Chapter 5 Bipolar Amplifiers

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# Bipolar Amplifiers

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

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

$$R_{out} = r_o$$
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.
DC Analysis vs. Small-Signal Analysis

- 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 $V_{\text{in}}$. 
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 $V_{cc}$, trying to establish a DC bias.
- Unfortunately, the output signal produced by the microphone is shorted to the power supply.
**Biasing with Base Resistor**

- Assuming a constant value for $V_{BE}$, one can solve for both $I_B$ and $I_C$ and determine the terminal voltages of the transistor.
- However, bias point is sensitive to $\beta$ variations.

\[
I_B = \frac{V_{CC} - V_{BE}}{R_B}, \quad I_C = \beta \frac{V_{CC} - V_{BE}}{R_B}
\]
Using resistor divider to set $V_{BE}$, it is possible to produce an $I_C$ that is relatively independent of $\beta$ if base current is small.

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

\[
I_C = I_S \exp\left(\frac{R_2}{R_1 + R_2} \frac{V_{CC}}{V_T}\right)
\]
Accounting for Base Current

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.

$$I_C = I_s \exp \left( \frac{V_{Th} - I_B R_{Th}}{V_T} \right)$$
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.
Self-Biasing Design Guidelines

(1) \( R_C \gg \frac{R_B}{\beta} \)

(2) \( \Delta V_{BE} \ll V_{CC} - V_{BE} \)

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

Sensitivity to $\beta$

Sensitive to Resistor Error

Always in Active Mode

$V_{CC}$

$R_B$, $R_C$, $Q_1$

$V_{CC}$

$R_1$, $R_C$, $Q_1$

$I_1$, $V_{RE}$

$R_1$, $R_2$, $R_E$, $V_{RE}$

$V_{CC}$

$R_B$, $R_C$, $Q_1$
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

Input Applied to Base

Output Sensed at Collector

$V_{cc}$

$R_C$

$V_{in}$

$V_{out}$

$Q_1$
Small Signal of CE Amplifier

\[ A_v = \frac{V_{out}}{V_{in}} \]

\[ -\frac{V_{out}}{R_C} = g_m v_\pi = g_m v_{in} \]

\[ A_v = -g_m R_C \]
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 $V_T$.

$V_{RC}$ 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) 800 mV

(b) 800 mV

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When measuring output impedance, the input port has to be grounded so that \( V_{in} = 0 \).
CE Stage Trade-offs

Voltage Headroom (Swings)

Voltage Gain

$g_m$ 

Input Impedance

$\frac{\beta}{g_m}$

Output Impedance

$R_c$

$R_c$
Inclusion of Early Effect

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

\[ A_v = -g_m (R_C \parallel r_o) \]
\[ R_{out} = R_C \parallel r_o \]
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.

\[
A_v = -g_m r_o
\]

\[
|A_v| = \frac{V_A}{V_T}
\]
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 $\beta$. 

\[ A_I = \frac{i_{out}}{i_{in}} \]

\[ A_I \bigg|_{CE} = \beta \]
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.

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

$$A_v = -\frac{R_C}{1 + \frac{1}{g_m} + R_E}$$
The input impedance of $Q_2$ can be combined in parallel with $R_E$ to yield an equivalent impedance that degenerates $Q_1$.

$$A_v = -\frac{R_C}{\frac{1}{g_{m1}} + R_E \parallel r_{\pi2}}$$
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.

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

\[V_A = \infty\]
\[v_X = r_\pi i_X + R_E (1 + \beta) i_X\]
\[R_{in} = \frac{v_X}{i_X} = r_\pi + (\beta + 1)R_E\]
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

![Circuit Diagram](image)

- If \(g_m \cdot R_E\) is much greater than unity, \(G_m\) is more linear.

\[
\begin{align*}
V_A &= \infty \\
i_{out} &= g_m \frac{v_{in}}{1 + (r_\pi^{-1} + g_m)R_E} \\
G_m &= \frac{i_{out}}{v_{in}} \approx \frac{g_m}{1 + g_m R_E}
\end{align*}
\]

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Degenerated CE Stage with Base Resistance

\[ V_A = \infty \]

\[ \frac{v_{out}}{v_{in}} = \frac{v_A}{v_{in}} \cdot \frac{v_{out}}{v_A} \]

\[ v_{out} = \frac{-\beta R_C}{v_{in}} \cdot r_\pi + (\beta + 1)R_E + R_B \]

\[ A_v \approx \frac{1}{1 + R_E + \frac{R_B}{\beta + 1}} \]
Input/Output Impedances

\[ V_A = \infty \]
\[ R_{in1} = r_\pi + (\beta + 1)R_E \]
\[ R_{in2} = R_B + r_\pi^2 + (\beta + 1)R_E \]
\[ R_{out} = R_C \]

- \( R_{in1} \) is more important in practice as \( R_B \) is often the output impedance of the previous stage.
Emitter Degeneration Example III

\[ A_v = \frac{- (R_C \parallel R_1)}{1 + R_2 + \frac{R_B}{\beta + 1}} \]

\[ R_{in} \Rightarrow (\beta + 1)R_2 \]

\[ R_{out} = R_C \parallel R_1 \]
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) \( R_E \gg r_\pi \)
   \[ R_{out} \approx r_O (1 + g_m r_\pi) \approx \beta r_O \]

2) \( R_E \ll r_\pi \)
   \[ R_{out} \approx (1 + g_m R_E) r_O \]
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.

\[ R_{\text{out}} = R_1 \parallel R_{\text{out1}} \iff R_{\text{out1}} = [1 + g_m (R_2 \parallel r_{\pi})] r_o \iff R_{\text{out}} = [1 + g_m (R_2 \parallel r_{\pi})] r_o \parallel R_1 \]
Example: Degeneration by Another Transistor

Called a “cascode”, the circuit offers many advantages that are described later in the book.

\[ R_{out} = |1 + g_{m1}(r_{o2} \parallel r_{\pi1})|r_{o1} \]
Study of Common-Emitter Topology

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

\[ A_v = -g_m (R_C \parallel r_O) \]

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

\[ R_{out} = R_C \parallel r_O \]
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.
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

\[ A_v = -g_m (R_C \parallel r_O) \]

\[ R_{in} = r_\pi \parallel R_1 \parallel R_2 \]

\[ R_{out} = R_C \parallel r_O \]
CE Stage with Robust Biasing

\[ A_v = \frac{-R_C}{\left(1 + R_E\right) g_m} \]

\[ R_{in} = \left[r_\pi + (\beta + 1)R_E\right] || R_1 || R_2 \]

\[ R_{out} = R_C \]
Removal of Degeneration for Signals at AC

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

\[ A_v = -g_m R_C \]
\[ R_{in} = r_\pi \parallel R_1 \parallel R_2 \]
\[ R_{out} = R_C \]
**Complete CE Stage**

\[
A_v = \frac{- R_C \parallel R_L}{\frac{1}{1 + R_E} + \frac{R_s \parallel R_1 \parallel R_2}{g_m \beta + 1}}
\]
Summary of CE Concepts

$A_v = -g_m R_C$

Headroom

Gain

$R_{in}$

$R_{out}$

$A_v = -g_m (R_C \parallel r_O)$

$A_v \cdot R_{in}$

$R_{out}$

$R_E$

$C_1$

$R_1$

$R_2$

$R_E$

$C_2$

$Q_1$

$R_C$

$R_1$

$R_2$
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.
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.
To maintain the transistor out of saturation, the maximum voltage drop across $R_C$ cannot exceed $V_{CC} - V_{BE}$.

\[
A_v = \frac{I_C}{V_T} \cdot R_C = \frac{V_{CC} - V_{BE}}{V_T}
\]
Simple CB Example

\[ A_v = g_m R_C = 17.2 \]
\[ R_1 = 22.3 \text{K}\Omega \]
\[ R_2 = 67.7 \text{K}\Omega \]
The input impedance of CB stage is much smaller than that of the CE stage.

\[ R_{in} = \frac{1}{g_m} \]
To avoid “reflections”, need impedance matching.

CB stage’s low input impedance can be used to create a match with 50 Ω.
The output impedance of CB stage is similar to that of CE stage.

\[ R_{out} = r_o \parallel R_C \]
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.

\[ A_v = \frac{R_C}{1 + \frac{R_s}{g_m}} \]
An antenna usually has low output impedance; therefore, a correspondingly low input impedance is required for the following stage.
The output impedance of CB stage is equal to $R_C$ in parallel with the impedance looking down into the collector.

\[
R_{\text{out1}} = \left[1 + g_m (R_E \parallel r_\pi)\right] r_O + (R_E \parallel r_\pi)
\]

\[
R_{\text{out}} = R_C \parallel R_{\text{out1}}
\]
The output impedances of CE, CB stages are the same if both circuits are under the same condition. This is because when calculating output impedance, the input port is grounded, which renders the same circuit for both CE and CB stages.
The statement “CB output impedance is higher than CE output impedance” is flawed.
With an addition of base resistance, the voltage gain degrades.
Comparison of CE and CB Stages with Base Resistance

- The voltage gain of CB amplifier with base resistance is exactly the same as that of CE stage with base resistance and emitter degeneration, except for a negative sign.
The input impedance of CB with base resistance is equal to \(1/g_m\) plus \(R_B\) divided by \((\beta+1)\). This is in contrast to degenerated CE stage, in which the resistance in series with the emitter is multiplied by \((\beta+1)\) when seen from the base.
Input Impedance Seen at Emitter and Base

\[ \frac{1}{g_m} + \frac{R_B}{\beta + 1} \]

\[ r_\pi + (\beta + 1) R_E \]
To find the $R_X$, we have to first find $R_{eq}$, treat it as the base resistance of $Q_2$ and divide it by $(\beta+1)$.

$$R_X = \frac{1}{g_{m2}} + \frac{1}{\beta+1} \left[ \frac{1}{g_{m1}} + \frac{R_B}{\beta+1} \right]$$
Bad Bias Technique for CB Stage

- Unfortunately, no emitter current can flow.
In haste, the student connects the emitter to ground, thinking it will provide a DC current path to bias the amplifier. Little did he/she know that the input signal has been shorted to ground as well. The circuit still does not amplify.
Proper Biasing for CB Stage

\[ R_{in} = \frac{1}{g_m} \parallel R_E \]

\[ \frac{V_{out}}{V_{in}} = \frac{1}{1 + (1 + g_m R_E) R_S} g_m R_C \]
The reduction of input impedance due to $R_E$ is bad because it shunts part of the input current to ground instead of to $Q_1$ (and $R_c$).
Resistive divider lowers the gain.

To remedy this problem, a capacitor is inserted from base to ground to short out the resistor divider at the frequency of interest.
For the circuit shown above, $R_E >> 1/g_m$.

- $R_1$ and $R_2$ are chosen so that $V_b$ is at the appropriate value and the current that flows thru the divider is much larger than the base current.
- Capacitors are chosen to be small compared to $1/g_m$ at the required frequency.
Emitter Follower (Common Collector Amplifier)

Input Applied to Base

Output Sensed at Emitter

$V_{in}$

$Q_1$

$V_{cc}$

$V_{out}$

$R_E$
When the input is increased by $\Delta V$, output is also increased by an amount that is less than $\Delta V$ due to the increase in collector current and hence the increase in potential drop across $R_E$.

However the absolute values of input and output differ by a $V_{BE}$. 

$\Delta V_{in}$ 

$\Delta V_{out}$
As shown above, the voltage gain is less than unity and positive.

\[
V_A = \infty
\]

\[
v_{out} = \frac{1}{1 + \frac{r_{\pi}}{\beta + 1} \cdot \frac{1}{R_E}} \approx \frac{R_E}{R_E + \frac{1}{g_m}}
\]
The voltage gain is unity because a constant collector current ($= I_1$) results in a constant $V_{BE}$, and hence $V_{out}$ follows $V_{in}$ exactly.

\[ V_A = \infty \]
\[ A_v = 1 \]
Analysis of Emitter Follower as a Voltage Divider

\[ V_{A} = \infty \]
Emitter Follower with Source Resistance

\[ V_{in} \quad \text{to} \quad V_{out} \]

\[ V_{out} = \frac{V_{in}}{R_E + \frac{R_S}{\beta + 1} g_m} \]

\[ V_A = \infty \]

\[ \frac{1}{g_m} + \frac{R_S}{\beta + 1} \]
The input impedance of emitter follower is exactly the same as that of CE stage with emitter degeneration. This is not surprising because the input impedance of CE with emitter degeneration does not depend on the collector resistance.
Since the emitter follower increases the load resistance to a much higher value, it is suited as a buffer between a CE stage and a heavy load resistance to alleviate the problem of gain degradation.
Emitter follower lowers the source impedance by a factor of \( \beta + 1 \), improving driving capability.
Emitter Follower with Early Effect

Since $r_o$ is in parallel with $R_E$, its effect can be easily incorporated into voltage gain and input and output impedance equations.

$$A_v = \frac{R_E \parallel r_O}{R_E \parallel r_O + \frac{R_s}{\beta + 1} + \frac{1}{g_m}}$$

$$R_{in} = r_x + (\beta + 1)(R_E \parallel r_O)$$

$$R_{out} = \frac{R_s}{\beta + 1} + \frac{1}{g_m} \parallel R_E \parallel r_O$$
There is a current gain of \((\beta+1)\) from base to emitter.

Effectively speaking, the load resistance is multiplied by \((\beta+1)\) as seen from the base.
A biasing technique similar to that of CE stage can be used for the emitter follower.

Also, $V_b$ can be close to $V_{cc}$ because the collector is also at $V_{cc}$. 
By putting a constant current source at the emitter, the bias current, $V_{BE}$, and $I_B R_B$ are fixed regardless of the supply value.
The three amplifier topologies studied so far have different properties and are used on different occasions.

- CE and CB have voltage gain with magnitude greater than one, while follower’s voltage gain is at most one.
Amplifier Example I

The keys in solving this problem are recognizing the AC ground between $R_1$ and $R_2$, and Thevenin transformation of the input network.

$\frac{v_{out}}{v_{in}} = - \frac{R_2 \parallel R_C}{R_1 \parallel R_S + \frac{1}{g_m} + R_E} \cdot \frac{R_1}{R_1 + R_S}$

$\beta + 1$
Amplifier Example II

Again, AC ground/short and Thevenin transformation are needed to transform the complex circuit into a simple stage with emitter degeneration.

\[
\frac{v_{out}}{v_{in}} = - \frac{R_C}{R_S \| R_1 + \frac{1}{\beta + 1} g_m R_1 + R_2} \cdot \frac{R_1}{R_1 + R_S}
\]

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The key for solving this problem is first identifying $R_{eq}$, which is the impedance seen at the emitter of $Q_2$ in parallel with the infinite output impedance of an ideal current source. Second, use the equations for degenerated CE stage with $R_E$ replaced by $R_{eq}$.

$$R_{in} = r_{\pi 1} + R_1 + r_{\pi 2}$$

$$A_v = \frac{- R_C}{1 + \frac{R_1}{g_{m1}} + \frac{1}{\beta + 1} + \frac{1}{g_{m2}}}$$
The key for solving this problem is recognizing that \( C_B \) at frequency of interest shorts out \( R_2 \) and provide a ground for \( R_1 \).

\( R_1 \) appears in parallel with \( R_C \) and the circuit simplifies to a simple CB stage.

\[
A_v = \frac{R_C \parallel R_1}{R_S + \frac{1}{g_m}}
\]
The key for solving this problem is recognizing the equivalent base resistance of $Q_1$ is the parallel connection of $R_E$ and the impedance seen at the emitter of $Q_2$. The formula for $R_{in}$ is:

$$R_{in} = \frac{1}{\beta + 1} \left( \frac{R_B}{\beta + 1} + \frac{1}{g_{m2}} \right) \parallel \frac{1}{g_{m1}} + \frac{1}{g_{m1}}$$
The key in solving this problem is recognizing a DC supply is actually an AC ground and using Thevenin transformation to simplify the circuit into an emitter follower.

\[
\begin{align*}
\frac{v_{out}}{v_{in}} &= \frac{R_E \parallel R_2 \parallel r_O}{R_E \parallel R_2 \parallel r_O} \cdot \frac{R_1}{R_1 + R_S} \\
R_{out} &= \frac{R_S \parallel R_1}{\beta + 1} + \frac{1}{g_m} \parallel R_E \parallel R_2 \parallel r_O
\end{align*}
\]
Impedances seen at the emitter of $Q_1$ and $Q_2$ can be lumped with $R_C$ and $R_E$, respectively, to form the equivalent emitter and collector impedances.

\[
R_{in} = r_{\pi 1} + (\beta + 1) \left( R_E + \frac{R_{B1}}{\beta + 1} + \frac{1}{g_{m2}} \right)
\]

\[
R_{out} = R_C + \frac{R_{B2}}{\beta + 1} + \frac{1}{g_{m3}}
\]

\[
A_v = - \frac{R_C + \frac{R_{B2}}{\beta + 1} + \frac{1}{g_{m3}}}{\frac{R_{B1}}{\beta + 1} + \frac{1}{g_{m2}} + \frac{1}{g_{m1}}}
\]
In practical op amps, the output resistance is not zero. It can be seen from the closed loop gain that the nonzero output resistance increases the gain error.
Many design problems are presented at the end of the chapter to study the effects of finite loop gain, restrictions on peak to peak swing to avoid slewing, and how to design for a certain gain error.