Electronic Devices

Lecture 15
Bipolar Junction Transistor

Dr. Roaa Mubarak

AC Analysis of BJT

- AC analysis of BJT included the large signal and small signal.
- Here we deal with small signal (large signal used power amplifiers).
- The analysis is complex so, we use a small signal model to replace the BJT.
- The total response = the dc response + the AC response.
- 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:

– re model

– Hybrid model

BJT Modeling

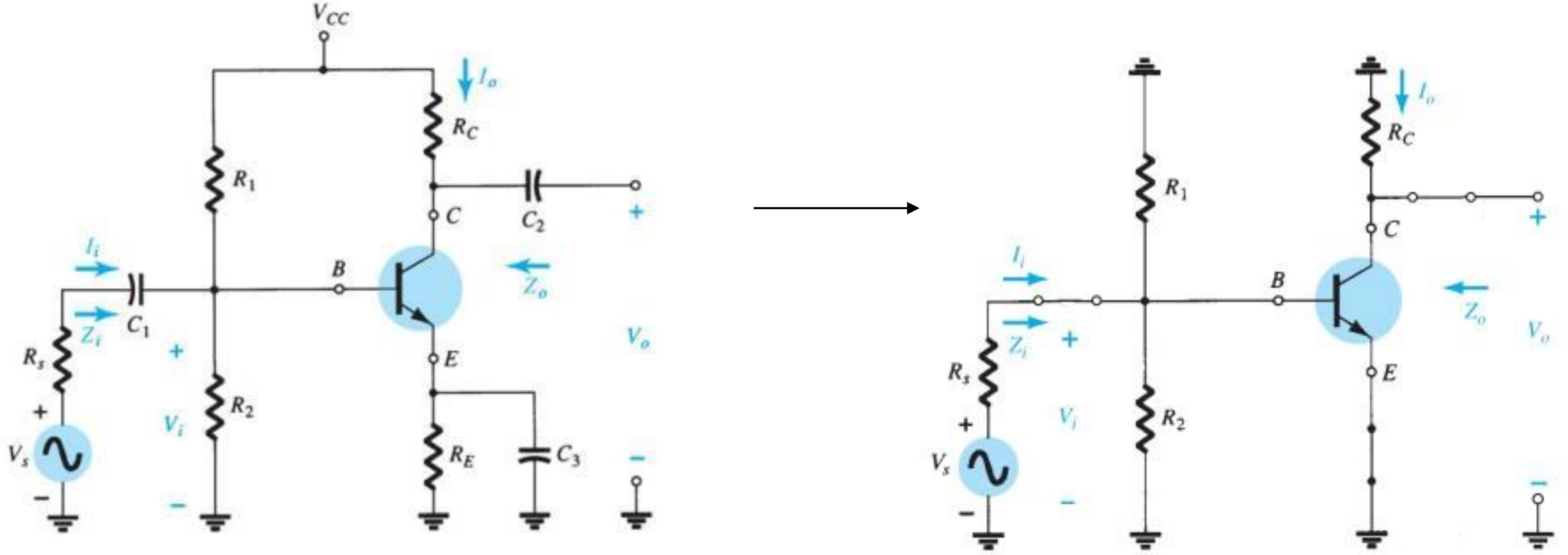
The ac equivalent of a transistor network is obtained by:

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

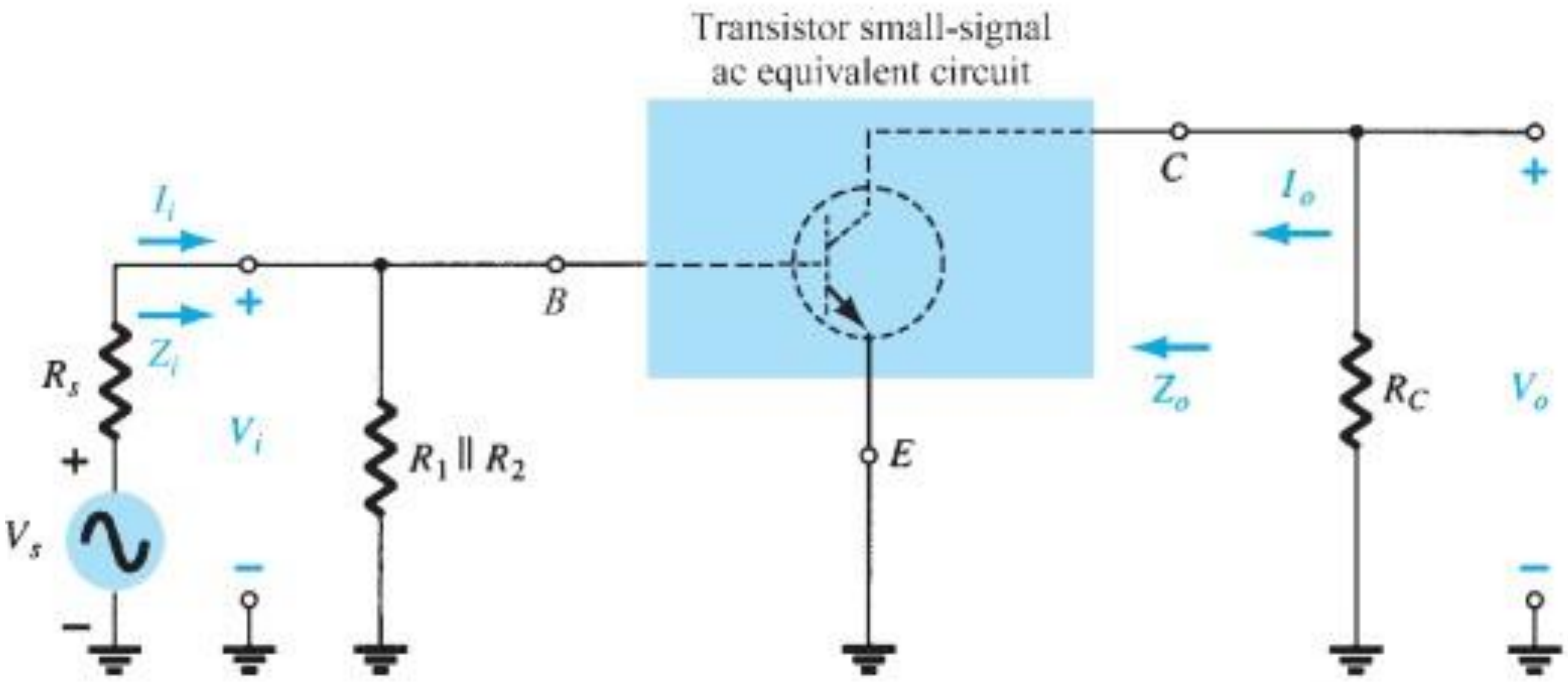


BJT small signal Modeling

5- replacing the BJT with appropriate model

– re transistor model

– Hybrid model

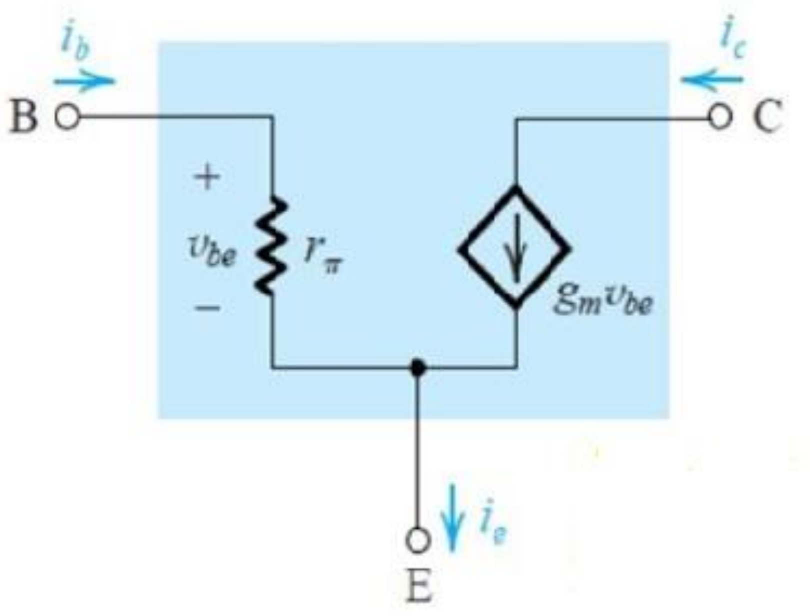


Hybrid model

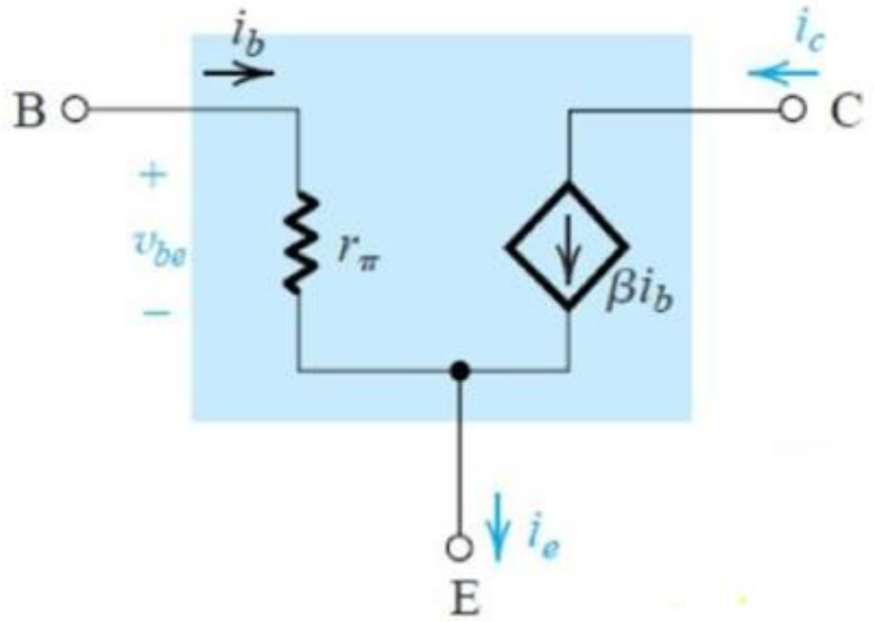
- The hybrid **π** model is most useful for analysis of high-frequency transistor applications.

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

Hybrid π model



Voltage Controlled Current Source "VCCS"



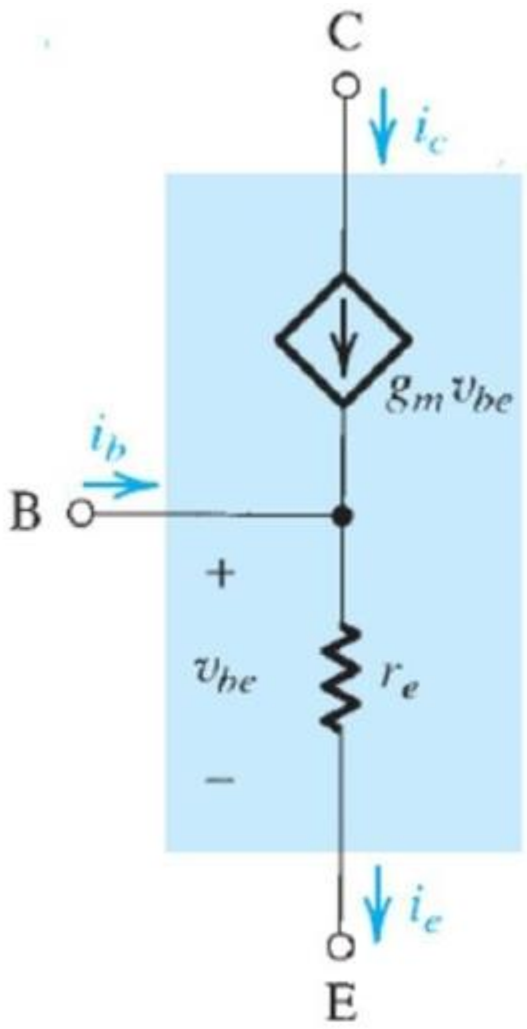
Current Controlled Current Source "CCCS"

$$g_m = \frac{I_C}{V_T}$$

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

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

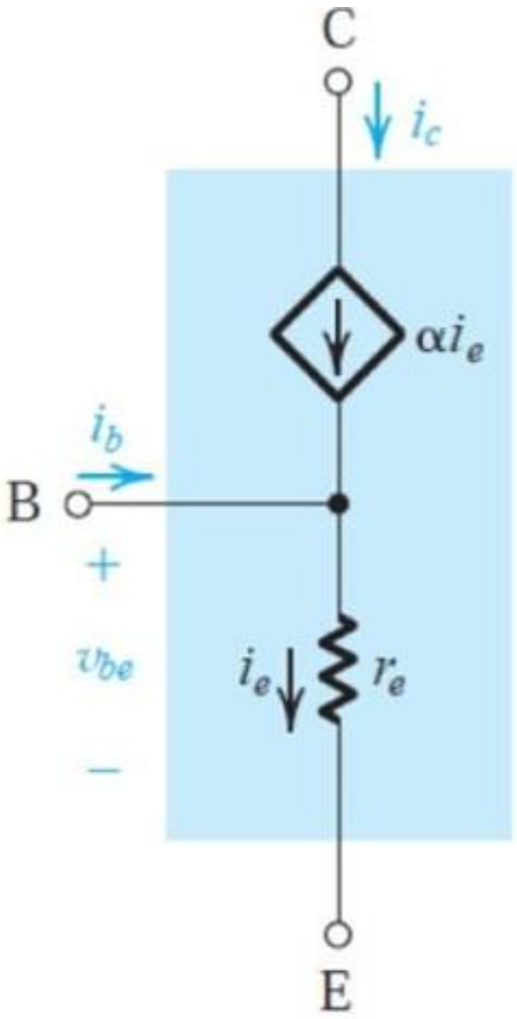
Hybrid T model



Voltage Controlled Current Source “VCCS”

$$g_m = \frac{I_C}{V_T}$$

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



Current Controlled Current Source “CCCS”

The steps for solving AC analysis of BJT

- **First DC Analysis**

Using the DC analysis to calculate the parameters of small signal model $g_m, r_{\boldsymbol{\pi}}$ *and* r_e .

- **Second AC Analysis**

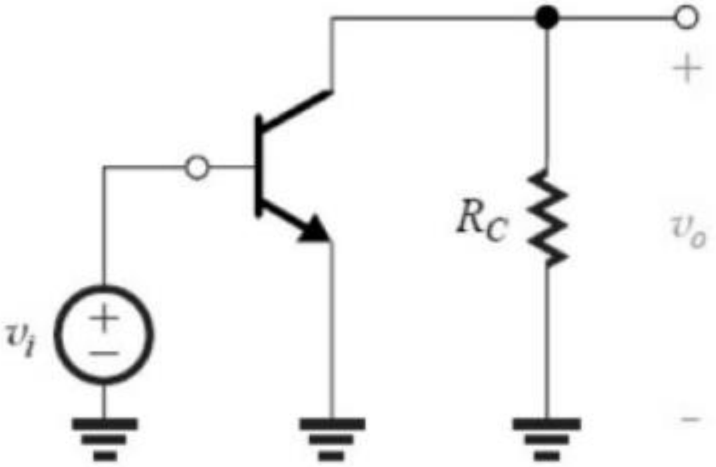
1- Replace all the capacitors by short circuits, the inductors by open circuits.

2-replace the voltage Dc source by short circuit, and replace the current DC source by open circuit.

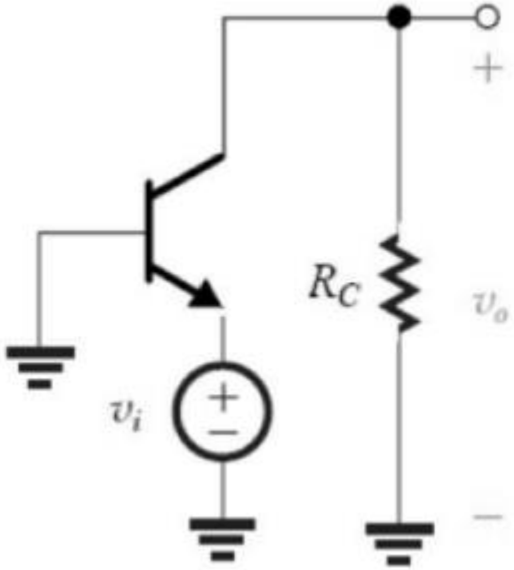
3- replace the BJT with one of small signal models.

4- Analyze the circuit to determine the amplifier gain.

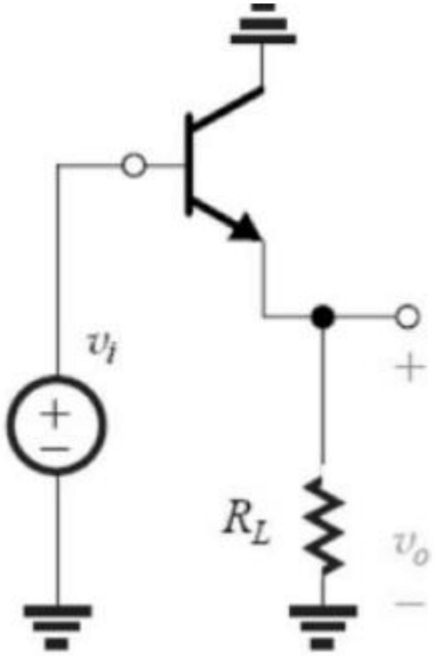
BJT Configurations



Common Emitter



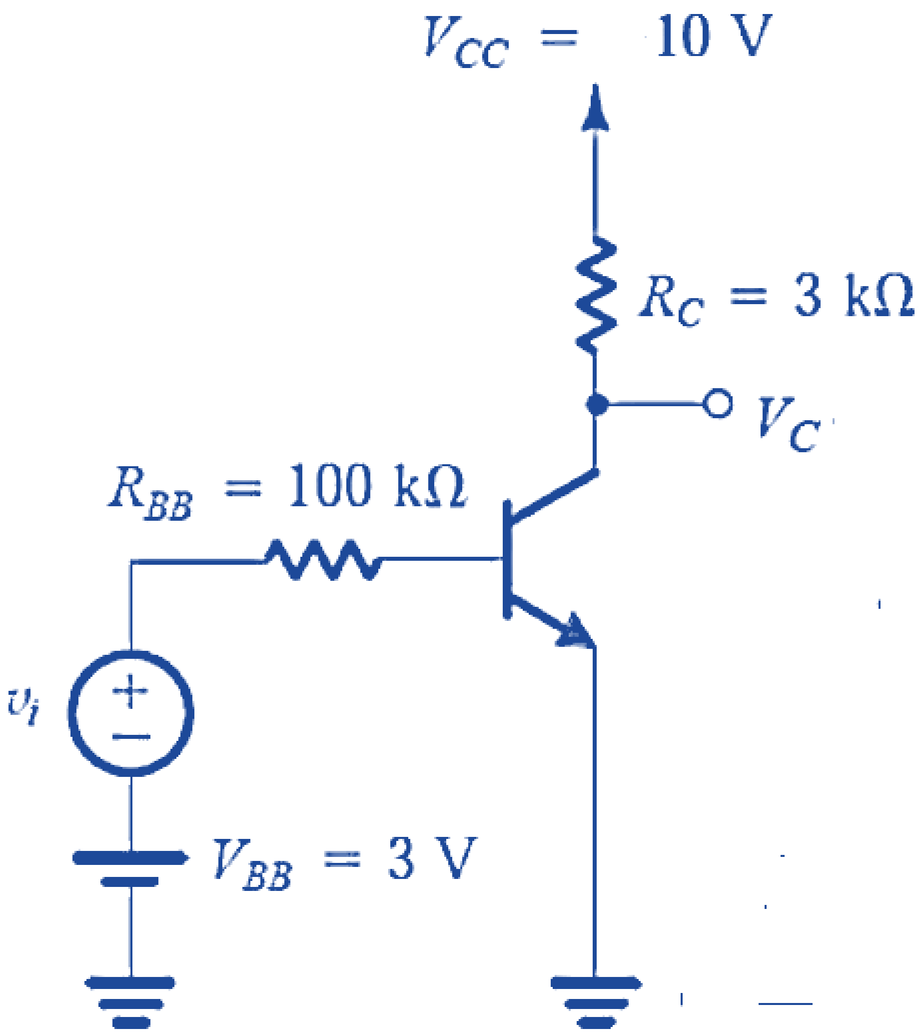
Common Base



Common Collector

Example

Determine the gain of the following amplifier as $\boldsymbol{\beta} = 100$



Solution

1- Using the DC analysis to determine the Q point

Assuming Active mode

By KVL in input loop:

-3 +100$I_B + 0.7 = 0$

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

$I_C = \boldsymbol{\beta} I_B$ = 2.3mA

$I_E = I_C + I_B = 2.323mA$

$V_o = V_c = V_{cc} - I_C R_c = 10 - (2.3)(3)$=3.1V

V_c > 0.7 then our assumption is true

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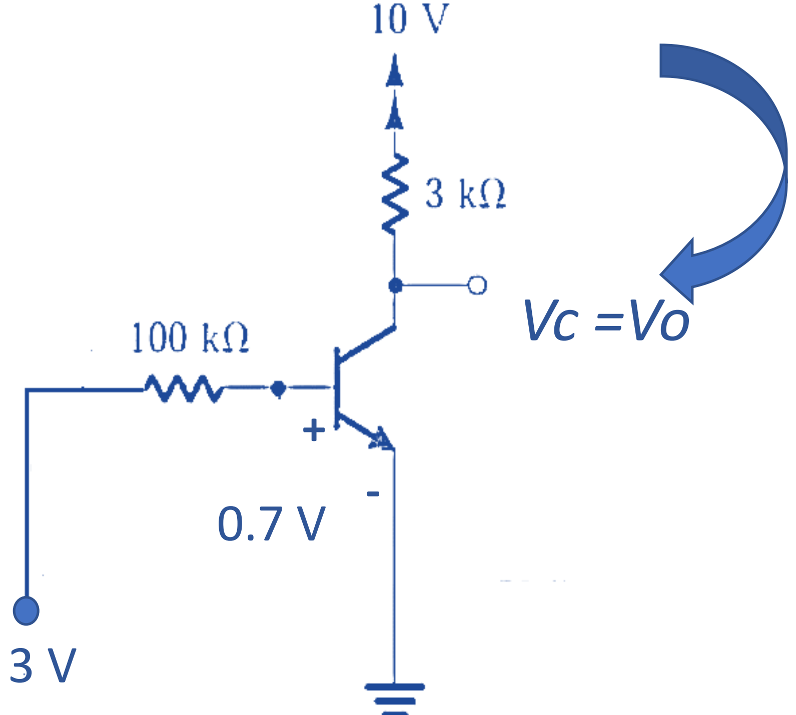
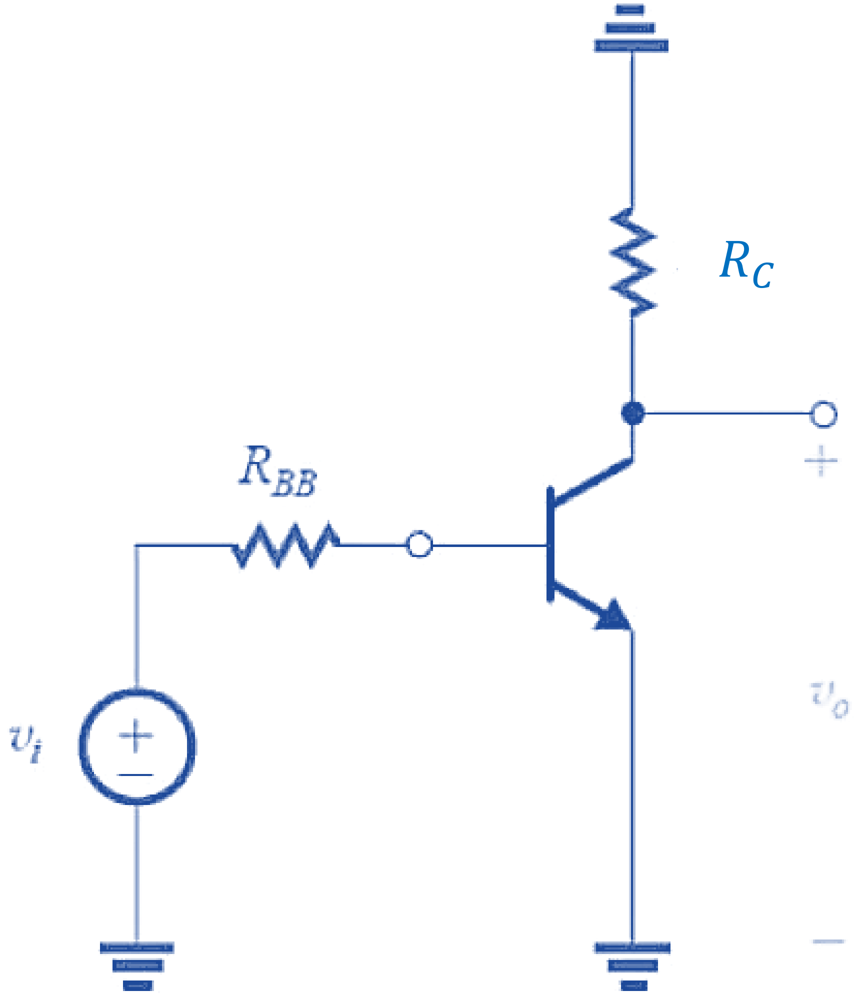


Solution

2- Determine the AC parameters.

$$g_m = \frac{I_C}{V_T} = \frac{2.3mA}{26mv} = 88\text{mA/v}$$

$$r_\pi = \frac{V_T}{I_B} = \frac{26mv}{0.023mA} = 1.13\text{k}\Omega$$



3- Draw the circuit with AC model (**π** Model)

Note: short circuit the DC voltage source and open circuit the DC current source

Solution

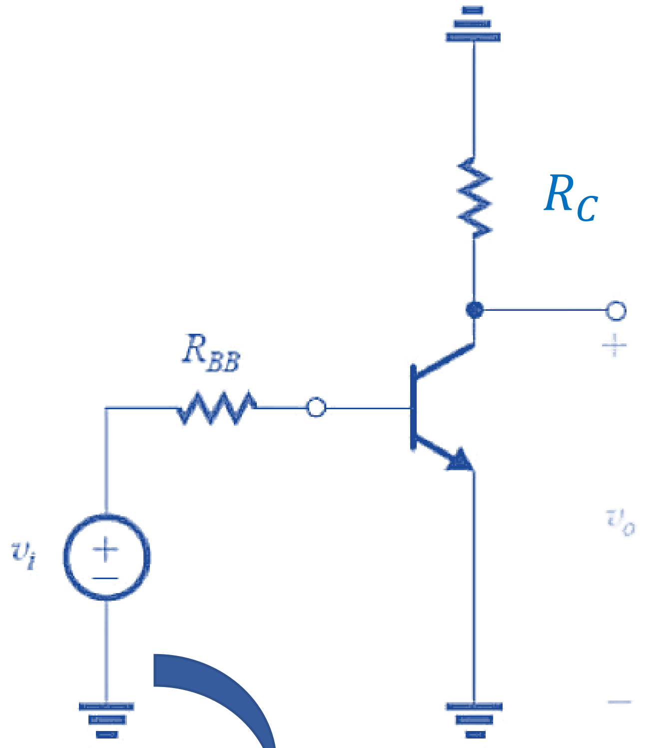
4- Analyze the small signal equivalent circuit

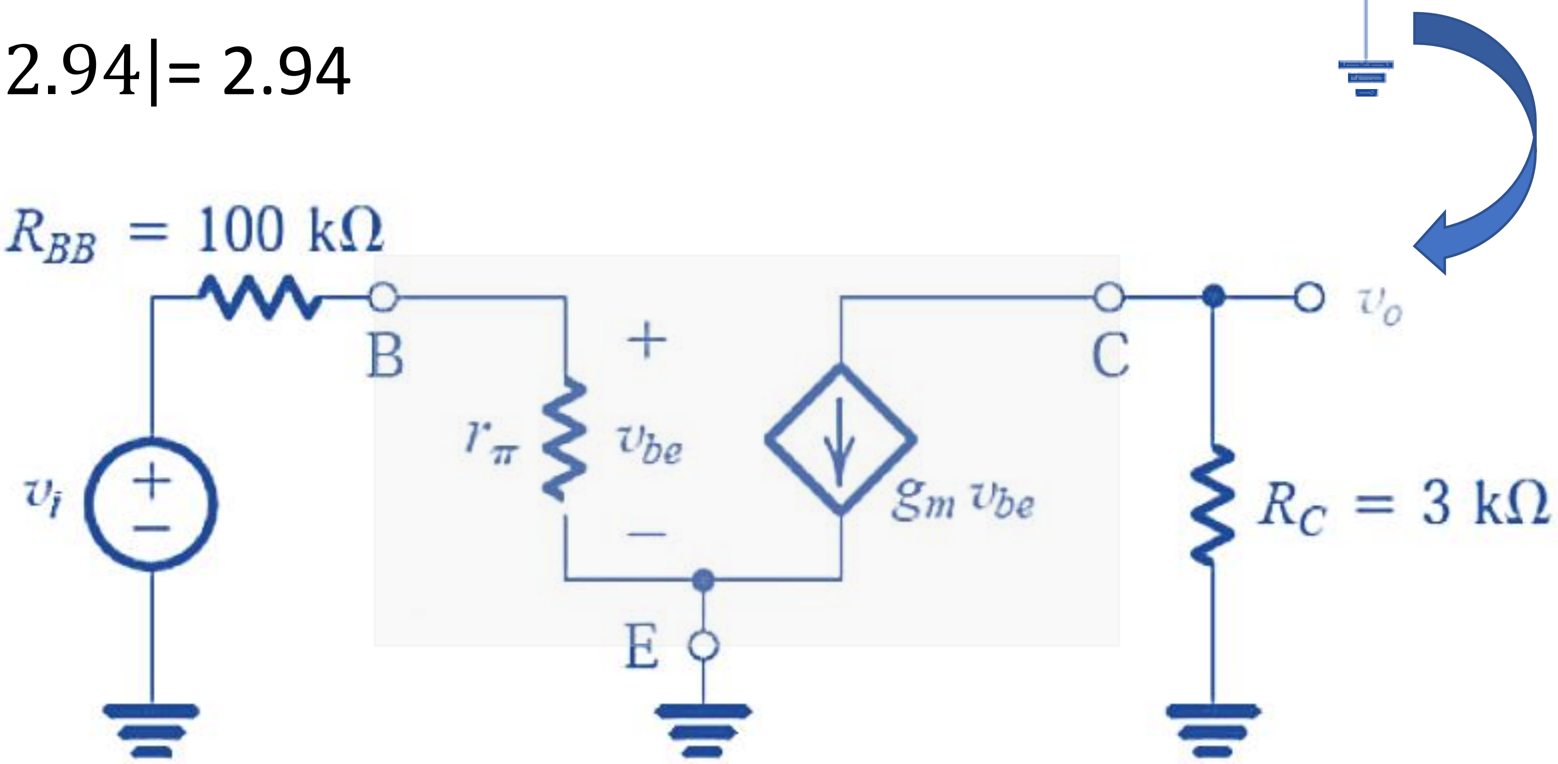
$v_o = -g_m v_{be} R_C$

$v_{be} = (\frac{r_\pi}{R_{BB}+r_\pi})v_i = (\frac{1.13}{101.13})v_i = 0.011v_i$

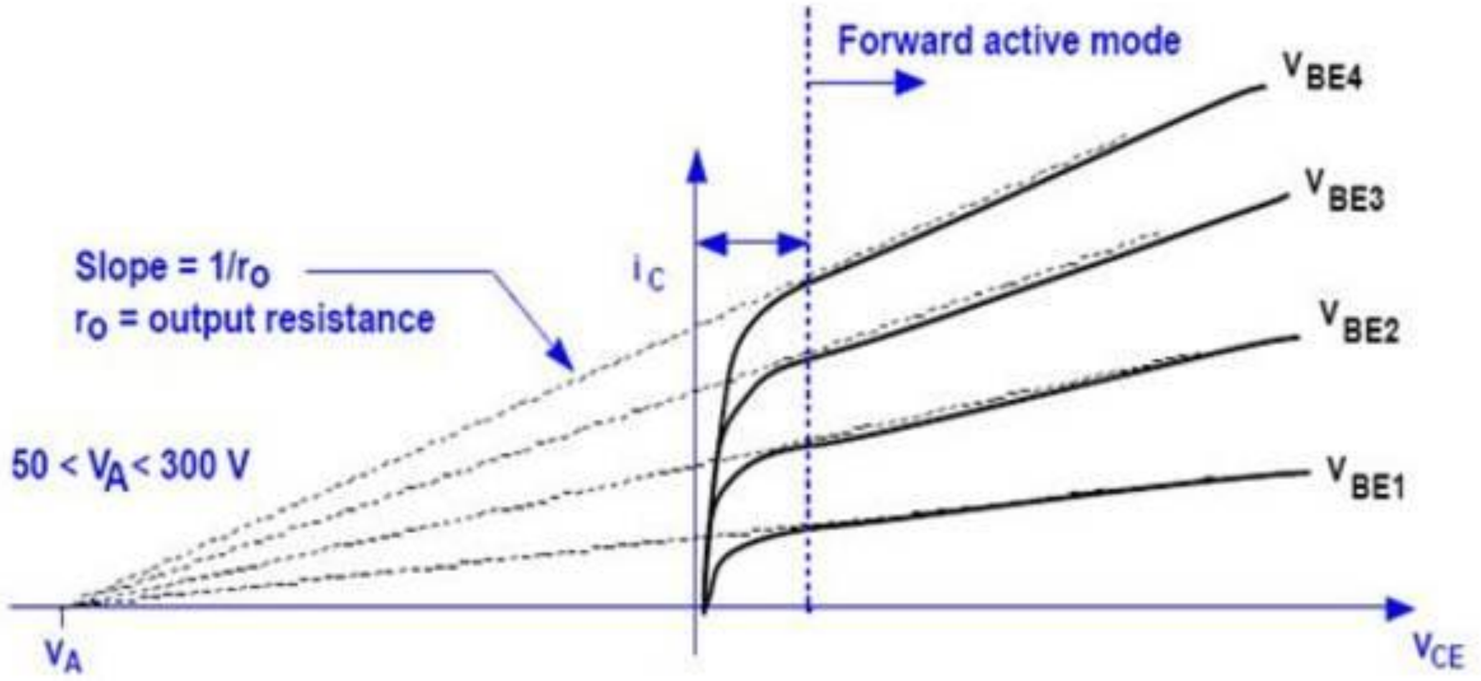
$v_o = -(88)(0.011)\ v_i(3) = -2.94\ v_i$

$A_v = \frac{v_o}{v_i} = |-2.94| = 2.94$





Early Effect

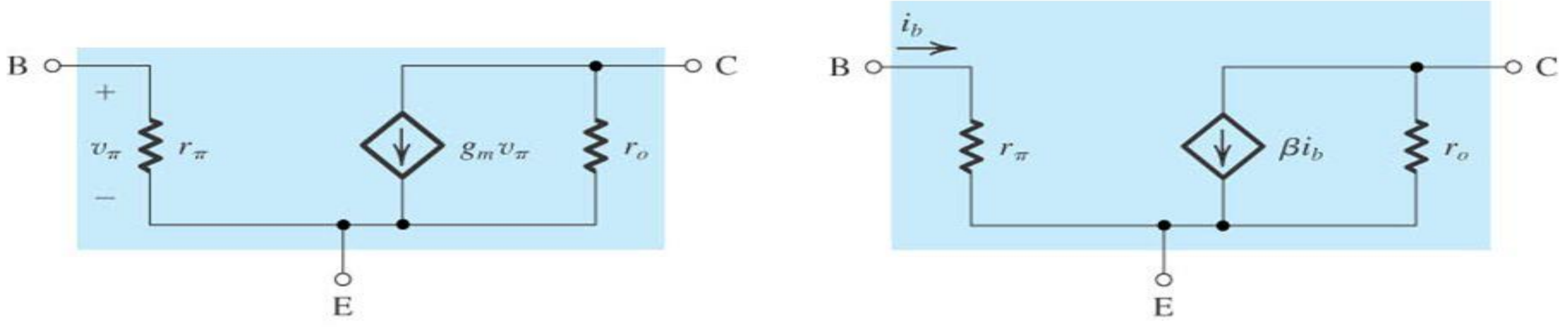


- The early effect is the variation in the width of the base in a bipolar transistor due to a variation in the applied base-to-collector voltage, and this causes the I_C depends not only on I_B but also on V_{CE}.

Early Effect

Early effect can be assigned in the ac signal model as an output resistance to the controlled source in the hybrid **π** model.

Hybrid π Model with Early Effect



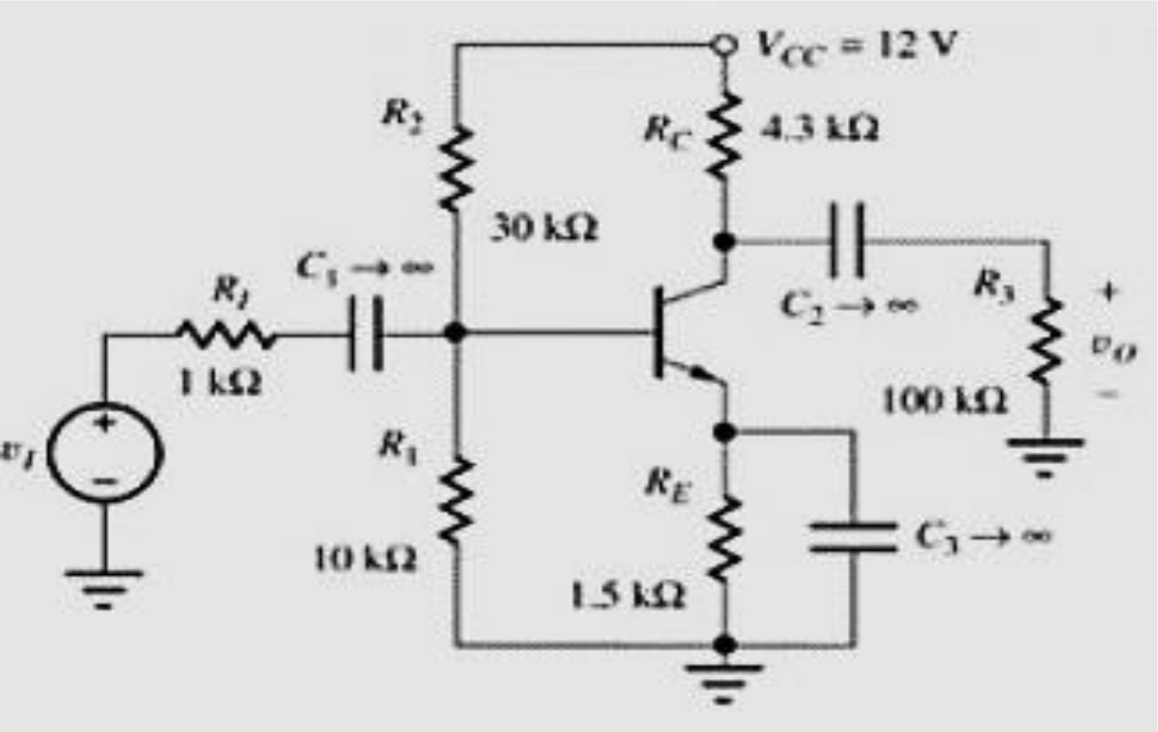
(a) (b)

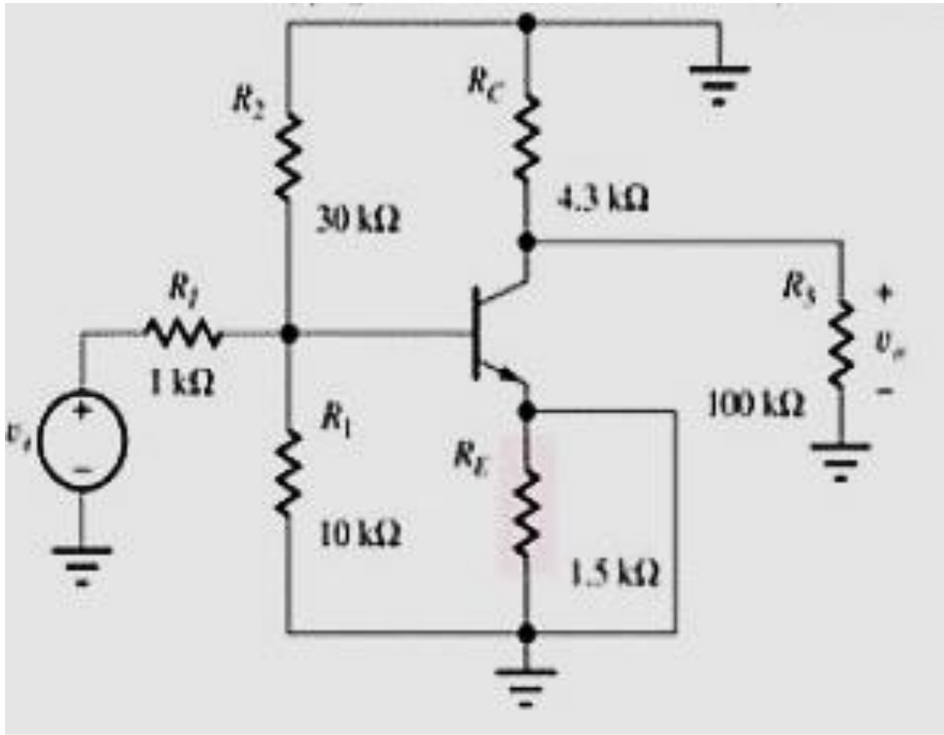
$$r_o = \frac{V_A + V_{CE}}{I_C} \approx \frac{V_A}{I_C}$$

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

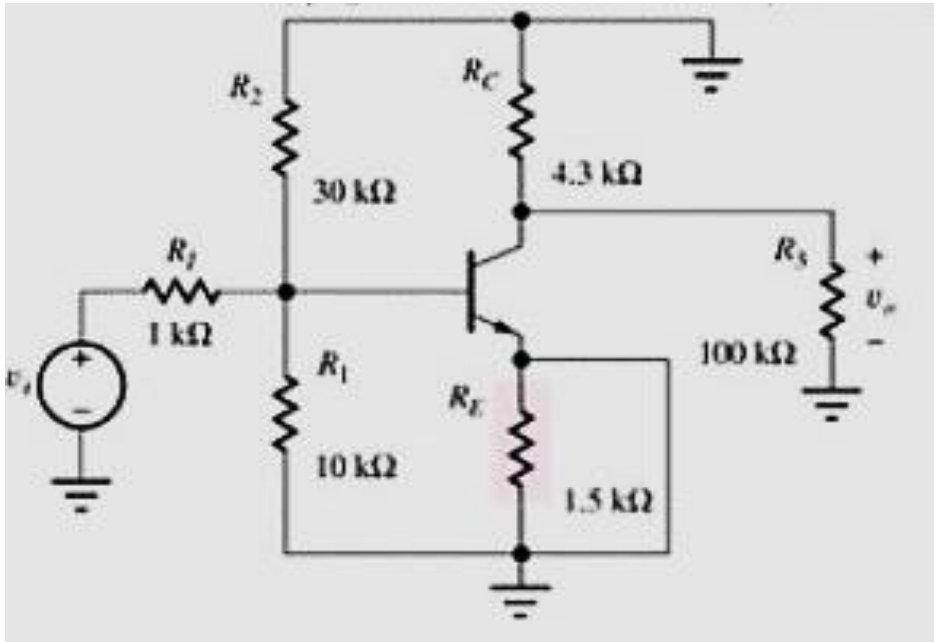
Example2

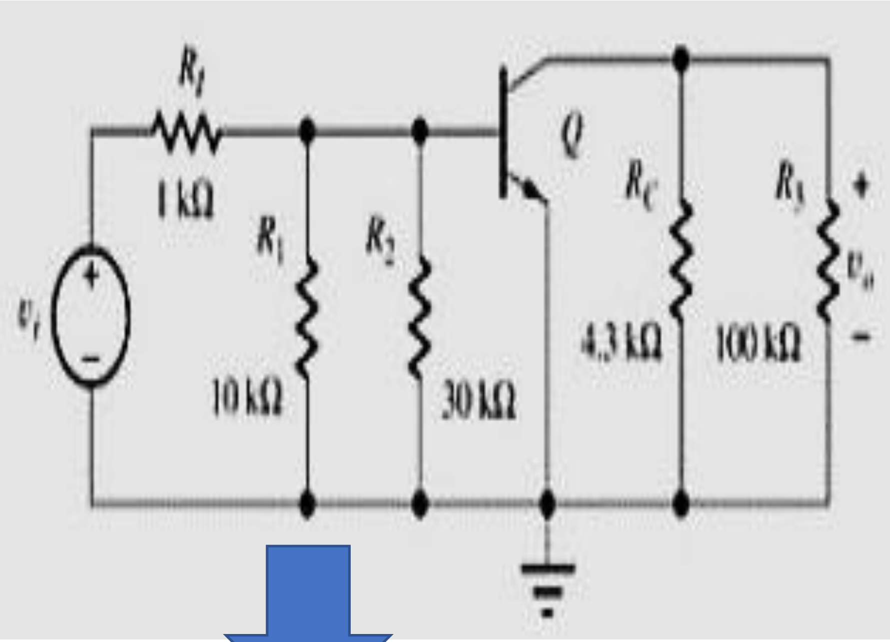
- Ac equivalent circuit

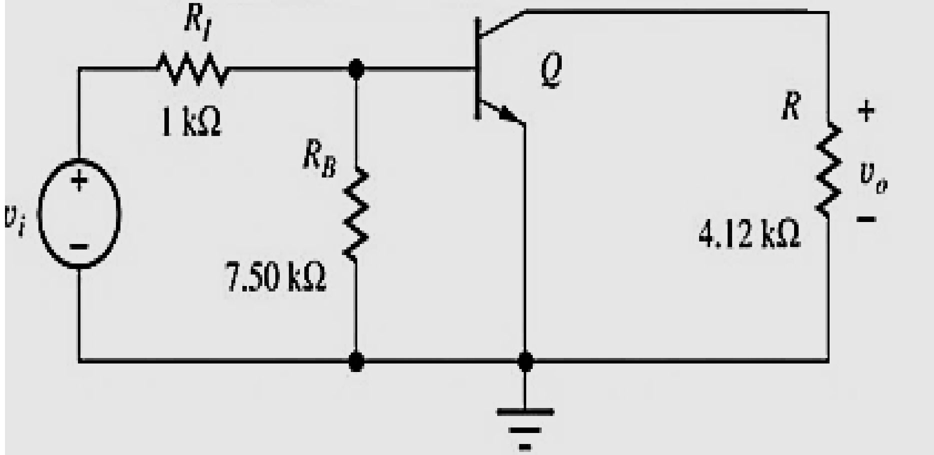




Example2



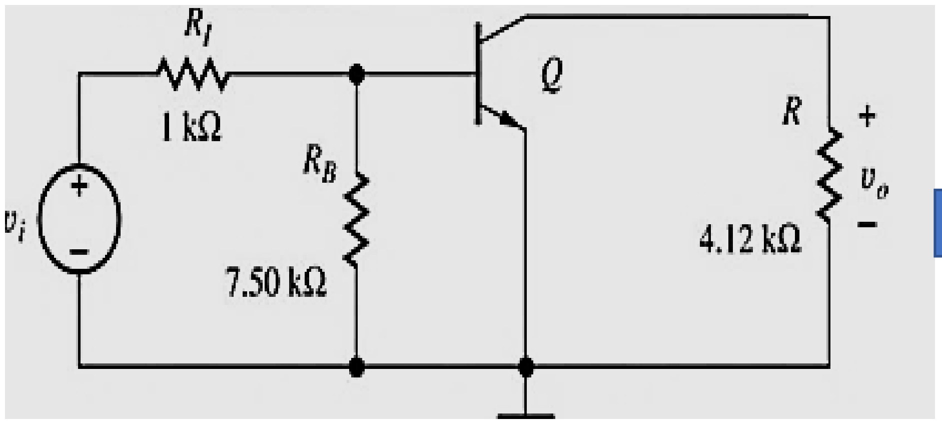


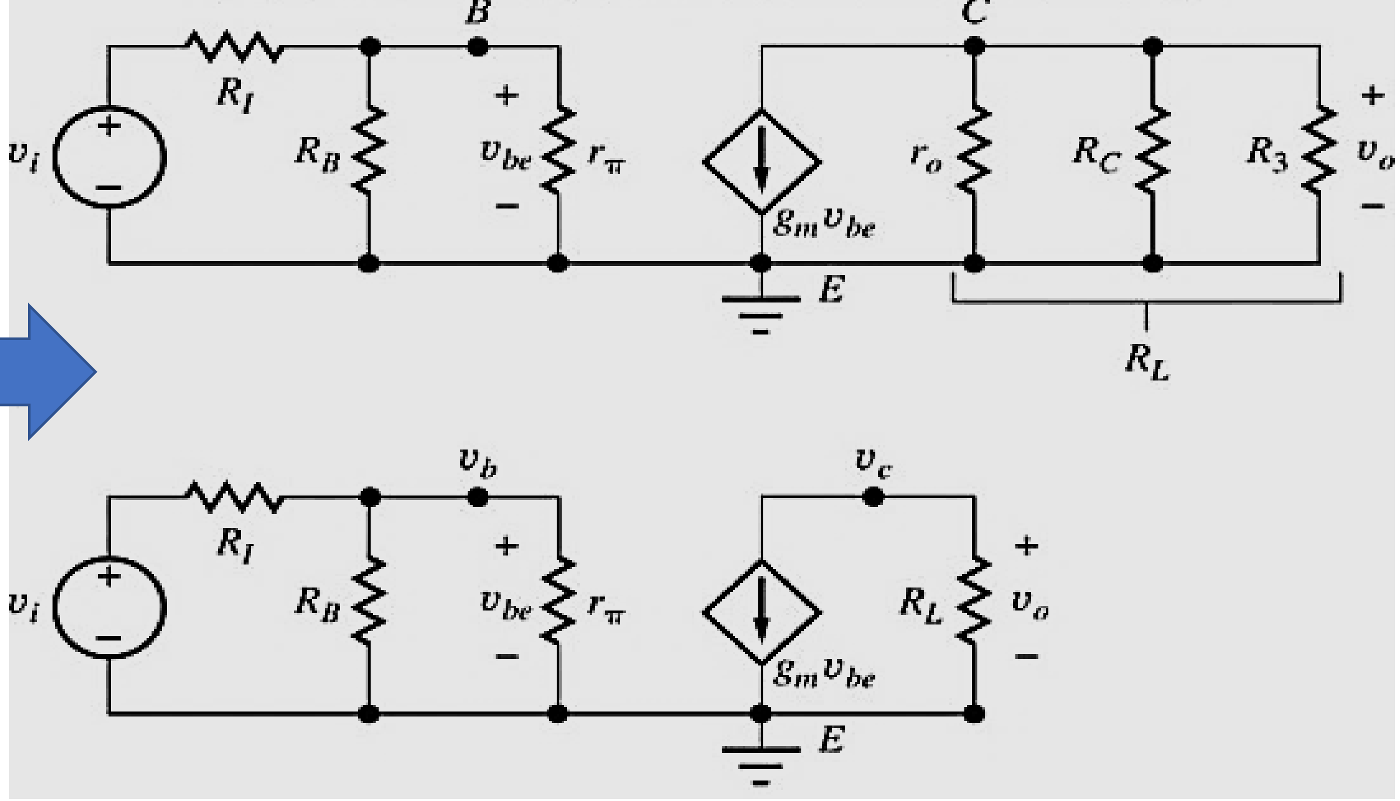


R_B = R_1 // R_2 = 10 kΩ //30 kΩ =7.5KΩ

$R = R_C$ // R_3 = 4.3 kΩ// 100 kΩ = 4.12KΩ

Example2





Terminal voltage gain between base and collector is:

$$A_{vt} = \frac{v_c}{v_b} = \frac{v_o}{v_{be}} = -g_m R_L$$

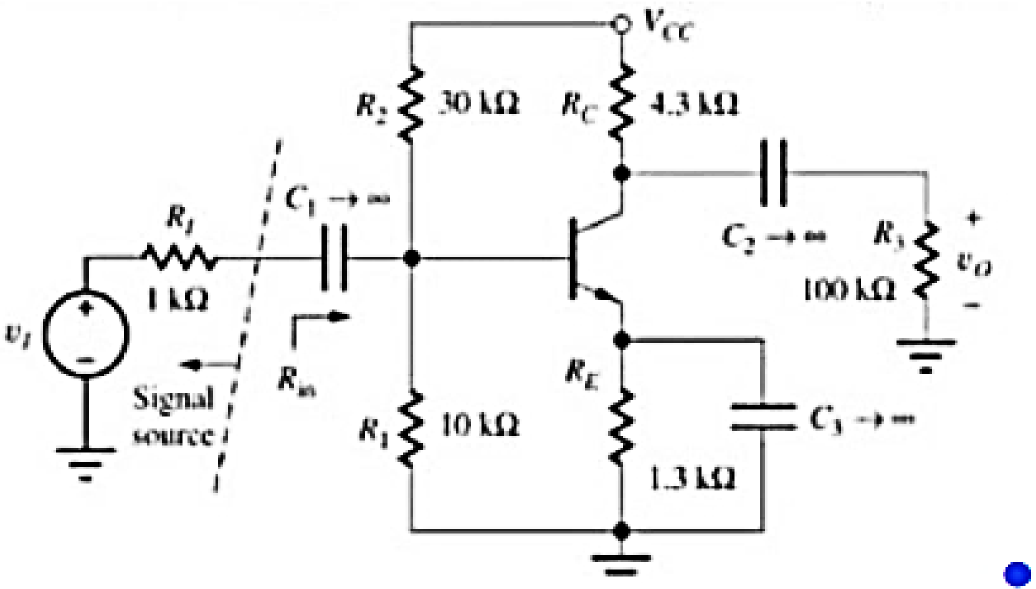
Overall voltage gain from source v_i to output voltage across R_3 is:

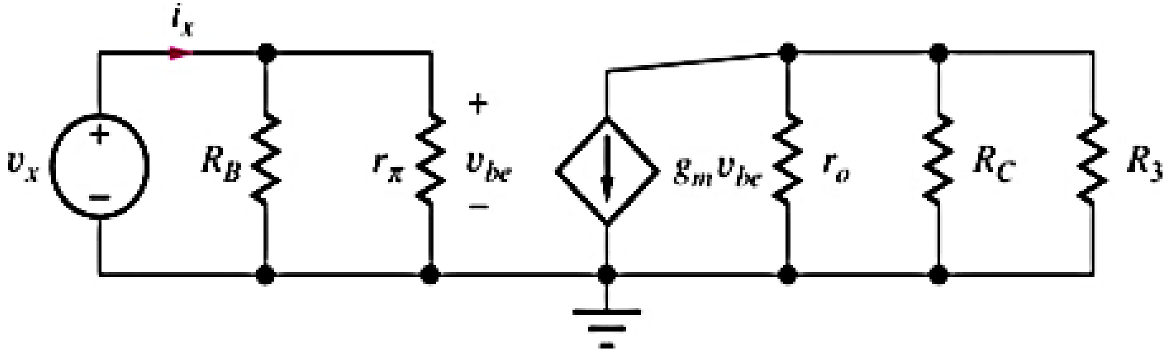
$$A_v = \frac{v_o}{v_i} = \left(\frac{v_o}{v_{be}}\right)\left(\frac{v_{be}}{v_i}\right) = A_{vt}\left(\frac{v_{be}}{v_i}\right)$$

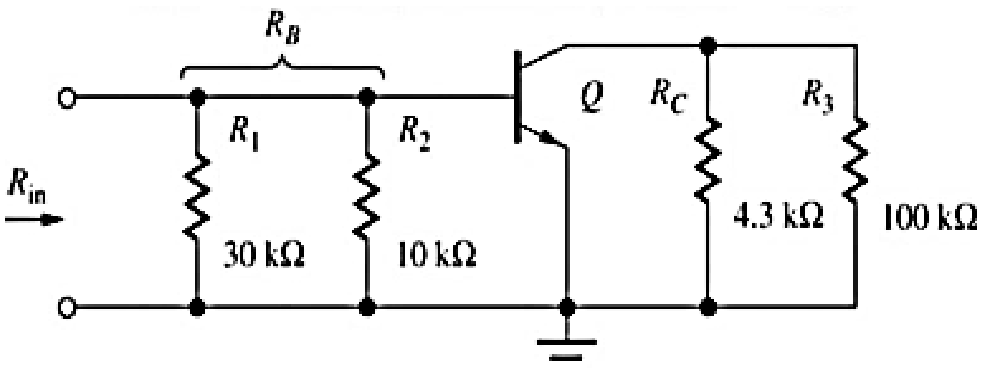
$$\therefore A_v = -g_m R_L \left[\frac{R_B \| r_\pi}{R_I + (R_B \| r_\pi)}\right]$$

- $R_L = r_o \,//\, R_C \,//\, R_3$

Input Resistance





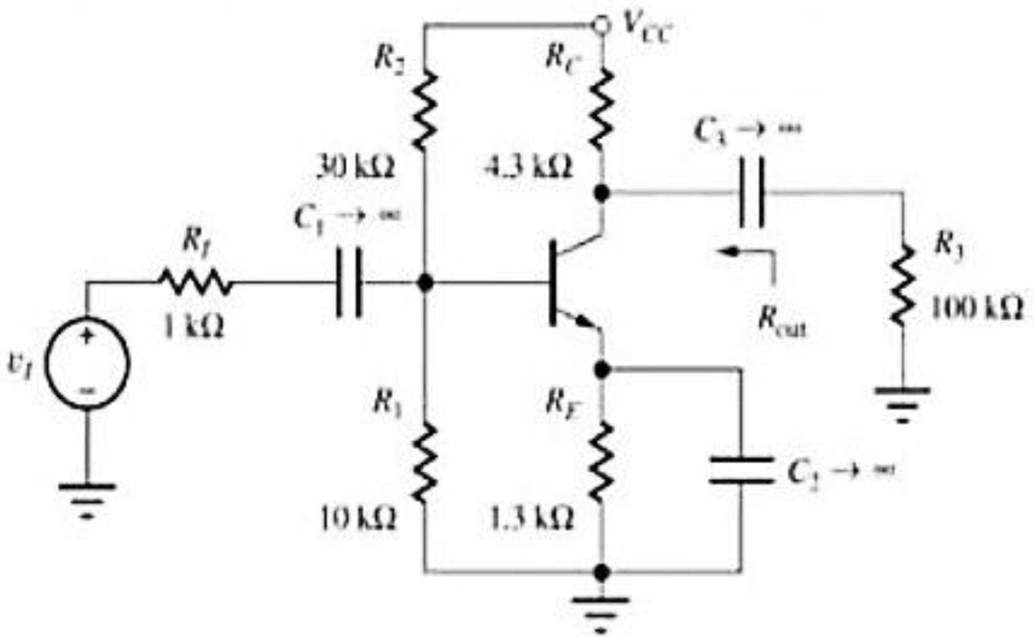


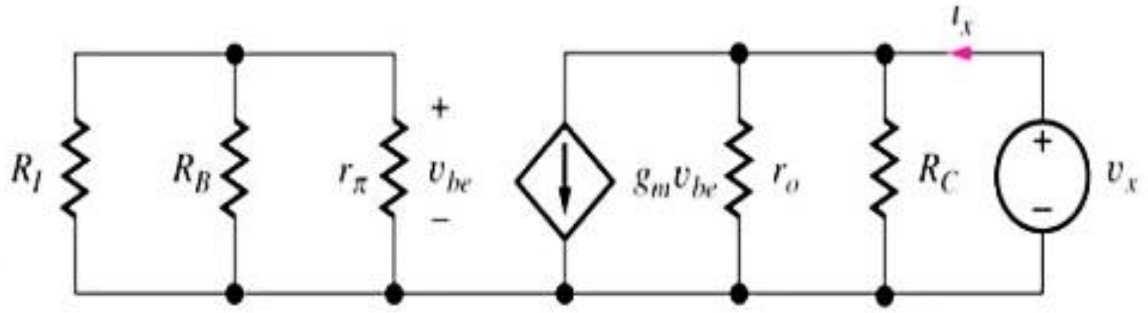
- The total resistance looking into the amplifier at coupling capacitor C_1 represents total resistance of the amplifier presented to signal source

$$v_x = i_x (R_B \| r_\pi)$$

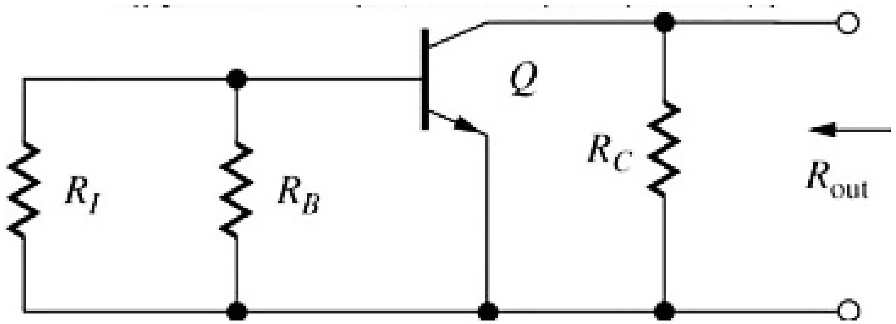
$$R_{in} = \frac{v_x}{i_x} = R_B \| r_\pi = R_1 \| R_2 \| r_\pi$$

Output Resistance





- Output resistance is the total equivalent resistance looking into the output of the amplifier at coupling capacitor C_3

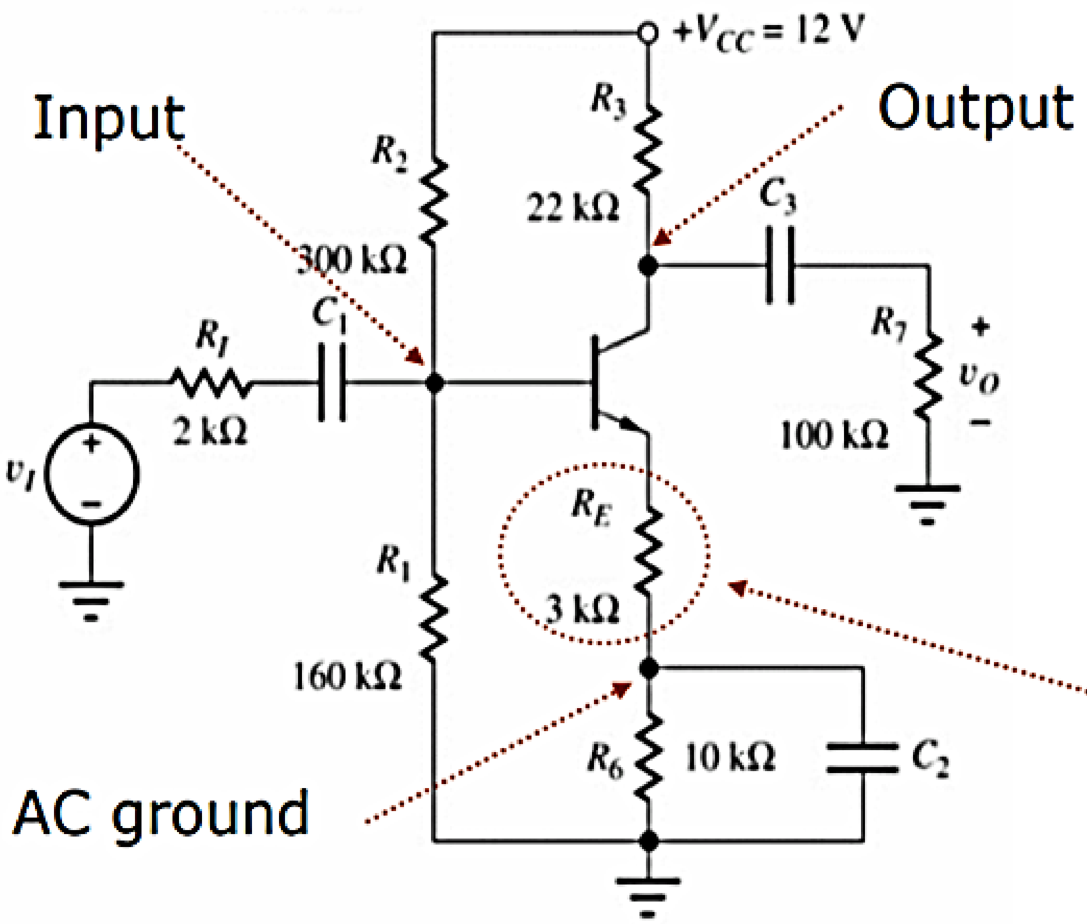


- To find R_{out}, input source is set to 0 and test source is applied at output

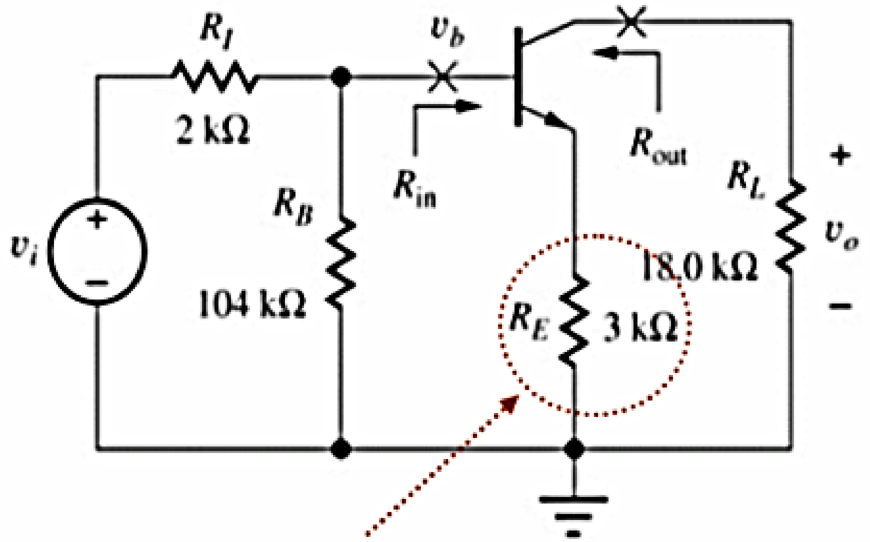
$$i_x = \frac{v_x}{R_C} + \frac{v_x}{r_o} + g_m v_{be} \qquad \text{But } v_{be}=0.$$

$$\therefore R_{out} = \frac{v_x}{i_x} = R_C \| r_o \cong R_C \quad \text{As } r_o >> R_C.$$

Example3



AC equivalent:



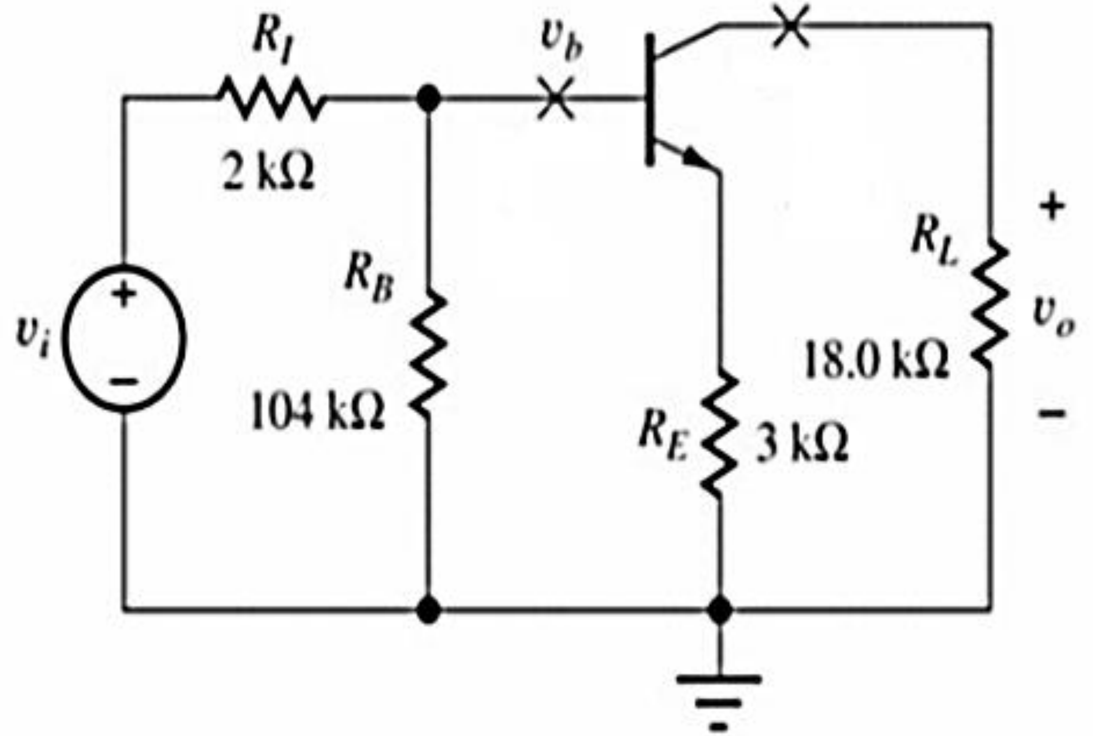
A resistor exists at the emitter of the ac equivalent circuit

Also called ***emitter degenerated*** CE amplifier

$R_B = R_1 \,//\, R_2$ = 160kΩ //300 kΩ =104KΩ

$R_L = R_7 \,//\, R_3 = 100\text{k}\Omega // 22\text{k}\Omega = 18\text{K}\Omega$

Example3



Overall voltage gain from v_i to v_o can be expressed as:

$$A_v \equiv \frac{v_o}{v_i} = \left(\frac{v_o}{v_b}\right)\left(\frac{v_b}{v_i}\right)$$

Define ***terminal voltage gain*** as:

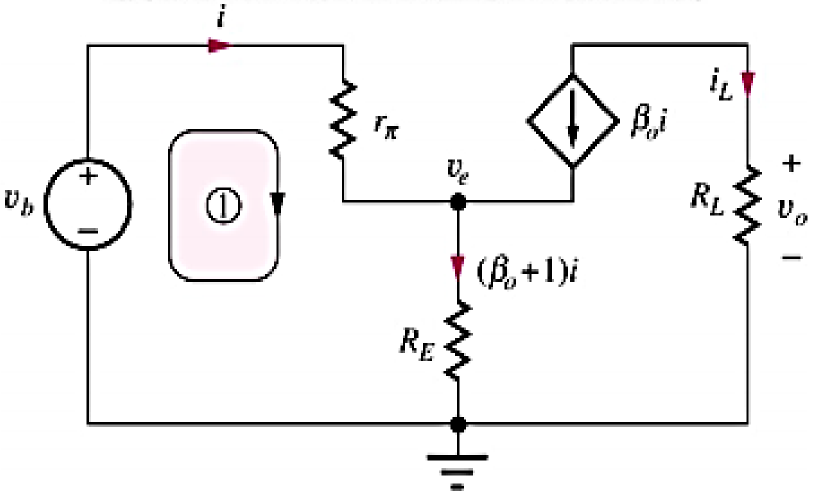
$$A_{vt} \equiv \frac{v_o}{v_b}$$

And it can be observed that:

$$v_b = \frac{R_B}{R_I + R_B} v_i$$

Example3

Use hybrid-π model (neglecting r_o):



$$v_b = ir_\pi + (\beta+1)iR_E$$
$$= i\left(r_\pi + (\beta+1)R_E\right)$$

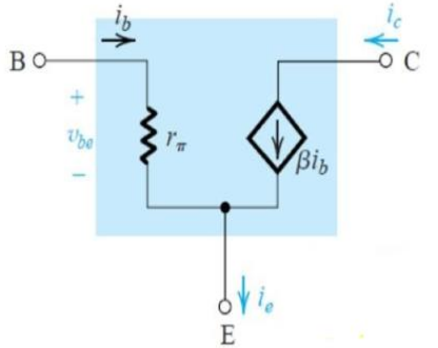
$$v_o = -\beta i R_L$$

$$A_{vt} \equiv \frac{v_o}{v_b} = -\frac{\beta R_L}{r_\pi + (\beta+1)R_E}$$

Using $r_\pi g_m = \beta$, we have

$$A_{vt} = -\frac{g_m r_\pi R_L}{r_\pi + (g_m r_\pi + 1)R_E} \cong -\frac{g_m R_L}{1 + g_m R_E}$$

for $g_m r_\pi = \beta >> 1$



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

Effect of R_E:

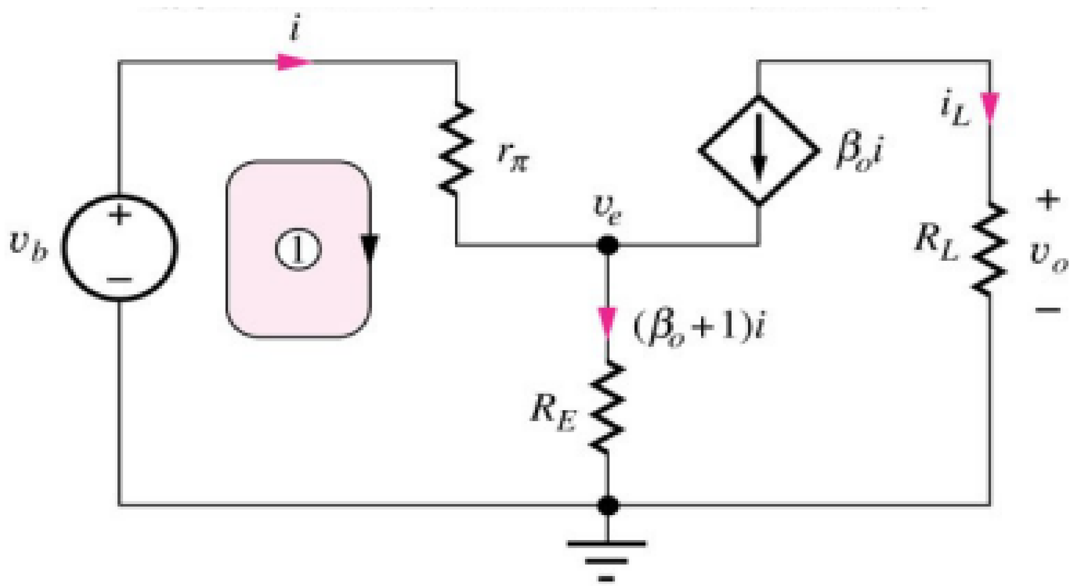
- For R_E=0, $A_{vt} \cong -g_m R_L$
  - Upper limit of A_{vt}
- For $g_m R_E$>>1, $A_{vt} = -R_L/R_E$
  - A_{vt} becomes less dependent on g_m which varies widely
- Increasing R_E decreases voltage gain!

Example3

Input Resistance

To find R_{in} → to find V_b/i:

$$v_b = i\left(r_\pi + (\beta+1)R_E\right)$$



$$R_{in} = \frac{v_b}{i} = r_\pi + (\beta+1)R_E$$
$$= r_\pi + (g_m r_\pi + 1)R_E$$
$$\cong r_\pi(1 + g_m R_E)$$

for $g_m r_\pi = \beta >> 1$

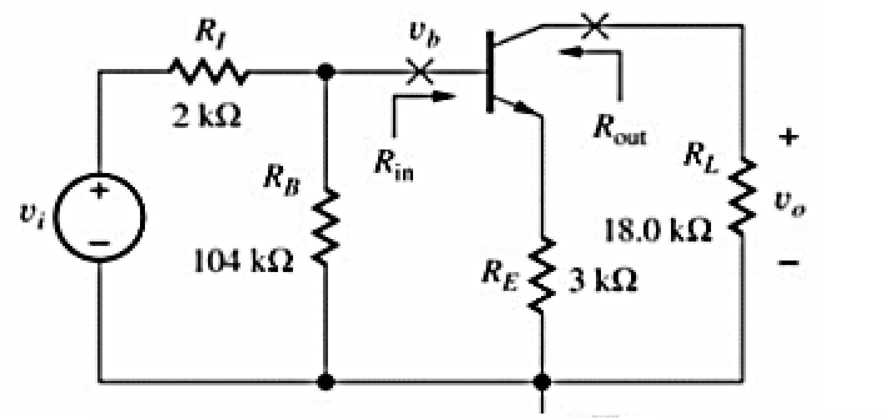
- Increasing R_E increases input resistance!

Example3

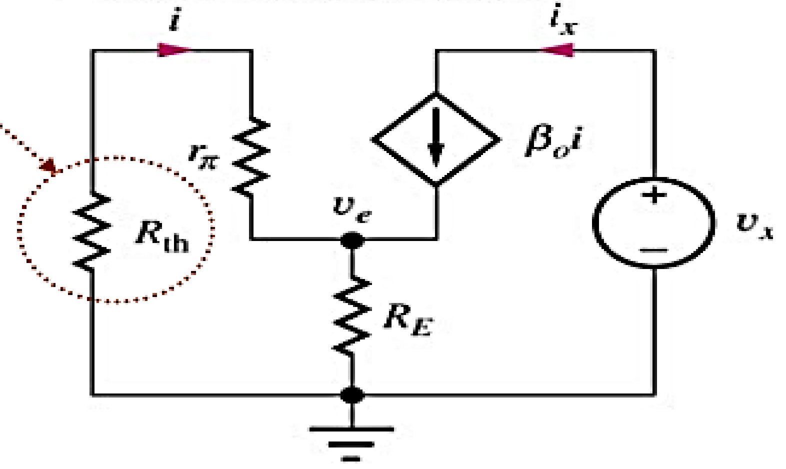
Output Resistance

To find R_{out}:

- Set v_i to zero
- Apply a test source at output
- $R_{out} = v_x/i_x$



$$R_{th} = R_I \, // \, R_B$$



$$v_e = (\beta+1) i R_E$$

KVL at left mesh:

$$i(R_{th} + r_\pi) + v_e = 0$$

$$\frac{v_e}{(\beta+1)R_E}(R_{th} + r_\pi) + v_e = 0$$

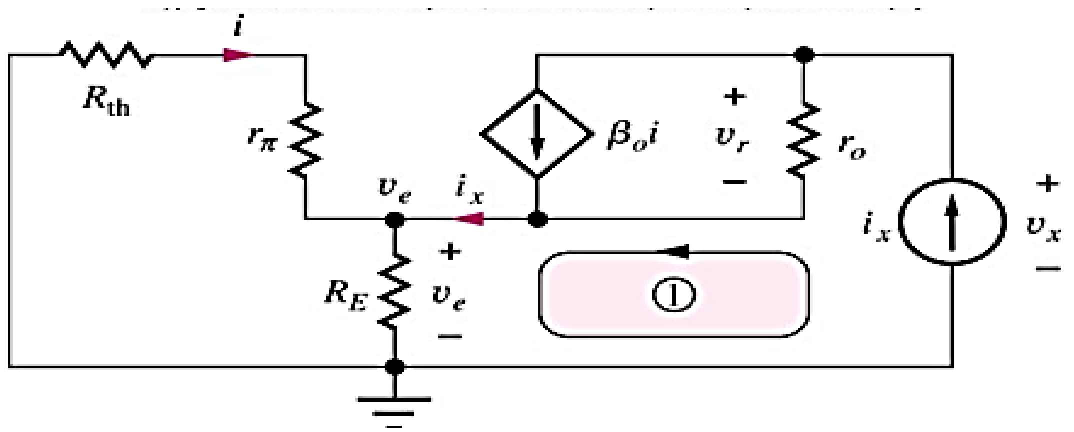
$$\Rightarrow v_e = 0$$

$$\therefore i = 0 \Rightarrow i_X = \beta i = 0 \qquad \therefore R_{out} = \frac{v_X}{i_X} = \infty$$

Example3

Output Resistance

Now, we also include r_o in our analysis:



KVL along loop 1:

$$v_x = v_r + v_e = (i_x - \beta i) r_o + v_e$$

Voltage at E:

$$v_e = i_x \left(\left(R_{th} + r_\pi \right) // R_E \right)$$

Current division at Emitter:

$$i = -i_x \frac{R_E}{R_E + R_{th} + r_\pi}$$

Put 2nd and 3rd equations into 1st equation:

$$\therefore v_x = r_o \left(i_x + \beta i_x \frac{R_E}{R_E + R_{th} + r_\pi} \right) + i_x \left(\left(R_{th} + r_\pi \right) // R_E \right)$$

$$\therefore R_{out} \equiv \frac{v_x}{i_x} \cong r_o \left(1 + \frac{\beta R_E}{R_E + R_{th} + r_\pi} \right)$$ for large value of r_o