كلية مدينة العلم الجامعة
قسم هندسة الحاسوب

محاضرات المرحلة الاولى لمادة الهندسة الالكترونية

اعداد

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The BJT As An Amplifier

المحاضرة الثالثة

References

Text Books :

1-ELECTRONIC DEVICES AND CIRCUIT THEORY

Eleventh Edition By

Robert L. Boylestad and Louis Nashelsky

2-ELECTRONIC DEVICES

Ninth Edition By

Thomas L. Floyd

The BJT as an Amplifier

- **Objectives**

  1. Biasing

  2. DC equations

  3. Transconductance

  4. Input resistance looking into the base

  5. Input resistance looking into the emitter

  6. Voltage gain

  7. Gummel plots

- **Lesson**

  1. Biasing

  1) For our amplifiers, the BJT must be biased in the FORWARD-ACTIVE

  2) However, it's a difficult challenge to establish a CONSTANT DC CURRENT

  3) Our goal: A Q point insensitive to TEMPERATURE , ß , V_{BE} .

The BJT as an Amplifier

2. DC Equations (learn 'em now)

1) $I_C = I_S e^{V_{BE}/V_T}$

2) $I_E = I_C / \alpha$

3) $I_B = I_C / \beta$

4) $V_C = V_{CC} - I_C R_C$

$$\alpha \equiv \frac{\beta}{\beta + 1} \approx 0.99$$

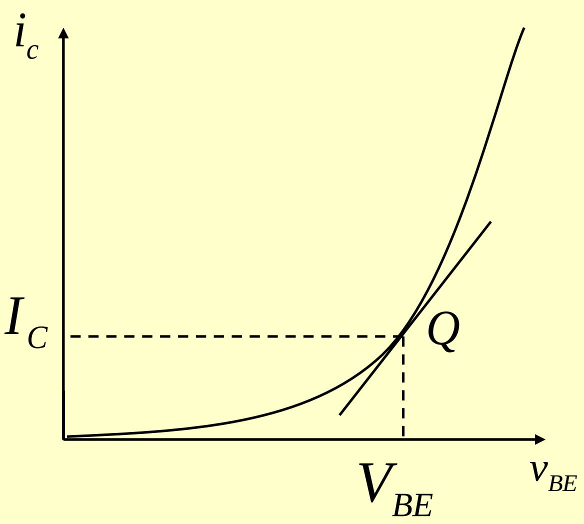
$$\beta \equiv \frac{\alpha}{\alpha + 1} \approx 100$$

3. Transconductance (remember the small-signal approximation from before?)

- **Valid only for $v_{BE} \leq 10$ mV**
- **Defined as the incremental change in output current for an incremental change in input voltage at a DC operating point…..**

$$g_m = \left. \frac{\delta i_C}{\delta v_{BE}} \right|_{i_C = I_C}$$

The BJT as an Amplifier



$$i_C = I_S e^{V_{BE}/V_T} = I_S e^{(V_{BE}+v_{be})/V_T} = I_S e^{V_{BE}/V_T} e^{v_{be}/V_T} = I_C e^{v_{be}/V_T}$$

If $v_{be} << V_T$ $\quad (e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \ldots\ldots)$

$$i_C \approx I_C(1 + \frac{V_{be}}{V_T}) = I_C + I_C \frac{v_{be}}{V_T} \Rightarrow i_c = \frac{I_C}{V_T} v_{be} = g_m v_{be}$$

- **Note that $i_C = I_C$ at $v_{BE} = V_{BE}$, so……**

$$g_m \equiv \frac{\delta}{\delta v_{BE}} I_S e^{v_{BE}/V_T} \bigg|_{i_C = I_C} = \boxed{\frac{I_C}{V_T}}$$

The BJT as an Amplifier

Input Resistance " *looking into* " the Base (*highlight this* in your text & on this page!)

- **Defined as the incremental change input voltage for an incremental change in base current at a DC operating point…**

$$r_\pi = \left.\frac{\delta v_{BE}}{\delta i_B}\right|_{i_C = I_C} = \beta \left.\frac{\delta v_{BE}}{\delta i_B}\right|_{i_C = I_C} = \boxed{\beta \frac{V_T}{I_C}}$$

- **Other important relationships (*be prepared to use any of these!)***

$$r_\pi = \frac{\beta}{g_m} \qquad r_\pi = \frac{V_T}{I_B}$$

The BJT as an Amplifier

Input Resistance "looking into " the Emitter (hightlight this in your text & on this page)

- Define as the incremental change in input voltage for an incremental change in emitter current at DC operating point…..

$$r_e = \left.\frac{\delta v_{BE}}{\delta i_E}\right|_{i_C = I_C} = \left.\frac{\beta}{\beta+1}\right|_{i_C = I_C} = \left(\frac{\beta+1}{\beta}\right)^{-1} \bullet \frac{V_T}{I_C}$$

- Other important relationship (be prepared to use either of them!)

$$r_e = \frac{V_T}{I_E} \qquad r_e = \frac{\alpha}{g_m} \approx \frac{1}{g_m}$$

The BJT as an Amplifier

Relationship between r_π and r_e

- The <u>same</u> input resistance . . . just " viewed from two different places ! "

$$r_\pi = \frac{V_T}{I_B}$$

$$r_e = \frac{V_T}{I_E}$$

$$\Rightarrow I_E = (\beta + 1) I_B$$

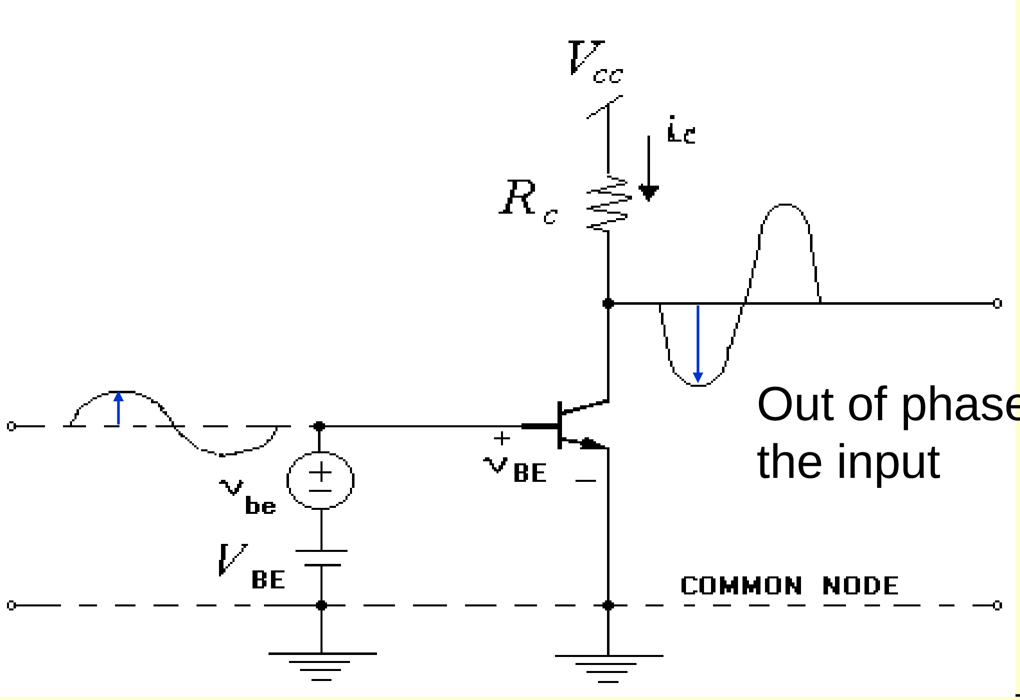
$$r_\pi = (\beta + 1) r_e$$

$$r_e = \frac{r_\pi}{\beta + 1}$$

The BJT as an Amplifier

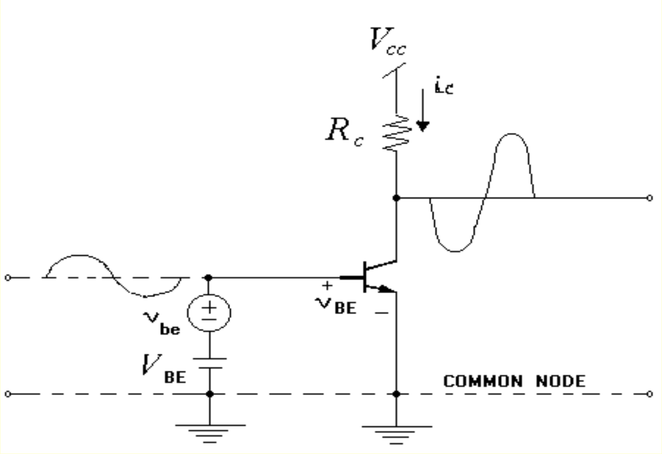
Lets look at Voltage Gain again

- A BJT senses v_{be} and causes a proportional current $g_{m}\,v_{be}$
- This is a VOLTAGE - CONTROLED CURRENT SOURCE
- So . . . How do we obtain an output voltage so that we get a voltage gain?



Out of phase with the input

Voltage Gain



$$
\begin{aligned}
v_C &= V_{CC} - i_C R_C \\
&= V_{CC} - (I_C + i_C) R_C \\
&= (V_{CC} - I_C R_C) - i_C R_C \\
&= V_C - i_C R_C
\end{aligned}
$$

Signal voltage:

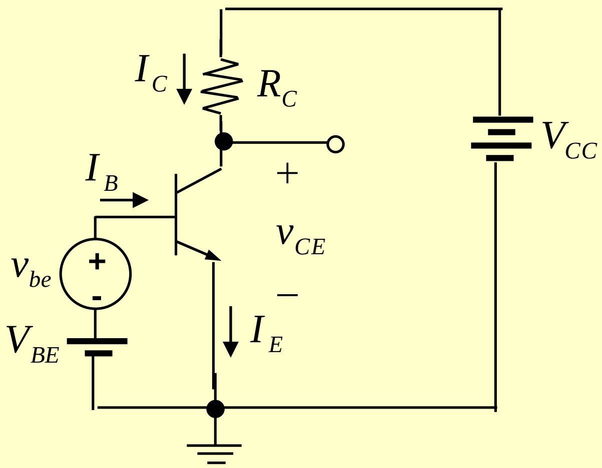
$$
\begin{aligned}
v_C &= -i_C R_C = -g_m v_{be} R_C \\
&= (-g_m R_C) v_{be}
\end{aligned}
$$

Voltage gain:

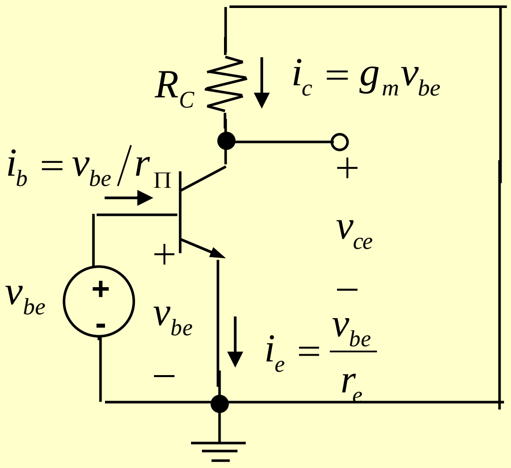
$$\text{Voltage gain} \equiv \frac{v_c}{v_{be}} = -g_m R_C$$

Small-signal equivalent circuit models

- Every current and voltage in the amplifier circuit is composed of two components: a dc component and a signal component.
- The dc components are determined from the dc circuit below on the left.
- By eliminating the dc voltages, we are left with the signal components (on the right). The resulting circuit is equivalent to the transistor as far as small-signal operation is concerned.



Amplifier circuit with dc sources



Amplifier circuit with dc sources eliminated

The Hybrid-Π Model

voltage-controlled current source

$$i_c = g_m v_{be} \quad \text{and} \quad i_b = v_{be}/r_\Pi$$

$$i_e = \frac{v_{be}}{r_\Pi} + g_m v_{be} = \frac{v_{be}}{r_\Pi}\left(1 + g_m r_\Pi\right)$$

$$= \frac{v_{be}}{r_\Pi}\left(1+\beta\right) = v_{be} \Big/ \left(\frac{r_\Pi}{1+\beta}\right)$$

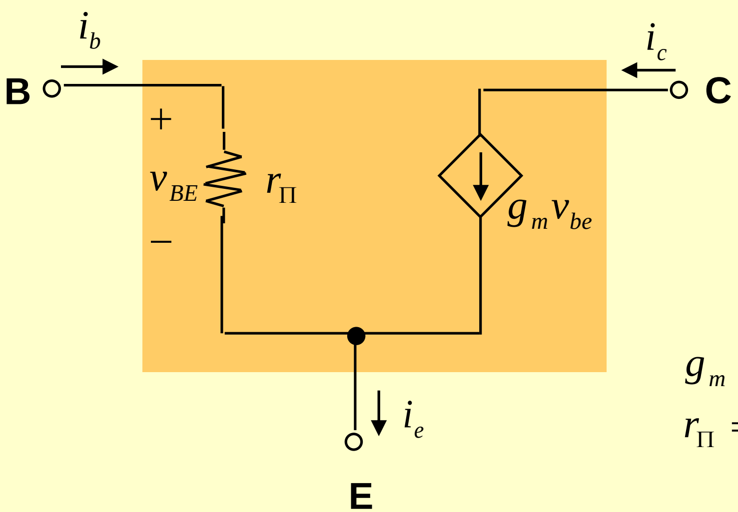
$$i_e = v_{be}/r_e$$

current-controlled current source

$$g_m v_{be} = g_m\left(i_b r_\Pi\right)$$

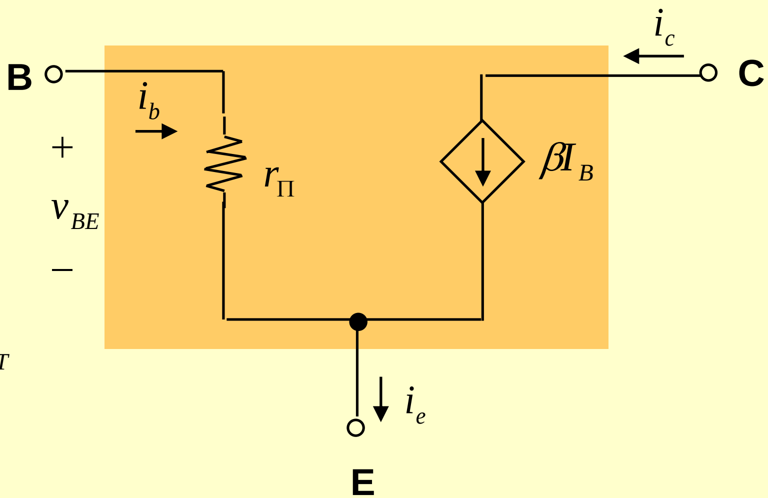
$$= \left(g_m r_\Pi\right) i_b$$

$$g_m v_{be} = \beta i_b$$



$$g_m = I_C/V_T$$

$$r_\Pi = \beta/g_m$$



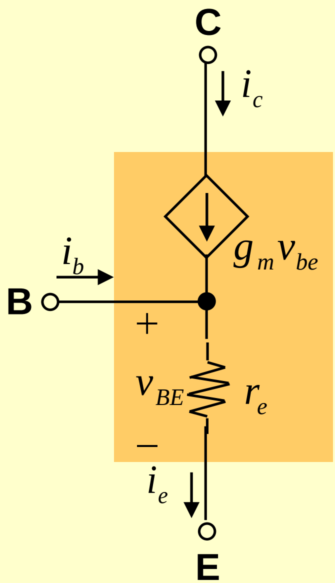
The T Model

- These models explicitly show the emitter resistance r_e rather than the base resistance r_p featured in the hybrid-π model.

$$i_b = \frac{v_{be}}{r_e} - g_m v_{be} = \frac{v_{be}}{r_e}\left(1 - g_m r_e\right)$$

$$= \frac{v_{be}}{r_e}\left(1-\alpha\right) = \frac{v_{be}}{r_e}\left(1 - \frac{\beta}{\beta+1}\right)$$

$$i_b = \frac{v_{be}}{\left(\beta+1\right)r_e} = \frac{v_{be}}{r_\Pi}$$

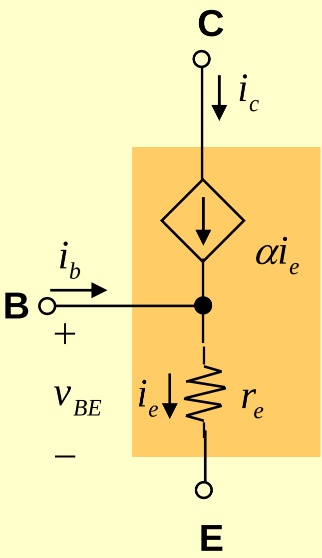


voltage-controlled current source

$$g_m v_{be} = g_m\left(i_e r_e\right)$$

$$= \left(g_m r_e\right) i_e$$

$$g_m v_{be} = \alpha i_e$$



current-controlled current source

Application of the Small-Signal Equivalent Circuits

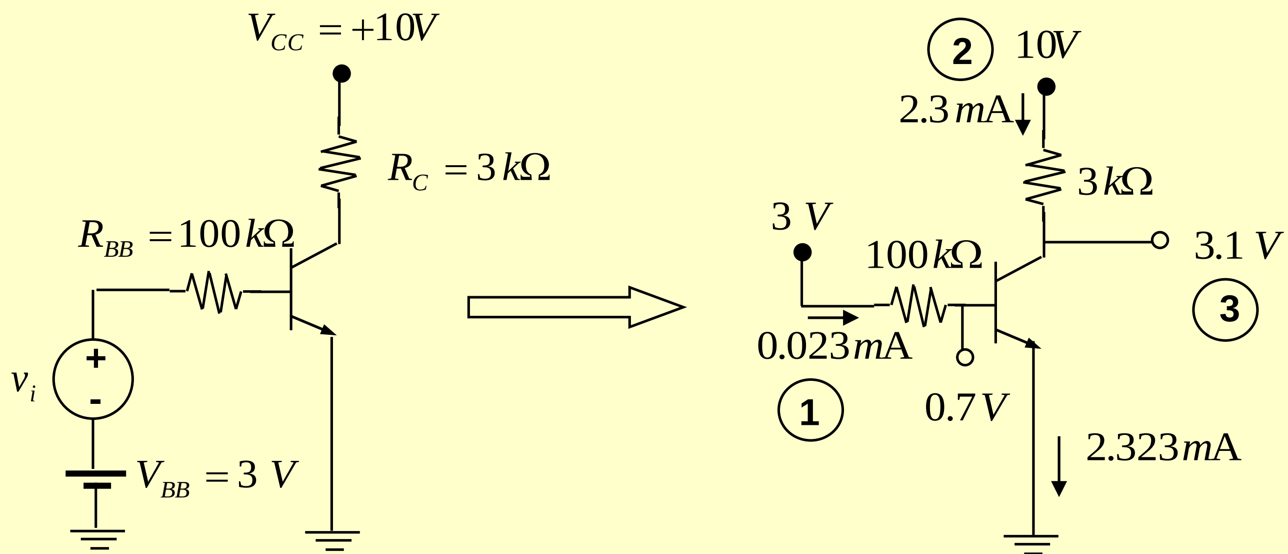
- The availability of the small-signal BJT circuit models makes the analysis of transistor amplifier circuits a systematic process consisting of the following steps:
  - Determine the dc operating point of the BJT and in particular the dc collector current IC.
  - Calculate the values of the small-signal model parameters:

$$g_m = \frac{I_C}{V_T}, \quad r_\Pi = \frac{\beta}{g_m}, \quad \text{and} \quad \mathrm{r}_e = \frac{V_T}{I_E} \approx \frac{1}{g_m}$$

  - Eliminate the dc sources by replacing each dc voltage source with a short circuit and each dc current source with an open circuit.
  - Replace the BJT with one of its small-signal equivalent circuit models. Although any one of the models can be used, one might be more convenient than the others for the particular circuit being analyzed. This point will be made clearer later in this chapter.
  - Analyze the resulting circuit to determine the required quantities (e.g., voltage gain, input resistance).

Example 4.9

- **We wish to analyze the transistor amplifier shown below to determine its voltage gain. Assume β = 100.**



1. Assume $v_i = 0$ to find the dc base current

$$I_B = \frac{V_{BB} - V_{BE}}{R_{BB}}$$

$$I_B \approx \frac{3 - 0.7}{100} = 0.023\,mA$$

2. The dc collector current will be

$$I_C = \beta I_B = 100 \times 0.023 = 2.3\,mA$$

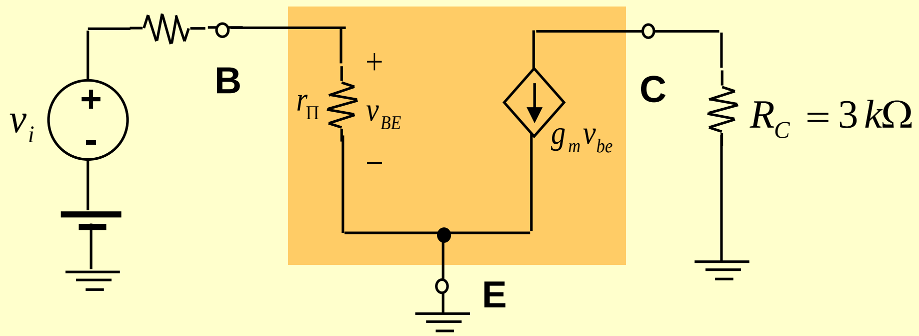
3. The dc voltage at the collector will be

$$V_C = V_{CC} - I_C R_C$$

$$V_C = 10 - 2.3 \times 3 = 3.1V$$

Example 4.9, cont'd

- **Having determined the operating point, we now proceed to determine the small-signal model parameters**



$$r_e = \frac{V_T}{I_E} = \frac{25\,mV}{(2.3/0.99)\,mA} = 10.8\,\Omega$$

$$g_m = \frac{I_C}{V_T} = \frac{2.3\,mA}{25\,mV} = 92\,mA/V$$

$$r_\Pi = \frac{\beta}{g_m} = \frac{100}{92} = 1.09\,k\Omega$$

$$v_{be} = v_i \frac{r_\Pi}{r_\Pi + R_{BB}}$$

$$= v_i \frac{1.09}{101.09} = 0.011\,v_i$$

$$v_o = -g_m v_{be} R_C$$

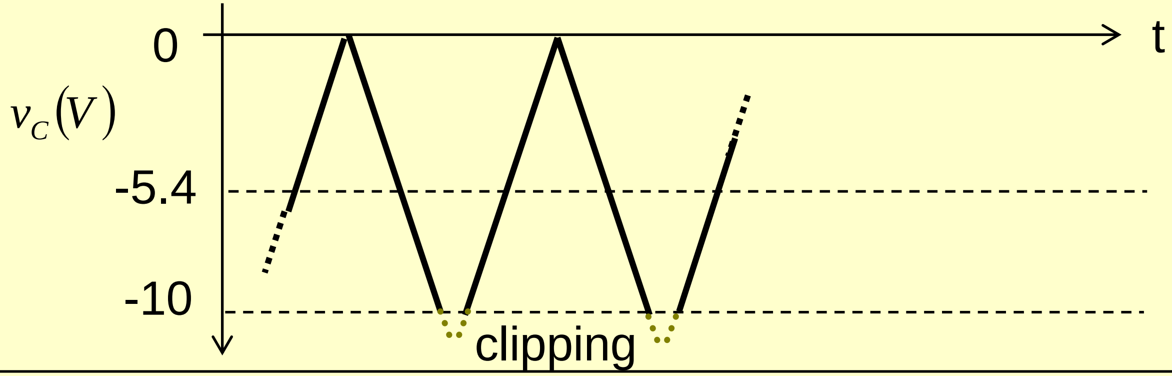
$$v_o = -92 \times 0.011\,v_i \times 3 = -3.04 v_i$$

Voltage gain :

$$\frac{v_o}{v_i} = -3.04\,V/V$$

A note about Output Signal Swing

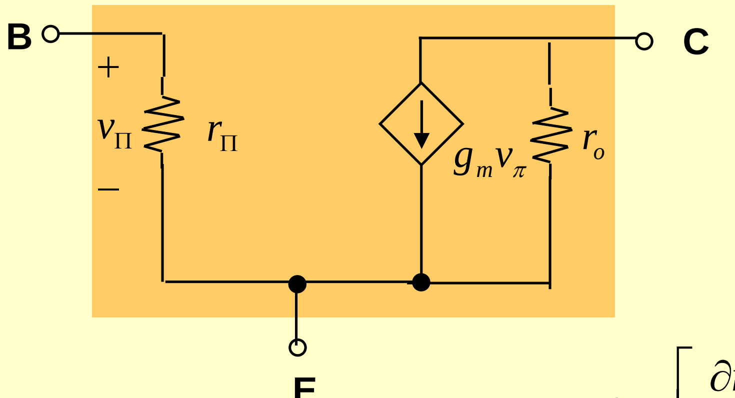
- The collector voltage (and vo) can have a maximum value of zero volts before the transistor goes from forward active mode to saturation mode since the base is grounded.
- When no input (ac) voltage is applied the output (collector) was found to be at a DC level of -5.4V.
- If we desire a symmetric output signal (about the -5.4V DC level) the signal would have to go to -5.4 - 5.4 or -10.8 Volts (this is a large output signal swing).
- This causes a problem, since our lower voltage supply is only -10V.
- In order to avoid possibly producing a distorted output signal the input signal range must be limited so that the output is not clipped as shown below. Limiting the input signal to smaller values to limit clipping is not the same as using a small signal to invoke the linear approximation as indicated in the next bullet item.
- Another important point to be made about the output signal is that it is shown to be linear in the figure below but in fact the i_C-v_{be} characteristic is not linear for a large output signal swing.



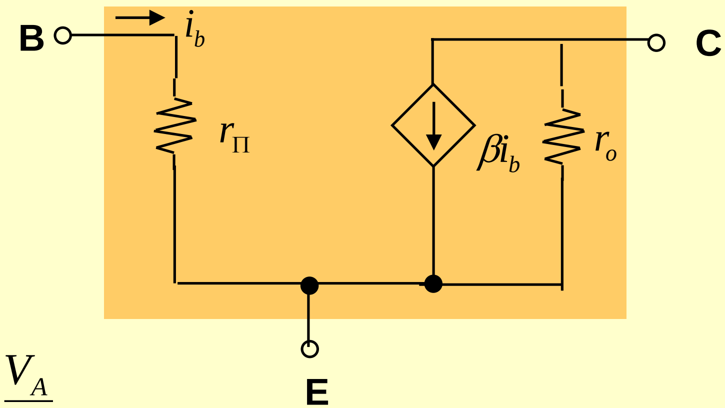
Modifying the Hybrid-π Model to Include the Early Effect

- **The Early effect causes the collector current to depend on vBE as well as vCE.**
- **The dependence on vCE is modeled by assigning a finite output resistance to the controlled current-source.**
- **By including ro in the equivalent circuit shown below, the gain will be somewhat reduced.**

voltage-controlled current source



current-controlled current source



$$r_o = \left[\frac{\partial i_C}{\partial v_{CE}} \right]^{-1}_{v_{be}=0} = \frac{V_A}{I_C}$$

$$v_o = -g_m v_{be} \left(R_C // r_o \right)$$

Summary of the BJT Small-Signal Model Parameters

- Keep these at your fingertips (I.e. formula sheet for an exam or homework or in lab)
  - See Table 4.3
- Model parameters in terms of DC bias currents

$$g_m = \frac{I_C}{V_T} \qquad r_e = \frac{V_T}{I_E} = \alpha\left(\frac{V_T}{I_C}\right)$$

$$r_\pi = \frac{V_T}{I_B} = \beta\left(\frac{V_T}{I_C}\right) \qquad r_o = \frac{V_A}{I_C}$$

- Model parameters in terms of the transconductance, g_m

$$r_e = \frac{\alpha}{g_m} \qquad r_\pi = \frac{\beta}{g_m}$$

- Model parameters in terms of r_e

$$g_m = \frac{\alpha}{r_e} \qquad r_\pi = (\beta + 1) r_e \qquad g_m + \frac{1}{r_\pi} = \frac{1}{r_e}$$

- Relationships between the common-emitter current gain and the common-base gain

$$\beta = \frac{\alpha}{1-\alpha} \qquad \alpha = \frac{\beta}{\beta + 1} \qquad \beta + 1 = \frac{1}{1-\alpha}$$