Indian Institute of Technology Jodhpur, Year 2018

Analog Electronics

(Course Code: EE314)

Lecture 9-10: BJT Small Signal, Biasing, Amplifiers

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Course related documents will be uploaded on http://home.iitj.ac.in/~sptiwari/EE314/

Note: The information provided in the slides are taken form text books for microelectronics (including Sedra & Smith, B. Razavi), and various other resources from internet, for **teaching/academic use only**

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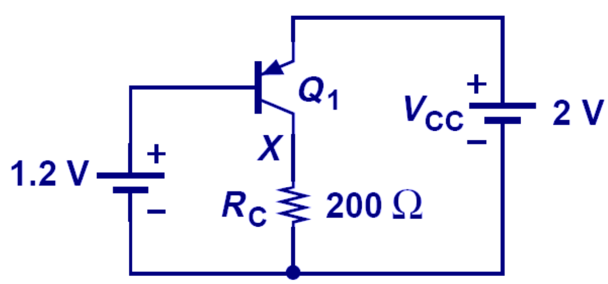
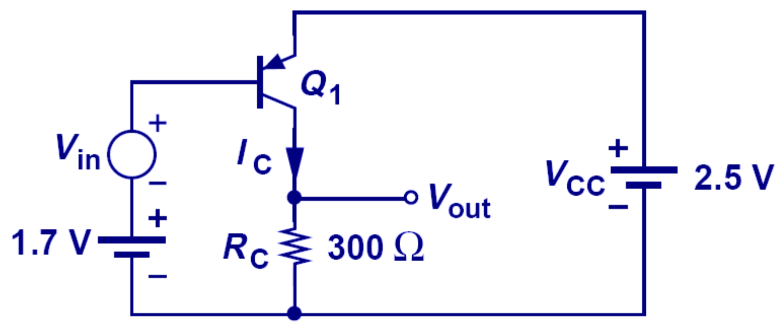
PNP BJT Biasing

- Note that the emitter is biased at a higher potential than the base and the collector.

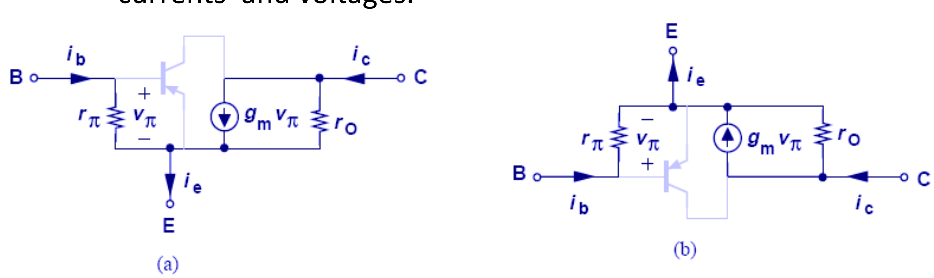


Small-Signal Analysis

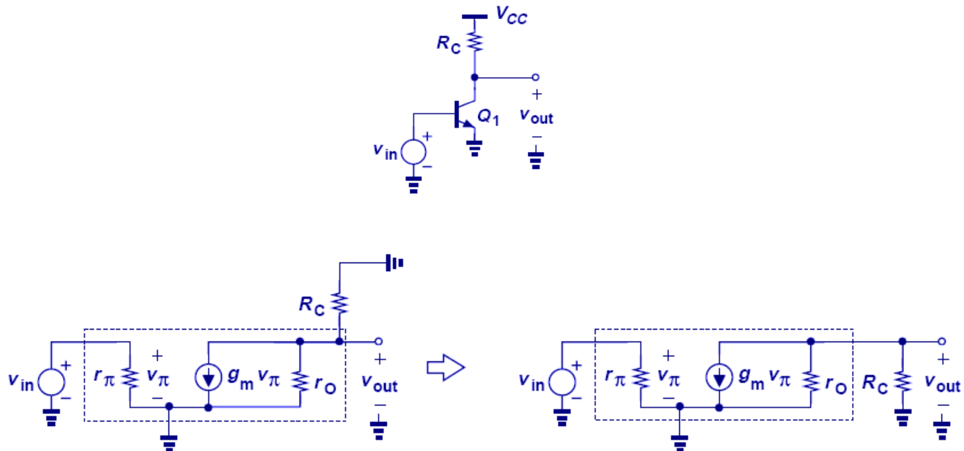


PNP BJT Small-Signal Model

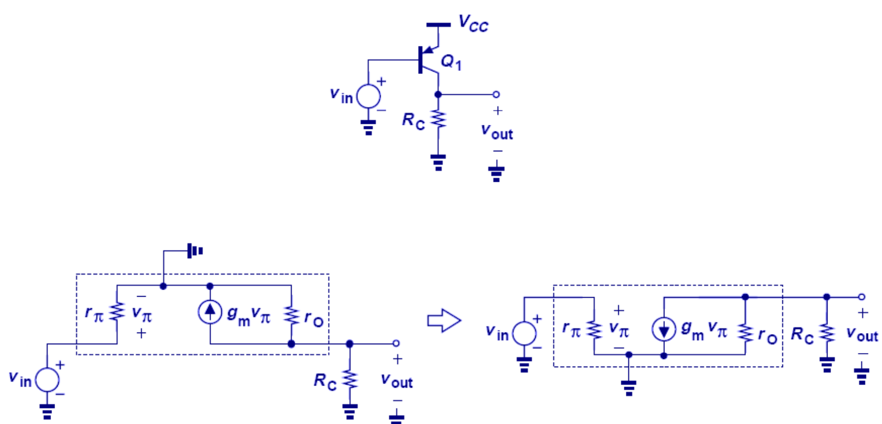
- The small-signal model for a PNP transistor is **identical to that of an NPN transistor**.
  - Note that the polarity of the small-signal currents and voltages are defined to be in the opposite direction with respect to the large-signal model. This is OK, because the small-signal model is used only to determine *changes* in currents and voltages.



Small-Signal Model Example 1

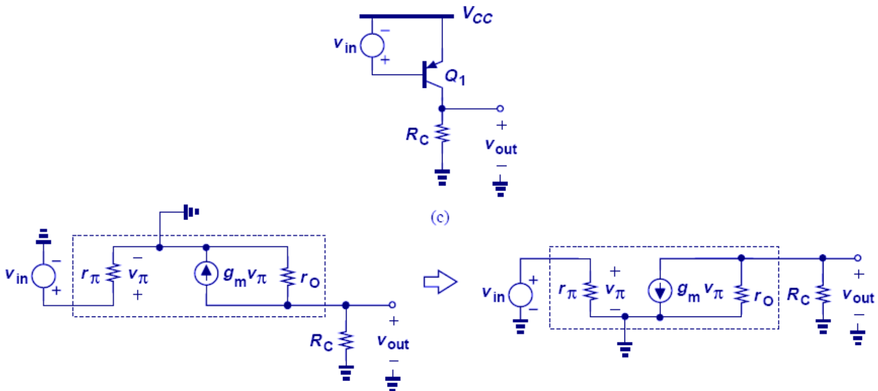


Small-Signal Model Example 2



- Note that the small-signal model is identical to that in the previous example.

Small-Signal Model Example 3



- Note that the small-signal model is identical to that in the previous examples.

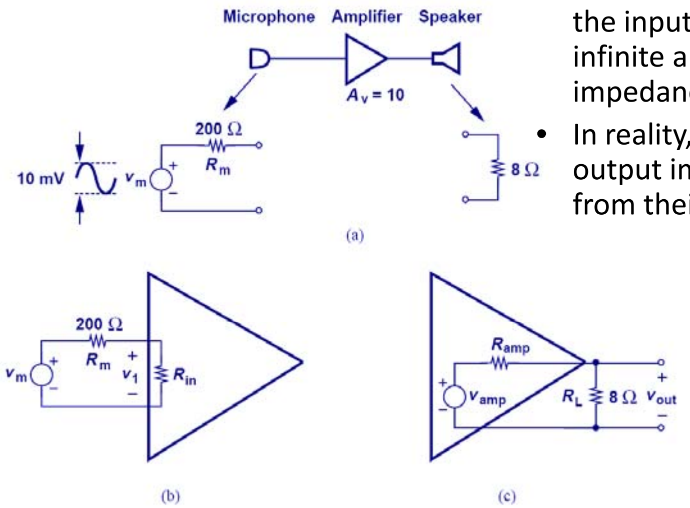
BJT Amplifiers: Overview

General Concepts
- Input and Output Impedances
- Biasing
- DC and Small-Signal Analysis

Operating Point Analysis
- Simple Biasing
- Emitter Degeneration
- Self-Biasing
- Biasing of PNP Devices

Amplifier Topologies
- Common-Emitter Stage
- Common-Base Stage
- Emtter Follower

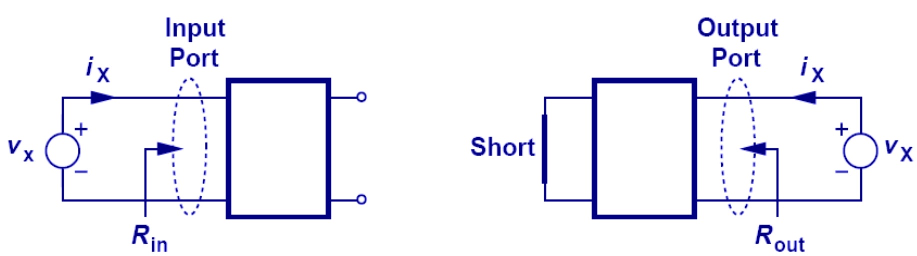
Voltage Amplifier



- In an ideal voltage amplifier, the input impedance is infinite and the output impedance is zero.
- In reality, the input and output impedances depart from their ideal values.

Input/Output Impedances

- The figures below show how input and output impedances are determined.
  - All independent sources are set to zero.



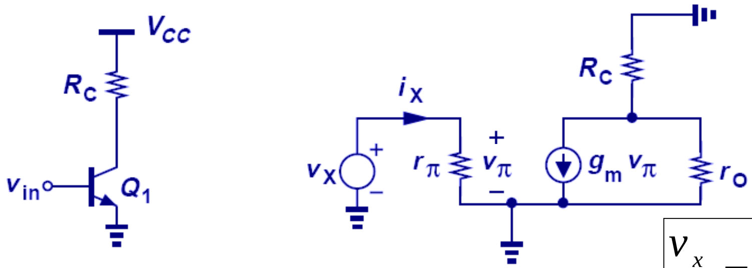
(a)

$$impedance \equiv \frac{v_x}{i_x}$$

(b)

Input Impedance Example

- Note that input/output impedances are usually regarded as small-signal quantities.
  - The input impedance is obtained by applying a small change in the input voltage and finding the resultant change in the input current:

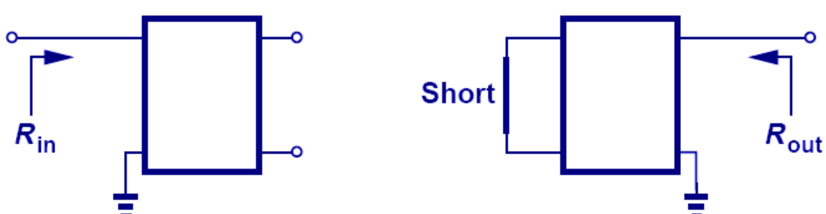


(a) (b)

$$\frac{v_x}{i_x} = r_\pi$$

Impedance at a Node

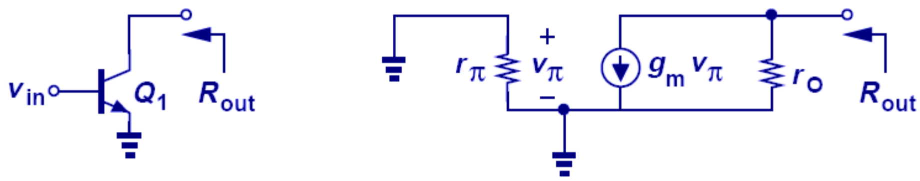
- When calculating I/O impedances at a port, we usually ground one terminal. We often refer to the "impedance seen at a node" rather than the impedance between two nodes (*i.e.* at a port).



(a) (b)

Impedance seen at the Collector

- The impedance seen at the collector is equal to the intrinsic output impedance of the transistor, if the emitter is grounded.



(a) (b)

$$R_{out} = r_o$$

Impedance seen at the Collector

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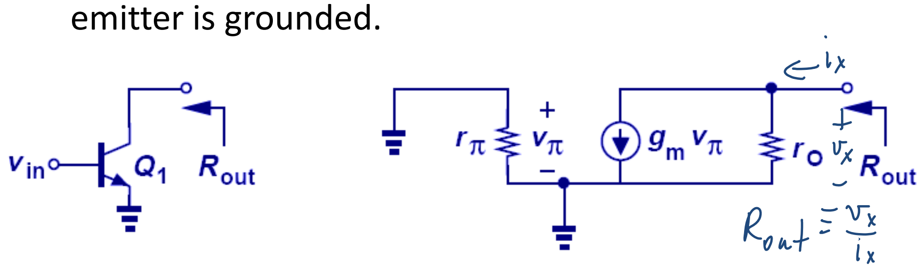
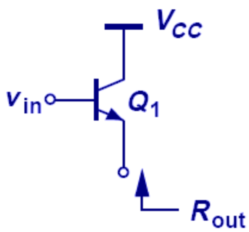


(a) (b)

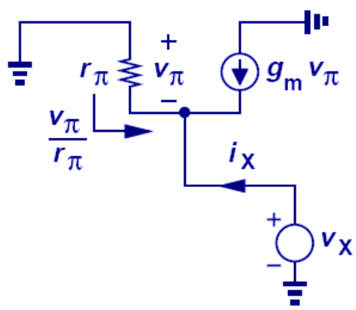
$$R_{out} = r_o$$

Impedance seen at the Emitter

- The impedance seen at the emitter is approximately equal to the inverse of its transconductance, if the base is grounded.



(a)



(b)

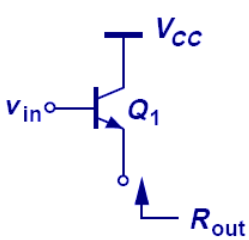
$$\frac{v_x}{i_x} = \frac{1}{g_m + \frac{1}{r_\pi}}$$

$$R_{out} \approx \frac{1}{g_m}$$

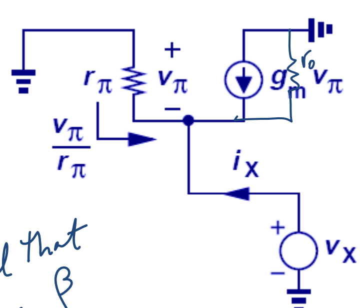
$$(V_A = \infty)$$

Impedance seen at the Emitter

- The impedance seen at the emitter is approximately equal to the inverse of its transconductance, if the base is grounded.



(a)



recall that $r_\pi = \frac{\beta}{g_m}$

(b)

$$\frac{v_x}{i_x} = \frac{1}{g_m + \frac{1}{r_\pi}}$$

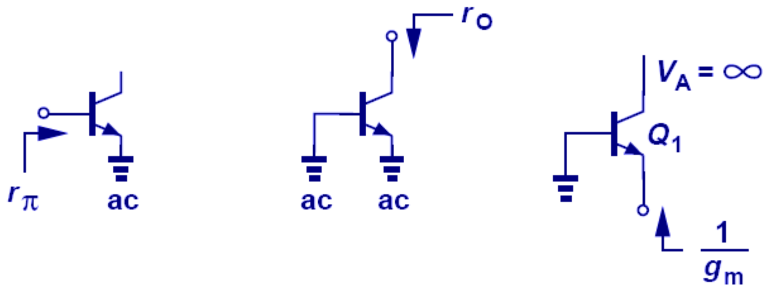
$$R_{out} \approx \frac{1}{g_m}$$

$$(V_A = \infty)$$

$r_o = \infty$

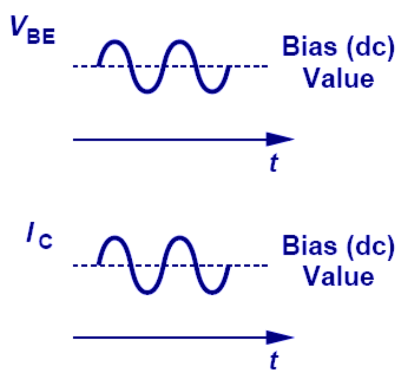
Summary of BJT Impedances

1. Looking into the base, the impedance is r_π if the emitter is (ac) grounded.
2. Looking into the collector, the impedance is r_o if emitter is (ac) grounded.
3. Looking into the emitter, the impedance is $1/g_m$ if base is (ac) grounded and Early effect is neglected.



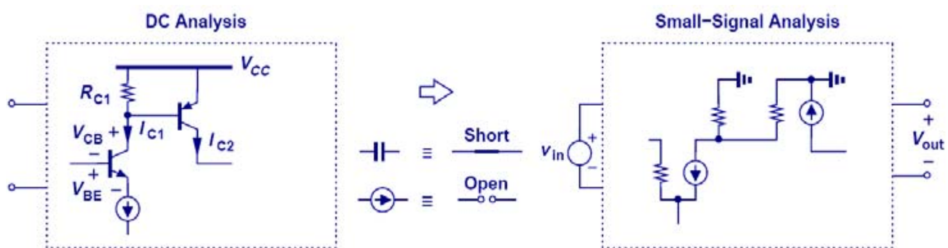
Biasing of BJT

- 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.



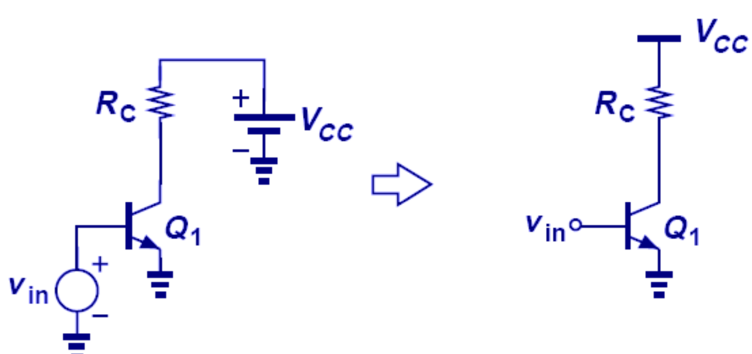
DC Analysis *vs.* Small-Signal Analysis

- Firstly, DC analysis is performed to determine the operating point and to obtain the small-signal model parameters.
- Secondly, independent sources are set to zero and the small-signal model is used.



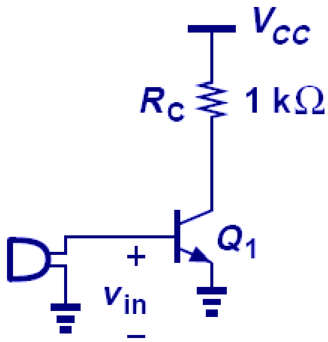
Simplified Notation

- 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 $v_{in.}$



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.



Example of Bad Biasing

- The microphone is connected to the amplifier in an attempt to amplify the small output signal of the microphone.
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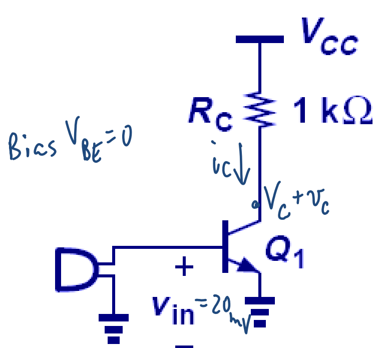
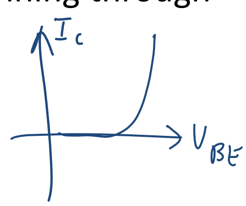
to a higher value.





$i_c = I_S e^{v_{in}/V_T}$

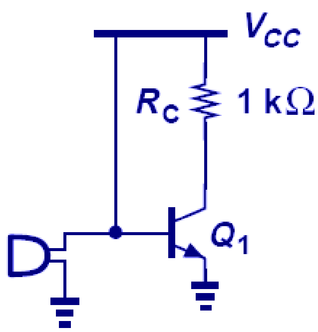
If $I_S = 6\times10^{-16}$ A, then

$i_c = 1.29\times10^{-15}$ A

$v_c = -i_c R_c = 1.29\times10^{-12}$ V (small!)

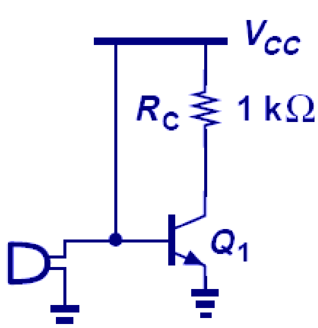
Another Example of Bad Biasing

- 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.



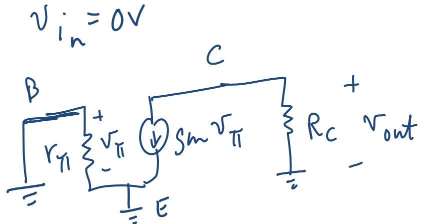
Another Example of Bad Biasing

- 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.



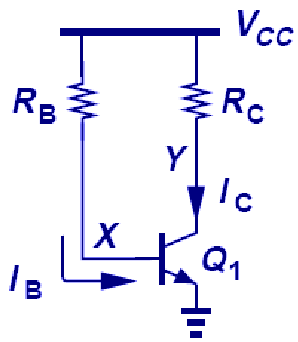
small-signal input voltage

$v_{in} = 0V$

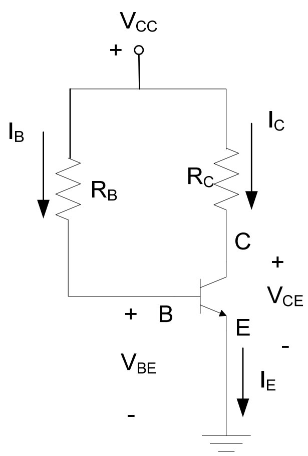


Biasing with Base Resistor

- 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 β variations.



Biasing with Base Resistor



Using KVL in the base-emitter loop,

$V_{CC} – I_B R_B – V_{BE} = 0$
or, $I_B = (V_{CC}-V_{BE})/R_B$

$I_C = \beta I_B = \beta(V_{CC}-V_{BE})/R_B$

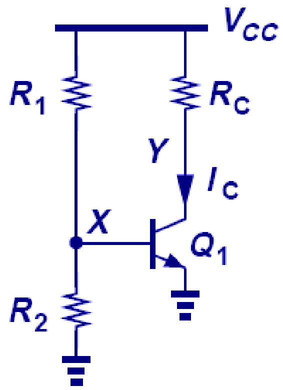
Using KVL in the collector-emitter loop,

$V_{CC} – I_C R_C – V_{CE} = 0$
or, $V_{CE} = V_{CC} - I_C R_C$

Q(V_{CE},I_C) is set

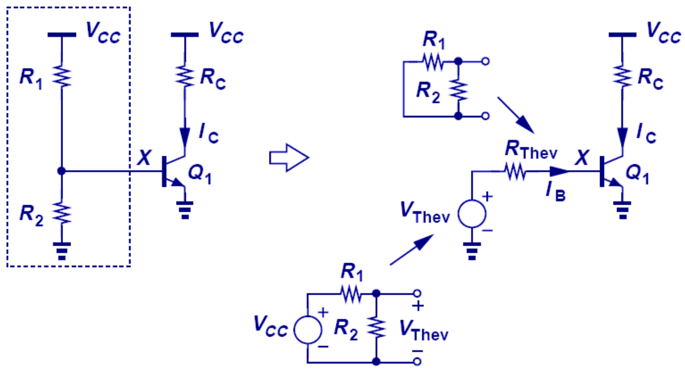
Improved Biasing: Resistive Divider

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



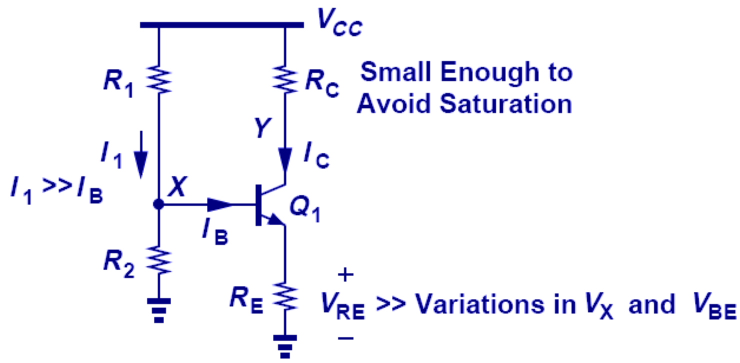
Accounting for Base Current

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



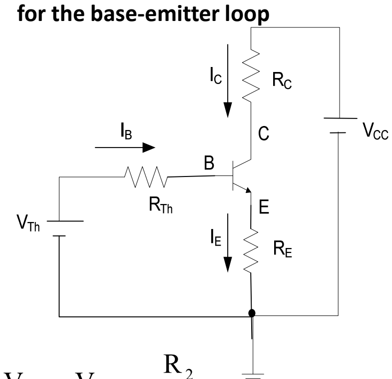
Emitter Degeneration Biasing

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



Emitter Degeneration Biasing

Thevenin's Equivalent Circuit for the base-emitter loop



$$V_{Th} = V_{CC}\frac{R_2}{(R_1 + R_2)}$$

$$R_{Th} = R_1 \| R_2 = \frac{R_1 R_2}{(R_1 + R_2)}$$

Base-Emitter Loop

$$V_{Th} - I_B R_{Th} - V_{BE} - (\beta + 1) I_B R_E = 0$$

$$\text{or, } I_B = \frac{V_{Th} - V_{BE}}{R_{Th} + (\beta + 1) R_E}$$

Collector- Emitter Loop

$$I_C = \beta I_B = \frac{\beta (V_{Th} - V_{BE})}{R_{Th} + (\beta + 1) R_E}$$

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E = V_{CC} - I_C R_C - (I_C + I_B) R_E$$

Emitter Degeneration Biasing

Bias Stabilization

$$I_C = \frac{\beta(V_{Th} - V_{BE})}{R_{Th} + (\beta+1)R_E} \qquad \left[V_{Th} = V_{CC}\frac{R_2}{(R_1+R_2)}\right]$$

If $R_{Th} << (\beta+1)R_E$, then

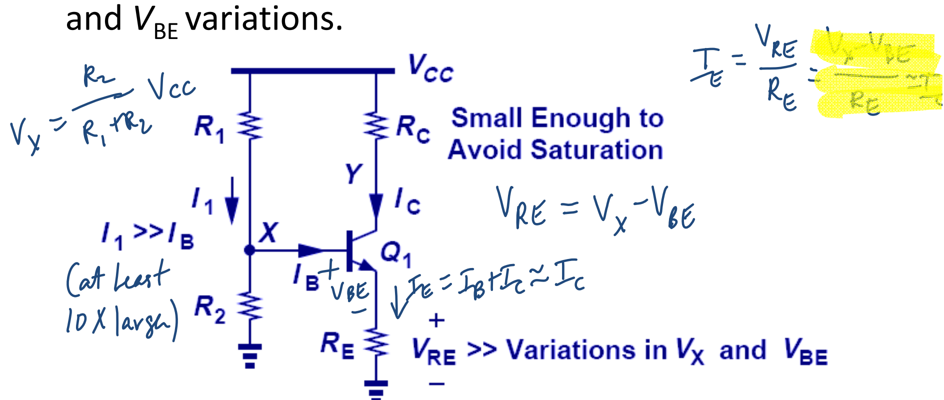
$$\left[R_{Th} = R_1 \| R_2 = \frac{R_1 R_2}{(R_1+R_2)}\right]$$

$$I_C \approx \frac{V_{Th} - V_{BE}}{R_E}$$

So, I_C is independent of β

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 β (if $I_1 >> I_B$) and V_{BE} variations.



Bias Circuit Design Procedure

1. Choose a value of I_C to provide the desired small-signal model parameters: g_m, r_π, *etc*.

   $g_m = \frac{I_C}{V_T}$; $r_\pi = \frac{\beta}{g_m}$

2. Considering the variations in R_1, R_2, and V_{BE}, choose a value for V_{RE}.

   $V_{RE} \approx I_C R_E$, 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.

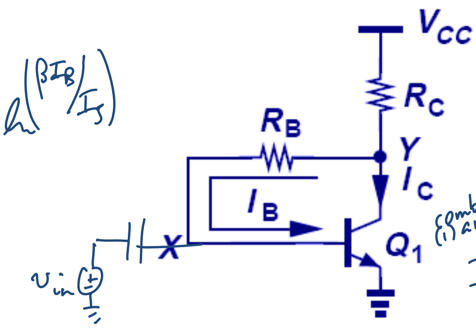
   $V_X = \frac{R_2}{R_1+R_2} V_{CC}$ and $I_1 >> I_B$

5. 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.

$V_{BE} = V_T \ln(\beta I_B / I_S)$



$V_Y = V_{CC} - I_C R_C$ (1)

$V_Y = V_{BE} + I_B R_B = V_{BE} + \frac{I_C}{\beta} R_B$ (2)

combining (1) and (2):

$I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta} \approx \frac{V_{CC} - V_{BE}}{R_C}$

Self-Biasing Design Guidelines

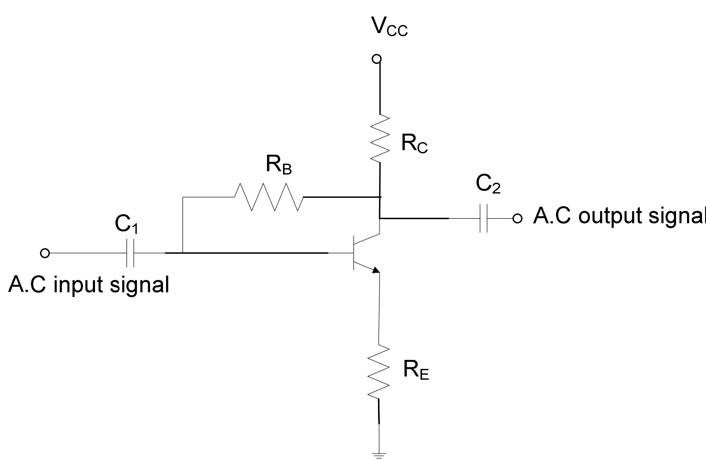
$$(1)\ \ R_C >> \frac{R_B}{\beta}$$

$$(2)\ \ \Delta V_{BE} << V_{CC} - V_{BE}$$

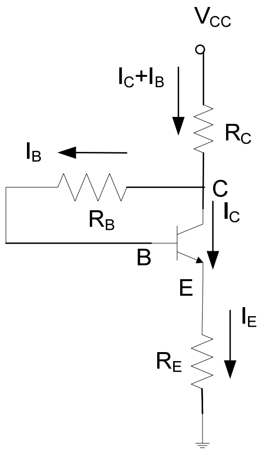
(1) provides insensitivity to β.

(2) provides insensitivity to variation in V_{BE}.

Emitter and Collector Feedback Bias



Emitter and Collector Feedback Bias



Applying KVL

or, V_{CC}- $(I_C+I_B)R_C$- I_BR_B-V_{BE}-$(\beta+1)I_BR_E$= 0

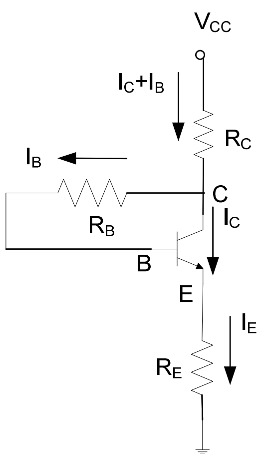
or, V_{CC}- $(\beta I_B+I_B)R_C$- I_BR_B-V_{BE}- $(\beta+1)I_BR_E$ = 0

or, V_{CC} – $\{R_B+(\beta+1)(R_C+R_E)\}I_B$-$V_{BE}$ = 0

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)(R_C + R_E)}$$

$$\mathbf{V_{CE} = V_{CC} - (I_C+I_B)(R_C+R_E)}$$

Emitter and Collector Feedback Bias



$$I_C = \frac{(V_{CC} - V_{BE})\beta}{R_B + (\beta + 1)(R_C + R_E)}$$

$$\mathbf{V_{CE} = V_{CC} - (I_C+I_B)(R_C+R_E)}$$

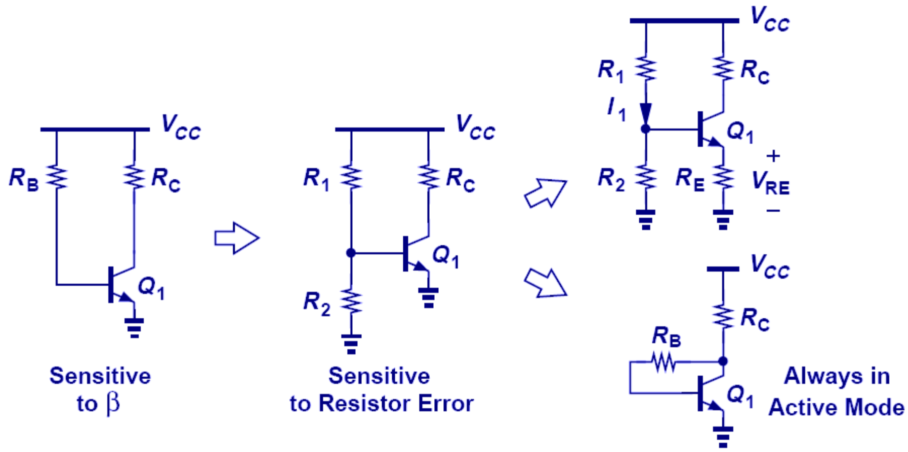
Bias Stabilization

If R_B<< $(\beta+1)(R_C+R_E)$, then

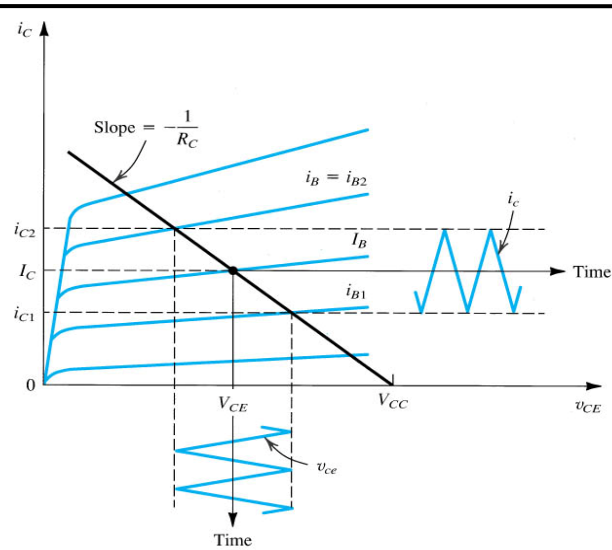
$$\text{or, } I_C \approx \frac{(V_{CC} - V_{BE})}{(R_C + R_E)}$$

So, I_C is independent of β

Summary of Biasing Techniques



Transistor as an Amplifier (ac in active region)



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.