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UTM
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Chapter 4 Bipolar Junction Transistor (BJT) AC Analysis

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Course Learning Outcomes

1. Apply the basic law and theorems of electronic devices to describe their basic operation.

2. Apply the basic law, theorems and methods of analysis to solve complex problem related to circuitry.

3. Work in a team and communicate effectively.

Small Signal Circuit Analysis

- BJT
  - DC Analysis
    - to determine the initial operating values of I_C, I_B and V_{CE} (Q-point). The Q-point which is in the middle of the DC load line is the optimum biasing condition of an amplifier
    - to ensure that the DC output voltage is in between the AC output voltage . The AC input voltage will make the AC output voltage to swing near the DC operating point
  - AC Analysis
    - to determine the values of input impedance (Z_i), output impedance (Z_O), voltage gain (A_v) and current gain (A_i)
    - For the purpose of analysing AC operations, the transistor can be replaced with a small signal equivalent circuit model when it is operating in the active region (having linear attributes)

AC Analysis

All DC supply is removed – replaced with zero potential (ground)

Reactance becomes low & capacitors can be considered short circuit

Determine the following quantities

- Input impedance, Z_i
- Output impedance, Z_o
- Voltage gain, A_v
- Current gain, A_i
- Power gain, A_p

AC Analysis

Start analysis with a DC equivalent circuit

Calculate DC voltage & current (I_C, I_B & V_{CE})

Obtain AC equivalent circuit by

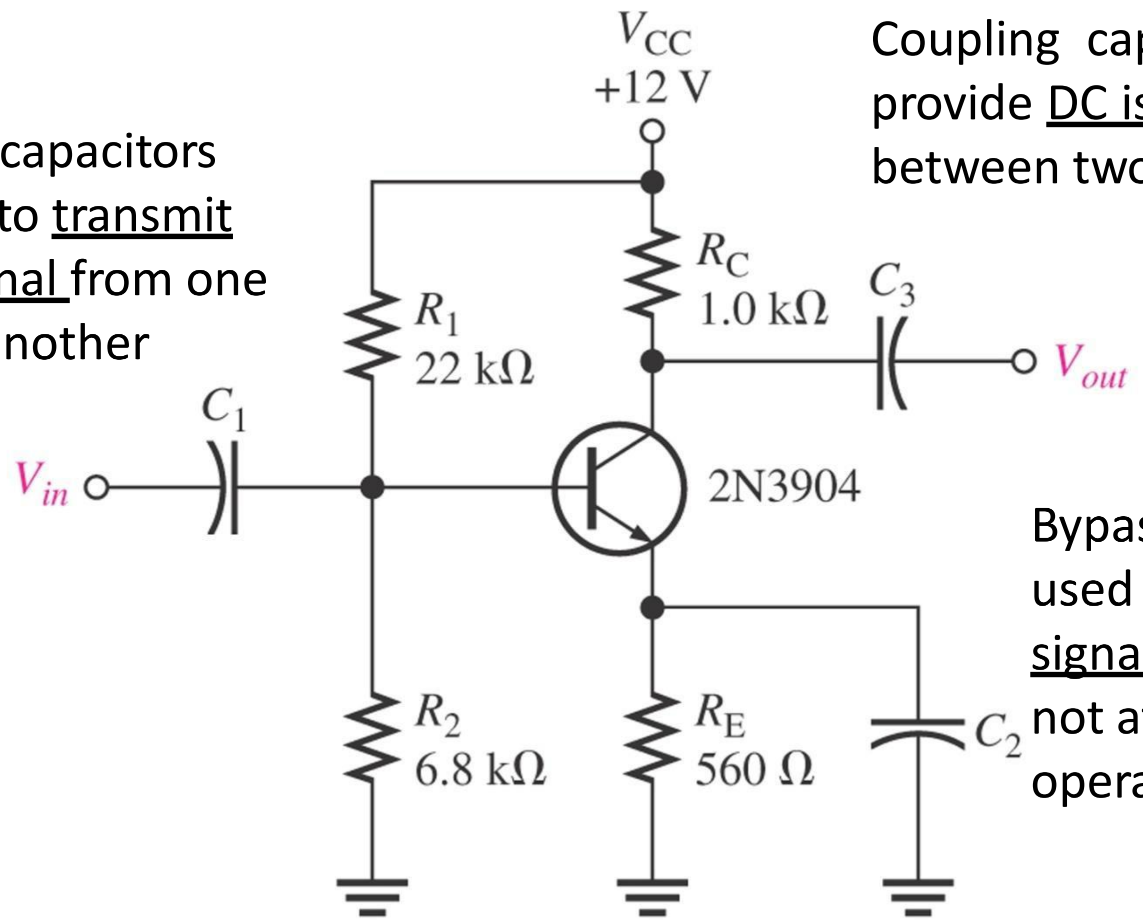
- Short circuiting all coupling capacitors and by-pass capacitors
- Ground all independent DC voltage supply & open all independent DC current sources
- Replace transistor with a hybrid-π model
- Draw equivalent circuit

Calculate AC desired parameters (Z_i , Z_o , A_v , A_i)

Function Of Capacitors In Amplifiers

Coupling capacitors are used to transmit an AC signal from one node to another

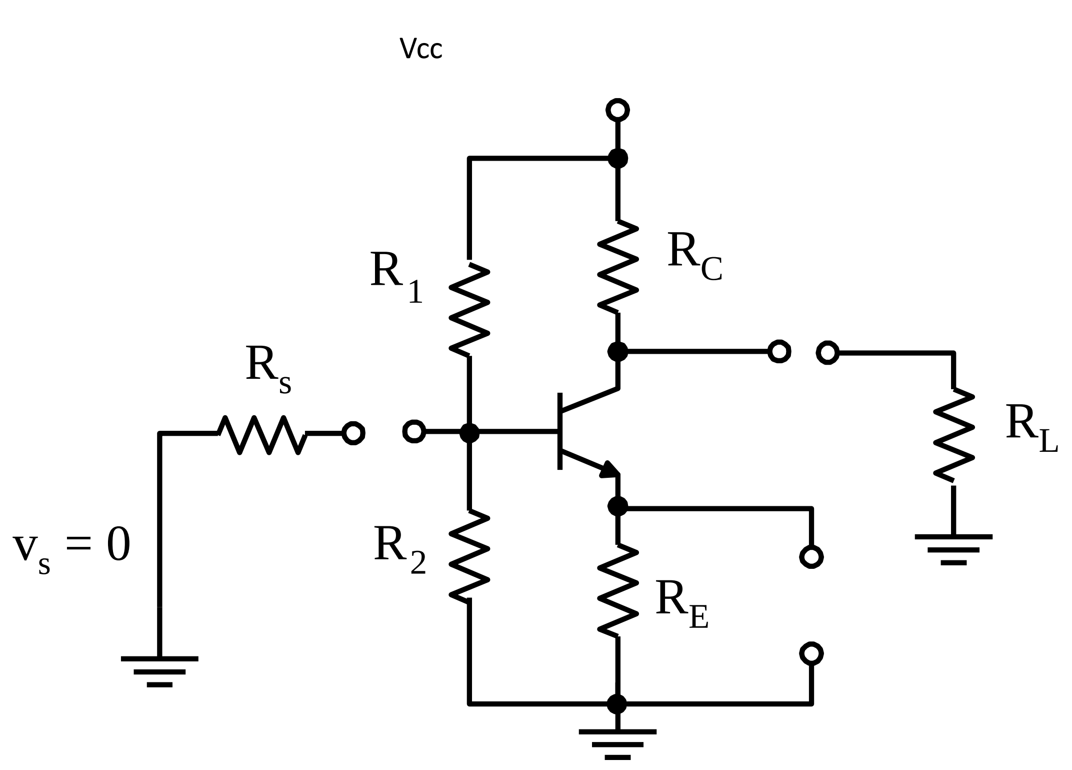
Coupling capacitors provide DC isolation between two nodes



Bypass capacitor is used to short circuit AC signals to ground (while not affecting the DC operation of the circuit)

DC Analysis

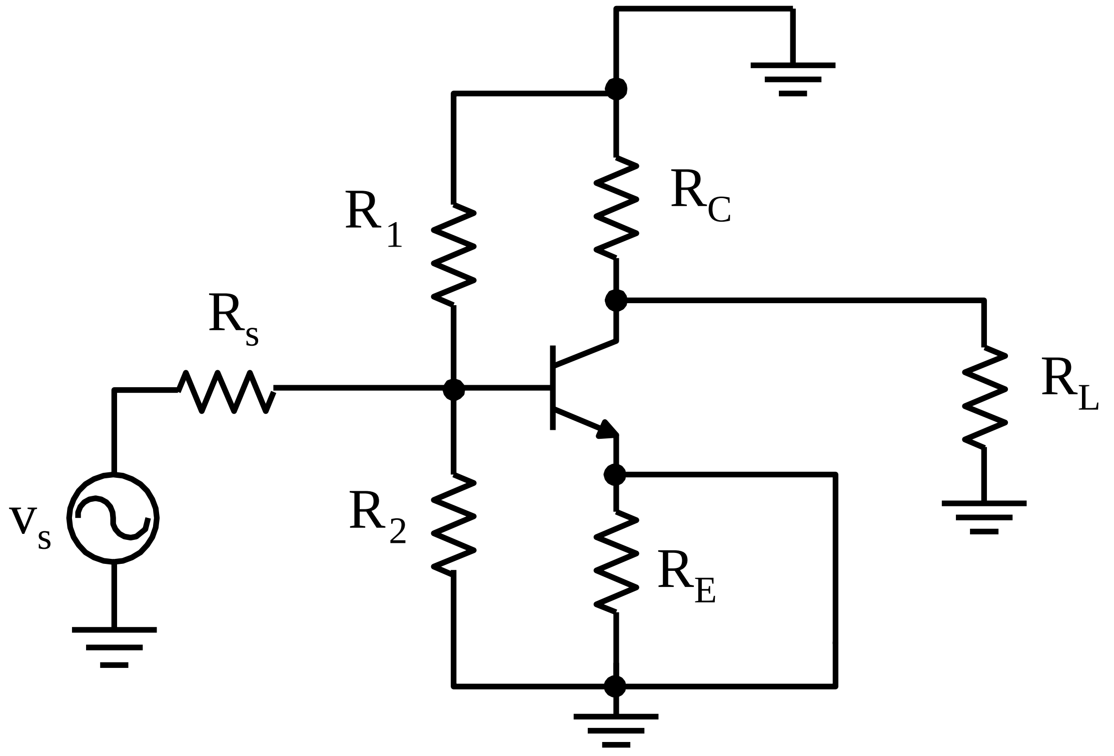
- Set AC source to zero.
- Replace the coupling capacitors and bypass capacitor with open circuits.



DC Equivalent Circuit

AC Analysis

- ❑ Set DC source to zero (ground)
- ❑ Replace the coupling capacitors and bypass capacitors with short circuit
- ❑ Analyze the AC operation



AC Equivalent Circuit

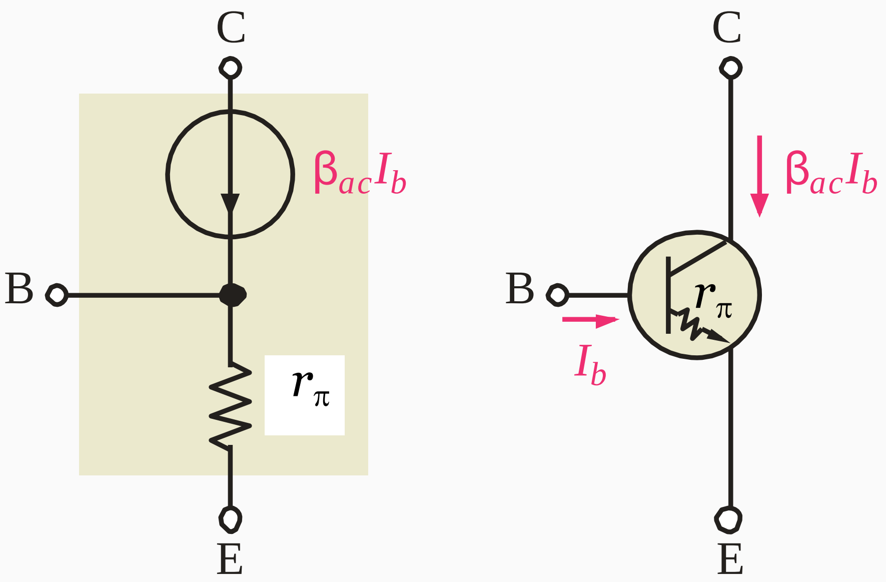
AC Equivalent Models

- Linear transistor can be replaced by AC equivalent model.
- Transistor AC equivalent models are:
  - Parameter-h Model
  - r_e Model
  - Parameter-y Model
  - Hybrid-π Model

Transistor AC Models

The simplified Hybrid-π are shown in relation to the transistor model

An important Hybrid-π is r_π. It appears as a small AC resistance between the Base and Emitter



Hybrid - π Model

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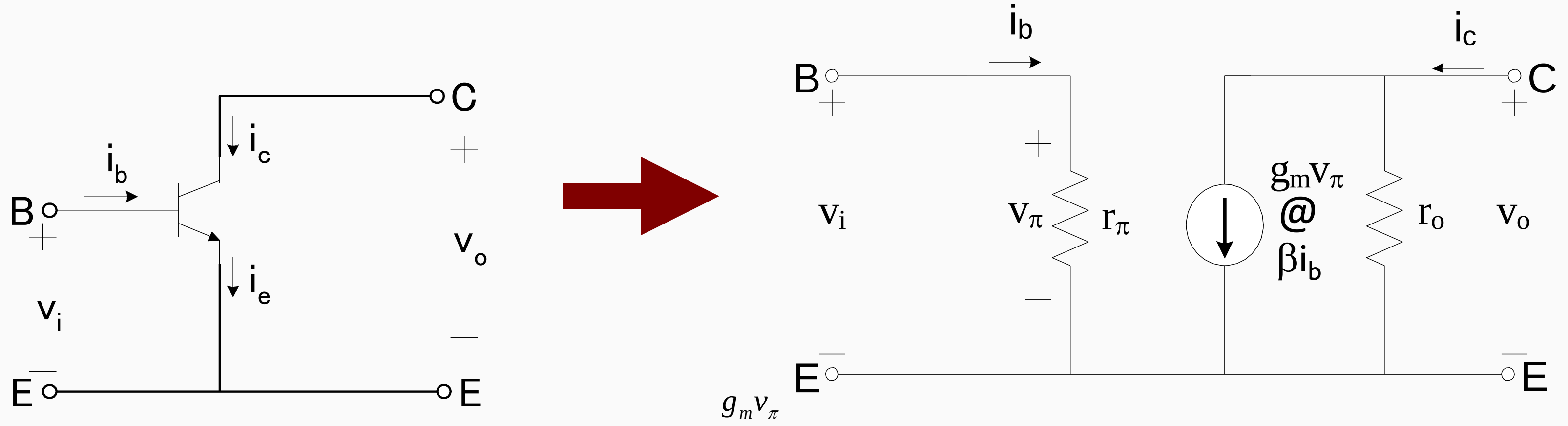
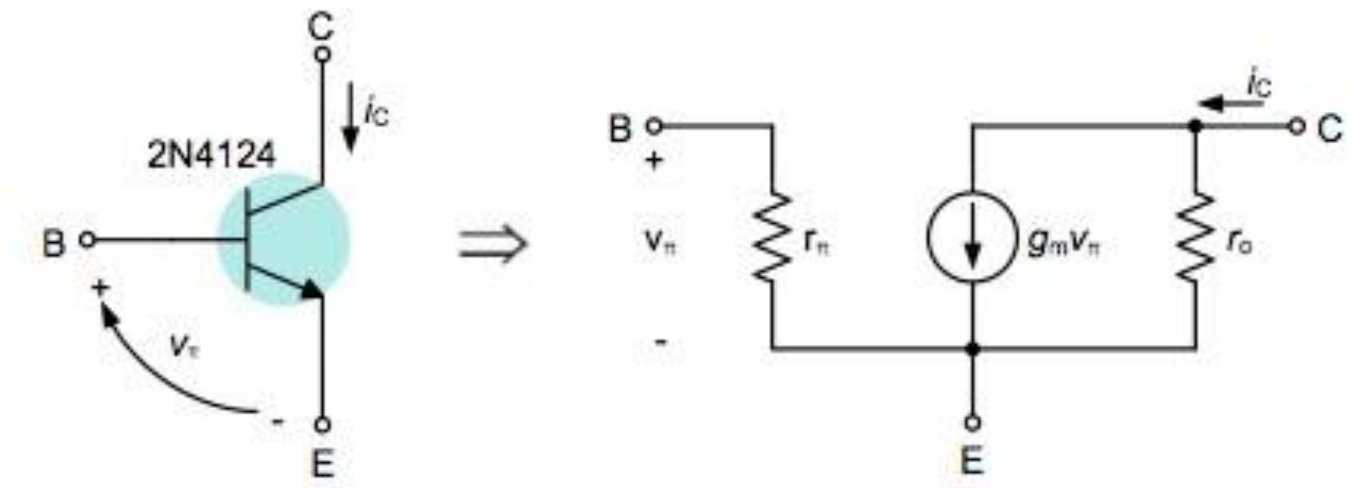


Voltage Controlled Current Source

$$\beta = h_{fe} \qquad r_o = \frac{1}{h_{oe}} = \frac{V_A}{I_C} \qquad g_m = \frac{I_C}{V_T} \qquad r_\pi = \frac{\beta}{g_m}$$

- In the Current Controlled Current Source (CCCS) model = βi_b
- In the Voltage Controlled Current Source (VCCS) model = $g_m v_\pi$
- Internal output impedance , r_o is very high & can be neglected(open circuit)
- Equivalent voltage temperature, V_T = 26mV at room temperature (25°C)
- Early Voltage , $V_A \cong 200V$

Hybrid - π Model



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

$$g_m = \frac{I_C}{V_T} = \frac{I_C}{26mV}$$

$$r_o = \frac{V_A}{I_C} = \frac{200V}{I_C}$$

$$V_T = \frac{kT}{q} = 26mV$$

k – Boltzman Constant (1.38×10^{-23} J/K)

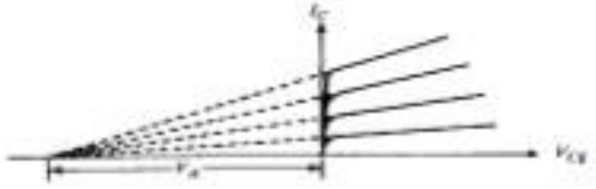
q – Electron Charge (1.6×10^{-19} C)

$T = 273^0 + T_C$ Kelvin

g_m - Transconductance

V_A - Early voltage

V_T - Voltage equivalent of temperature



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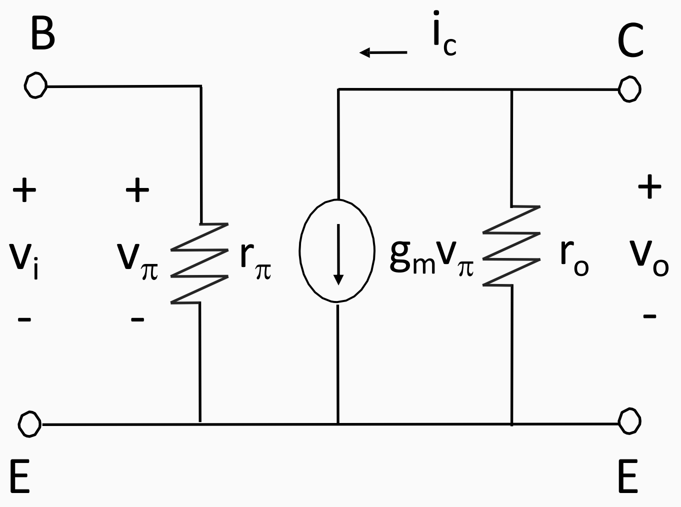
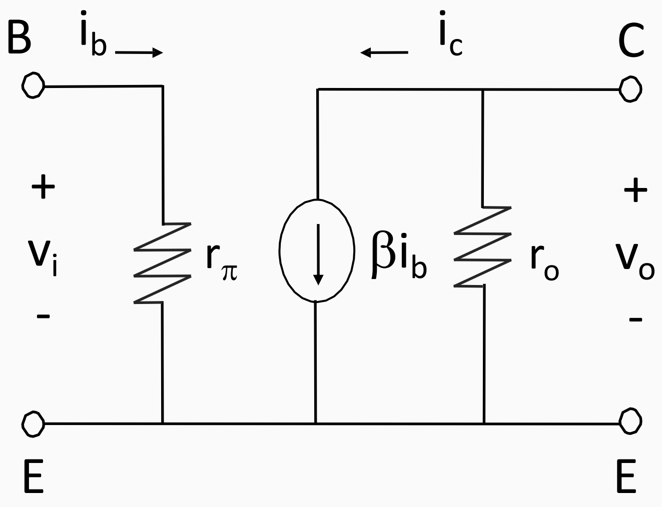
Hybrid - π Model



VCCS Model



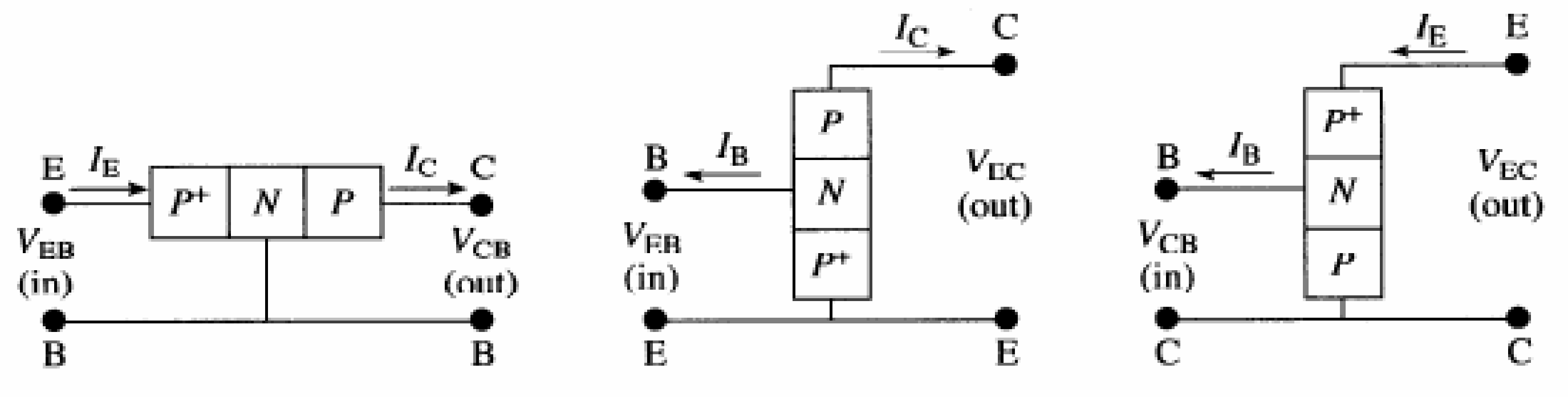
CCCS Model

EQUATION TO REMEMBER!

$$\beta = h_{fe} \qquad r_o = \frac{1}{h_{oe}} = \frac{V_A}{I_C} \qquad g_m = \frac{I_C}{V_T} \qquad r_\pi = \frac{\beta}{g_m}$$

Transistor Configuration

- Transistor configuration – is a connection of transistor to get variety operation.
- 3 types of transistor configuration:
  - Common Collector (CC).
  - Common Base (CB).
  - Common Emitter (CE).
- Common means the circuit has a single reference for both the input voltage to the transistor and the output voltage



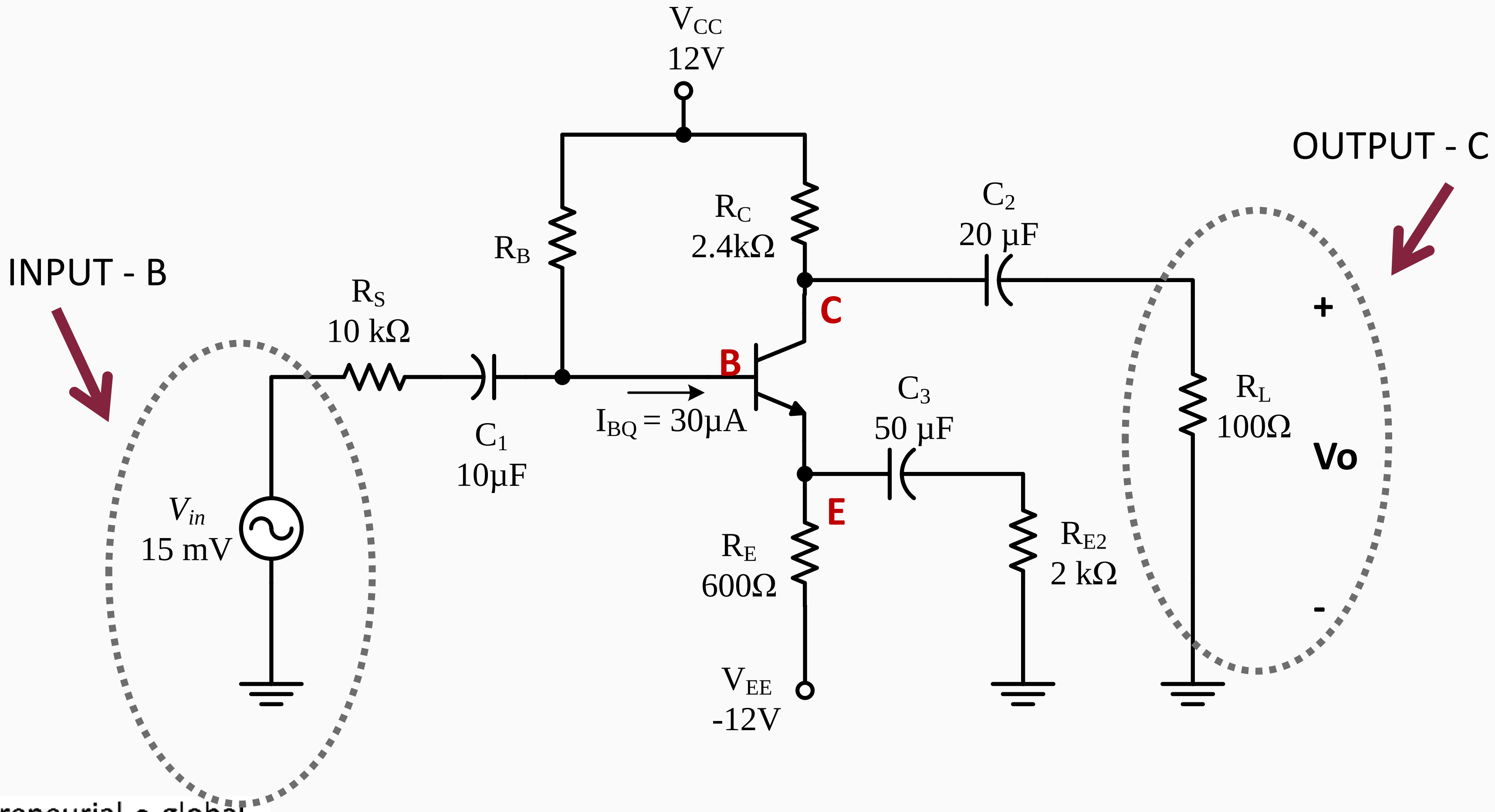
(a) Common base (b) Common emitter (c) Common collector

Transistor Configuration

	Common Emitter	Common Collector	Common Base
Input terminal	Base	Base	Emitter
Output Terminal	Collector	Emitter	Collector
Common (Gnd)	Emitter	Collector	Base

Example

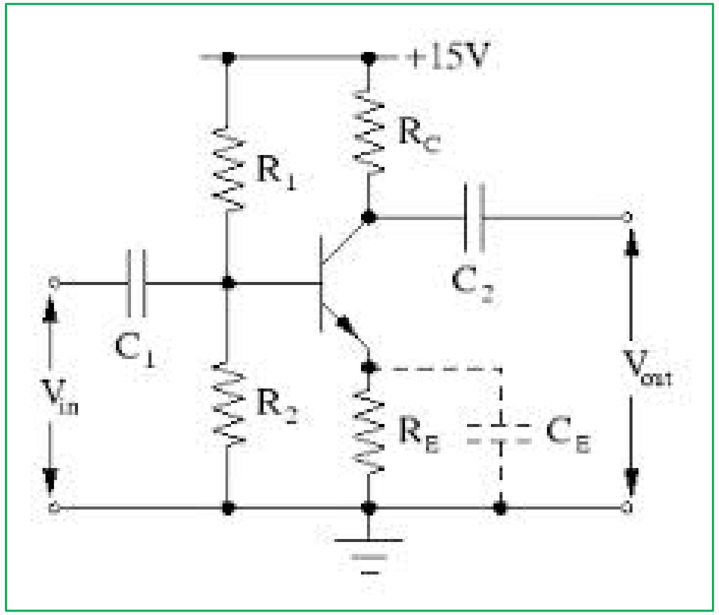
Determine the configuration of the following BJT circuit?



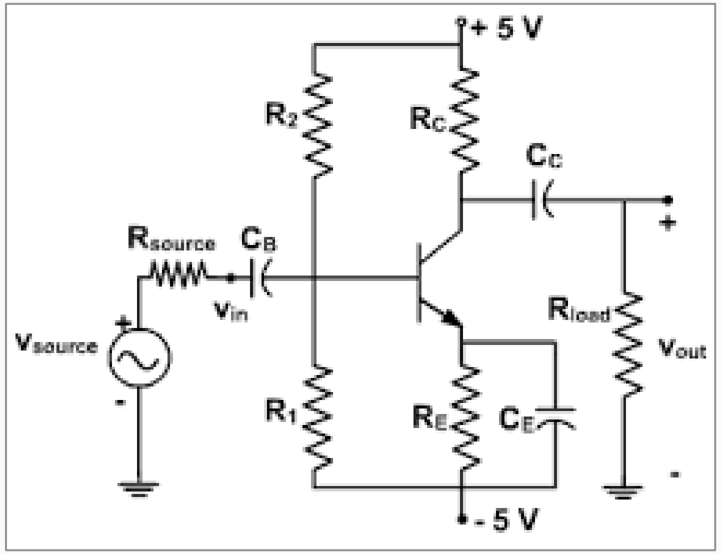
Exercise

Determine the configuration of the following BJT circuit?

A



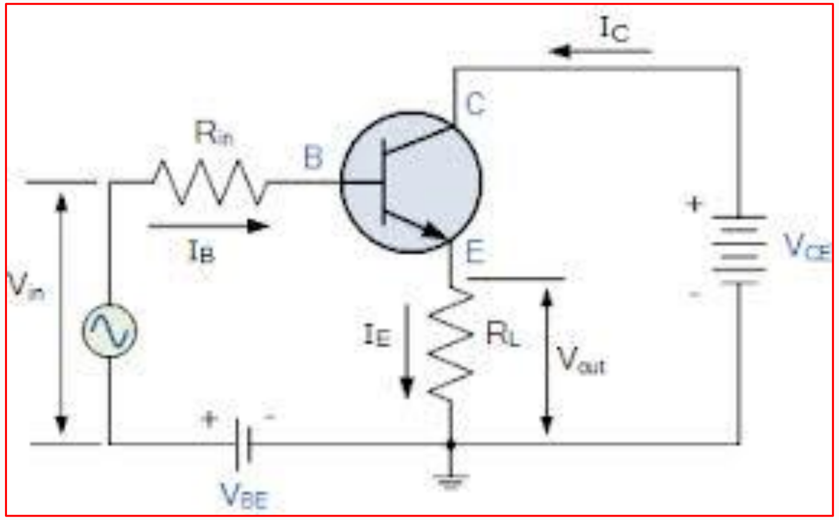
B



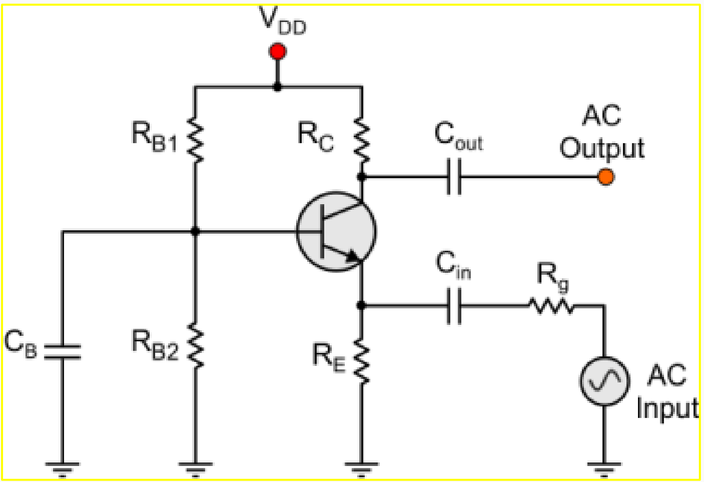
Exercise

Determine the configuration of the following BJT circuit?

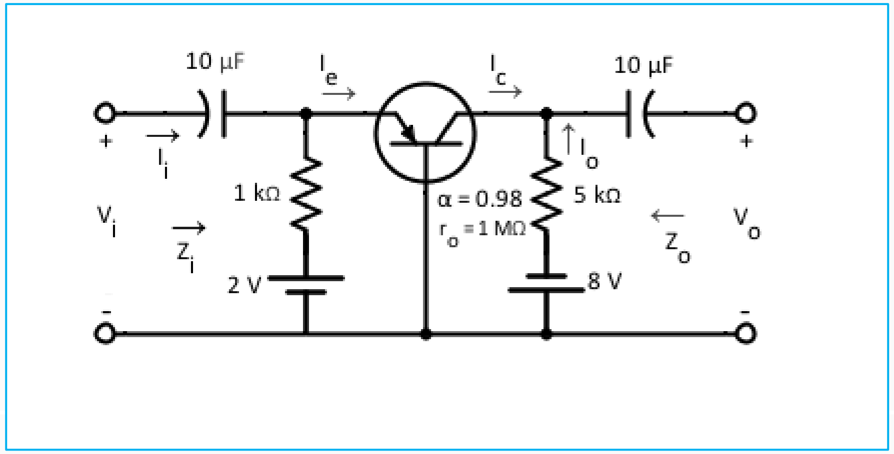
C



D

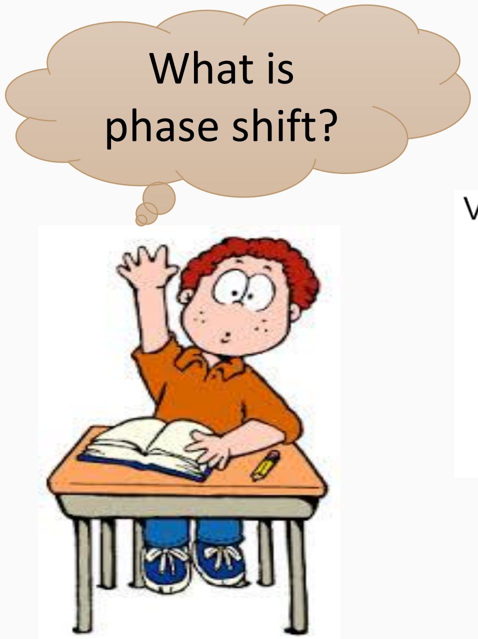


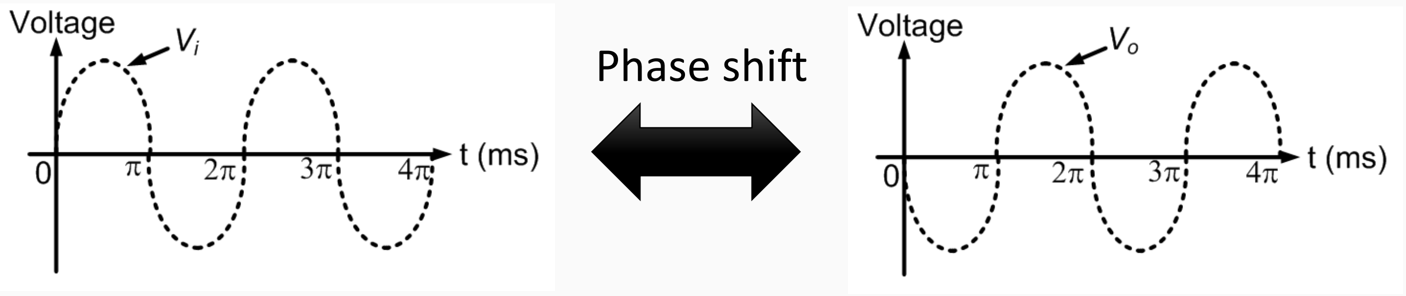
E



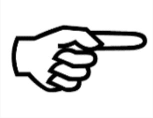
Common Emitter

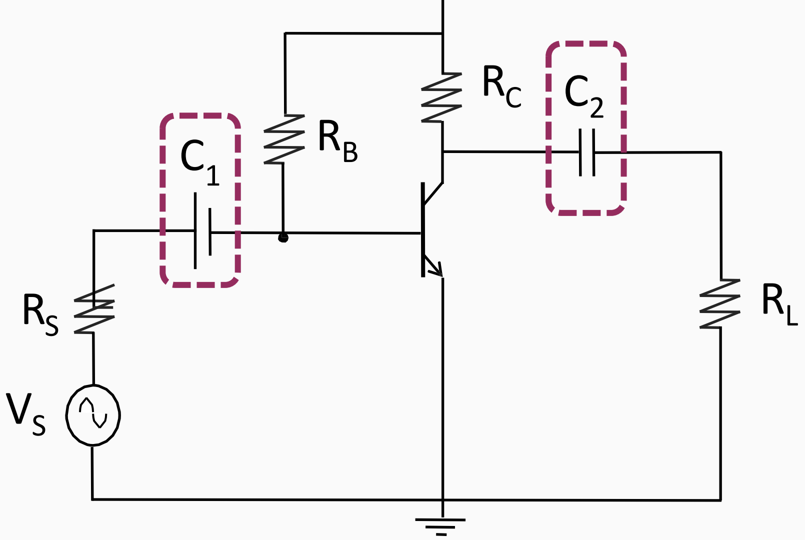
- Input – Applied to BASE
- Output – From COLLECTOR
- High Voltage Gain, A_V and high Current Gain, A_i
- Phase shift between input and output is 180°



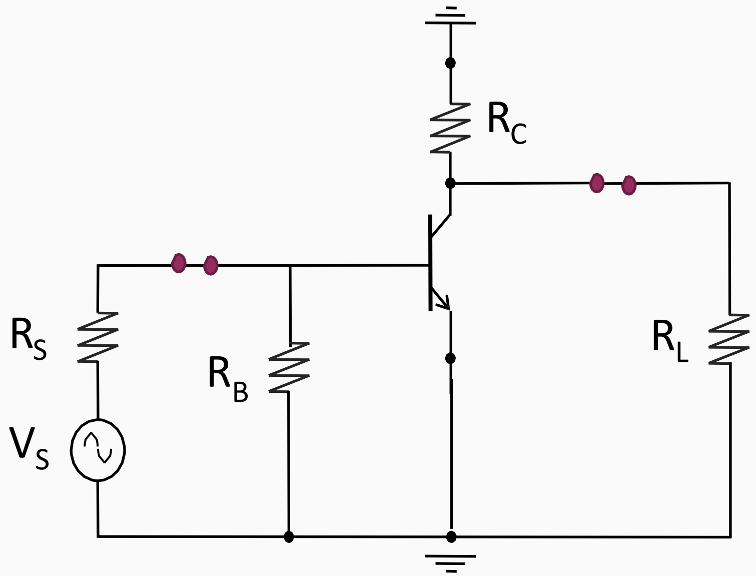


Common Emitter: Fixed Bias Without By Pass Capacitor





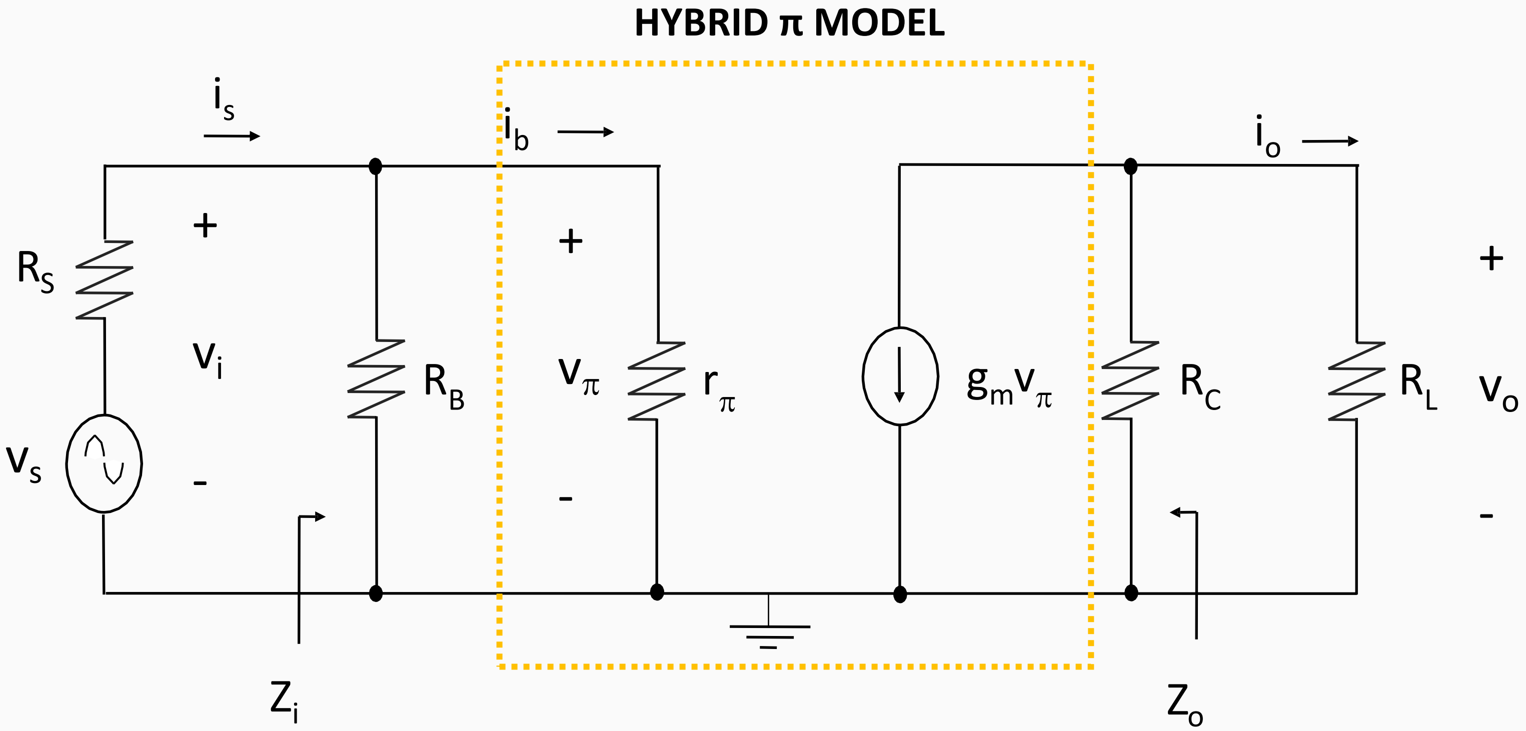
CE Amplifier



DC source grounded and capacitors are shorted

- ❑ Set all DC source to zero/ground
- ❑ Replace the coupling capacitors and bypass capacitors with short circuit
- ❑ Rearrange circuit to make it simple and draw the AC equivalent circuit.

Common Emitter: Fixed Bias



Input impedance:

$$Z_i = R_B \parallel r_\pi$$

Output impedance:

$$Z_o = R_C$$

Common Emitter : Fixed Bias

Voltage gain:

$$A_{vs} = \frac{v_o}{v_s}$$

$$v_o = -g_m v_\pi \left(R_C \| R_L \right)$$

$$v_\pi = v_i = \frac{Z_i}{Z_i + R_S} v_s$$

$$A = \frac{v_o}{v_\pi} \times \frac{v_\pi}{v_i} \times \frac{v_i}{v_s}$$

$$\boxed{A_{vs} = -g_m \left(R_C \| R_L \right) \frac{Z_i}{Z_i + R_S}}$$

Current gain:

$$A_i = \frac{i_o}{i_i}$$

$$i_o = \frac{R_C}{R_C + R_L} \left(-g_m v_\pi \right)$$

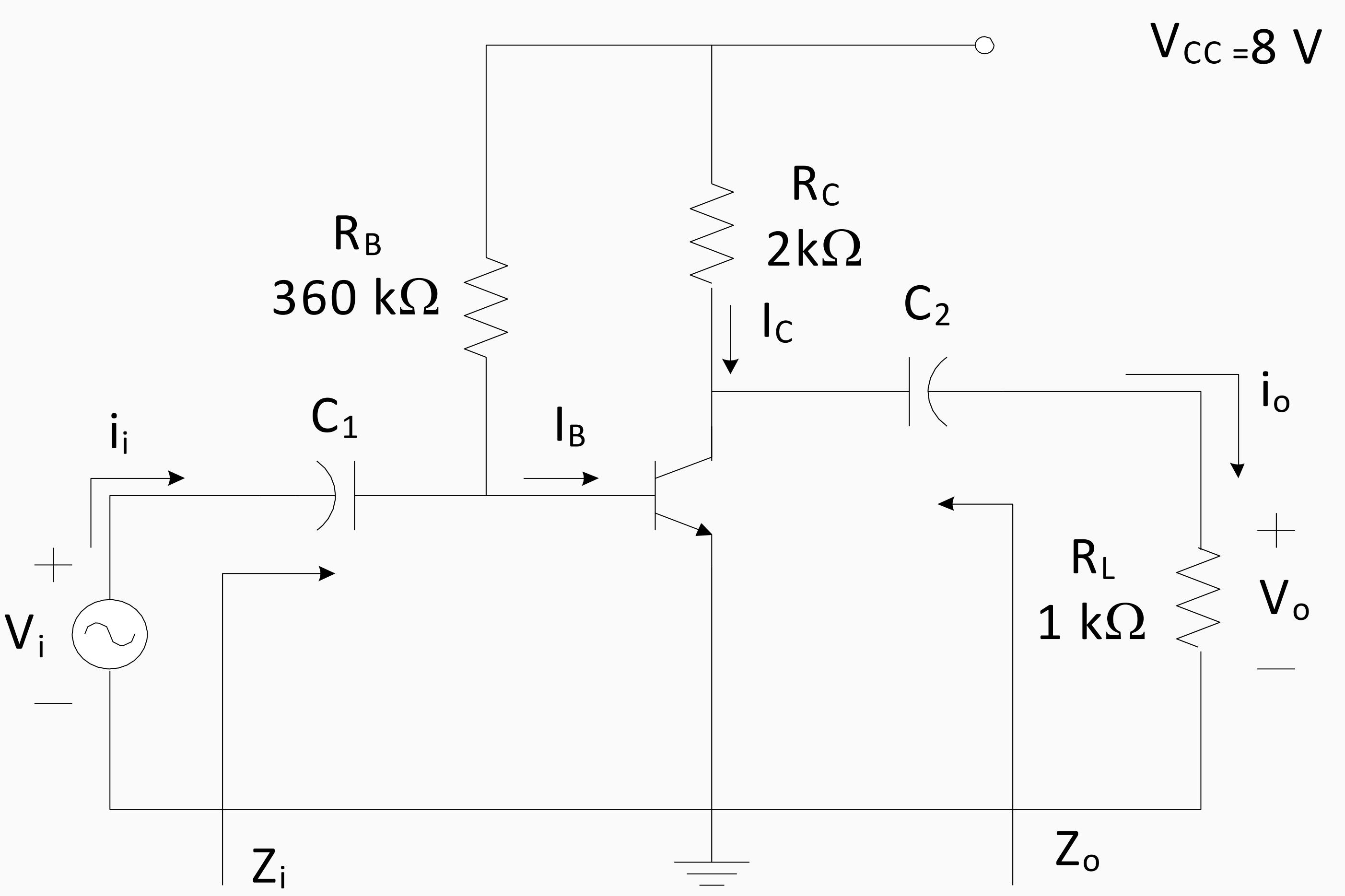
$$v_\pi = v_i = i_i Z_i$$

$$A_i = \frac{i_o}{v_\pi} \times \frac{v_\pi}{v_i} \times \frac{v_i}{i_i}$$

$$\boxed{A_i = -\frac{R_C}{R_C + R_L} g_m Z_i}$$

ANY PHASE SHIFT?

Common Emitter : Fixed Bias (Exercise)

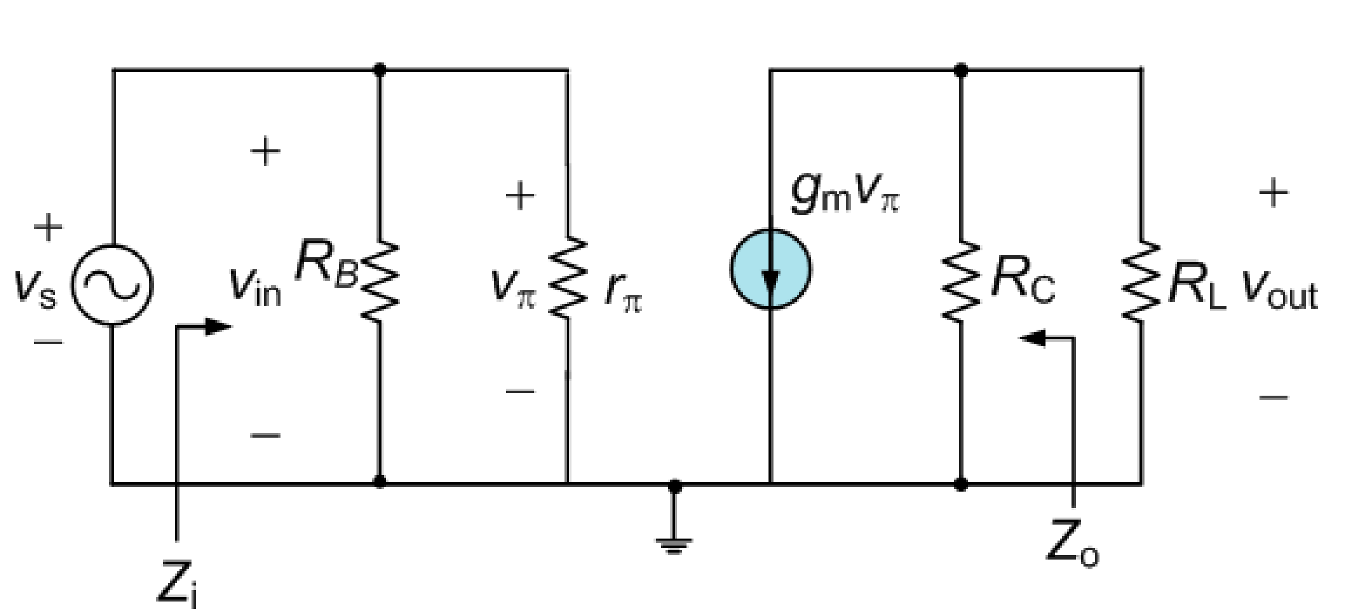


V_{BE} = 0.7 V
$\beta_{DC} = \beta_{AC}$ = 100
V_T = 26 mV

Draw the AC equivalent circuit and find Av and Ai.

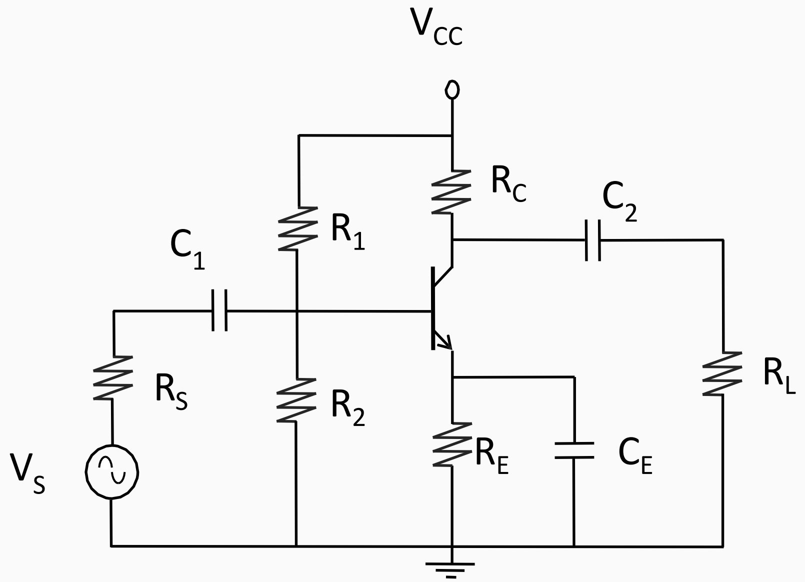
Common Emitter : Fixed Bias (Solution)

1) Draw the DC equivalent circuit – ground all DC supply and short all capacitors.
2) Draw the AC equivalent circuit

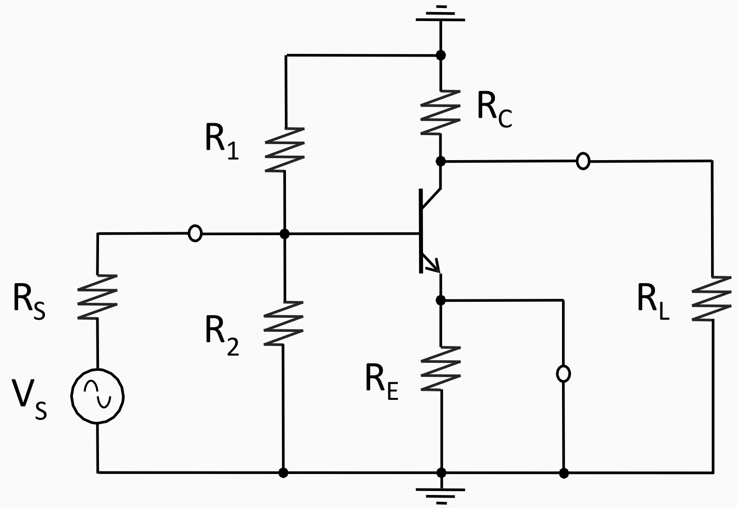


Common Emitter: Voltage Divider Bias

- Voltage Divider Bias

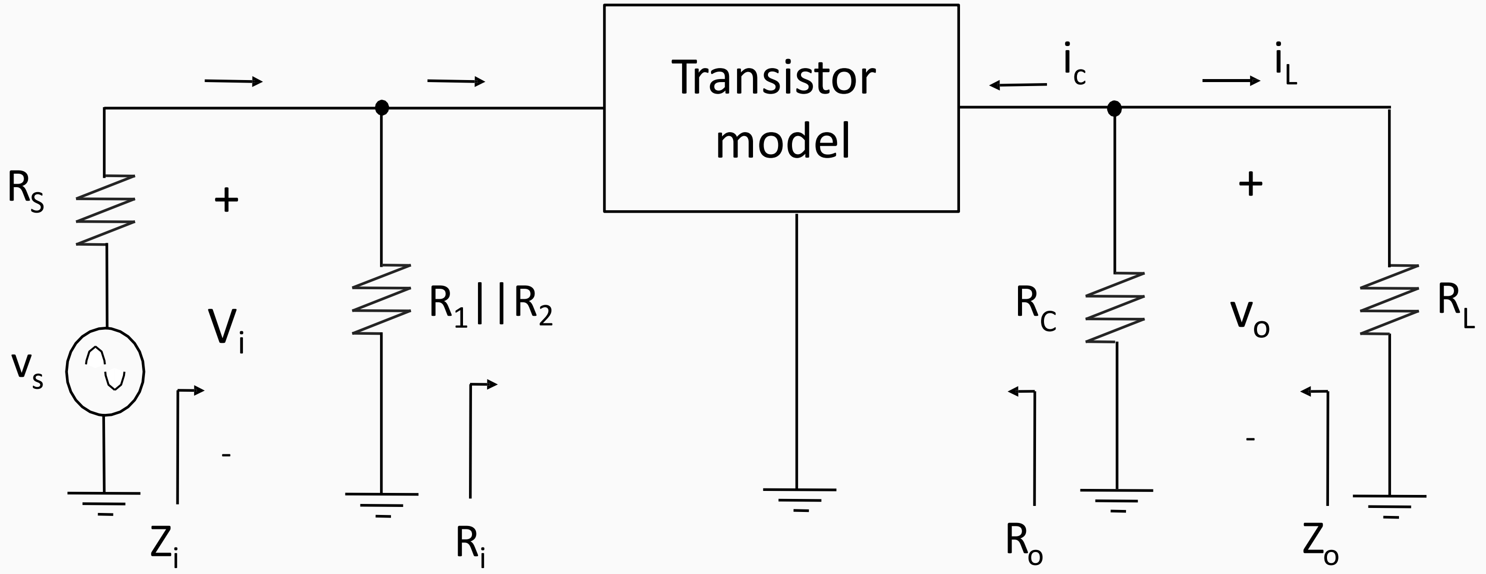


CE Amplifier



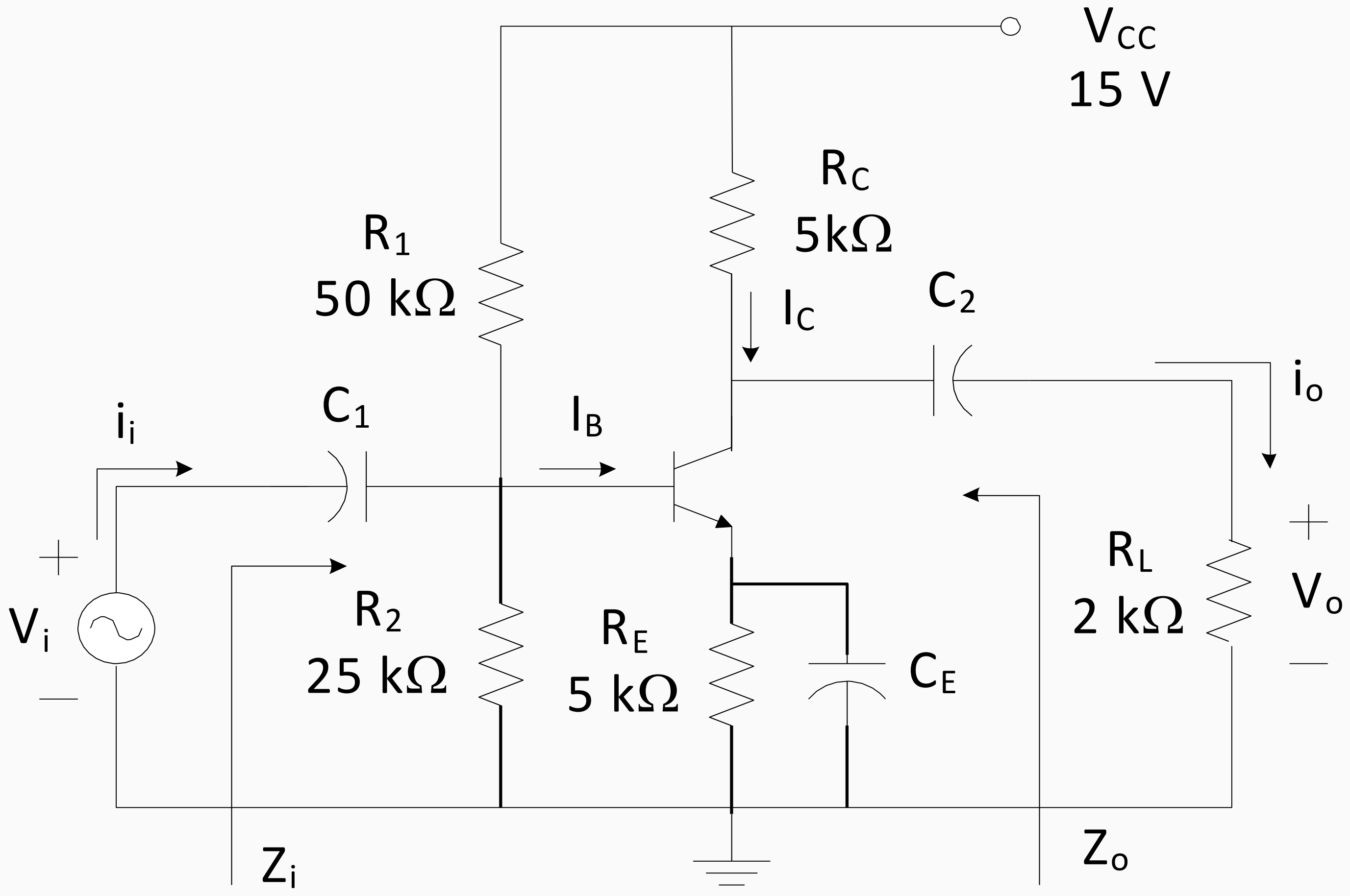
DC source grounded and capacitors are shorted

Common Emitter: Voltage Divider Bias



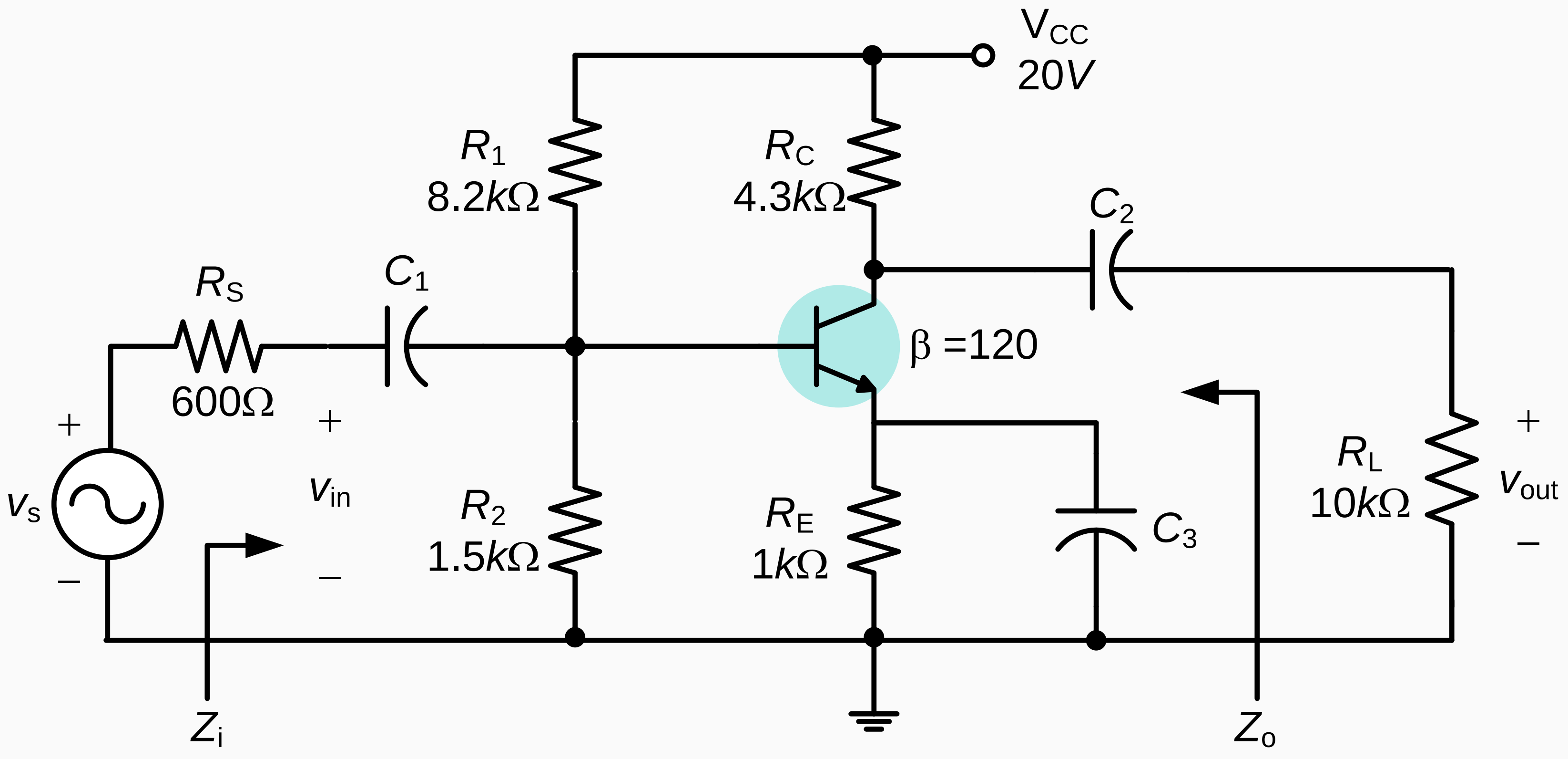
Exercise

Draw the AC equivalent circuit for the following voltage divider bias circuit:

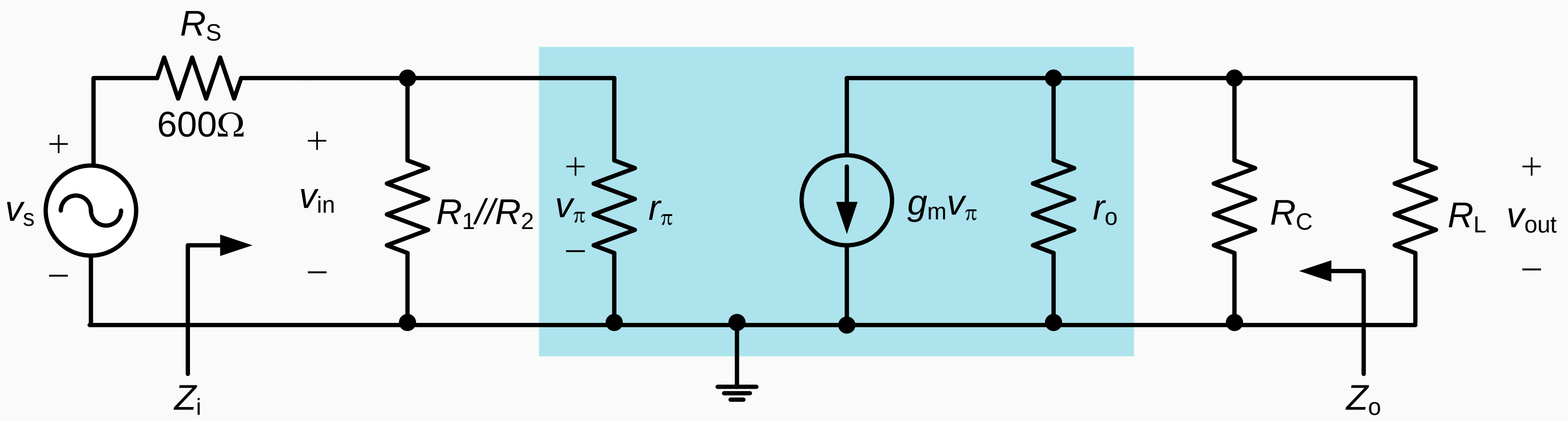


Common Emitter: Voltage Divider Bias Example

Determine the values of Z_i, Z_o, $A_{v(oc)}$, A_v, A_{vs}, A_i and A_{is} for the amplifier circuit below.
Given V_A=200V and I_C = 2.37mA



Solution



Input impedance: $Z_i = R_1 \| R_2 \| r_\pi = 8.2k\Omega \| 1.5k\Omega \| 1.32k\Omega = 647\Omega$

Output impedance: $Z_o = r_o \| R_C = 84.4k\Omega \| 4.3k\Omega = 4.09k\Omega$

Voltage gain: $A_{v(oc)} = \dfrac{v_{out}}{v_{in}} = -g_m(r_o \| R_C) = \text{-}(91.2mS)(4.09k\Omega) = -373$

$$A_v = \frac{v_{out}}{v_{in}} = A_{v(oc)}\left(\frac{R_L}{Z_o + R_L}\right) = (-373)\left(\frac{10k\Omega}{4.09k\Omega + 10k\Omega}\right) = -265$$

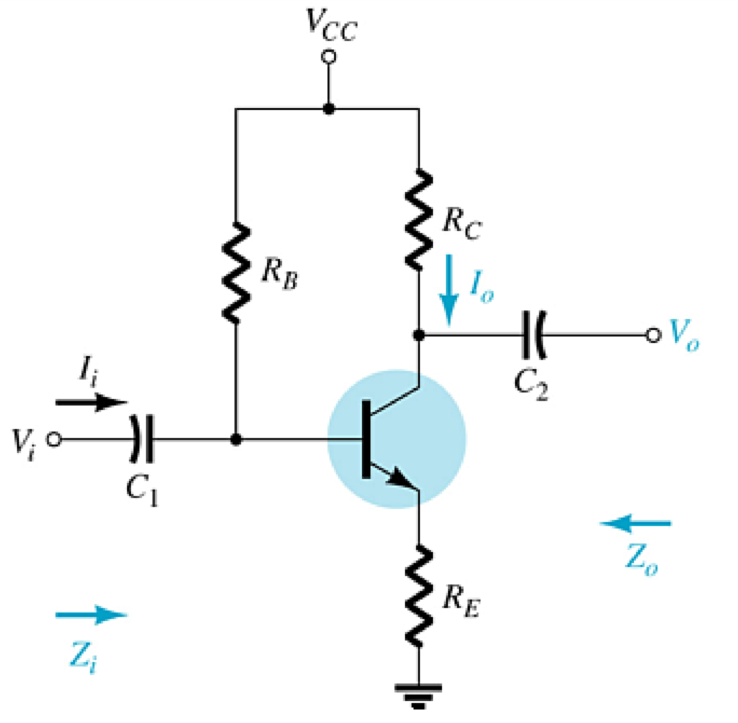
$$A_{vs} = \frac{v_{out}}{v_s} = A_v\left(\frac{Z_i}{R_s + Z_i}\right) = (-265)\left(\frac{647\Omega}{600\Omega + 647\Omega}\right) = -137.5$$

Current gain:

$$A_i = \frac{i_{out}}{i_{in}} = A_{v(oc)}\left(\frac{Z_i}{Z_o + R_L}\right) = (-373)\left(\frac{647\Omega}{4.09k\Omega + 10k\Omega}\right) = -17.13$$

$$A_{is} = \frac{i_{out}}{i_s} = A_i\left(\frac{R_s}{R_s + Z_i}\right) = (-17.13)\left(\frac{600\Omega}{600\Omega + 647\Omega}\right) = -8.24$$

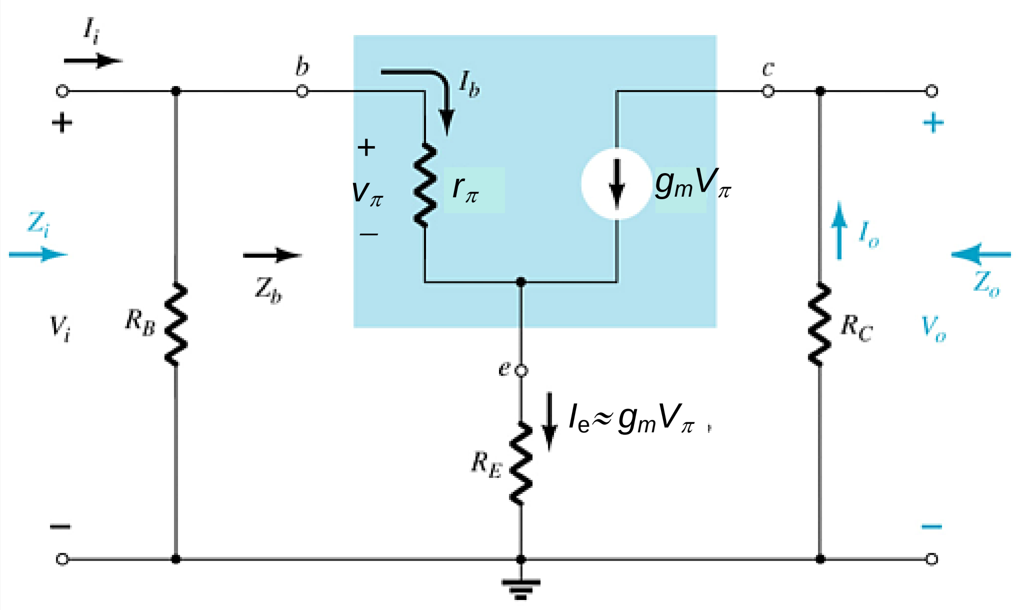
Common Emitter: Unbypassed R_E



The removal of the bypass capacitor results in:

- ❑ an increase in the input impedance, Z_i & output impedance, Z_o
- ❑ a reduction in its voltage gain, A_V

Common Emitter: Unbypassed R_E



Input impedance:

$$Z_i = R_B \| Z_b$$

$$Z_b = r_\pi + (\beta + 1) R_E$$

Output impedance (ignore r_o):

$$Z_o = R_C$$

Voltage gain:

$$A_{v(oc)} = \frac{v_o}{v_i} = -\frac{g_m v_\pi R_C}{i_b Z_b}\bigg|_{Z_b = r_\pi + (\beta+1)R_E}$$

$$= -\frac{g_m i_b r_\pi R_C}{i_b\left(r_\pi + g_m r_\pi R_E\right)} = -\frac{g_m R_C}{1 + g_m R_E}$$

$$A_{v(oc)} = \frac{v_o}{v_i} \cong -\frac{R_C}{R_E}\bigg|_{g_m R_E >> 1}$$

Current gain:

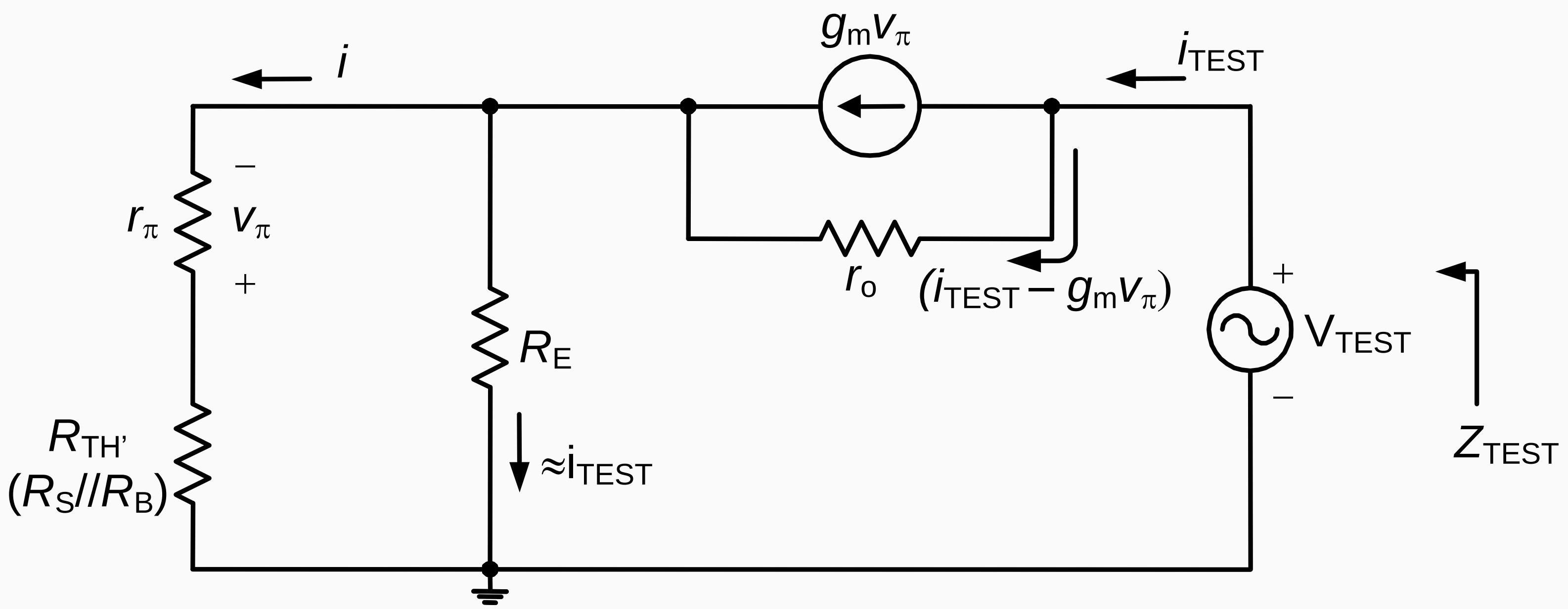
$$A_i = \frac{i_o}{i_i} = -\frac{g_m r_\pi R_B}{R_B + Z_b} = -\frac{\beta R_B}{R_B + Z_b}$$

Current gain from voltage gain:

$$A_i = A_{v(oc)}\left(\frac{Z_i}{Z_o + R_L}\right) = A_{v(oc)}\left(\frac{Z_i}{R_C}\right)$$

Common Emitter: Unbypassed R_E

To determine Z_o using imaginary voltage source (alternative approach)



$$Z_{TEST} = \frac{v_{TEST}}{i_{TEST}}$$

$$v_{TEST} \approx (i_{TEST} - g_m v_\pi) r_O + i_{TEST} R_E$$

$$\approx i_{TEST} r_O - g_m v_\pi r_O + i_{TEST} R_E$$

Common Emitter: Unbypassed R_E

$$i = \frac{R_E}{R_E + (r_\pi + R_{TH'})} \times i_{TEST}$$

$$v_\pi = -ir_\pi = \frac{-R_E r_\pi}{R_E + r_\pi + R_{TH'}} \times i_{TEST}$$

$$v_{TEST} = i_{TEST} r_O - g_m r_O \left[\frac{-R_E r_\pi}{R_E + r_\pi + R_{TH'}} \right] \times i_{TEST} + i_{TEST} R_E$$

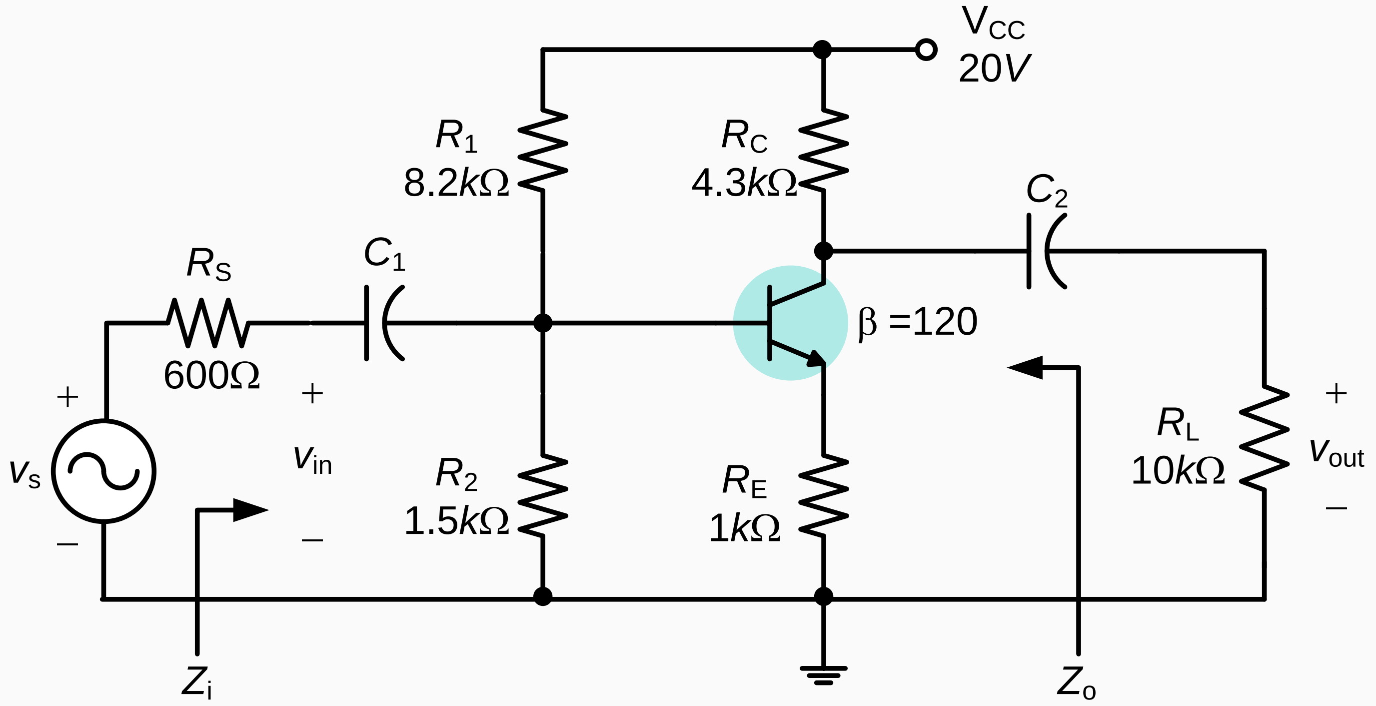
$$= i_{TEST} \left[r_O + \frac{g_m r_O R_E r_\pi}{R_E + r_\pi + R_{TH'}} + R_E \right]$$

$$\therefore Z_{TEST} = \frac{v_{TEST}}{i_{TEST}} = r_O + \frac{g_m r_O R_E r_\pi}{R_E + r_\pi + R_{TH'}} + R_E$$

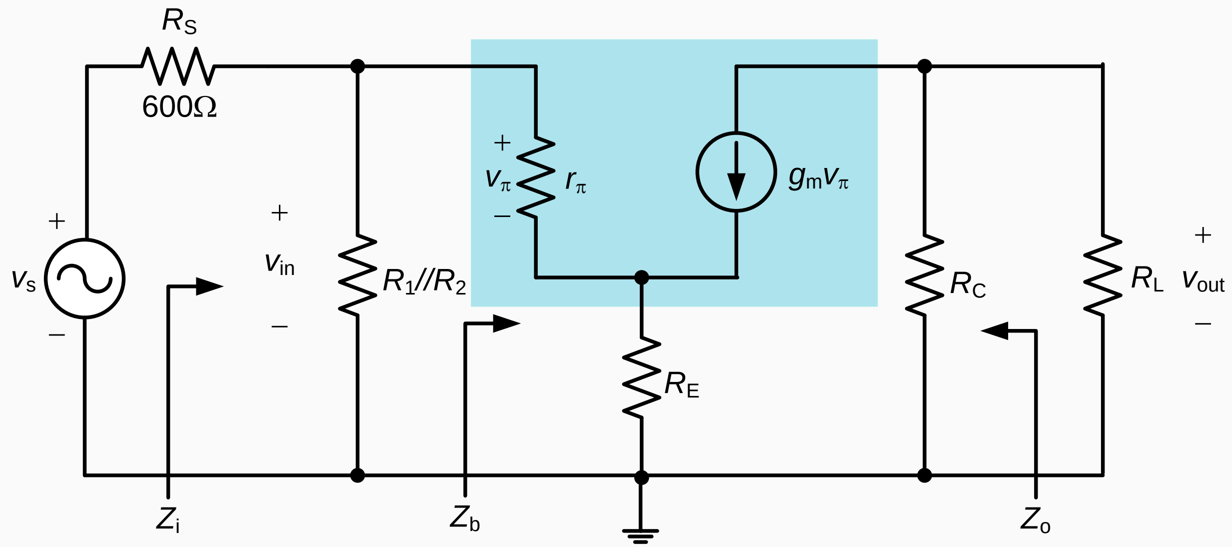
$$\therefore Z_O = (Z_{TEST} \| R_C) \approx R_C$$

Example of Common Emitter: Unbypassed R_E

Determine the values of Z_i, Z_o, $A_{v(oc)}$, A_v, A_{vs}, A_i, A_{is} and A_p for the amplifier circuit shown below. Given $V_A = \infty$ and $I_C = 2.37\text{mA}$



Example of Common Emitter: Unbypassed R_E



Input impedance:

$$Z_b = r_\pi + (\beta + 1)R_E = 1.32k\Omega + (121)(1k\Omega) = 122.32k\Omega$$

$$Z_i = R_1 \| R_2 \| Z_b = 8.2k\Omega \| 1.5k\Omega \| 122.32k\Omega = 1.26k\Omega$$

Output impedance: $Z_o = R_C = 4.3k\Omega$

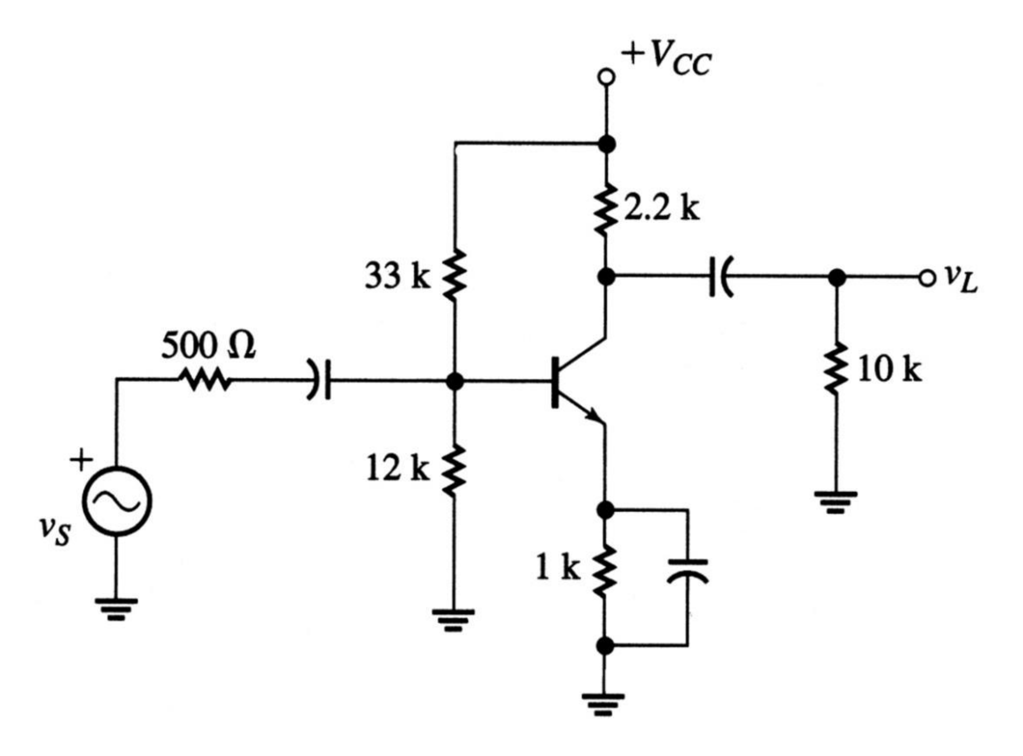
Voltage gain: $A_{v(oc)} = \frac{v_{out}}{v_{in}} = -\frac{g_m R_C}{1 + g_m R_E} = -\frac{(912mS)(4.09k\Omega)}{1 + (912mS)(1k\Omega)} = -4.25$

Exercise

Draw the small signal ac equivalent circuit. If $+V_{CC}$ = 12V, $V_A = \infty$, V_{BE} = 0.7V and β = 80, calculate the values of :

(a) Input and output impedances

(b) Voltage gain A_V and A_{VS}



Exercise

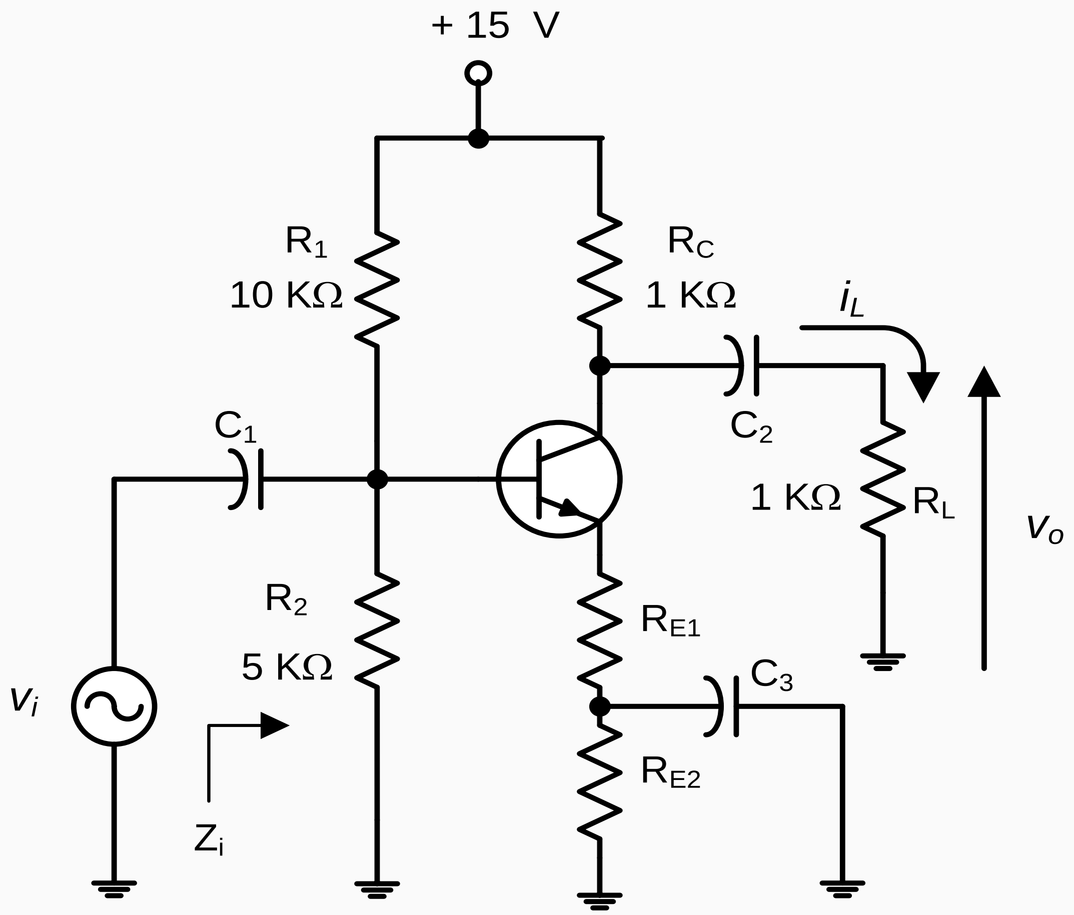
Given $\beta = h_{fe} = 200$, $V_{BE} = 0.6$ V, $V_{CEQ} = 10$ V, $V_A \to \infty$, A_v(dB) at middle frequency = 14dB.

(a) Draw the mid-frequency AC equivalent circuit.

(b) Determine R_{E1} and R_{E2}.

(c) Determine the amplifier input impedance, Z_i.

(d) Ratio of i_L/v_i.



$R_{E1} = 56.67\Omega$; $R_{E2} = 7.27k\Omega$;
$Z_i = 2.86k\Omega$; $i_L/v_i = 4.99mS$