Electronic Circuits

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BJT Transistor Modeling

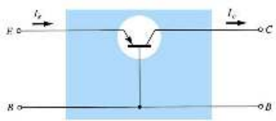
- A model is an equivalent circuit that represents the AC characteristics of the transistor.
- A model uses circuit elements that approximate the behavior of the transistor.
- There are two models commonly used in small signal AC analysis of a transistor:
  - r_e model
  - Hybrid equivalent model

The r_e Transistor Model

- BJTs are basically **current-controlled** devices; therefore the r_e model uses a diode and a current source to duplicate the behavior of the transistor.
- One disadvantage to this model is its sensitivity to the DC level. This model is designed for specific circuit conditions.

Common-Base Configuration

$I_c = \alpha I_e \qquad r_e = \frac{26\,\mathrm{mV}}{I_e}$

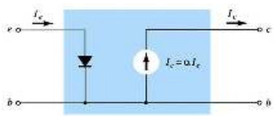


Input impedance:

$Z_i = r_e$

Output impedance:

$Z_o \cong \infty\Omega$



Voltage gain:

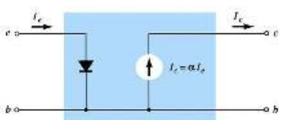
$A_V = \frac{\alpha R_L}{r_e} \cong \frac{R_L}{r_e}$

Current gain:

$A_i = -\alpha \cong -1$

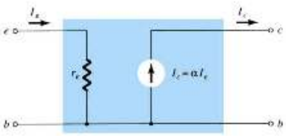
Common-Emitter Configuration

The diode r_e model can be replaced by the resistor r_e.



$I_e = (\beta + 1) I_b \cong \beta I_b$

$r_e = \frac{26\,\mathrm{mV}}{I_e}$



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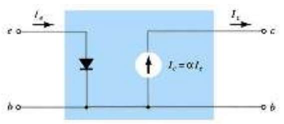
Common-Emitter Configuration

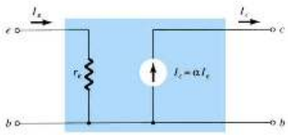


Input impedance:

$Z_i = \beta r_e$

Output impedance:

$Z_o = r_o \cong \infty\Omega$



Voltage gain:

$A_V = -\frac{R_L}{r_e}$

Current gain:

$A_i = \beta\big|_{r_o = \infty}$

Common-Collector Configuration

Input impedance:

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

Output impedance:

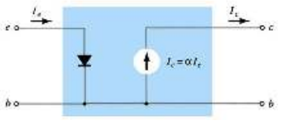
$$Z_o = r_e \parallel R_E$$

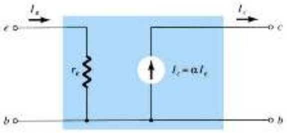
Voltage gain:

$$A_v = \frac{R_E}{R_E + r_e}$$

Current gain:

$$A_i = \beta + 1$$

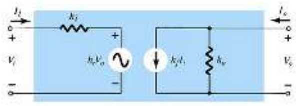




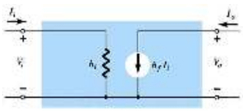
The Hybrid Equivalent Model

The following hybrid parameters are developed and used for modeling the transistor. These parameters can be found on the specification sheet for a transistor.

- h_i = input resistance
- h_r = reverse transfer voltage ratio (V_i/V_o) $\cong 0$
- h_f = forward transfer current ratio (I_o/I_i)
- h_o = output conductance



Simplified General h-Parameter Model



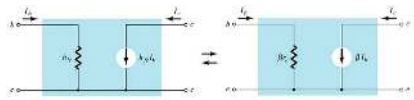
- h_i = input resistance
- h_f = forward transfer current ratio (I_o/I_i)

r_e vs. h-Parameter Model

Common-Emitter

$h_{ie} = \beta r_e$

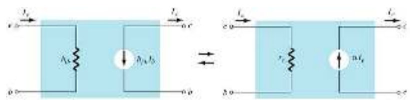
$h_{fe} = \beta_{ac}$



Common-Base

$h_{ib} = r_e$

$h_{fb} = -\alpha \cong -1$



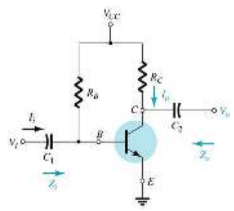
The Hybrid π Model

The hybrid π model is most useful for analysis of high-frequency transistor applications.

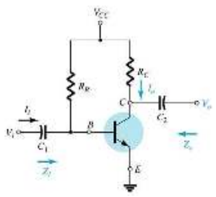
At lower frequencies the hybrid π model closely approximate the r_e parameters, and can be replaced by them.

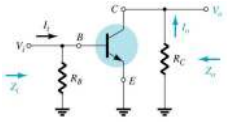
Common-Emitter Fixed-Bias Configuration

- The input is applied to the base
- The output is from the collector
  - High input impedance
  - Low output impedance
- High voltage and current gain
- Phase shift between input and output is 180°

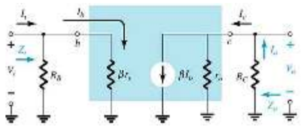


Common-Emitter Fixed-Bias Configuration





AC equivalent



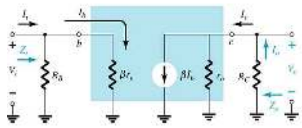
r_e model

Common-Emitter Fixed-Bias Calculations

Input impedance:

$$Z_i = R_B \parallel \beta r_e$$

$$Z_i \cong \beta r_e \big|_{R_E \geq 10\beta r_e}$$



Output impedance:

$$Z_o = R_C \parallel r_o$$

$$Z_o \cong R_C \big|_{r_o \geq 10 R_C}$$

Voltage gain:

$$A_v = \frac{V_o}{V_i} = -\frac{(R_C \parallel r_o)}{r_e}$$

$$A_v = -\frac{R_C}{r_e}\Big|_{r_o \geq 10 R_C}$$

Current gain:

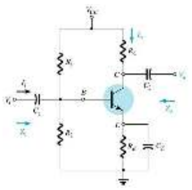
$$A_i = \frac{I_o}{I_i} = \frac{\beta R_B r_o}{(r_o + R_C)(R_B + \beta r_e)}$$

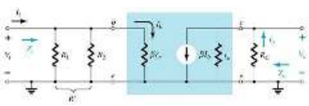
$$A_i \cong \beta \big|_{r_o \geq 10 R_C,\, R_B \geq 10\beta r_e}$$

Current gain from voltage gain:

$$A_i = -A_v \frac{Z_i}{R_C}$$

Common-Emitter Voltage-Divider Bias





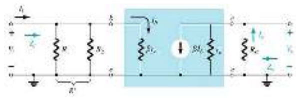
r_e model requires you to determine β, r_e, and r_o.

Common-Emitter Voltage-Divider Bias Calculations

Input impedance:

$$R' = R_1 \parallel R_2$$

$$Z_i = R' \parallel \beta r_e$$



Output impedance:

$$Z_o = R_C \parallel r_o$$

$$Z_o \cong R_C \big|_{r_o \geq 10 R_C}$$

Voltage gain:

$$A_v = \frac{V_o}{V_i} = \frac{-R_C \parallel r_o}{r_e}$$

$$A_v = \frac{V_o}{V_i} \cong -\frac{R_C}{r_e}\Big|_{r_o \geq 10 R_C}$$

Current gain:

$$A_i = \frac{I_o}{I_i} = \frac{\beta R' r_o}{(r_o + R_C)(R' + \beta r_e)}$$

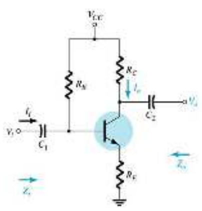
$$A_i = \frac{I_o}{I_i} \cong \frac{\beta R'}{R' + \beta r_e}\Big|_{r_o \geq 10 R_C}$$

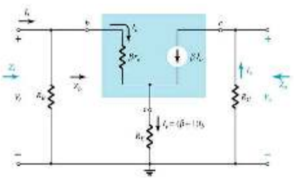
$$A_i = \frac{I_o}{I_i} \cong \beta \big|_{r_o \geq 10 R_C,\, R' \geq 10\beta r_e}$$

Current gain from voltage gain:

$$A_i = -A_v \frac{Z_i}{R_C}$$

Common-Emitter Emitter-Bias Configuration





Impedance Calculations

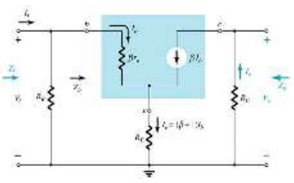
Input impedance:

$$Z_i = R_B \parallel Z_b$$

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

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

$$Z_b \cong \beta R_E$$



Output impedance:

$$Z_o = R_C$$

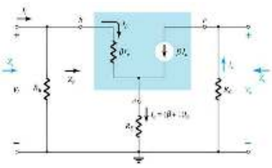
Gain Calculations

Voltage gain:

$$A_v = \frac{V_o}{V_i} = -\frac{\beta R_C}{Z_b}$$

$$A_v = \frac{V_o}{V_i} = -\frac{R_C}{r_e + R_E}\Big|_{Z_b = \beta(r_e + R_E)}$$

$$A_v = \frac{V_o}{V_i} \cong -\frac{R_C}{R_E}\Big|_{Z_b \cong \beta R_E}$$



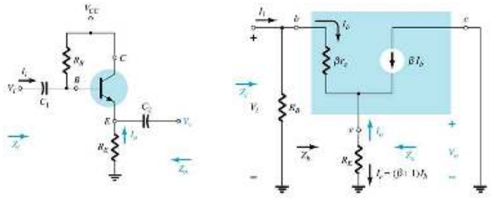
Current gain:

$$A_i = \frac{I_o}{I_i} = \frac{\beta R_B}{R_B + Z_b}$$

Current gain from voltage gain:

$$A_i = -A_v \frac{Z_i}{R_C}$$

Emitter-Follower Configuration

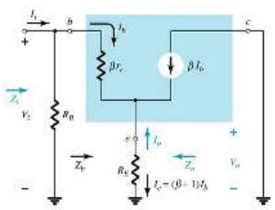


- This is also known as the common-collector configuration.
- The input is applied to the base and the output is taken from the emitter.
- There is no phase shift between input and output.

Impedance Calculations

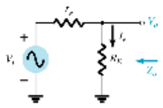
Input impedance:

$$Z_i = R_B \parallel Z_b$$
$$Z_b = \beta r_e + (\beta + 1)R_E$$
$$Z_b \cong \beta(r_e + R_E)$$
$$Z_b \cong \beta R_E$$



Output impedance:

$$Z_o = R_E \parallel r_e$$
$$Z_o \cong r_e\Big|_{R_E \gg r_e}$$

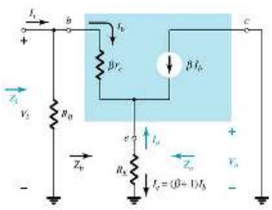


Gain Calculations

Voltage gain:

$$A_v = \frac{V_o}{V_i} = \frac{R_E}{R_E + r_e}$$

$$A_v = \frac{V_o}{V_i} \cong 1\Big|_{R_E \gg r_e,\, R_E + r_e \cong R_E}$$



Current gain:

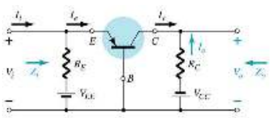
$$A_i \cong -\frac{\beta R_B}{R_B + Z_b}$$

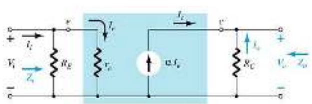
Current gain from voltage gain:

$$A_i = -A_v \frac{Z_i}{R_E}$$

Common-Base Configuration

- The input is applied to the emitter.
- The output is taken from the collector.
- Low input impedance.
- High output impedance.
- Current gain less than unity.
- Very high voltage gain.
- No phase shift between input and output.





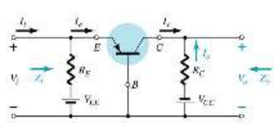
Calculations

Input impedance:

$$Z_i = R_E \parallel r_e$$

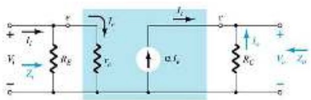
Output impedance:

$$Z_o = R_C$$



Voltage gain:

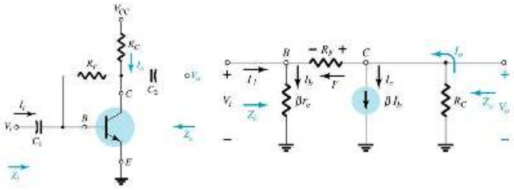
$$A_v = \frac{V_o}{V_i} = \frac{\alpha R_C}{r_e} \cong \frac{R_C}{r_e}$$



Current gain:

$$A_i = \frac{I_o}{I_i} = -\alpha \cong -1$$

Common-Emitter Collector Feedback Configuration



- This is a variation of the common-emitter fixed-bias configuration
- Input is applied to the base
- Output is taken from the collector
- There is a 180° phase shift between input and output

Calculations

Input impedance:

$$Z_i = \frac{r_e}{\frac{1}{\beta} + \frac{R_C}{R_F}}$$

Output impedance:

$$Z_o \cong R_C \parallel R_F$$

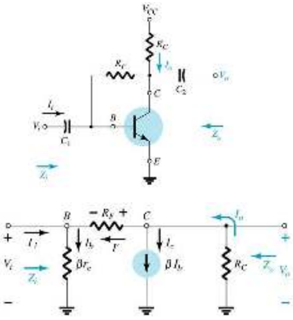
Voltage gain:

$$A_v = \frac{V_o}{V_i} = -\frac{R_C}{r_e}$$

Current gain:

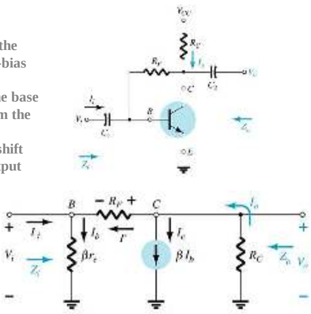
$$A_i = \frac{I_o}{I_i} = \frac{\beta R_F}{R_F + \beta R_C}$$

$$A_i = \frac{I_o}{I_i} \cong \frac{R_F}{R_C}$$

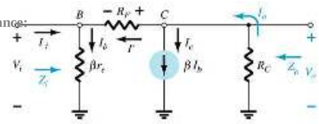


Collector DC Feedback Configuration

- This is a variation of the common-emitter, fixed-bias configuration
- The input is applied to the base
- The output is taken from the collector
- There is a 180° phase shift between input and output



Calculations



Input impedance:

$$Z_i = \frac{r_e}{\frac{1}{\beta} + \frac{R_C}{R_F}}$$

Output impedance:

$$Z_o \cong R_C \parallel R_F$$

Voltage gain:

$$A_v = \frac{V_o}{V_i} = -\frac{R_C}{r_e}$$

Current gain:

$$A_i = \frac{I_o}{I_i} = \frac{\beta R_F}{R_F + \beta R_C}$$

$$A_i = \frac{I_o}{I_i} \cong \frac{R_F}{R_C}$$

Two-Port Systems Approach

This approach:

- Reduces a circuit to a two-port system
- Provides a "Thévenin look" at the output terminals
- Makes it easier to determine the effects of a changing load

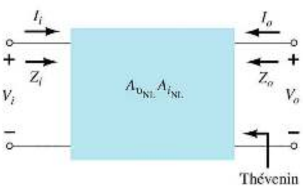
With V_i set to 0 V:

$$Z_{Th} = Z_o = R_o$$

The voltage across the open terminals is:

$$E_{Th} = A_{vNL} V_i$$

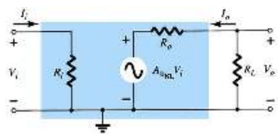
where A_{vNL} is the no-load voltage gain.



Effect of Load Impedance on Gain

This model can be applied to any current- or voltage-controlled amplifier.

Adding a load reduces the gain of the amplifier:



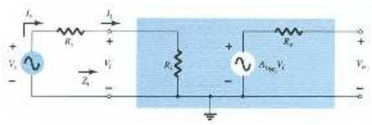
$$A_v = \frac{V_o}{V_i} = \frac{R_L}{R_L + R_o} A_{vNL}$$

$$A_i = -A_v \frac{Z_i}{R_L}$$

Effect of Source Impedance on Gain

The fraction of applied signal that reaches the input of the amplifier is:

$$V_i = \frac{R_i V_s}{R_i + R_s}$$



The internal resistance of the signal source reduces the overall gain:

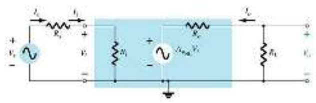
$$A_{vs} = \frac{V_o}{V_s} = \frac{R_i}{R_i + R_s} A_{vNL}$$

Combined Effects of R_S and R_L on Voltage Gain

Effects of R_L:

$$A_v = \frac{V_o}{V_i} = \frac{R_L A_{vNL}}{R_L + R_o}$$

$$A_i = -A_v \frac{R_i}{R_L}$$



Effects of R_L and R_S:

$$A_{vs} = \frac{V_o}{V_s} = \frac{R_i}{R_i + R_s} \frac{R_L}{R_L + R_o} A_{vNL}$$

$$A_{is} = -A_{vs} \frac{R_s + R_i}{R_L}$$

Cascaded Systems

- The output of one amplifier is the input to the next amplifier
- The overall voltage gain is determined by the product of gains of the individual stages
- The DC bias circuits are isolated from each other by the coupling capacitors
- The DC calculations are independent of the cascading
- The AC calculations for gain and impedance are interdependent

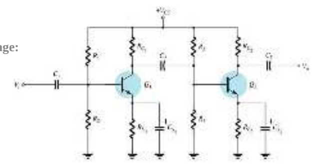
R-C Coupled BJT Amplifiers

Input impedance, first stage:

$$Z_i = R_1 \| R_2 \| \beta r_e$$

Output impedance, second stage:

$$Z_o = R_C$$



Voltage gain:

$$A_{v1} = \frac{R_C \| R_1 \| R_2 \| \beta r_e}{r_e}$$

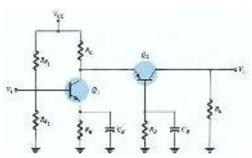
$$A_{v2} = \frac{R_C}{r_e}$$

$$A_v = A_{v1} A_{v2}$$

Cascode Connection

This example is a CE–CB combination. This arrangement provides high input impedance but a low voltage gain.

The low voltage gain of the input stage reduces the Miller input capacitance, making this combination suitable for high-frequency applications.

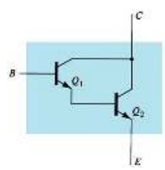


Darlington Connection

The Darlington circuit provides a very high current gain—the product of the individual current gains:

$$\beta_D = \beta_1 \beta_2$$

The practical significance is that the circuit provides a very high input impedance.



DC Bias of Darlington Circuits

Base current:

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \beta_D R_E}$$

Emitter current:

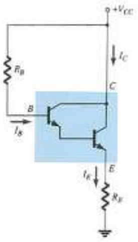
$$I_E = (\beta_D + 1) I_B \cong \beta_D I_B$$

Emitter voltage:

$$V_E = I_E R_E$$

Base voltage:

$$V_B = V_E + V_{BE}$$

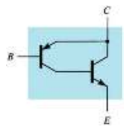


Feedback Pair

This is a two-transistor circuit that operates like a Darlington pair, *but it is not a Darlington pair*.

It has similar characteristics:

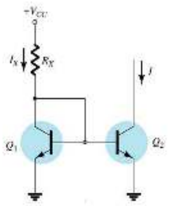
- High current gain
- Voltage gain near unity
- Low output impedance
- High input impedance



The difference is that a Darlington uses a pair of like transistors, whereas the feedback-pair configuration uses complementary transistors.

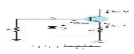
Current Mirror Circuits

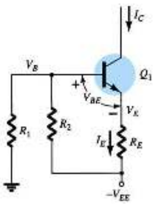
Current mirror circuits provide constant current in integrated circuits.



Current Source Circuits

Constant-current sources can be built using FETs, BJTs, and combinations of these devices.

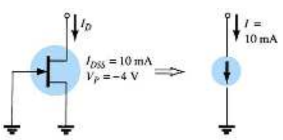




$I_E \cong I_C$

more…

Current Source Circuits



$V_{GS} = 0V$

$I_D = I_{DSS} = 10\text{ mA}$

Fixed-Bias Configuration

Input impedance:

$$Z_i = R_B \parallel h_{ie}$$

Output impedance:

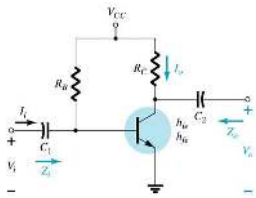
$$Z_o = R_C \parallel 1/h_{oe}$$

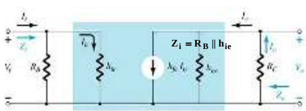
Voltage gain:

$$A_v = \frac{V_o}{V_i} = -\frac{h_{fe}(R_C \parallel 1/h_oe)}{h_{ie}}$$

Current gain:

$$A_i = \frac{I_o}{I_i} \cong h_{fe}$$





Voltage-Divider Configuration

Input impedance:

$Z_i = R' \| h_{ie}$

Output impedance:

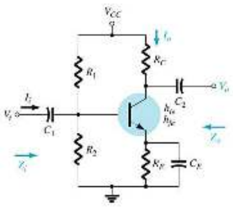
$Z_o \cong R_C$

Voltage gain:

$$A_v = -\frac{h_{fe}(R_C \| 1/h_{oe})}{h_{ie}}$$

Current gain:

$$A_i = -\frac{h_{fe}R'}{R' + h_{ie}}$$



Emitter-Follower Configuration

Input impedance:

$Z_b = h_{fe}R_E$

$Z_i = R_o \| Z_b$

Output impedance:

$$Z_o \cong R_E \| \frac{h_{ie}}{h_{fe}}$$

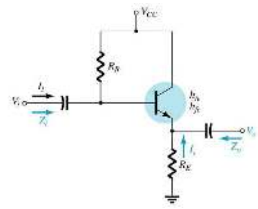
Voltage gain:

$$A_v = \frac{V_o}{V_i} = \frac{R_E}{R_E + h_{ie}/h_{fe}}$$

Current gain:

$$A_i = \frac{h_{fe}R_B}{R_B + Z_b}$$

$$A_i = -A_v \frac{Z_i}{R_E}$$



Common-Base Configuration

Input impedance:

$Z_i = R_E \| h_{ib}$

Output impedance:

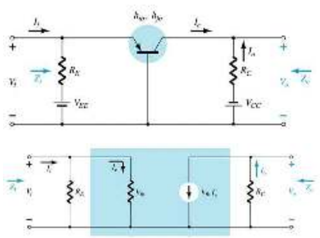
$Z_o = R_C$

Voltage gain:

$$A_v = \frac{V_o}{V_i} = -\frac{h_{fb}R_C}{h_{ib}}$$

Current gain:

$$A_i = \frac{I_o}{I_i} = h_{fb} \cong -1$$



Troubleshooting

Check the DC bias voltages

✓ If not correct, check power supply, resistors, transistor. Also check the coupling capacitor between amplifier stages.

Check the AC voltages

✓ If not correct check transistor, capacitors and the loading effect of the next stage.