Introduction to Amplifiers

- Amplifiers: transistors biased in the flat-part of the i-v curves
  - BJT: forward-active region
  - MOSFET: saturation region
- In these regions, transistors can provide high voltage, current and power gains
- Bias is provided to stabilize the operating point (the Q-Point) in the desired region of operation
- Q-point also determines
  - Small-signal parameters of transistor
  - Voltage gain, input resistance, output resistance
  - Maximum input and output signal amplitudes
  - Power consumption
Transistor Amplifiers
BJT Amplifier Concept

The BJT is biased in the active region by dc voltage source $V_{BE}$. e.g., Q-point is set at $(I_C, V_{CE}) = (1.5 \, mA, 5 \, V)$ with $I_B = 15 \, \mu A$ ($\beta_F = 100$)

Total base-emitter voltage is: $v_{BE} = V_{BE} + v_{be}$

Collector-emitter voltage is: $v_{CE} = V_{CC} - i_C R_C$ This is the load line equation.

Transistor Amplifiers
BJT Amplifier (cont.)

If changes in operating currents and voltages are small enough, then $I_C$ and $V_{CE}$ waveforms are undistorted replicas of the input signal.

A small voltage change at the base causes a large voltage change at collector. Voltage gain is given by:

$$A_v = \frac{V_{CE}}{V_{BE}} = 1.65 \angle 180^\circ = 206 \angle 180^\circ = -206$$

Minus sign indicates $180^\circ$ phase shift between the input and output signals.

8 mV peak change in $v_{BE}$ gives 5 mA change in $I_B$ and 0.5 mA change in $I_C$.

0.5 mA change in $I_C$ produces a 1.65 V change in $V_{CE}$. 
### MOSFET Amplifier Concept

MOSFET is biased in active region by dc voltage source $V_{GS}$. E.g., Q-point is set at $(I_D, V_{DS}) = (1.56 \, mA, 4.8 \, V)$ with $V_{GS} = 3.5 \, V$.

Total gate-source voltage is: $v_{GS} = V_{GS} + v_{gs}$

1 $V_{PP}$ change in $v_{GS}$ yields 1.25 $mA_{PP}$ change in $i_D$ and a 4 $V_{PP}$ change in $v_{DS}$.

### Coupling and Bypass Capacitors

- Capacitors are designed to provide negligible impedance at frequencies of interest and provide open circuits at dc.
- $C_1$ and $C_2$ are low impedance coupling capacitors or dc blocking capacitors whose reactance at the signal frequency is designed to be negligible.
- $C_3$ is a bypass capacitor that provides a low impedance path for ac current from emitter to ground, thereby removing $R_E$ (required for good Q-point stability) from the circuit when ac signals are considered.
Transistor Amplifiers
dc and ac Analysis – Two Step Analysis

• dc analysis:
  – Find dc equivalent circuit by replacing all capacitors by open circuits and inductors by short circuits.
  – Find Q-point from dc equivalent circuit by using appropriate large-signal transistor model.

• ac analysis:
  – Find ac equivalent circuit by replacing all capacitors by short circuits, inductors by open circuits, dc voltage sources by ground connections and dc current sources by open circuits.
  – Replace transistor by its small-signal model
  – Use small-signal ac equivalent to analyze ac characteristics of amplifier.
  – Combine end results of dc and ac analysis to yield total voltages and currents in the network.

Transistor Amplifiers
dc Equivalent Circuit for BJT Amplifier

• All capacitors in the original amplifier circuit are replaced by open circuits, disconnecting $v_I$, $R_I$, and $R_3$ from circuit.
Transistor Amplifiers

ac Equivalent Circuit for BJT Amplifier

\[ R_B = R_1 \parallel R_2 = 100 \Omega \parallel 300 \Omega \]
\[ R = R_1 \parallel R_3 = 22 \Omega \parallel 100 \Omega \]

Capacitors are replaced by short circuits

Transistor Amplifiers

dc and ac Equivalents for a MOSFET Amplifier

Full circuit  \hspace{1cm}  dc equivalent

ac equivalent  \hspace{1cm}  Simplified ac equivalent
Small-Signal Operation
Diode Small-Signal Model

- The slope of the diode characteristic at the Q-point is called the diode conductance and is given by:

\[ g_d = \frac{\partial i_d}{\partial v_D} \bigg|_{Q-point} = \frac{I_s}{V_T} \exp\left(\frac{V_D}{V_T}\right) = \frac{I_D}{V_T} \]

- Diode resistance is given by:

\[ r_d = \frac{1}{g_d} \]

Small-Signal Operation
Diode Small-Signal Model (cont.)

- \( g_d \) is small but non-zero for \( I_D = 0 \) because slope of diode equation is nonzero at the origin.

- At the origin, the diode conductance and resistance are given by:

\[ g_d = \frac{I_s}{V_T} \quad \text{and} \quad r_d = \frac{V_T}{I_s} \]
**Small-Signal Operation**

**BJT Hybrid-Pi Model**

- The hybrid-pi small-signal model is the intrinsic representation of the BJT.
- Small-signal parameters are controlled by the Q-point and are independent of geometry of the BJT.

**Transconductance:**
\[ g_m = \frac{I_C}{V_T} \approx 40I_C \]

**Input resistance:**
\[ r_i = \frac{\beta_o V_T}{I_C} = \frac{\beta_o}{g_m} \quad \text{or} \quad \beta_o = g_m r_i \]

**Output resistance:**
\[ r_o = \frac{V_A + V_{CE}}{I_C} = \frac{V_A}{I_C} \]

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**BJT Small-Signal Operation**

**Small-Signal Model for pnp Transistor**

- For the pnp transistor
  \[ i_B = I_B - i_B \]
  \[ i_C = I_C - i_c = \beta_f I_B - \beta_f i_B \]

- Signal current injected into base causes decrease in total collector current which is equivalent to increase in signal current entering collector.

- So the small-signal models for the npn and pnp devices are identical!
Common-Emitter Amplifiers
Small-Signal Analysis - ac Equivalent Circuit

- ac equivalent circuit is constructed by assuming that all capacitances have zero impedance at signal frequency and dc voltage sources are ac ground.
- Assume that Q-point is already known.

Common-Emitter Amplifiers
Small-Signal Equivalent Circuit

- Input voltage is applied to the base terminal
- Output signal appears at collector terminal
- Emitter is common to both input and output signals
  Thus circuit is termed a Common-Emitter (C-E) Amplifier.
- The terminal gain of the C-E amplifier is the gain from the base terminal to the collector terminal

\[ A_{VT}^{CE} = \frac{V_c}{V_b} = -g_m R_L \]

\[ R_L = r_o R_C \parallel R_3 \]
Common-Emitter Amplifiers
Input Resistance and Signal Source Gain

Define $R_{ib}$ as the input resistance looking into the base of the transistor:

$$ R_{ib} = \frac{v_{ib}}{i_{b}} = r_{a} $$

The input resistance presented to $v_{i}$ is:

$$ R_{in} = R_{i} + R_{ib}R_{ib} = R_{i} + R_{ib}r_{a} $$

The signal source voltage gain is:

$$ A_{v}^{CE} = \frac{v_{o}}{v_{i}} = \frac{v_{o}}{v_{b}} \frac{v_{b}}{v_{i}} = A_{v}^{CE} \frac{R_{L}}{R_{i} + R_{ib}r_{a}} $$

Common-Emitter Amplifiers
“Rule of Thumb” Design Estimate

$$ A_{v}^{CE} = A_{v}^{CE} \frac{R_{L}}{R_{i} + R_{ib}r_{a}} = A_{v}^{CE} = -g_{m}R_{L} \quad R_{L} = r_{c}R_{C} $$

Typically: $r_{a} >> R_{C}$ and $R_{i} >> R_{C}$

$$ A_{v}^{CE} = -g_{m}R_{C} = -40I_{C}R_{C} $$

$I_{C}R_{C}$ represents the voltage dropped across collector resistor $R_{C}$

A typical design point is $I_{C}R_{C} = \frac{V_{CC}}{3}$

$$ \therefore A_{v}^{CE} = -40 \frac{V_{CC}}{3} = -13.3V_{CC} $$

To help account for all the approximations and have a number that is easy to remember, our "rule-of-thumb" estimate for the voltage gain becomes

$$ A_{v}^{CE} \approx -10V_{CC} $$
Common-Emitter Amplifiers
Voltage Gain Example

- Problem: Calculate voltage gain, input resistance and maximum input signal level for a common-emitter amplifier
- Given data: $\beta_F = 100$, $V_A = 75$ V, Q-point is $(0.245 \text{ mA}, 3.39 \text{ V})$
- Assumptions: Transistor is in active region, $\beta_o = \beta_F$. Signals are low enough to be considered small signals. Room temperature.

- Analysis:
  
  $g_m = 40I_C = 40(0.245\text{ mA}) = 9.80 \text{ mS}$
  
  $r_s = \frac{\beta_F}{g_m} = \frac{100}{9.80 \text{ mS}} = 10.2 \text{ k}\Omega$

  $r_c = \frac{V_A + V_{CE}}{I_C} = \frac{75\text{ V} + 3.39\text{ V}}{0.245\text{ mA}} = 320 \text{ k}\Omega$

  $R_B = R_I = 160\text{ k}\Omega$

  $R_{CE} = 104\text{ k}\Omega$

  $R_{BCE} = 0.2\text{ k}\Omega = 9.29 \text{ k}\Omega$

  $R_{in} = R_B + R_{BCE} = 10.3 \text{ k}\Omega$

  $v_{ib} = v_i \left( \frac{R_B}{R_B + R_{BCE}} \right)$

  $\therefore v_{ib} \leq 0.005\text{ V}$, $v_i \leq 5\text{ mV}

  v_{ib} \leq 5.54\text{ mV} \left( \frac{10.3\text{ k}\Omega}{9.29\text{ k}\Omega} \right) = 5.54 \text{ mV}$

Check the rule-of-thumb estimate: $A_{v,CE}^{CF} = -10(12) = -120$ (ballpark estimate)

What is the maximum amplitude of the output signal: $v_c \leq 5.54\text{ mV}(-151) = 0.837 \text{ V}$
Common-Emitter Amplifiers
Voltage Gain Example (cont.)

- Simulation Results: The graph below presents the output voltage for an input voltage that is a 5-mV, 10-kHz sine wave.

- Note that although the sine wave at first looks good, the positive and negative peak amplitudes are different indicating the presence of distortion. The input is near our small-signal limit for linear operation.

![Graph showing output voltage for a 5-mV, 10-kHz sine wave.](image)

Dual Supply Operation - Example

- Problem: Find voltage gain, input and output resistances for the circuit above.
- Given: $\beta_F = 65$, $V_A = 50$ V
- Assumptions: Active-region operation, $V_{BE} = 0.7$ V, small signal operating conditions.

Analysis: To find the Q-point, the dc equivalent circuit is constructed.

$$10^3 I_B + V_{BE} + (\beta_F + 1) I_B (1.6 \times 10^4) = 5$$

$\therefore I_B = 3.71 \mu A$

$I_c = 65 I_B = 241 \mu A$

$I_e = 66 I_B = 245 \mu A$

$$5 \times 10^4 I_e - V_{CE} - (1.6 \times 10^4) I_e = (-5) = 0$$

$\therefore V_{CE} = 3.67$ V

![Diagram of the dual supply operation circuit.](image)
Common-Emitter Amplifiers
Dual Supply Operation - Example (cont.)

Next we construct the ac equivalent and simplify it.

\[ g_m = 40I_C = 9.64 \times 10^{-3} \, S \]
\[ r_e = \frac{\beta_o}{40I_C} = 6.74 \, k\Omega \]
\[ r_o = \frac{V_i + V_{CE}}{I_C} = 223 \, k\Omega \]

\[ R_{in} = R_e \| r_o = 6.31 \, k\Omega \]

\[ A_{VC} = \frac{V_o}{V_i} = -g_m \left( \frac{R_{out}}{R_e} \right) \left( \frac{R_o}{R_e + R_o} \right) = -84.0 \]

Gain Estimate: \( A_{VC} = -10 \left( V_{CC} + V_{EE} \right) = -100 \)