headroom**

To maintain the transistor out of saturation, the maximum voltage drop across $R_C$ cannot exceed $V_{CC} - V_{BE}$. 

$$A_v = \frac{I_C}{V_T} R_C = \frac{V_{CC} - V_{BE}}{V_T}$$

- **CB Core**
- **Tradeoff between Gain and Headroom**
The input impedance of CB stage is much smaller than that of the CE stage.
To avoid “reflections”, need impedance matching.

CB stage’s low input impedance can be used to create a match with 50 Ω.

Output Impedance of CB Stage

The output impedance of CB stage is similar to that of CE stage.
With an inclusion of a source resistor, the input signal is attenuated before it reaches the emitter of the amplifier; therefore, we see a lower voltage gain.
This is similar to CE stage emitter degeneration; only the phase is reversed.

An antenna usually has low output impedance; therefore, a correspondingly low input impedance is required for the following stage.