ANNOUNCEMENTS

• MIDTERM #1 will be held in class on Thursday, October 11
  – Review session will be held on Friday, October 5
• MIDTERM #2 will be held in class on Tuesday, November 13

OUTLINE

• BJT Amplifiers (cont’d)
  – Biasing
  – Amplifier topologies
  – Common-emitter topology

Reading: Chapter 5.1.2-5.3.1
Biasing of BJT

• Transistors must be biased because
  1. They must operate in the active region, and
  2. Their small-signal model parameters are set by the bias conditions.
DC Analysis vs. Small-Signal Analysis

• Firstly, DC analysis is performed to determine the DC operating point and to obtain the small-signal model parameters.

• Secondly, independent sources are set to zero and the small-signal model is used.
Simplified Notation

- Hereafter, the voltage source that supplies power to the circuit is replaced by a horizontal bar labeled $V_{CC}$, and input signal is simplified as one node labeled $v_{in}$.

\[ \text{Diagram} \]
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 is no DC bias current running through the transistor to set the transconductance.

\[ V_{in} = 20 \text{ mV} \]

\[ V_{C+V_c} \]

\[ I_c = I_S e^{\frac{V_{in}}{V_T}} \]

If \( I_S = 6 \times 10^{-16} \text{ A} \), then

\[ I_c = 1.29 \times 10^{-15} \text{ A} \]

\[ V_c = -I_c R_c = 1.29 \times 10^{-12} \text{ V} \] (small!)
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.

$$V_{CC}$$

$R_C \approx 1 \, k\Omega$

$Q_1$

Small-signal input voltage

$V_{in} = 0 \, V$
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, the bias point is sensitive to $\beta$ variations.

\[ I_B = \frac{V_{CC} - V_{BE}}{R_B} \]

Guess $V_{BE} = 0.8V \rightarrow I_B = \frac{V_{CC} - 0.8}{R_B}$

Calculate $V_{BE} = V_T \ln \frac{I_C}{I_S}$. Iterate to find consistent solution.

Check to make sure BJT is in active mode:

\[ V_Y = V_{CC} - I_C R_C \leq \text{want } V_Y \text{ to be } > V_X \]
Improved Biasing: Resistive Divider

- Using a resistive divider to set $V_{BE}$, it is possible to produce an $I_C$ that is relatively insensitive to variations in $\beta$, if the base current is small.

$$V_x \approx \frac{R_2}{R_1 + R_2} V_{CC} \quad \text{if} \quad I_B \ll I_I$$

$$I_C = I_S e^{V_{BE}/V_T} = I_S e^{(R_2/(R_1 + R_2))V_{CC}/V_T}$$

$V_{CC}$ is sensitive to variations in $R_1||R_2$.
Accounting for Base Current

- With a proper ratio of $R_1$ to $R_2$, $I_C$ can be relatively insensitive to $\beta$. However, its exponential dependence on $R_1//R_2$ makes it less useful.

$$\frac{R_1R_2}{R_1+R_2}$$
Emitter Degeneration Biasing

- $R_E$ helps to "absorb" the change in $V_X$ so that $V_{BE}$ stays relatively constant.
- This bias technique is less sensitive to $\beta$ (if $I_1 >> I_B$) and $V_{BE}$ variations.

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

\[ I_1 >> I_B \quad \text{(at least 10X larger)} \]

\[ V_{RE} = V_X - V_{BE} \]

\[ T = \frac{V_{RE}}{R_E} \]

\[ I_C = I_B + I_C \approx I_C \]

\[ V_{RE} >> \text{Variations in } V_X \text{ and } V_{BE} \]
Bias Circuit Design Procedure

1. Choose a value of $I_C$ to provide the desired small-signal model parameters: $g_m$, $r_\pi$, etc.

   \[ g_m = \frac{I_C}{V_T}, \quad r_\pi = \frac{\beta}{g_m} \]

2. Considering the variations in $R_1$, $R_2$, and $V_{BE}$, choose a value for $V_{RE}$. \( V_{RE} \approx \frac{I_C}{R_E} \), e.g., 200 mV → determine $R_E$

3. With $V_{RE}$ chosen, and $V_{BE}$ calculated, $V_x$ can be determined.

   \[ V_{BE} = V_T \ln \frac{I_C}{I_S} \quad V_x = V_{RE} + V_{BE} \]

4. Select $R_1$ and $R_2$ to provide $V_x$. \( V_x = \frac{R_1}{R_1 + R_2} V_{CC} \)

   and $I_I \gg I_B$, choose $R_C$ to guarantee active mode operation.
Self-Biasing Technique

- This bias technique utilizes the collector voltage to provide the necessary $V_x$ and $I_B$.
- One important characteristic of this approach is that the collector has a higher potential than the base, thus guaranteeing active-mode operation of the BJT.

\[ V_{BE} = V_T \log\left(\frac{\beta I_B}{I_s}\right) \]

\[ V_y = V_{CC} - I_x R_C \quad (1) \]

\[ V_y = V_{BE} + I_B R_B \]

\[ I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B} \approx \frac{V_{CC} - V_{BE}}{R_C} \]
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

- **Sensitive to $\beta$**

- **Sensitive to Resistor Error**

- **Always in Active Mode**
PNP BJT Biasing Techniques

- The same principles that apply to NPN BJT biasing also apply to PNP BJT biasing, with only voltage and current polarity modifications.
Possible BJT Amplifier Topologies

- There are 3 possible ways to apply an input to an amplifier and 3 possible ways to sense its output.
- In practice, only 3 out of the possible 6 input/output combinations are useful.
Common-Emitter (CE) Topology
Small Signal of CE Amplifier

\[ v_{in} = v_{\pi} \]

\[ V_{out} = -\left( g_m v_{\pi} \right) R_C \]

Voltage gain \( A_v \equiv \frac{V_{out}}{V_{in}} = -g_m R_C \)
Limitation on CE Voltage Gain

- Since $g_m = I_C/V_T$, the CE voltage gain can be written as a function of $V_{RC}$, where $V_{RC} = V_{CC} - V_{CE}$.
- $V_{CE}$ should be larger than $V_{BE}$ for the BJT to be operating in active mode.

\[ |A_v| = \frac{I_C R_C}{V_T} = \frac{V_{RC}}{V_T} \]

\[ V_{RC} < V_{CC} - V_{BE} \]
Voltage-Gain / Headroom Tradeoff

(a) $V_{cc}$

(b) $V_C(t)$

should be greater than $V_{BE}$ to ensure active mode operation.
I/O Impedances of CE Stage

- When measuring output impedance, the input port has to be grounded so that \( v_{\text{in}} = 0 \).

\[
R_{\text{in}} = \frac{v_X}{i_X} = r_\pi \\
R_{\text{out}} = \frac{v_X}{i_X} = R_C
\]
CE Stage Design Trade-offs

Voltage Headroom (Swings)

$g_m$

Voltage Gain

$-g_m R_C$

Input Impedance

$\frac{\beta}{g_m}$

Output Impedance

$R_C$

(larger is better)

(smaller is better)
Inclusion of the Early Effect

- The Early effect results in reduced voltage gain of the CE amplifier.

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

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

\( R_C r_O < R_C \), approaches \( R_C \) if \( r_O \gg R_C \)
Intrinsic Gain

- As $R_C$ goes to infinity, the voltage gain approaches its maximum possible value, $g_m \times r_o$, which is referred to as the *intrinsic gain*. Transistor "figure of merit."
- The intrinsic gain is independent of the bias current:

$$A_v \equiv -g_m r_o = -\left(\frac{I_C}{V_T}\right)\left(\frac{V_A}{I_c}\right)$$

$$|A_v| = \frac{V_A}{V_T} \quad \text{independent of } I_c$$
Current Gain, $A_I$

- The **current gain** is defined as the ratio of current delivered to the load to current flowing into the input.
- For a CE stage, it is equal to $\beta$.

$$
A_I = \frac{i_{out}}{i_{in}}
$$

$$
A_I \bigg|_{CE} = \beta = \frac{i_c}{i_b}
$$