Lecture #4
BJT Modeling and $r_e$ Transistor Model (small signal analysis)

Instructor:
Dr. Ahmad El-Banna
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Merged in two lectures only 😊
Agenda

- Amplification in the AC Domain
- BJT transistor Modeling
- The $r_e$ Transistor Model (small signal analysis)
- Effect of $R_L$ and $R_s$ (System approach)
- Determining the Current Gain
- Summary Table
AMPLIFICATION IN THE AC DOMAIN
Amplification in the AC Domain

\[ \eta = \frac{P_o}{P_i} \] cannot be greater than 1.

In fact, a conversion efficiency is defined by \( \eta = \frac{P_{o(ac)}}{P_{i(dc)}} \), where \( P_{o(ac)} \) is the ac power to the load and \( P_{i(dc)} \) is the dc power supplied.

- The superposition theorem is applicable for the analysis and design of the dc and ac components of a BJT network, permitting the separation of the analysis of the dc and ac responses of the system.
BJT TRANSISTOR MODELING
BJT Transistor Modeling

- A **model** is a combination of circuit elements, properly chosen, that best approximates the actual behavior of a semiconductor device under specific operating conditions.

Ac analysis

- Defining the important parameters of any system.
BJT Transistor Modeling

- the ac equivalent of a transistor network is obtained by:
  1. Setting all dc sources to zero and replacing them by a short-circuit equivalent
  2. Replacing all capacitors by a short-circuit equivalent
  3. Removing all elements bypassed by the short-circuit equivalents introduced by steps 1 and 2
  4. Redrawing the network in a more convenient and logical form
THE $r_e$ TRANSISTOR MODEL

- Common Emitter Configuration
- Common Base Configuration
- Common Collector Configuration
- $r_e$ Model in Different Bias Circuits
The $r_e$ Transistor Model (CE)

**FIG. 5.8**
Finding the input equivalent circuit for a BJT transistor.

**FIG. 5.12**
BJT equivalent circuit.

**FIG. 5.13**
Defining the level of $Z_i$.

$Z_i = \frac{V_i}{I_b} = \frac{V_{be}}{I_b}$

$V_{be} = I_{be} = (l_c + I_b) r_e = (\beta I_b + I_b) r_e$

$Z_i = \frac{V_{be}}{I_b} = \frac{(\beta + 1) I_b r_e}{I_b}$

$Z_i = (\beta + 1) r_e \equiv \beta r_e$

**FIG. 5.15**
Defining the Early voltage and the output impedance of a transistor.

**FIG. 5.14**
Improved BJT equivalent circuit.

**FIG. 5.16**
$r_e$ model for the common-emitter transistor configuration including effects of $r_o$.
The $r_e$ Transistor Model (CB)

**FIG. 5.17**
(a) Common-base BJT transistor; (b) equivalent circuit for configuration of (a).

**FIG. 5.18**
Common base $r_e$ equivalent circuit.
The $r_e$ Transistor Model (CC)

- For the common-collector configuration, the model defined for the common-emitter configuration is normally applied rather than defining a model for the common-collector configuration.

**nnp versus pnp**

- The dc analysis of nnp and pnp configurations is quite different in the sense that the currents will have opposite directions and the voltages opposite polarities.
- However, for an ac analysis where the signal will progress between positive and negative values, the ac equivalent circuit will be the same.
C.E. Fixed Bias Configuration

**FIG. 5.20**
Common-emitter fixed-bias configuration.

**FIG. 5.21**
Network of Fig. 5.20 following the removal of the effects of $V_{CC}$, $C_1$, and $C_2$.

**FIG. 5.22**
Substituting the $r_e$ model into the network of Fig. 5.21.

**Phase Relationship**

**FIG. 5.24**
Demonstrating the $180^\circ$ phase shift between input and output waveforms.

**FIG. 5.23**
Determining $Z_o$ for the network of Fig. 5.22.

- $Z_i = R_B || \beta r_e$ ohms
- $Z_i = \beta r_e$ ohms
- $Z_o = R_C || r_o$ ohms
- $Z_o \approx R_C$
- $r_o = 10 R_C$
- $V_o = -\beta I_b (R_C || r_o)$
- $I_b = \frac{V_i}{\beta r_e}$
- $V_o = -\beta \left( \frac{V_i}{\beta r_e} \right) (R_C || r_o)$
- $A_v = \frac{V_o}{V_i} = -\frac{(R_C || r_o)}{r_e}$
- $A_v \approx -\frac{R_C}{r_e}$, $r_o \geq 10 R_C$
Voltage-Divider Bias

**FIG. 5.26**
Voltage-divider bias configuration.

**FIG. 5.27**
Substituting the $r_e$ equivalent circuit into the ac equivalent network of Fig. 5.26.

\[
R' = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2}
\]

\[
Z_i = R' \beta r_e
\]

\[
Z_o = R \parallel r_o
\]

\[
Z_o \approx R_C \quad (r_o \approx 10R_C)
\]

\[
V_o = -(\beta I_b)(R_C \parallel r_e)
\]

\[
I_b = \frac{V_i}{\beta r_e}
\]

\[
V_o = -\beta \left(\frac{V_i}{\beta r_e}\right) (R_C \parallel r_o)
\]

\[
A_i = \frac{V_o}{V_i} = \frac{-R_C \parallel r_o}{r_o}
\]

\[
A_v = \frac{V_o}{V_i} \approx \frac{R_C}{r_o} \quad (r_o \approx 10R_C)
\]

180° phase shift
C.E. Emitter Bias Configuration

Unbypassed

\[ V_i = I_b \beta r_e + I_e R_E \]
\[ V_i = I_b \beta r_e + (\beta + 1)I_e R_E \]
\[ Z_b = \frac{V_i}{I_b} = \beta r_e + (\beta + 1)R_E \]
\[ Z_b = \beta r_e + (\beta + 1)R_E \]
\[ Z_b \approx \beta(r_e + R_E) \]
\[ Z_b \approx \beta R_E \]

FIG. 5.29
CE emitter-bias configuration.

FIG. 5.30
Substituting the \( r_e \) equivalent circuit into the ac equivalent network of Fig. 5.29.

\[ Z_i = R_B \parallel Z_b \]
\[ Z_o = R_C \]
\[ I_h = \frac{V_i}{Z_b} \]
\[ V_o = -I_o R_C = -\beta I_b R_C \]
\[ = -\beta \left( \frac{V_i}{Z_b} \right) R_C \]
\[ A_v = \frac{V_o}{V_i} = -\frac{\beta R_C}{Z_b} \]
\[ Z_o \approx \beta R_E \]
\[ A_v = \frac{V_o}{V_i} \approx -\frac{R_C}{r_e + R_E} \]

180° phase shift
C.E. Emitter Bias Configuration.

Effect of $r_o$

$$Z_b = \beta r_e + \left[ \frac{(\beta + 1) + R_c/r_o}{1 + (R_c + R_E)/r_o} \right] R_E$$

$R_c/r_o$ is always much less than $(\beta + 1)$.

$$Z_b \approx \beta r_e + \frac{(\beta + 1) R_E}{1 + (R_c + R_E)/r_o}$$

For $r_o \geq 10(R_c + R_E)$,

$$Z_b \approx \beta r_e + (\beta + 1) R_E$$

$$Z_b \approx \beta (r_e + R_E) \quad r_o \geq 10(R_c + R_E)$$

$$Z_o = R_c \ll \left[ \frac{r_o + \frac{\beta (r_o + r_e)}{1 + \beta r_e/r_E}}{1 + \frac{r_e}{R_E}} \right]$$

$r_o \gg r_e$,

$$Z_o \approx R_c \left[ 1 + \frac{\beta}{1 + \frac{\beta r_e}{R_E}} \right]$$

$$Z_o \approx R_c \ll \left[ 1 + \frac{1}{\beta} + \frac{r_e}{R_E} \right]$$

Typically $1/\beta$ and $r_e/R_E$ are less than one with a sum usually less than one.

$$Z_o \approx R_c$$

Any level of $r_o$

$$A_v = \frac{V_o}{V_i} = \frac{\beta R_c}{Z_b} \left[ 1 + \frac{r_e}{r_o} \right] + \frac{R_c}{r_o}$$

$$r_e \ll 1.$$
Emitter Follower Configuration

\[ Z_i = R_B \parallel Z_D \]

\[ Z_b = \beta r_e + (\beta + 1)R_E \]

\[ Z_o = \beta (r_e + R_E) \]

\[ Z_o \approx \beta R_E \quad \text{for} \quad R_E \gg r_e \]

\[
V_o = \frac{R_E V_i}{R_E + r_e}
\]

\[
A_v = \frac{V_o}{V_i} = \frac{R_E}{R_E + r_e}
\]

Because \( R_E \) is usually much greater than \( r_e \),

\[ R_E + r_e \approx R_E; \]

\[ A_v = \frac{V_o}{V_i} \approx 1 \]

in phase

\[
I_e = (\beta + 1)I_b = (\beta + 1)\frac{V_i}{Z_b}
\]

\[
I_e = \frac{(\beta + 1)V_i}{\beta r_e + (\beta + 1)R_E}
\]

\[
I_e = \frac{V_i}{[\beta r_e/(\beta + 1)] + R_E}
\]

\[ (\beta + 1) \approx \beta \]

\[ \frac{\beta r_e}{\beta + 1} \approx \frac{\beta r_e}{\beta} = r_e \]

\[
I_e = \frac{V_i}{r_e + R_E}
\]

\[ Z_o = R_E | r_e \]

\[ Z_o \approx r_e \]

**FIG. 5.36**
Emitter-follower configuration.

**FIG. 5.37**
Substituting the \( r_e \) equivalent circuit into the ac equivalent network of Fig. 5.36.

**FIG. 5.38**
Defining the output impedance for the emitter-follower configuration.
Emitter Follower Configuration..

Effect of $r_o$

$$Z_b = \beta r_e + \frac{(\beta + 1)R_E}{1 + \frac{R_E}{r_o}}$$

$$r_o \cong 10R_E$$

$$Z_o = r_o \| R_E \| \frac{\beta r_e}{(\beta + 1)}$$

$$Z_o = r_o \| R_E \| r_e$$

$$Z_b \cong \beta(r_e + R_E) \quad r_o \cong 10R_E$$

$$A_v = \frac{(\beta + 1)R_E/Z_b}{1 + \frac{R_E}{r_o}}$$

$$A_v \cong \beta R_E$$

$$Z_b \cong \beta(r_e + R_E)$$

$$A_v \equiv \frac{\beta R_E}{\beta(r_e + R_E)}$$

$$A_v \approx \frac{R_E}{r_e + R_E} \quad r_e \cong 10R_E$$
Common-Base Configuration

\[ Z_i = R_E \parallel r_c \]

\[ Z_o = R_C \]

\[ I_e = I_i \]

\[ I_o = -\alpha I_c = -\alpha I_i \]

\[ A_i = \frac{I_o}{I_i} = -\alpha \approx -1 \]

\[ V_o = -I_oR_C = -(\alpha I_c)R_C = \alpha I_eR_C \]

\[ I_e = \frac{V_i}{r_c} \]

\[ V_o = \alpha \left( \frac{V_i}{r_c} \right) R_C \]

\[ A_v = \frac{V_o}{V_i} = \frac{\alpha R_C}{r_c} \approx \frac{R_C}{r_c} \]

**Phase Relationship** The fact that \( A_v \) is a positive number shows that \( V_o \) and \( V_i \) are in phase for the common-base configuration.

**Effect of \( r_o \)** For the common-base configuration, \( r_o = 1/h_{ob} \) is typically in the megohm range and sufficiently larger than the parallel resistance \( R_C \) to permit the approximation \( r_o \parallel R_C \approx R_C \).
Collector-Feedback Configuration

**FIG. 5.45**
Collector feedback configuration.

\[ I_o = I' + \beta I_b \]
\[ I' = \frac{V_o - V_i}{R_F} \]
\[ V_o = -I_o R_C = -(I' + \beta I_b) R_C \]
\[ V_i = I_b \beta r_e \]
\[ I' = \frac{(I' + \beta I_b) R_C - I_b \beta r_e}{R_F} \]
\[ I'(1 + \frac{R_C}{R_F}) = -\beta I_b \frac{(R_C + r_e)}{R_F} \]

**FIG. 5.46**
Substituting the \( r_e \) equivalent circuit into the ac equivalent network of Fig. 5.45.

\[ I_i = I_b - I' = I_b + \beta I_b \frac{(R_C + r_e)}{R_C + R_F} \]
\[ I_i = I_b \left(1 + \frac{\beta (R_C + r_e)}{R_C + R_F}\right) \]
\[ Z_i = \frac{V_i}{I_i} = \frac{I_b \beta r_e}{I_b \left(1 + \frac{\beta (R_C + r_e)}{R_C + R_F}\right)} = \frac{\beta r_e}{1 + \frac{\beta (R_C + r_e)}{R_C + R_F}} \]
\[ R_C \gg r_e \]
\[ Z_i = \frac{r_e}{1 + \frac{R_C}{\beta (R_C + R_F)}} \]

**FIG. 5.47**
Defining \( Z_o \) for the collector feedback configuration.

\[ Z_o \equiv R_C || R_F \]
\[ V_o = -I_o R_C = -(I' + \beta I_b) R_C \]
\[ = -\left(-\beta I_b \frac{(R_C + r_e)}{R_C + R_F} + \beta I_b\right) R_C \]
\[ V_o = -\beta I_b \left(1 - \frac{(R_C + r_e)}{R_C + R_F}\right) R_C \]

\[ A_v = \frac{V_o}{V_i} = -\beta I_b \left(1 - \frac{(R_C + r_e)}{R_C + R_F}\right) \frac{R_C}{\beta r_e K_e} \]
\[ = -\left(1 - \frac{(R_C + r_e)}{R_C + R_F}\right) \frac{R_C}{r_e} \]
\[ A_v = -\left(1 - \frac{R_C + R_F - R_C}{R_C + R_F}\right) \frac{R_C}{r_e} \]

180° phase shift

\[ \frac{A_v}{r_e} \approx \frac{R_C}{r_e} \]
Collector-Feedback Configuration..

Effect of $r_o$

\[
Z_i = \frac{1 + \frac{R_C}{R_F}r_o}{\frac{1}{\beta r_e} + \frac{1}{R_F} + \frac{R_C}{\beta r_e R_F} + \frac{R_C}{R_F r_e}}
\]

\[r_o \geq 10R_C\]

\[
Z_i \approx \frac{1}{\beta} \left[ \frac{1 + \frac{R_C}{R_F}}{r_e} \right] = \frac{1}{\beta} + \frac{1}{R_F} + \frac{R_C}{\beta R_F + R_C}
\]

Applying $R_C \gg r_e$ and $\frac{R_C}{\beta}$,

\[
Z_i \approx \frac{1}{\beta} + \frac{R_C}{R_F} + \frac{R_C}{\beta R_F} = \frac{1}{\beta} \left( \frac{R_F + \beta R_C}{R_F} \right) + \frac{R_C}{\beta R_F + R_C}
\]

but, since $R_F$ typically $\gg R_C$, $R_F + R_C \approx R_F$ and $\frac{R_F}{R_F + R_C} = 1$

\[
Z_i \approx \frac{r_e}{\beta} + \frac{1}{\beta} + \frac{R_C}{R_C + R_F}
\]

For $r_o \geq 10R_C$,

\[
Z_o = r_o R_C \parallel R_F
\]

\[
Z_o \approx R_C R_F \quad r_o \approx 10R_C
\]

\[
Z_o \approx R_C \quad r_o \approx 10R_C R_F \gg R_C
\]

For $r_o \geq 10R_C$,

\[
A_v = -\left( \frac{R_F}{R_C + R_F} \right) r_o \quad r_o \approx 10R_C
\]

\[
A_v \approx -\left( \frac{R_F}{R_C + R_F} \right) r_e \quad r_o \approx 10R_C
\]

and for $R_F \gg R_C$

\[
A_v \approx \frac{R_C}{r_e} \quad r_o \approx 10R_C, \quad R_F \gg R_C
\]
Collector DC Feedback Configuration

**FIG. 5.50**
Collector dc feedback configuration.

\[ Z_i = R_F I \beta r_e \]

\[ Z_o = R_C R_F \cos r_o \]

\[ R' = r_o R_F R_C \]

\[ V_o = -\beta I_R R' \]

\[ I_b = \frac{V_i}{\beta r_e} \]

\[ A_v = \frac{V_o}{V_i} = \frac{r_o R_F R_C}{r_e} \]

\[ A_i = \frac{V_o}{V_i} \approx \frac{R_F R_C}{r_e} \quad r_o \geq 10 R_C \quad 180^\circ \text{ phase shift} \]
EFFECT OF $R_L$ AND $R_S$ (SYSTEM APPROACH)
Effect of $R_L$ and $R_s$

- The loaded voltage gain of an amplifier is always less than the no-load gain.
- The gain obtained with a source resistance in place will always be less than that obtained under loaded or unloaded conditions due to the drop in applied voltage across the source resistance.
- For the same configuration $A_{vNL} > A_{vL} > A_{vs}$.
- For a particular design, the larger the level of $R_L$, the greater is the level of ac gain.
- For a particular amplifier, the smaller the internal resistance of the signal source, the greater is the overall gain.
- For any network that have coupling capacitors, the source and load resistance do not affect the dc biasing levels.

**FIG. 5.54**
Amplifier configurations: (a) unloaded; (b) loaded; (c) loaded with a source resistance.

$A_{vNL} = \frac{V_o}{V_i}$

$A_{vL} = \frac{V_o}{V_i}$ with $R_L$

$A_{vs} = \frac{V_o}{V_s}$ with $R_s$ and $R_f$
**Effect of \( R_L \) and \( R_s \)**

\[
R_L = r_o \| R_C \| R_L = R_C \| R_L
\]

\[
V_o = -\beta I_b R_L = -\beta I_b (R_C | R_L)
\]

\[
I_b = \frac{V_i}{\beta r_e}
\]

\[
V_i = \frac{V_i}{Z_i + R_s}
\]

\[
\frac{V_i}{V_s} = \frac{Z_i}{Z_i + R_s}
\]

\[
A_{vL} = \frac{V_o}{V_i} = \frac{R_C | R_L}{r_e}
\]

\[
A_{vS} = \frac{Z_i}{Z_i + R_s}
\]

\[
A_{vS} = \frac{V_o}{V_i} \cdot \frac{V_i}{V_s} = A_{vL} \frac{Z_i}{Z_i + R_s}
\]

\[
A_{vS} = \frac{Z_i}{Z_i + R_s} A_{vL}
\]

**Voltage-divider ct.**

\[
Z_i = R_B \| \beta r_e
\]

\[
Z_o = R_C | r_o
\]

**Emitter-Follower Ct.**

\[
Z_i = R_1 \| R_2 \| \beta r_e
\]

\[
Z_o = R_C | r_o
\]

\[
A_{vL} = \frac{V_o}{V_i} = \frac{R_C \| R_L}{r_e}
\]

\[
A_{vL} = \frac{V_o}{V_i} = \frac{R_E \| R_L}{R_E \| R_L + r_e}
\]

\[
Z_i = R_B \| Z_b
\]

\[
Z_b = \beta (R_E \| R_L)
\]

\[
Z_o = r_e
\]
DETERMINING THE CURRENT GAIN
Determining the Current gain

For each transistor configuration, the current gain can be determined directly from the voltage gain, the defined load, and the input impedance.

\[ A_i = \frac{I_o}{I_i} \]

\[ A_{iL} = \frac{I_o}{I_i} = \frac{-V_o}{V_i} = -\frac{V_o}{V_i} \cdot \frac{Z_i}{R_L} \]

\[ I_i = \frac{V_i}{Z_i} \quad \text{and} \quad I_o = -\frac{V_o}{R_L} \]

\[ A_{iL} = -A_v \cdot \frac{Z_i}{R_L} \]
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### Unloaded BJT Transistor Amplifiers

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<tr>
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<th>( Z_i )</th>
<th>( Z_o )</th>
<th>( A_v )</th>
<th>( A_I )</th>
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<tr>
<td><strong>Fixed-bias:</strong></td>
<td>( V_{CC} )</td>
<td>( r_e )</td>
<td>( \frac{R_C}{r_e} )</td>
<td>( \frac{\beta R_C r_o}{(r_o + r_e)(R_C + \beta r_e)} )</td>
</tr>
<tr>
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<td>( r_o ) ( \equiv ) ( R_C )</td>
<td>( r_e )</td>
<td>( \frac{R_C}{r_e} )</td>
<td>( \frac{\beta R_C r_o}{(r_o + r_e)(R_C + \beta r_e)} )</td>
</tr>
<tr>
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<td>( (r_o \geq 10R_C) )</td>
<td>( (r_o \geq 10R_C) )</td>
<td>( (r_o \geq 10R_C) )</td>
<td>( (r_o \geq 10R_C) )</td>
</tr>
<tr>
<td><strong>Voltage-divider bias:</strong></td>
<td>( V_{CC} )</td>
<td>( r_e )</td>
<td>( \frac{r_C}{r_e} )</td>
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<td>( (r_o \geq 10R_C) )</td>
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<td><strong>Collector feedback:</strong></td>
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### BJT Transistor Amplifiers Including the Effect of $R_s$ and $R_L$

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<th>Configuration</th>
<th>$A_{vI} = \frac{V_o}{V_i}$</th>
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<th>$Z_o$</th>
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<td>$\frac{-(R_L \parallel R_C)}{r_e}$</td>
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<td>$R_E \left( \frac{R'_1}{R'_1} \beta + r_e \right)$</td>
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\( ECE \ 312 \), Lec#4, Oct 2014

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• For more details, refer to:

• The lecture is available online at:
  • [http://bu.edu.eg/staff/ahmad.elbanna-courses/11966](http://bu.edu.eg/staff/ahmad.elbanna-courses/11966)

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  • ahmad.elbanna@fes.bu.edu.eg