Dr. Phung Thi Kieu Ha

Electronic Circuits and Applications

Lesson 2. BJT small-signal amplifier

Learning Contents

1. Introduction
2. BJT biasing
3. Small-signal equivalent circuit
4. Analysis of CB, CE, CC circuit
5. DC & AC design

Learning Goals

1. Be able to determine the DC levels of important BJT configurations and determine whether the network is operating properly
2. Become familiar with the r_e model for the BJT transistor,
3. Learn to use the r_e equivalent model to find the important AC parameters for an amplifier.
4. Develop some skills in troubleshooting AC amplifier networks

1. Introduction

1.1. Small-signal amplifier

1.2. BJT amplifier operation

1.3. BJT operating point

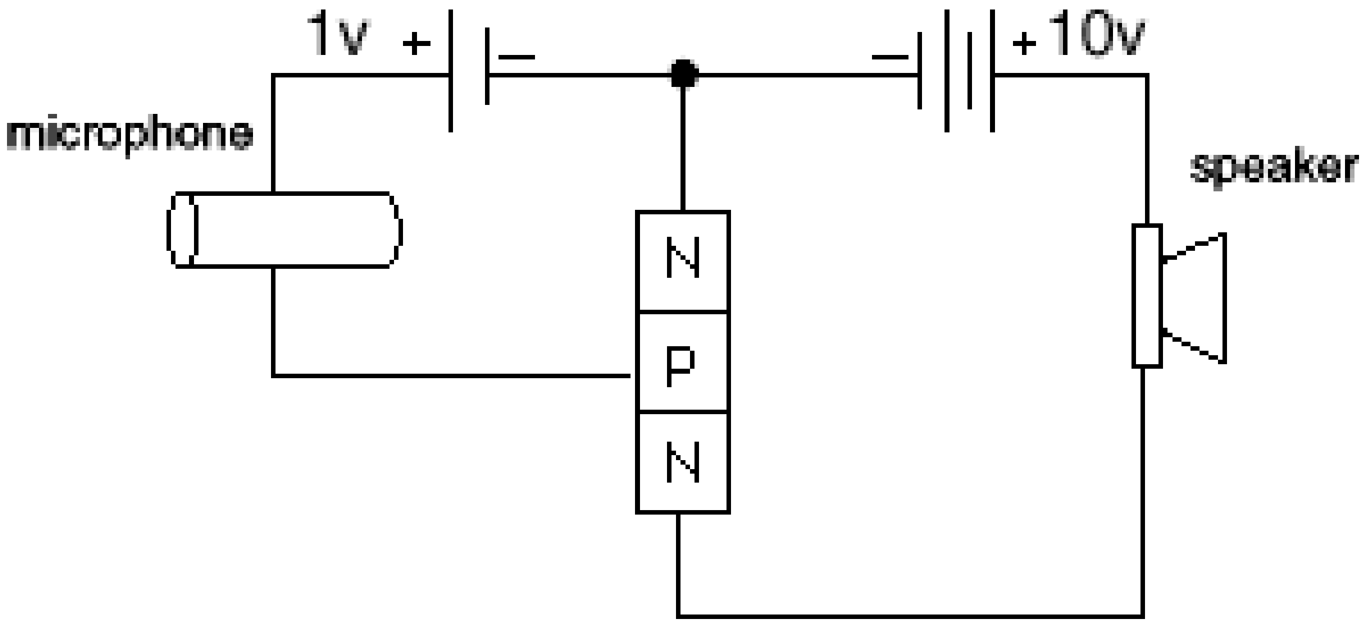
1. Introduction

1.1. Small-signal amplifier

- Input signal is relatively weak
- Generated output signal is small fluctuation with respect to quiescent (Q) point value
- Circuit can be reduced to a linearized equivalent circuit around its operating point with sufficient accuracy.
- Circuit model ignores simultaneous variations in the gain and supply values

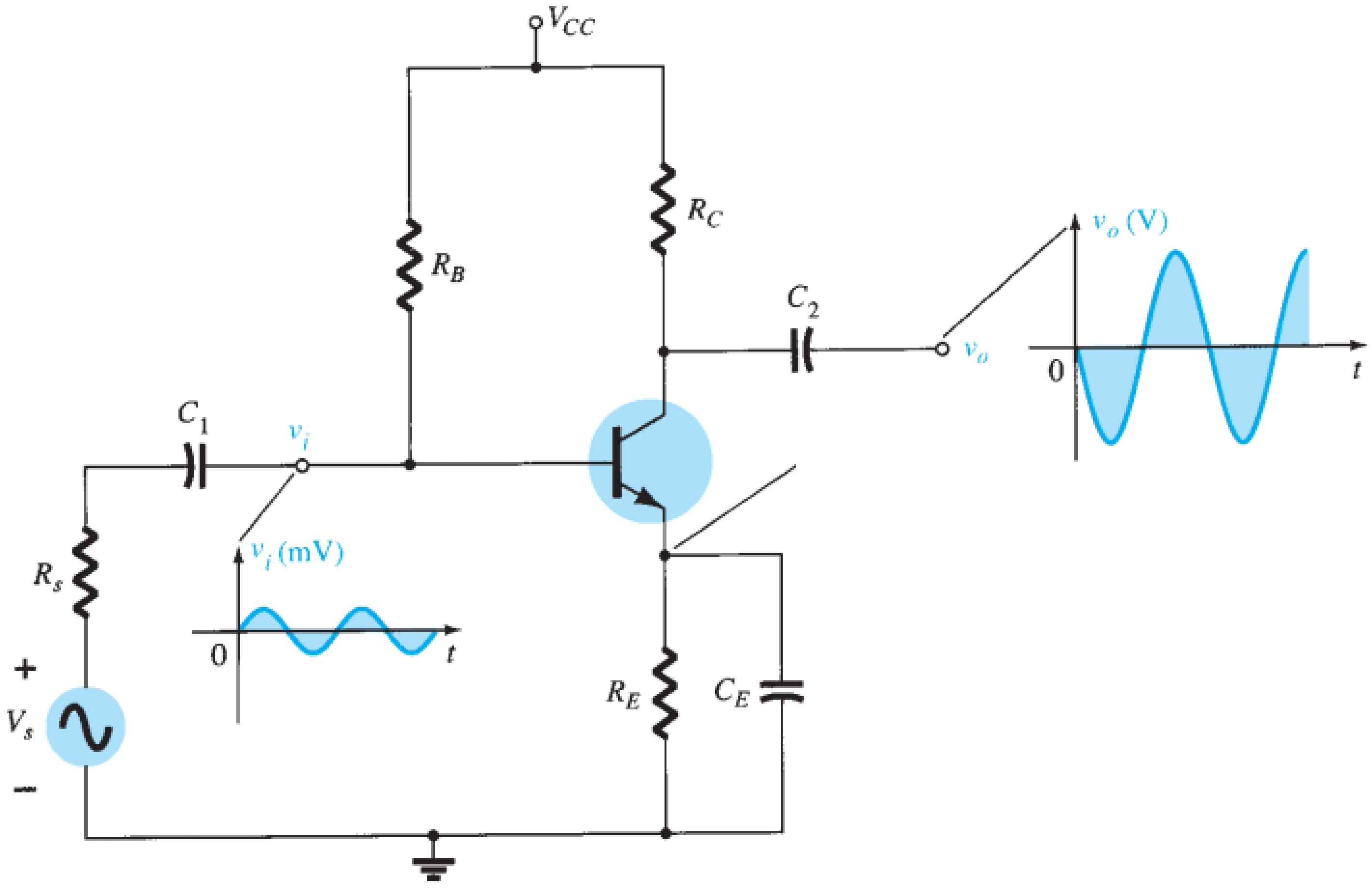
1. Introduction

1.2. BJT amplifier operation

- DC sources supply the active device BJT
- 

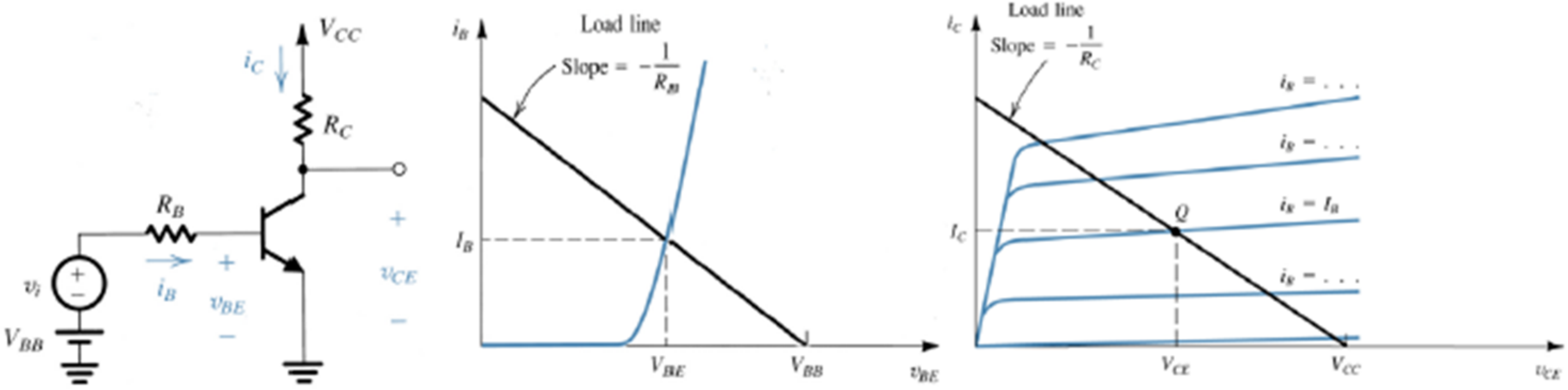
1. Introduction

1.2. BJT amplifier operation



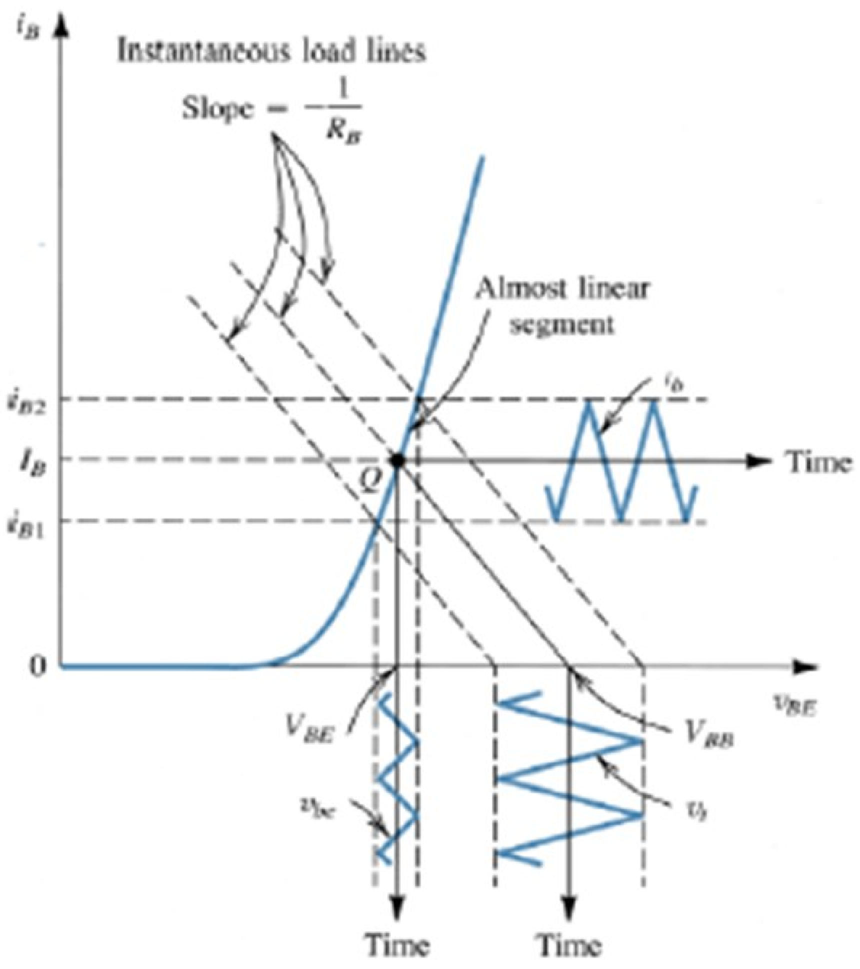
1. Introduction

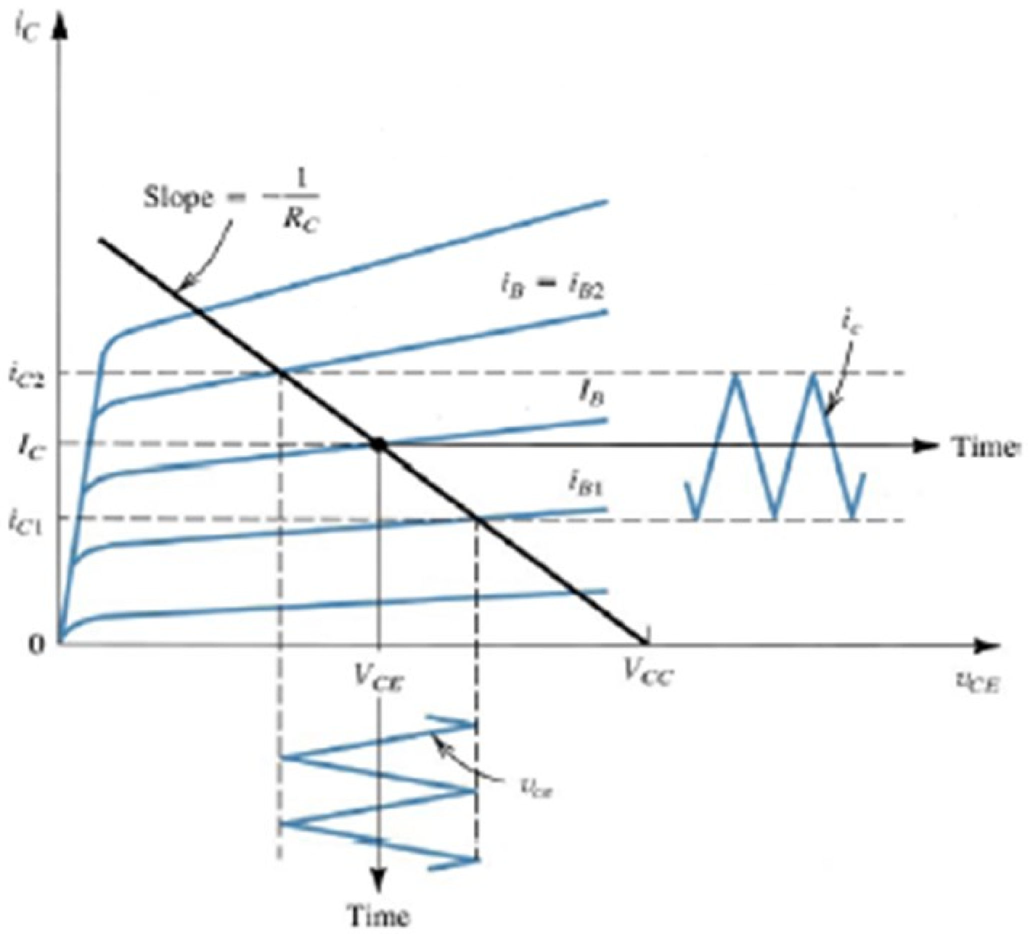
1.2. BJT amplifier operation



1. Introduction

1.2. BJT amplifier operation

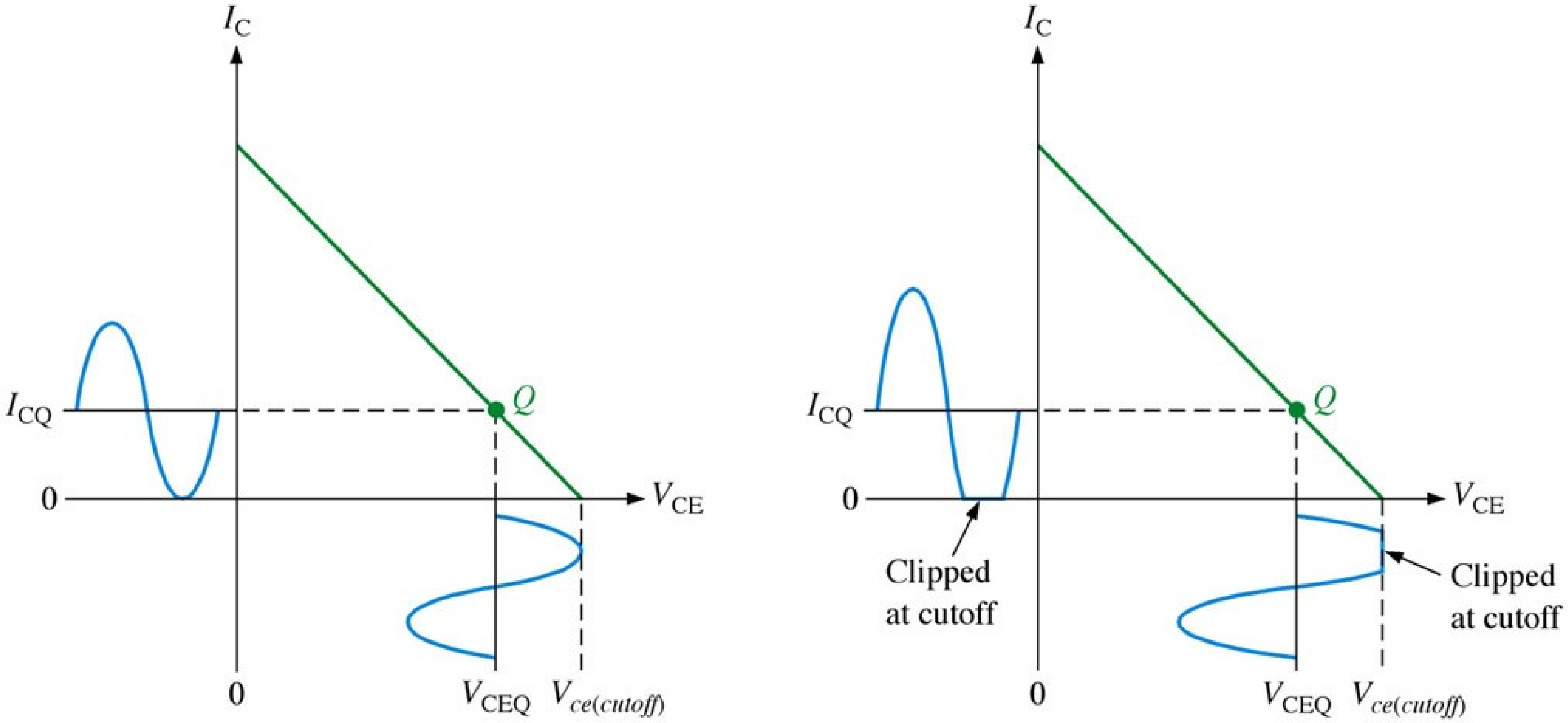




1. Introduction

1.2. BJT amplifier operation

- Q near cut-off region: the positive swing of the output voltage might be cut if input increases



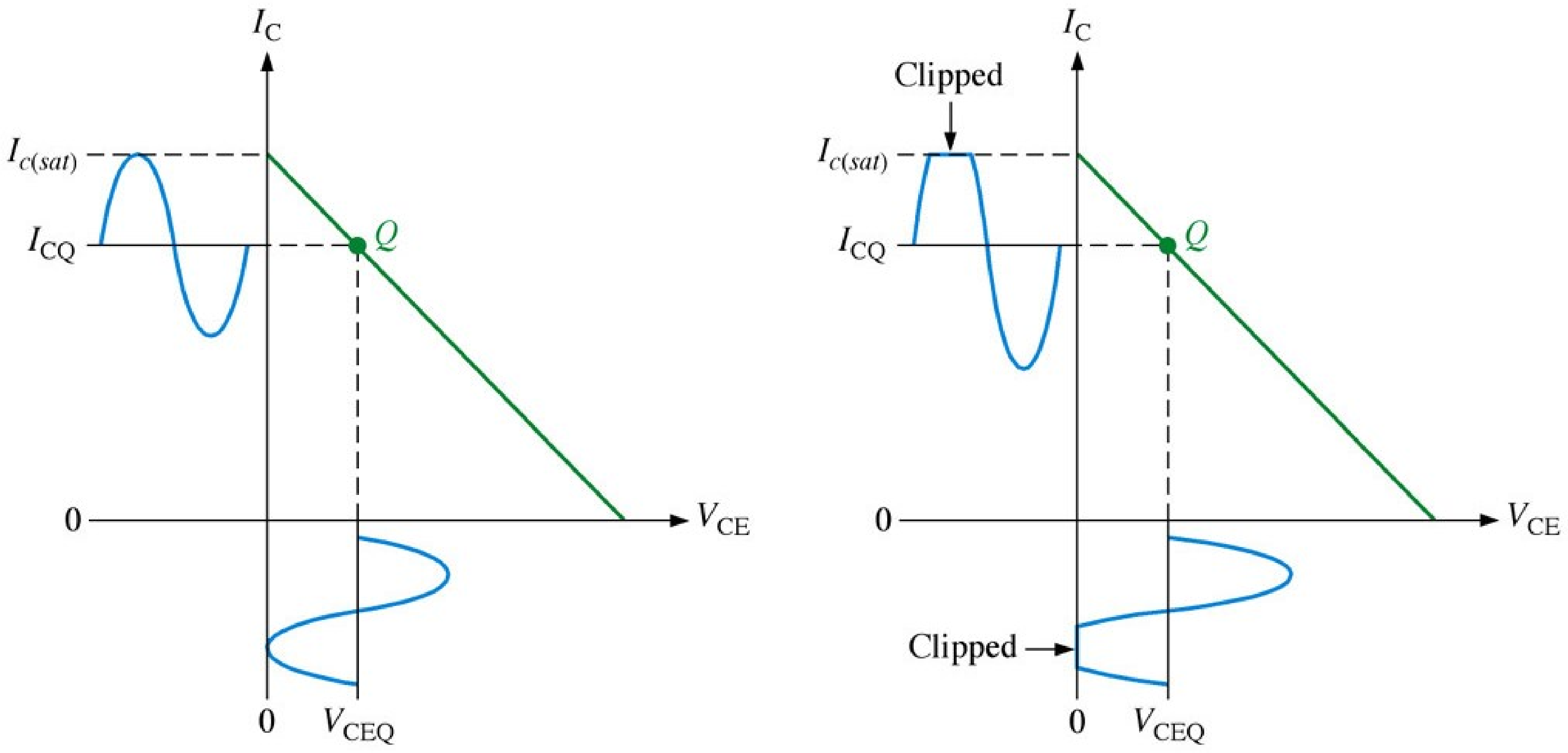
(a) Amplitude of V_{ce} and I_c limited by cutoff

(b) Transistor driven into cutoff by a further increase in input amplitude

1. Introduction

1.2. BJT amplifier operation

- Q near saturation: the negative swing of the output voltage might be cut if input increases

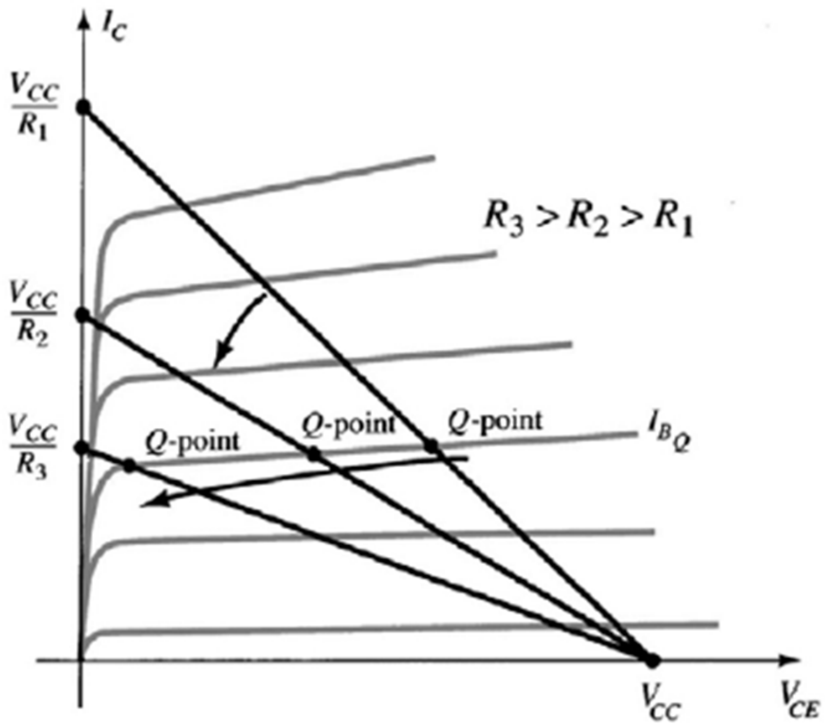


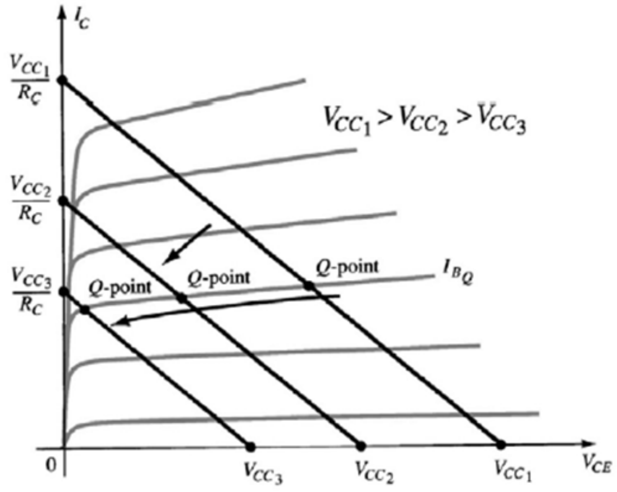
(a) Amplitude of V_{ce} and I_c limited by saturation

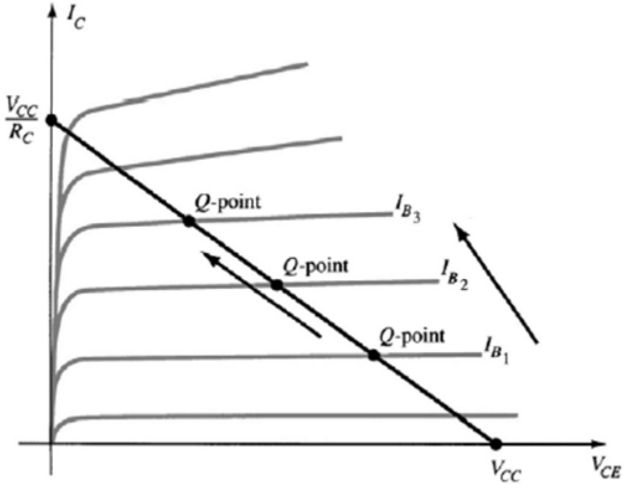
(b) Transistor driven into saturation by a further increase in input amplitude

1. Introduction

1.2. BJT amplifier operation



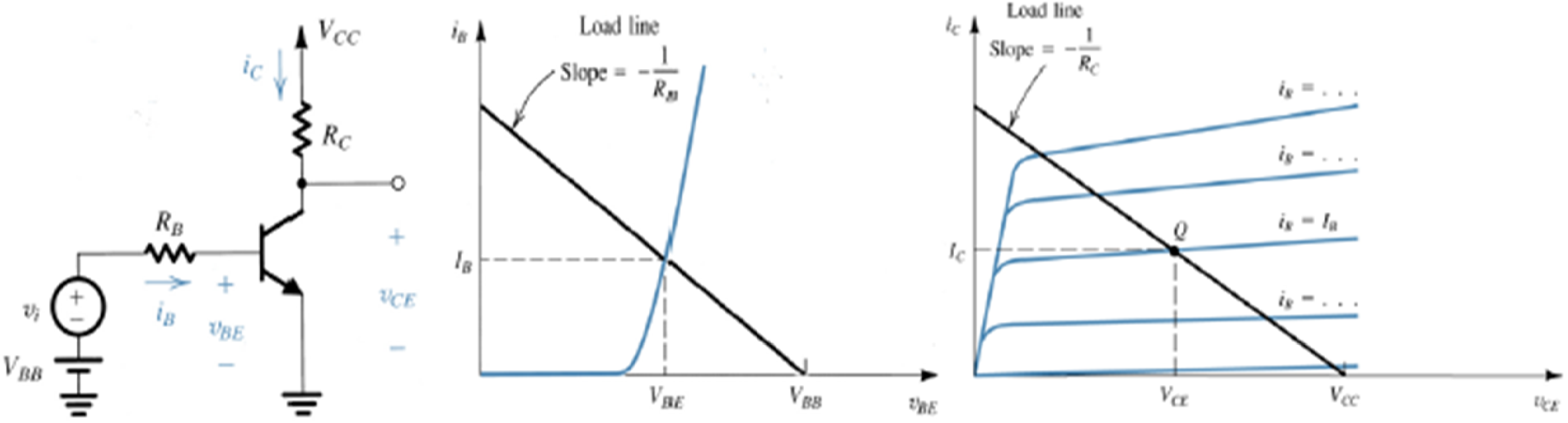




1. Introduction

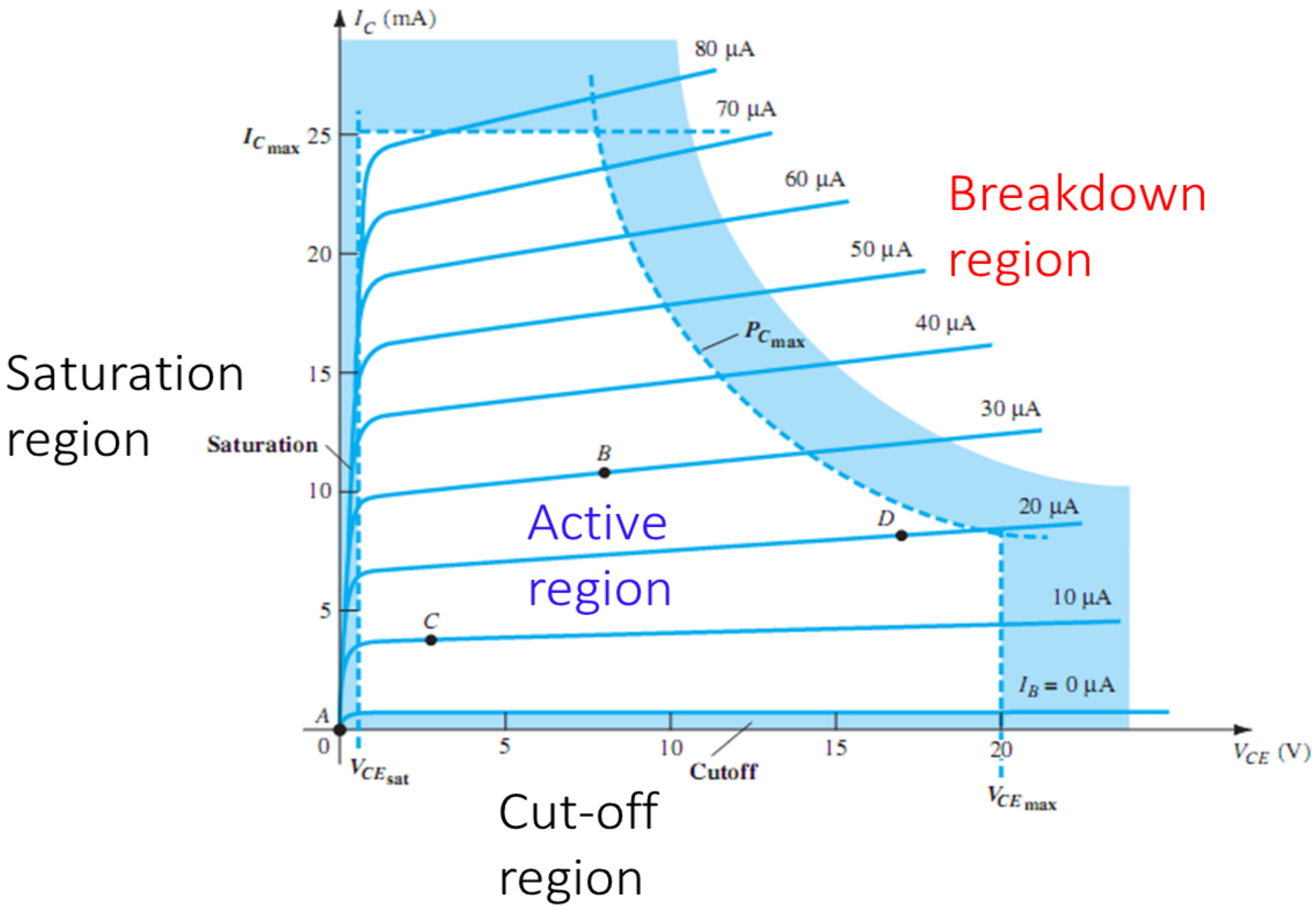
1.3. BJT Operating point

- Operating point = DC current & voltage level of operation



1. Introduction

1.3. BJT Operating point



1. Introduction

1.3. BJT Operating point

- For a BJT operating in active/amplifier region, the collector current is multiple of base current with the constant coefficient, called the amplified current parameter (β).

$$V_{BE} \approx 0{,}7V\ (Si)\ \text{or}\ V_{BE} \approx 0{,}3(Ge)\ *$$

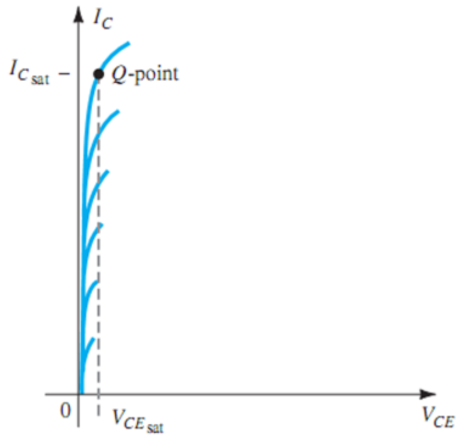
$$I_E = I_C + I_B$$

$$I_C = \beta I_B \qquad \text{or} \qquad I_C \approx \alpha I_E$$

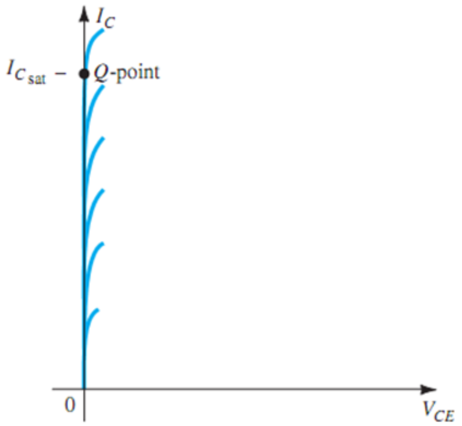
1. Introduction

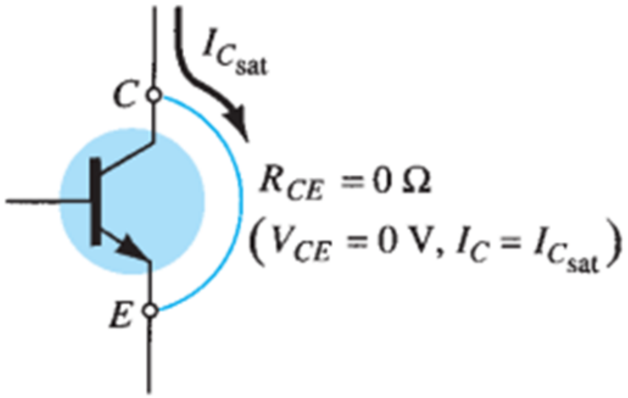
1.3. BJT Operating point

For a BJT operating in saturation region the current reach the maximum value for a particular design.



I_{Csat} is some idea of the possible max collector current (to stay below for a linear amplification)



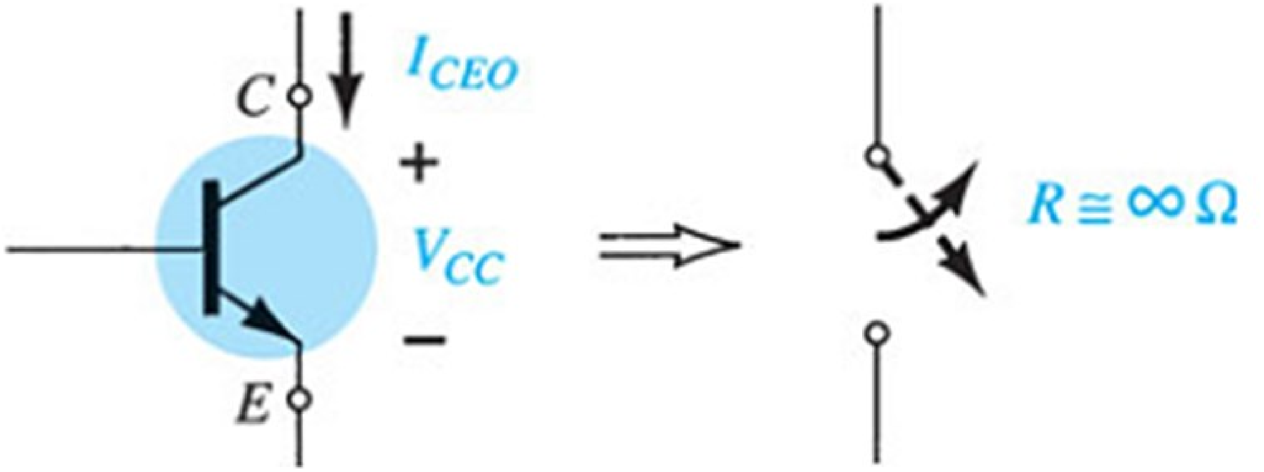


$$\boxed{I_{C_{sat}} = \frac{V_{CC}}{R_C}}$$

1. Introduction

1.3. BJT Operating point

For a BJT operating in cutoff region



- Cutoff region defined by $I_B \approx 0\mu A$ or $I_E \approx 0\mu A$
- Equivalent to an open-circuit, R_{cutoff} of BJT is very very large
- Voltage U_{CE} is nearly maximum value

2. BJT biasing

2.1. Amplifier mode of BJT

2.2. Fix-base configuration

2.3. Voltage-divider configuration

2.4. Voltage-feedback configuration

2. BJT biasing

2.1. Amplifier mode of BJT

For signal amplifying, operating point should be in "active region" => BE junction in forward-biasing & BC junction in reversed-biasing

In detail

NPN: $V_E < V_B < V_C$

or PNP: $V_E > V_B > V_C$

NOTE

$V_{BE} \approx 0{,}7V$ (Si) or $V_{BE} \approx 0{,}3$(Ge) *

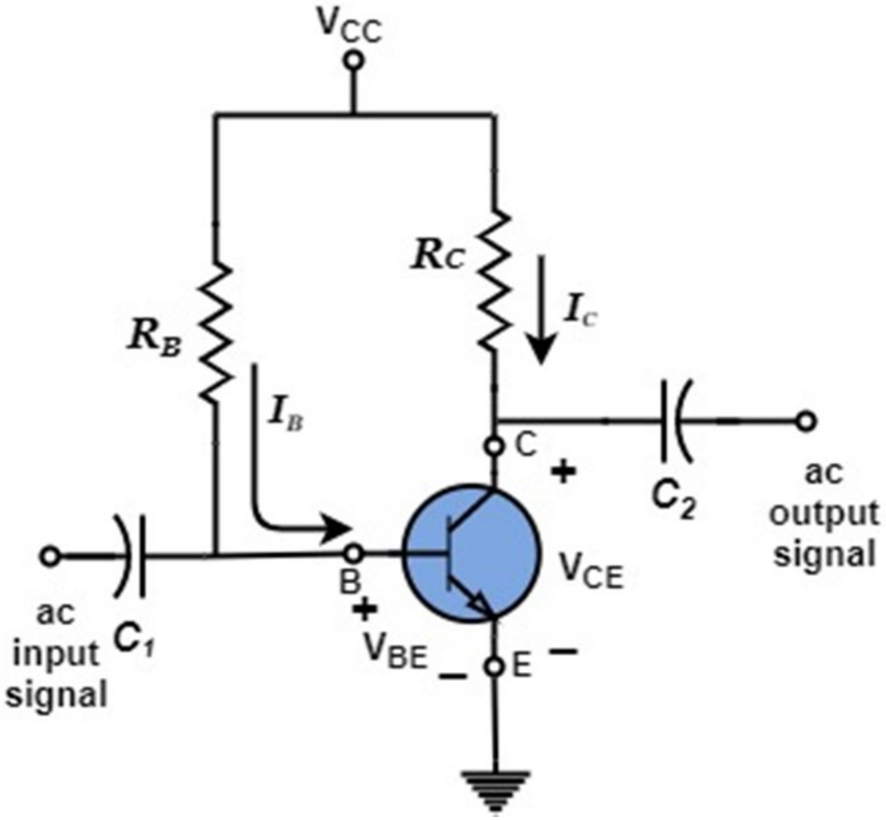
$I_E = I_C + I_B$

$I_C = \beta I_B$ or $I_C \approx \alpha I_E$

**if not specified, BJT is made from Si*

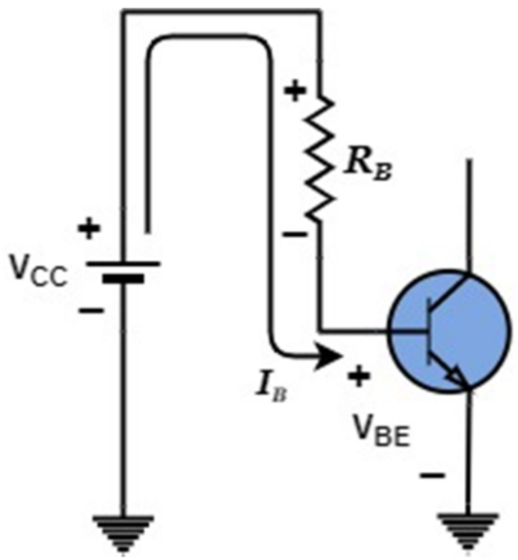
2. BJT biasing

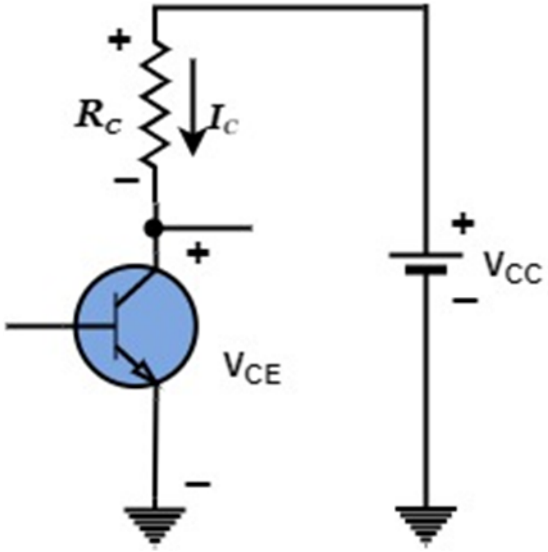
2.2. Fix-base configuration



2. BJT biasing

2.2. Fix-base configuration





Loop BE:

$V_{CC} - I_B R_B - U_{BE} = 0$

$\Rightarrow I_B = (V_{CC} - U_{BE})/R_B$

$I_C = \beta * I_B$

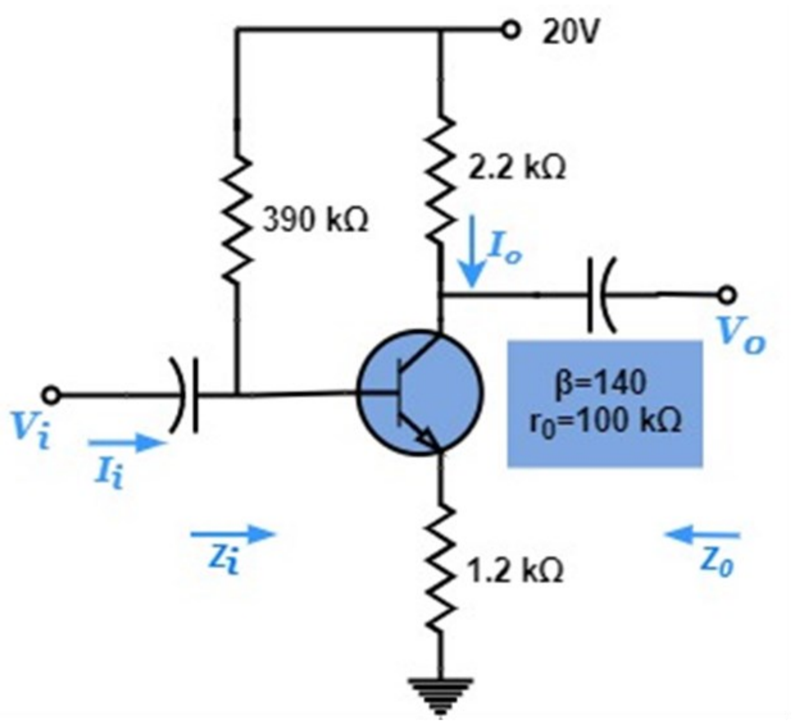
Loop CE :

$\Rightarrow U_{CE} = V_{CC} - I_C R_C$

Simple but unstable

2. BJT biasing

2.2. Fix-base configuration



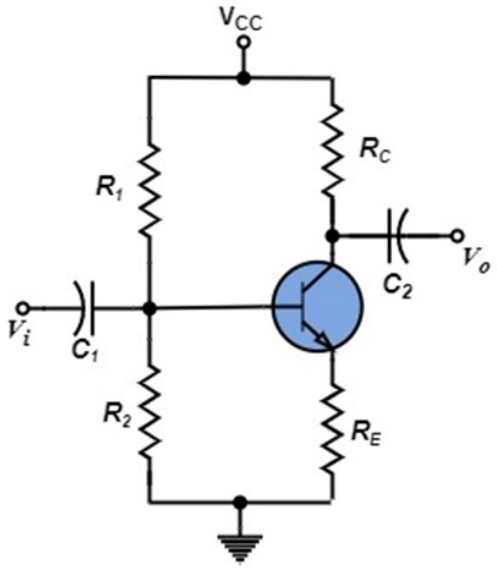
$I_B = (V_{cc}\text{-}U_{BE})/(R_B+\beta R_E)$
$= 34.6\mu A$

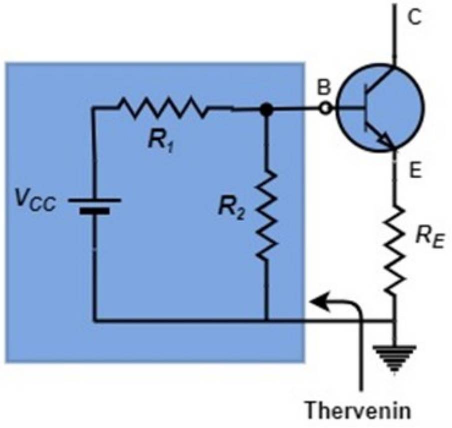
$I_C = \beta * I_B$
$= 4.84mA$

$V_{CE} = V_{CC} - I_C*R_C - I_E*R_E$
$= 3.5V$

2. BJT biasing

2.3. Voltage-divider configuration

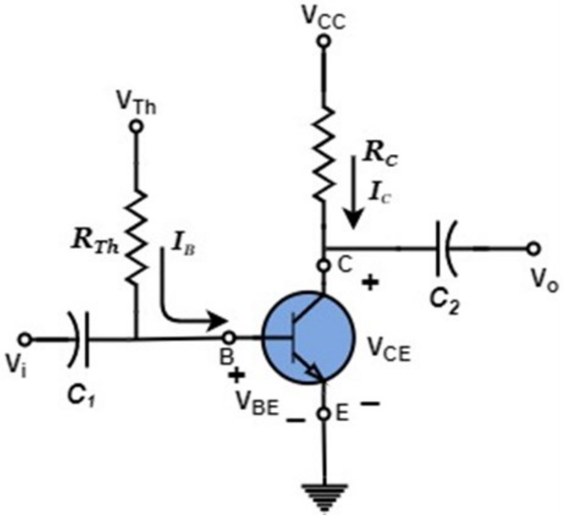




Thévenin theorem:

$R_{BB}=R_1//R_2$

$E_{BB}=R_2V_{cc}/(R_1+R_2)$

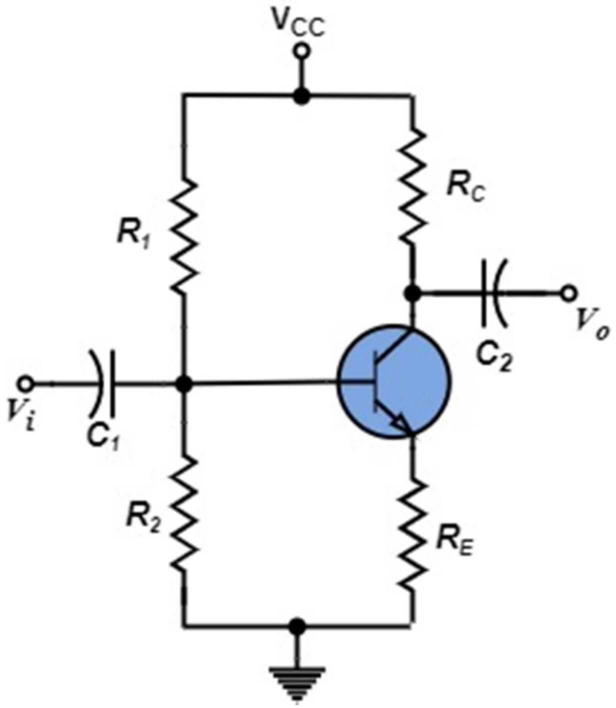


Redraw new circuit which is equivalent to the fixed base configuration

2. BJT biasing

2.3. Voltage-divider configuration

- Voltage-divider configuration



Approximation approach

If $\beta * R_E \geq 10R_2$ -> $I_2 \approx I_1$

$\Rightarrow V_B = R_2 * V_{CC}/(R_1+R_2)$

$\Rightarrow V_E = V_B - U_{BE}$

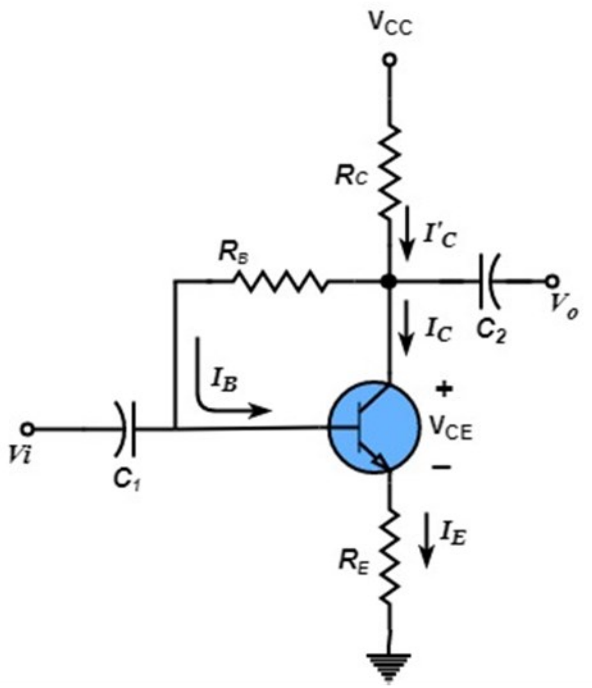
$\Rightarrow I_C \approx I_E = V_E/R_E$

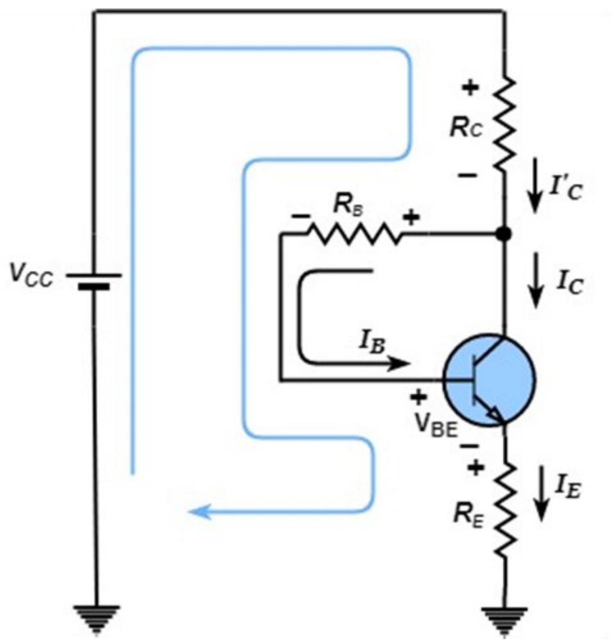
$\Rightarrow U_{CE} = V_{CC} - I_C(R_C+R_E)$

Current and voltage are independent with β

2. BJT biasing

2.4. Voltage-feedback configuration





Loop BE:

$$V_{CC} - I'_C R_C - I_B R_B - U_{BE} - I_E R_E = 0$$

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

with $I'_C \approx I_C \quad I_E \approx I_C$

3. AC equivalent model

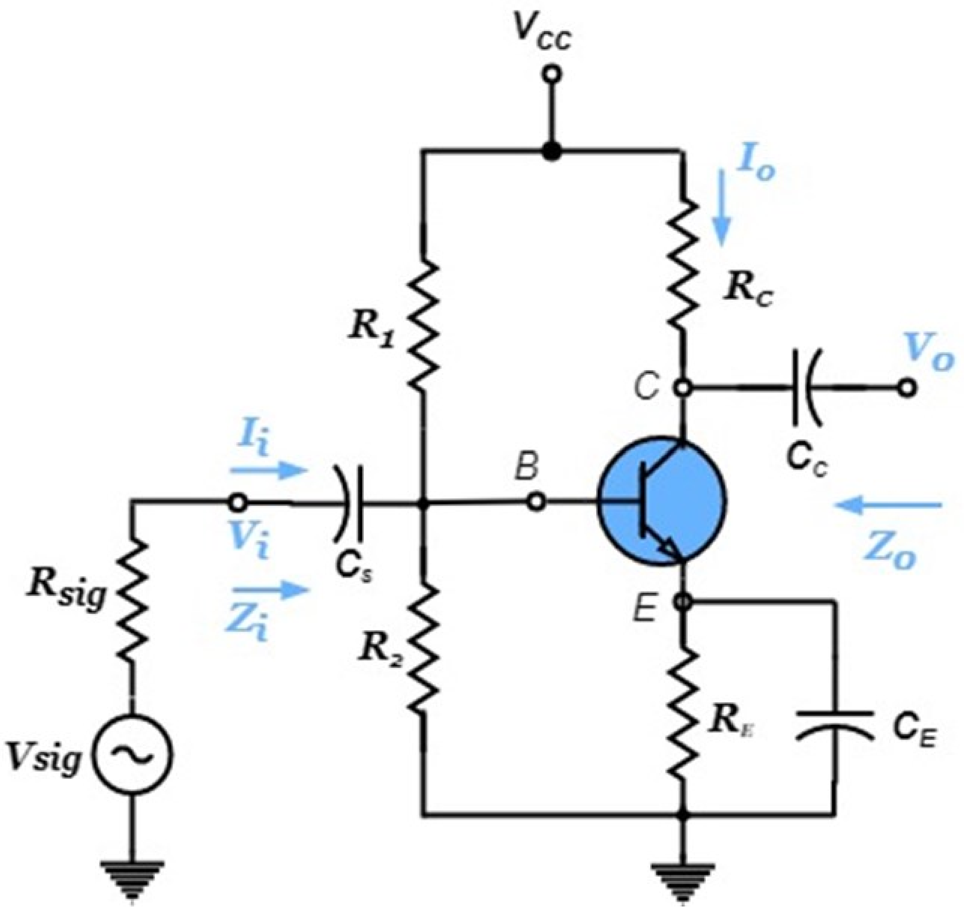
3.1. Introduction

3.2. re equivalent circuit of Common-Base

3.3. re equivalent circuit of Common-Emitter

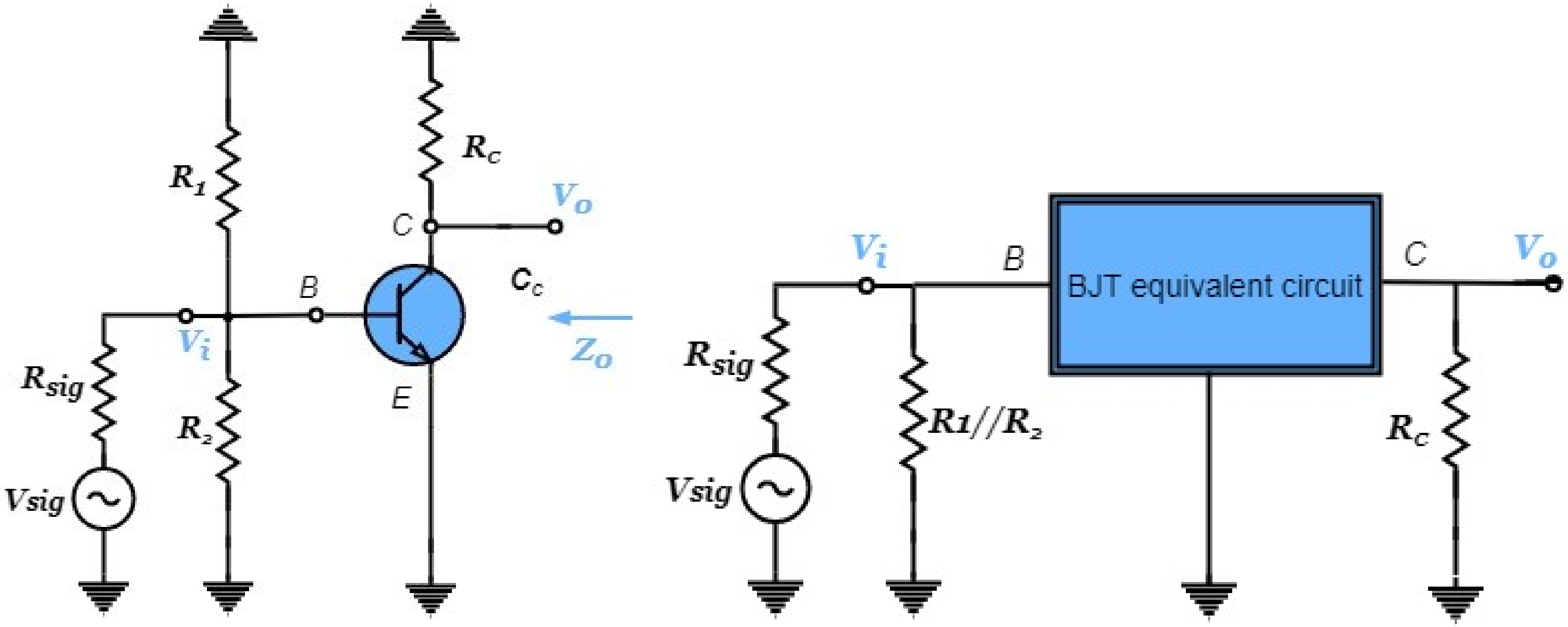
3. AC equivalent model

3.1. Introduction



3. AC equivalent model

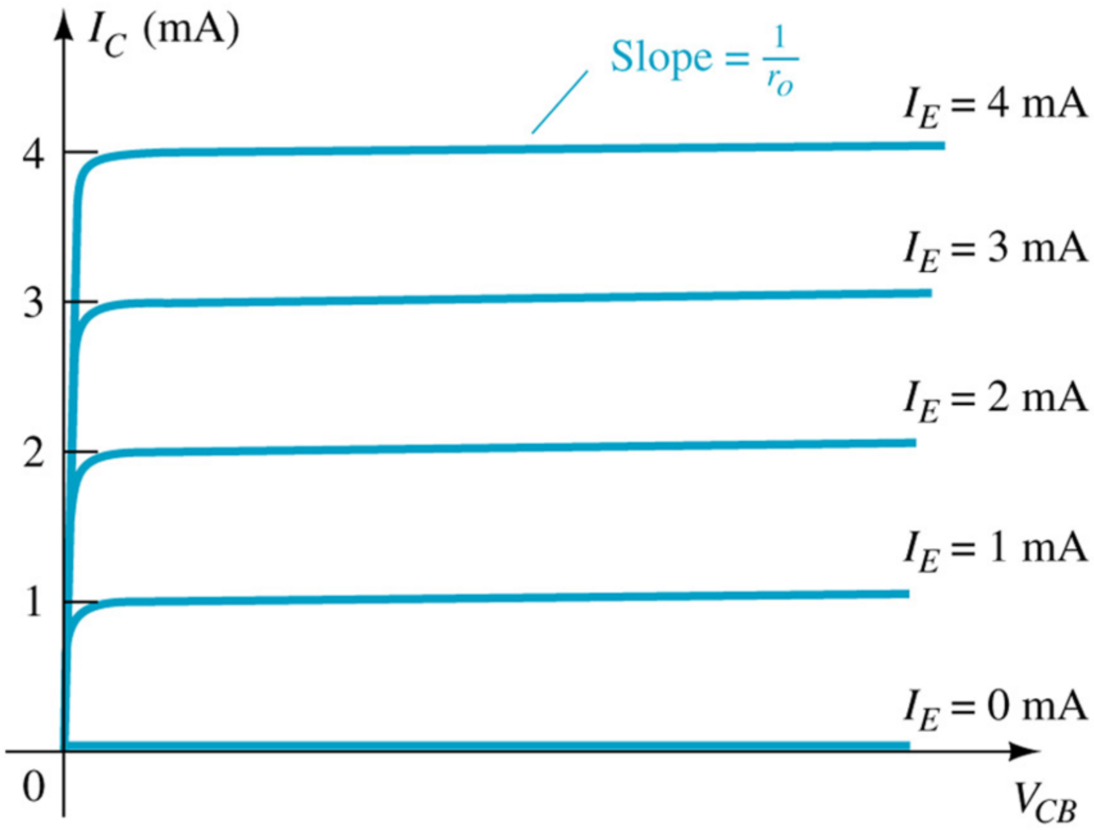
3.1. Introduction



- When analyzing the circuit in AC mode:
  - ✓Consider the capacitors as short-circuit
  - ✓Consider the DC sources at 0 volt

3. AC equivalent model

3.2. re equivalent model for Common Base



3. AC equivalent model

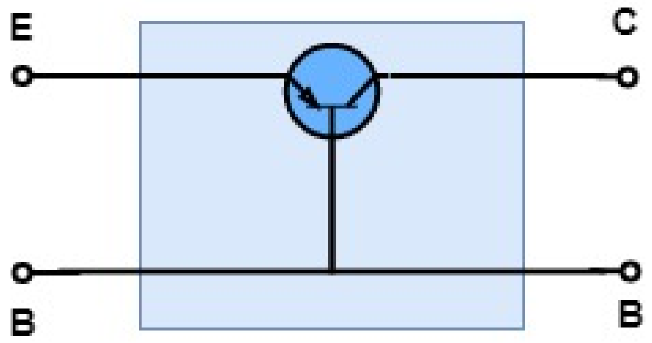
3.2. re equivalent model for Common Base

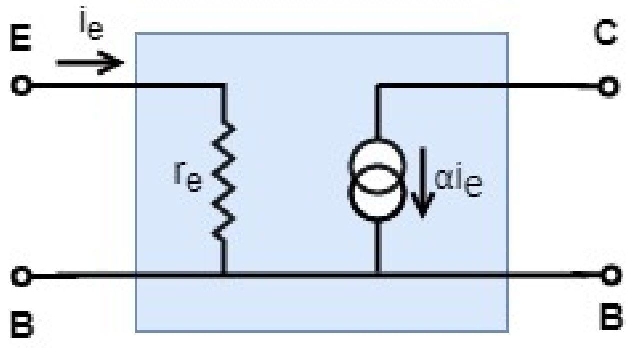
- Separation of input and output
- Input: input current i_e and r_e is AC resistor of a normal diode

  $r_e = 26mV/I_E$

- Output: a controlling current i_e,

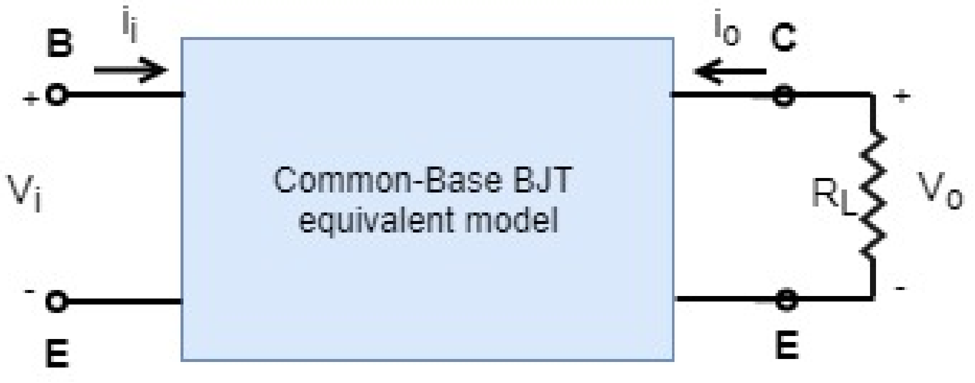
  $i_c = \alpha * i_e$





3. AC equivalent model

3.2. re equivalent model for Common Base



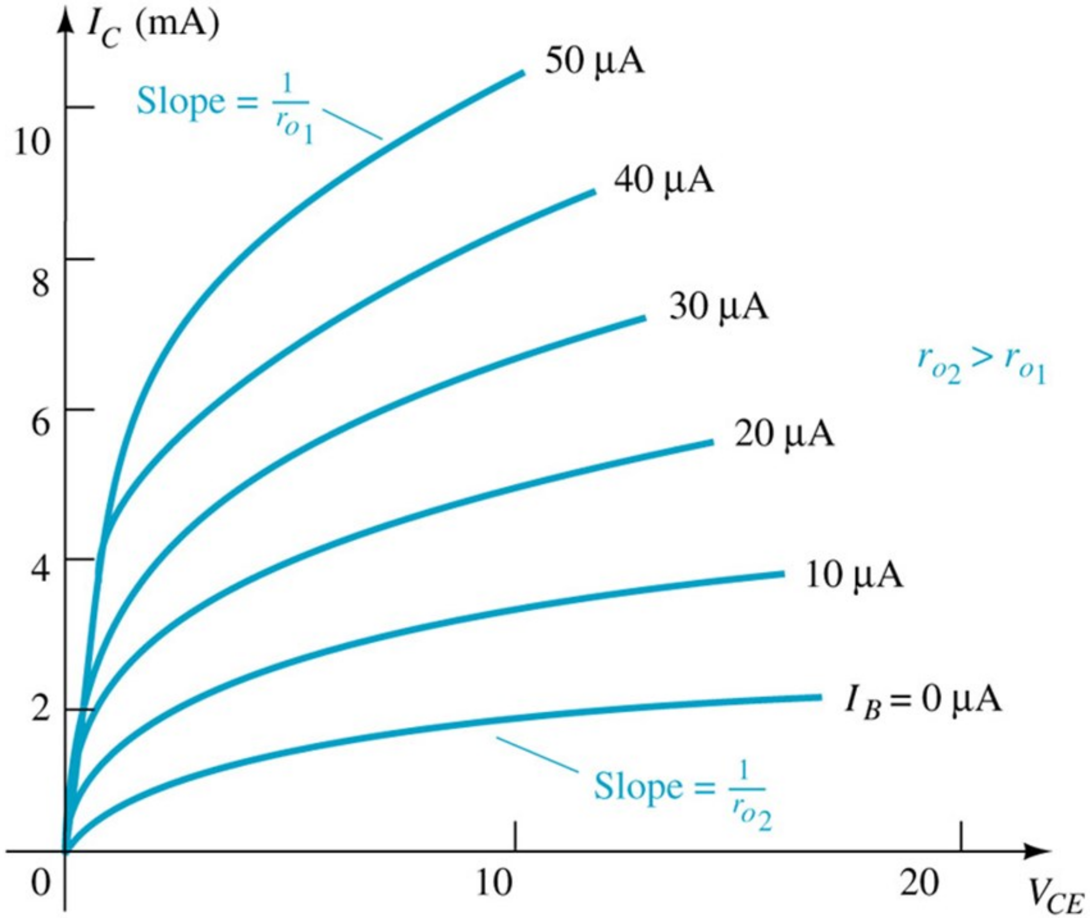
- $Z_i = r_e$ (nΩ-50Ω)
- $Z_o = r_o \approx \infty$ (nMΩ)

  Z_o is the slope of the output characteristic
- $A_v = \alpha * R_L / r_e \approx R_L / r_e$

  Voltage gain rather large and V_o & V_i in phase
- $A_i = -\alpha \approx -1$

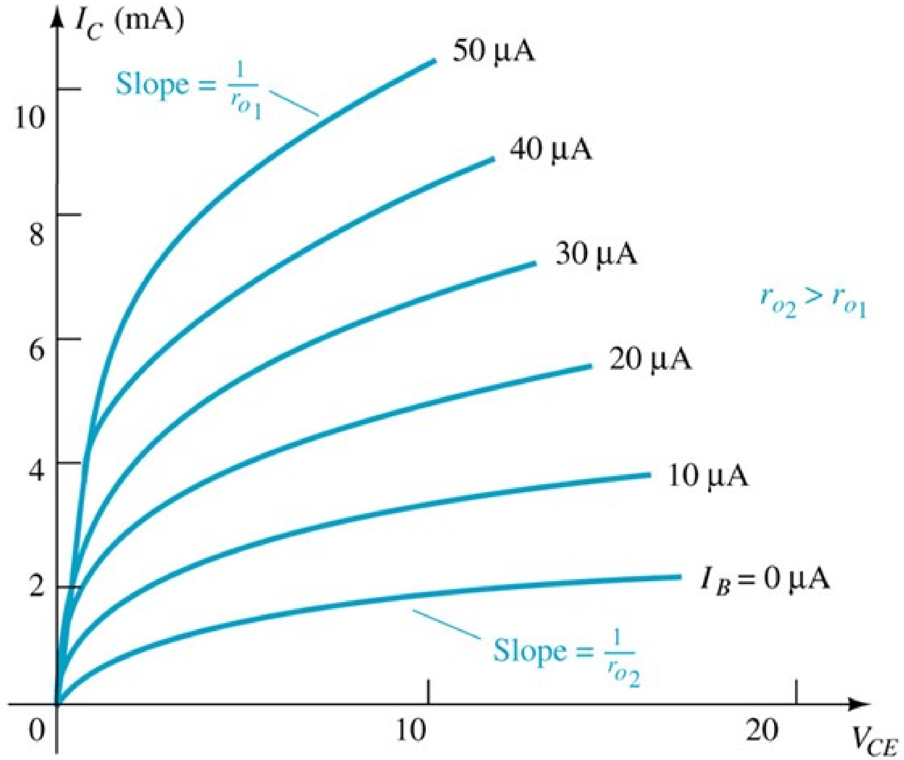
3. AC equivalent model

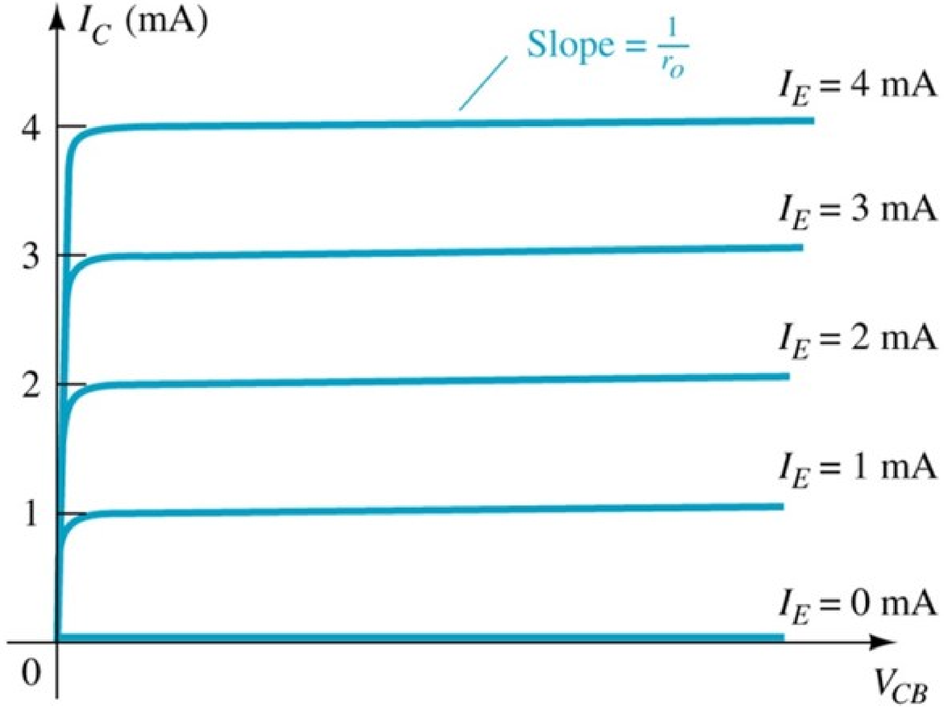
3.3. re equivalent model for Common Emitter



3. AC equivalent model

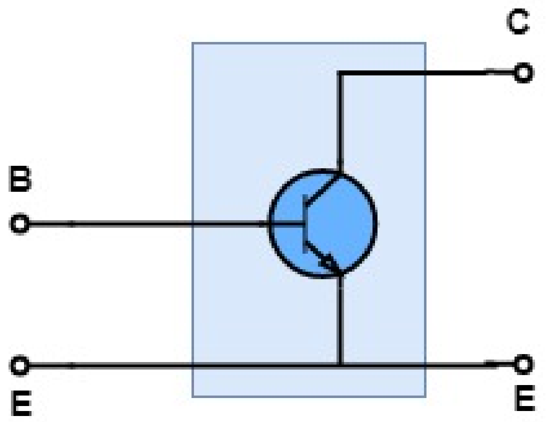
3.3. re equivalent model for Common Emitter

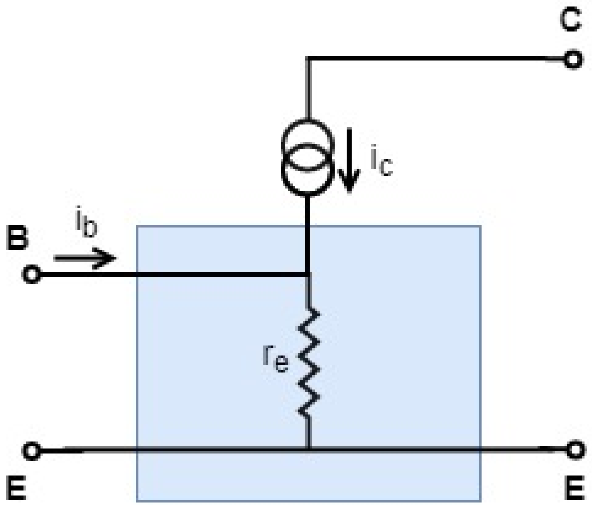




3. AC equivalent model

3.3. re equivalent model for Common Emitter





- Input current i_b and an AC resistor of a normal diode

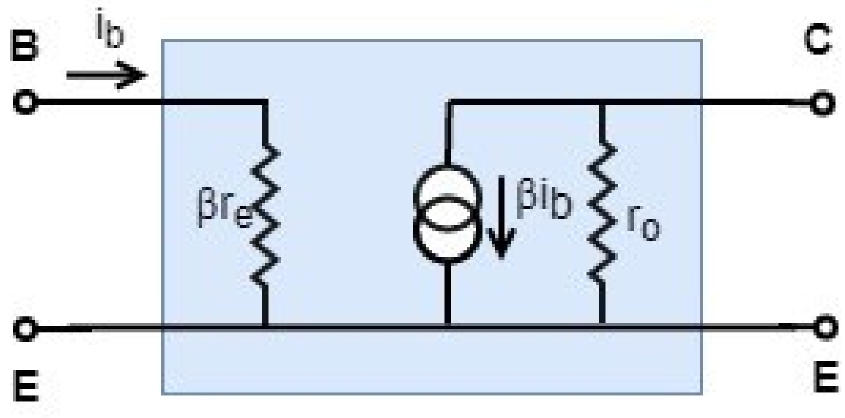
$$r_e = 26mV/I_E$$

- Output: a source of a controlled collector current

$$i_c = \beta * i_b$$

3. AC equivalent model

3.3. re equivalent model for Common Emitter



$Z_i = v_{be}/i_b \approx \beta r_e$ (n100Ω – nKΩ)

$Z_o = r_o$ (40-50KΩ)

$A_v = - R_L/r_e$ ($r_o = \infty$)

$A_i = i_c/i_b = \beta$

Medium Z_i, Z_o & rather large A_v, A_i

3. AC equivalent model

3.3. re equivalent model for Common Emitter

Common Emitter	Common Base
$Z_i = v_{be}/i_b \approx \beta r_e$ (n100Ω – nKΩ)	$Z_i = r_e$ (nΩ-50Ω)
$Z_o = r_o$ (40-50KΩ)	$Z_o = r_o$ (nMΩ) Z_o is the slope of the output characteristic
$A_v = - R_L/r_e$ (consider $r_o = \infty$)	$A_v = \alpha * R_L/r_e \approx R_L/r_e$ V_o & V_i in phase
$A_i = i_c/i_b = \beta$ Medium Z_i, Z_o & rather large A_v, A_i	Ai = $-\alpha \approx -1$

3. AC equivalent model

3.4. re equivalent model for Common Collector

- Use Common Emitter model

4. Use cases of CB/CE/CC circuits

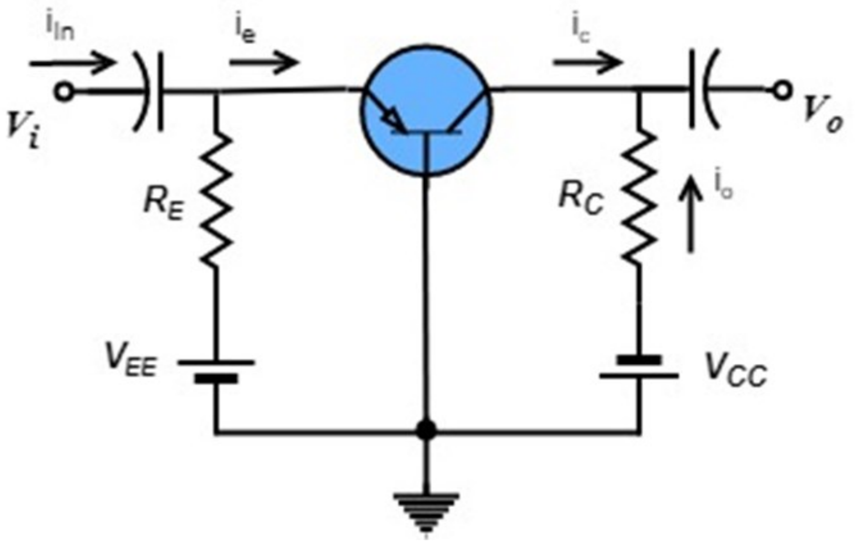
4.1. Common-Base

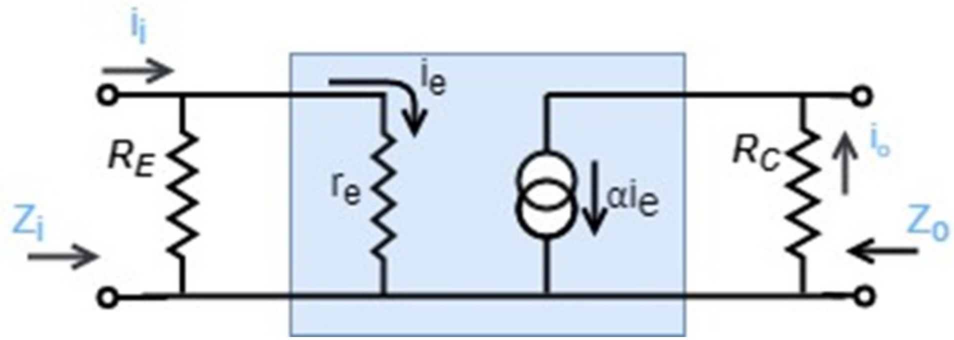
4.2. Common-Emitter

4.3. Common-Collector

4. Use cases of CB/CE/CC circuits

4.1. Common-Base





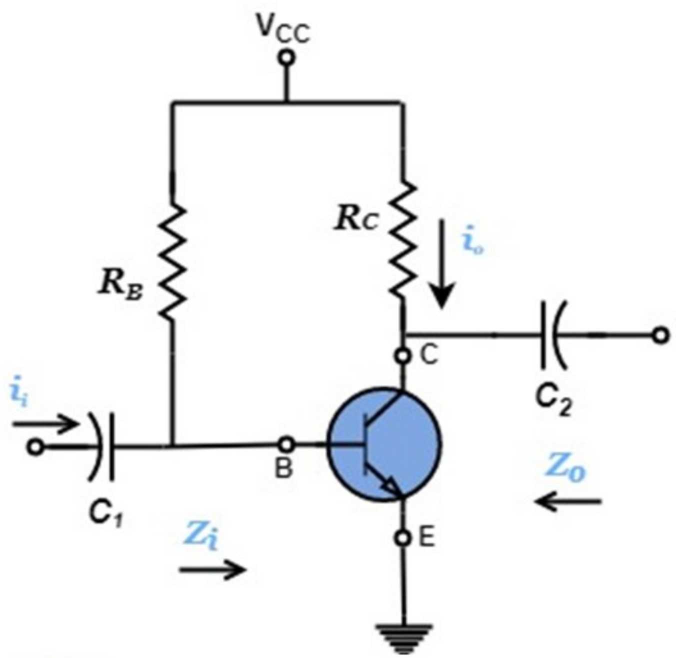
4. Use cases of CB/CE/CC circuits

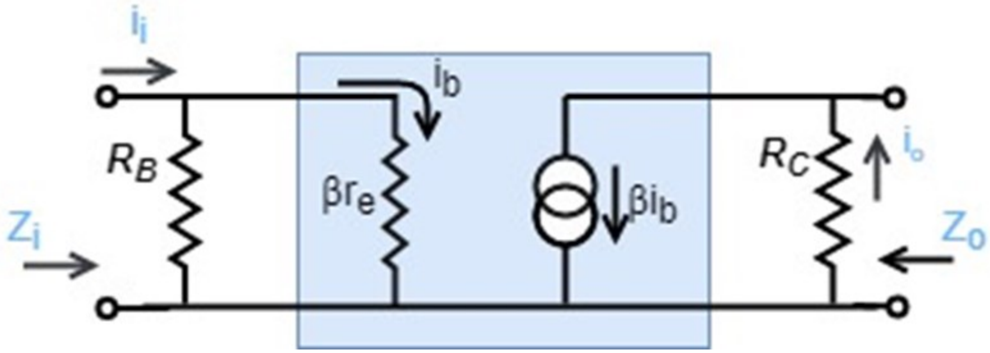
4.1. Common-Base

$Z_i = R_e \| r_e$	Rather small
$Z_o = R_c$	Rather large
$A_v = \alpha R_c/r_e \approx R_c/r_e$	Rather large, V_i & V_o in phase
$A_i = -\alpha \approx -1$	No current gain

4. Use cases of CB/CE/CC circuits

4.1. Common Emitter with Fix-base current bias





4. Use cases of CB/CE/CC circuits

4.2. Common Emitter with Fix-base current bias

$Z_i = R_b || \beta r_e \approx \beta r_e$ when $R_b \geq 10\beta r_e$

$Z_o = R_c || r_o \approx R_c$ when $r_o \geq 10R_c$

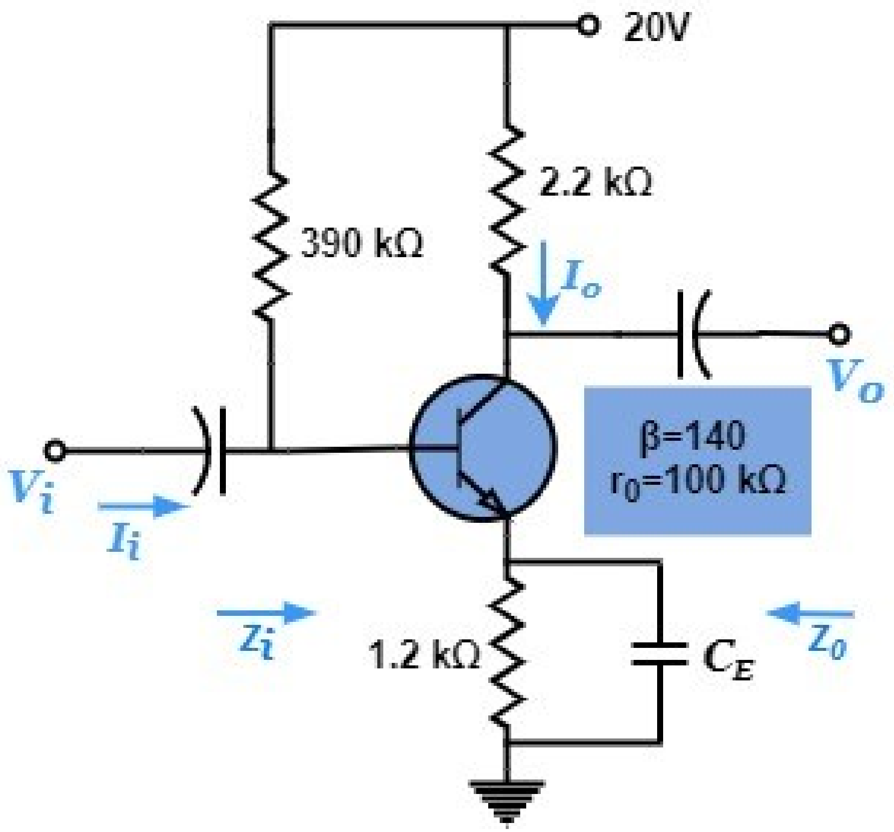
$A_v = -(R_c || r_o)/r_e \approx -R_c/r_e$ when $r_o \geq 10R_c$

$A_i = \beta R_b r_o / [(r_o+R_c)(R_b+\beta r_e)] \approx \beta$

- Medium input & output resistance
- V_i & V_o in reversed phase

4. Use cases of CB/CE/CC circuits

4.2. Common Emitter with Fix-base current bias



DC operating point

$I_E = 4.85mA$

$V_{CE} = 3.5V$

$r_e = 26mV/I_E = 5.36\Omega$

AC parameters

$Z_{in} = 390K//\beta r_e = 0.75K\Omega$

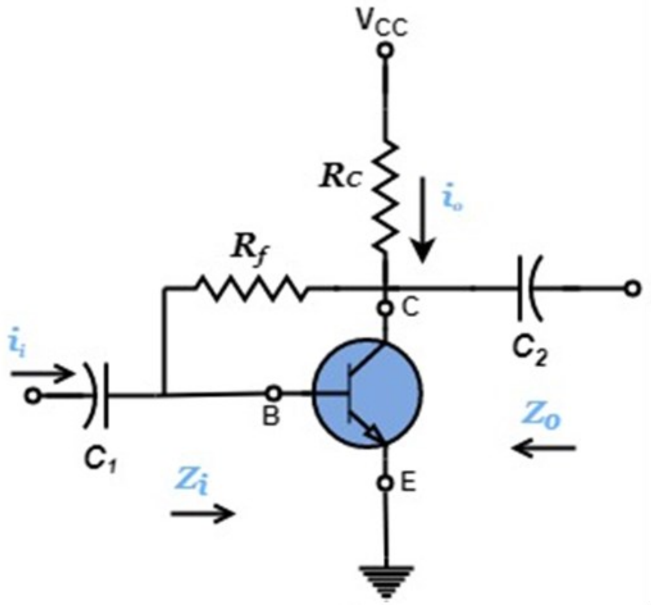
$Z_{out} = 2.2K\Omega$

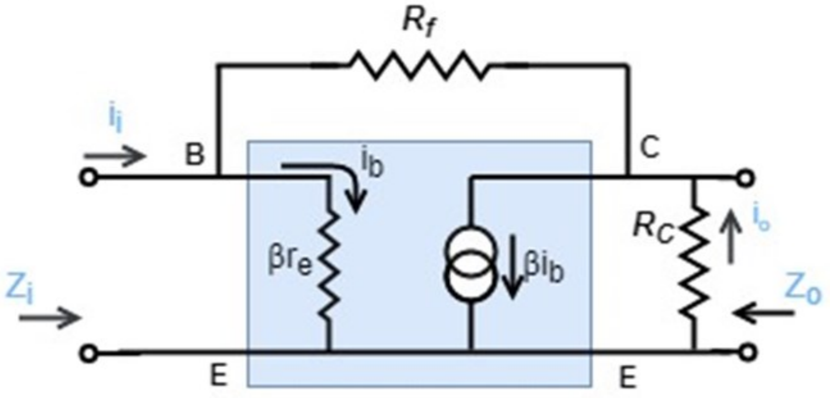
$A_v = - R_C/r_e = 410$

However, the output voltage is limited at around 3V since the DC V_{CE} is 3.5V

4. Use cases of CB/CE/CC circuits

4.3. Common Emitter with voltage feedback bias





4. Use cases of CB/CE/CC circuits

4.3. Common Emitter with voltage feedback bias

$Z_i \quad = \; r_e/(1/\beta + R_c/R_f)$

$Z_o \quad = \; R_c//R_f$

$A_v \quad = \; -R_c/r_e$

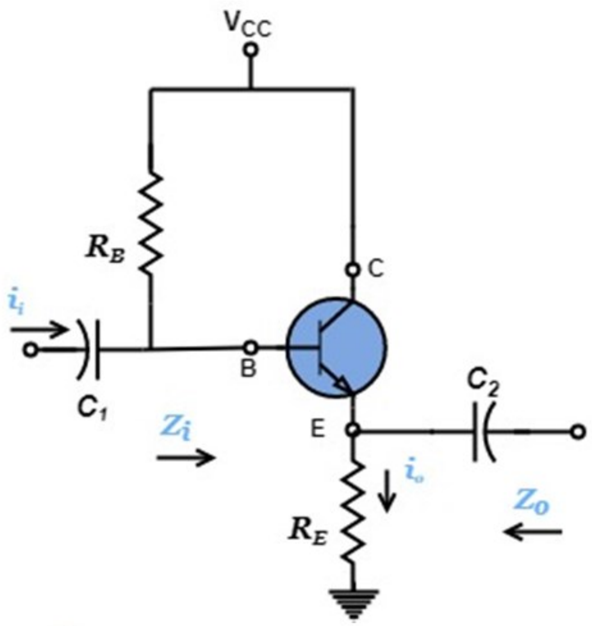
$A_i \quad = \; \beta R_f/(R_f + \beta R_c) \quad \approx R_f/R_c$ when $\beta R_c >> R_f$

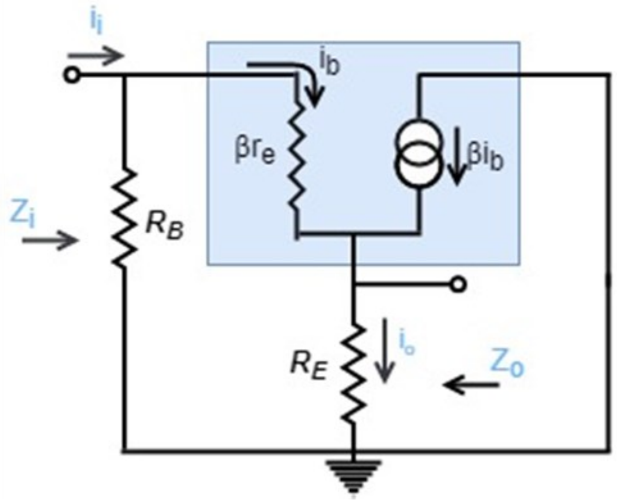
NOTE: - considering $r_o = \infty$

- see Ref book for the case of realistic r_o

4. Use cases of CB/CE/CC circuits

4.3. Common Collector with voltage feedback bias





4. Use cases of CB/CE/CC circuits

4.3. Common Collector with voltage feedback bias

$Z_i \quad = R_B \,||\, [\beta r_e+(\beta+1)R_E] \quad \approx R_B \,||\, \beta(r_e+R_E)$

$Z_o \quad = R_E||r_e \quad \approx r_e$ vì RE >> re

$A_v \quad = R_E/(R_E+re) \quad \approx 1$

$A_i \quad = - \beta R_B/[R_B+ \beta(r_e+R_E)]$

- Very high input impedance but low output impedance
- “Repeat” the input voltage at the output => “emitter repeater
- Impedance matching

5. DC biasing vs AC performance

5.1. Common-Emitter amplifier with/without RE

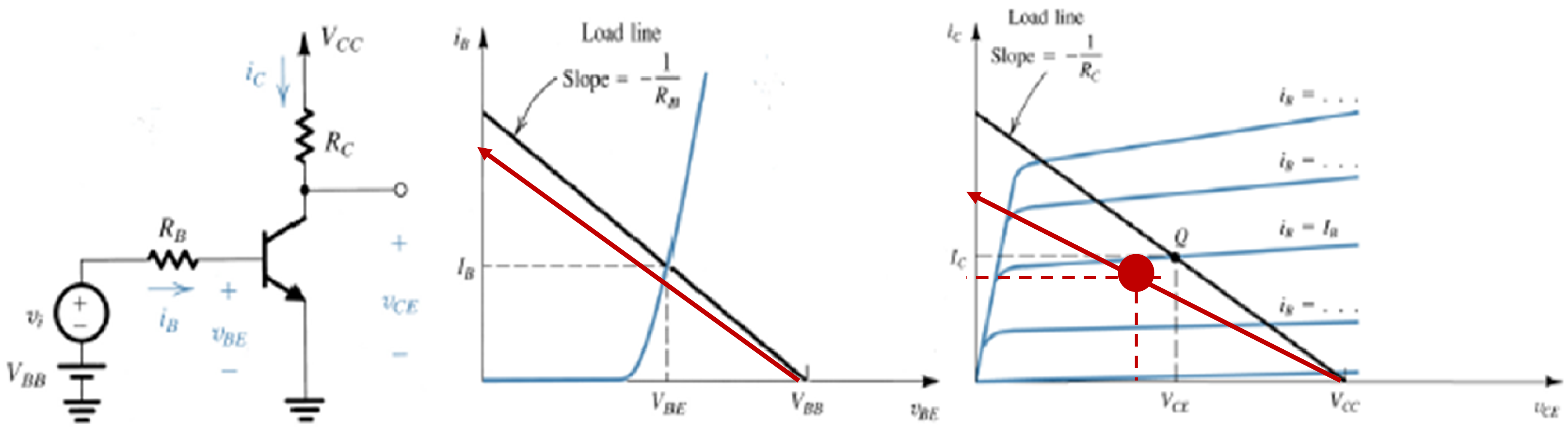
5.2. Trouble shooting

5.3. Notes on design

5. DC biasing vs AC performance

5.1. Common-Emitter amplifier with/without RE

DC current & voltage level of operation change when R_E is added



5. DC biasing vs AC performance

5.1. Common-Emitter amplifier with/without RE

DC operating point and the bias stabilization of R_E

- Without R_E

$$V_{CC} - U_{BE} - I_B R_B = 0$$

$$I_B = (V_{CC}-U_{BE})/R_B$$

$$I_C = \beta * I_B$$

$$U_{CE} = V_{CC} - I_C R_C$$

- With R_E

$$V_{CC} - U_{BE} - I_B R_B - I_E R_E = 0$$

$$I_B = (V_{CC}-U_{BE})/(R_B + \beta R_E)$$

$$I_C = \beta * I_B$$

$$U_{CE} = V_{CC} - I_C R_C - I_E R_E$$

- Less dependent on variation of β

5. DC biasing vs AC performance

5.1. Common-Emitter amplifier with/without RE

AC parameters change when R_E is added

- Without R_E

$Z_i = R_B // \beta r_e$

$Z_o = R_C$

$A_v = -R_C / r_e$

- With R_E

$Z_i = R_B // \beta(r_e + R_E)$

$Z_o = R_C$

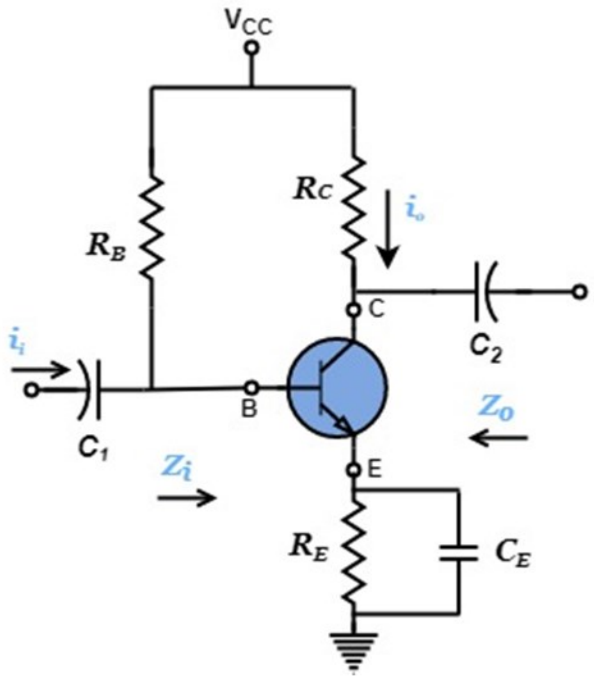
$A_v = -R_C / (r_e + R_E)$

To avoid voltage gain reduction,

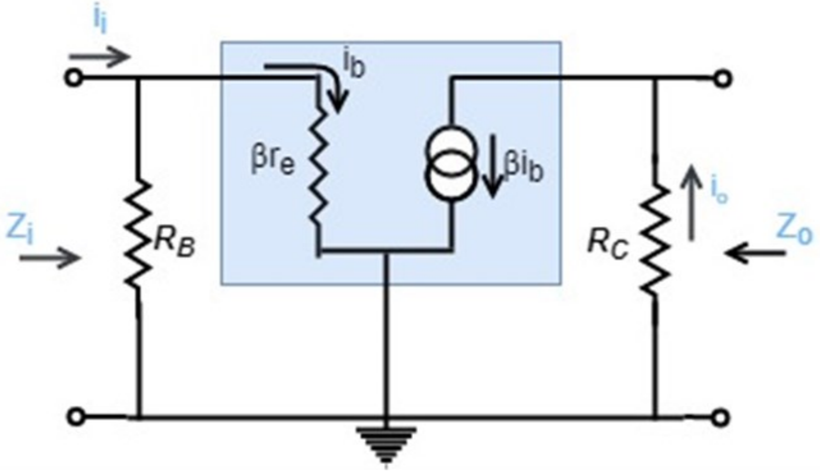
bypass R_E by capacitor C_E

5. DC biasing vs AC performance

5.1. Common-Emitter amplifier with/without RE



With C_E

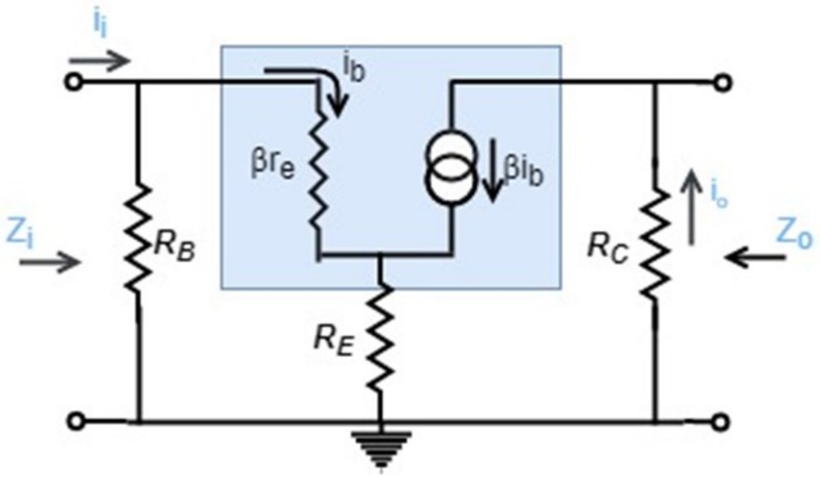


$Z_i = R_B // \beta r_e$

$Z_o = R_C$

$A_v = -R_C / r_e$

Without C_E



$Z_i = R_B // \beta(r_e + R_E)$

$Z_o = R_C$

$A_v = -R_C / (r_e + R_E)$

5. DC biasing vs AC performance

5.1. Common-Emitter amplifier with/without RE

AC parameters R_E is bypassed by C_E

- R_E With C_E

$Z_i = R_B // \beta r_e$

$Z_o = R_C$

$A_v = -R_C / r_e$

- R_E With C_E

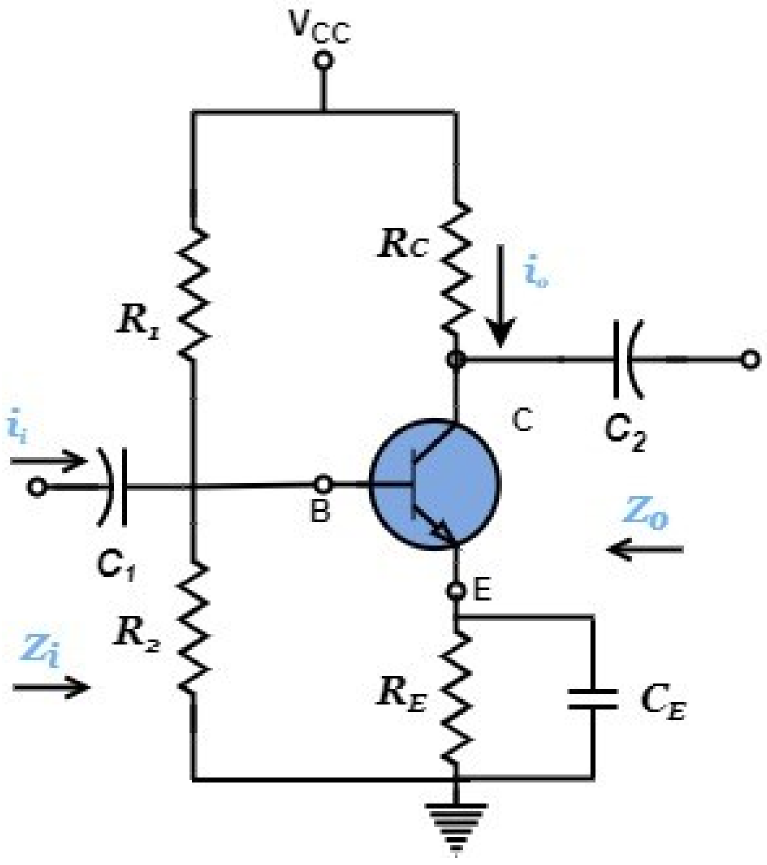
$Z_i = R_B // \beta(r_e + R_E)$

$Z_o = R_C$

$A_v = -R_C / (r_e + R_E)$

5. DC biasing vs AC performance

5.1. Common-Emitter amplifier with/without RE



Voltage divider configuration

$\beta * R_E \geq 10R_2$ -> $I_{R2} \approx I_{R1}$

$V_B = R_2 * V_{CC}/(R_1+R_2)$

$V_E = V_B - U_{BE}$

$I_C \approx I_E$ while $I_E = V_E/R_E$

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

DC Current & Voltage independent with β

Bypassed R_E by capacitor C_E to maximize the voltage gain

Av = - Rc/re

5. DC biasing vs AC performance

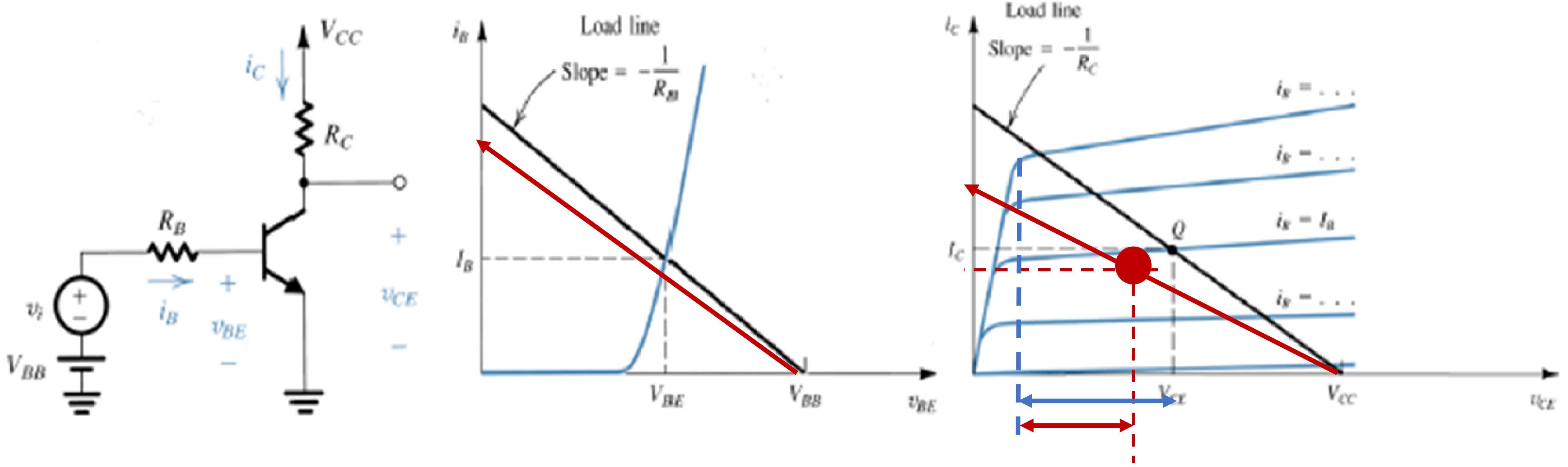
5.1. Common-Emitter amplifier with/without RE

- How to choose an appropriate R_E?
- Tradeoff of R_E :
  - ✓temperature stabilization by large R_E
  - ✓not too large as it will limit the range of the AC swings: to maximize AC output signal, R_B/R_E as small as possible
- Recommend: $V_{RE} \sim 1/10 – ¼$ DC source

5. DC biasing vs AC performance

5.1. Common-Emitter amplifier with/without RE

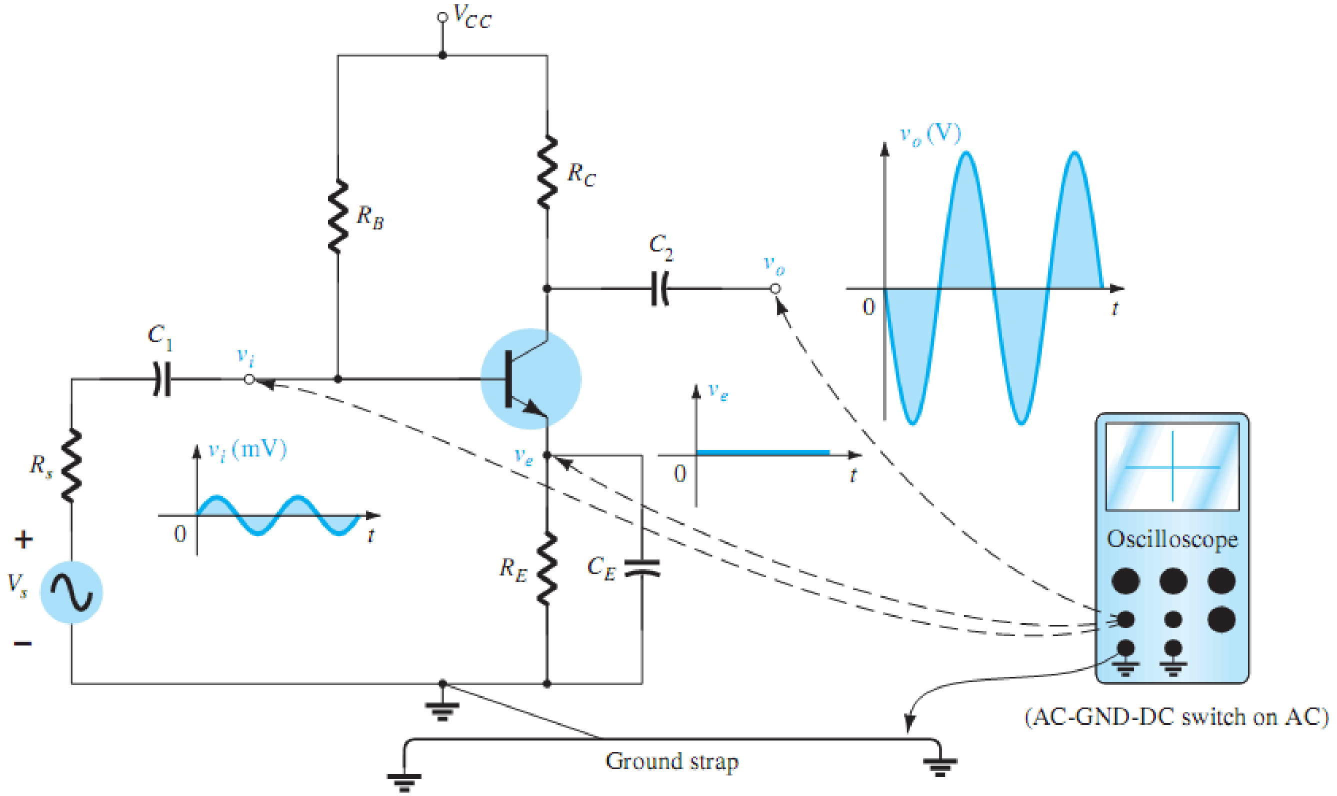
DC current & voltage level of operation change when R_E is added



5. DC biasing vs AC performance

5.2. Trouble Shooting

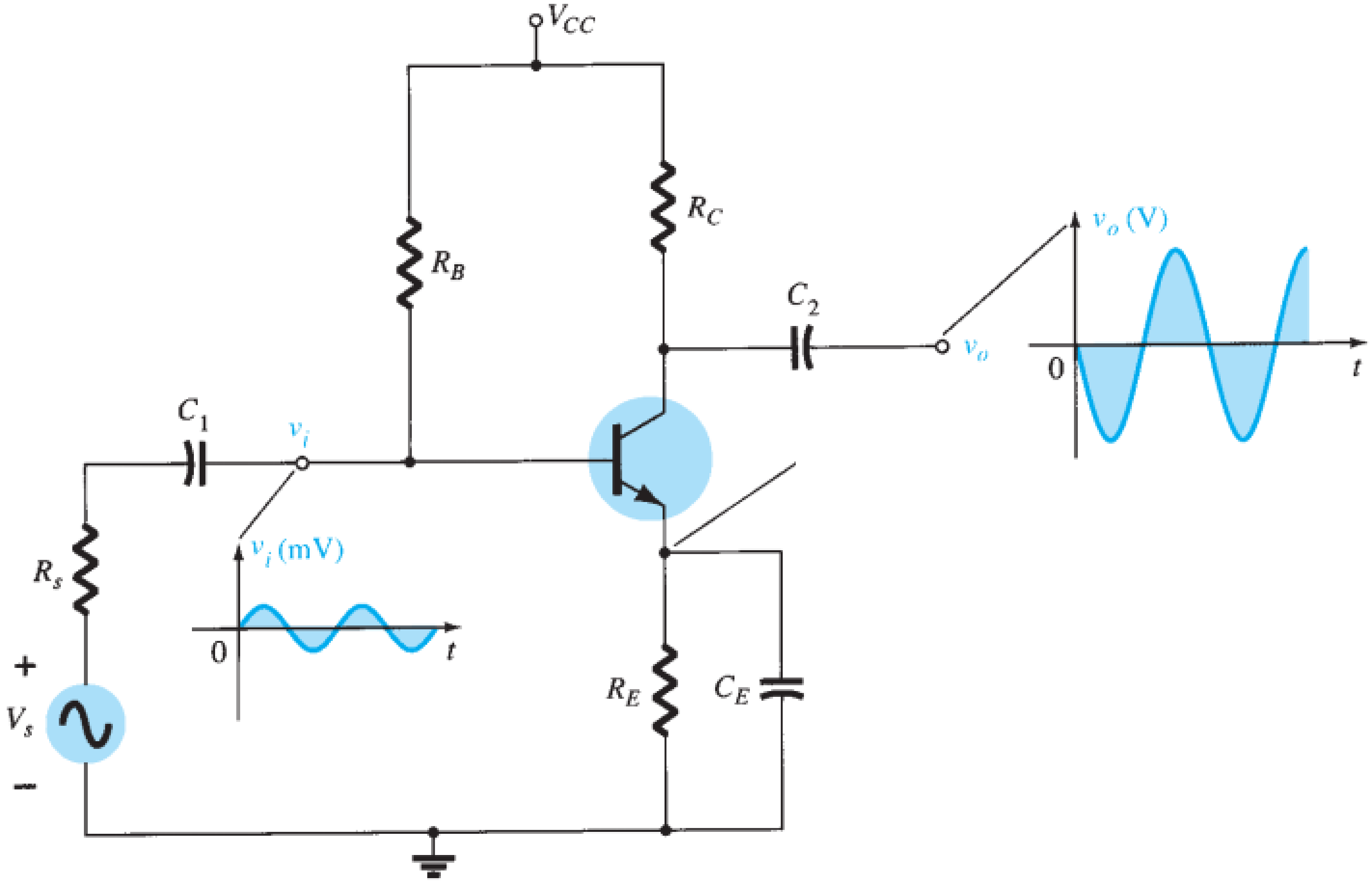
- A “right” BJT amplifier should work as follows



5. DC biasing vs AC performance

5.2. Trouble shooting

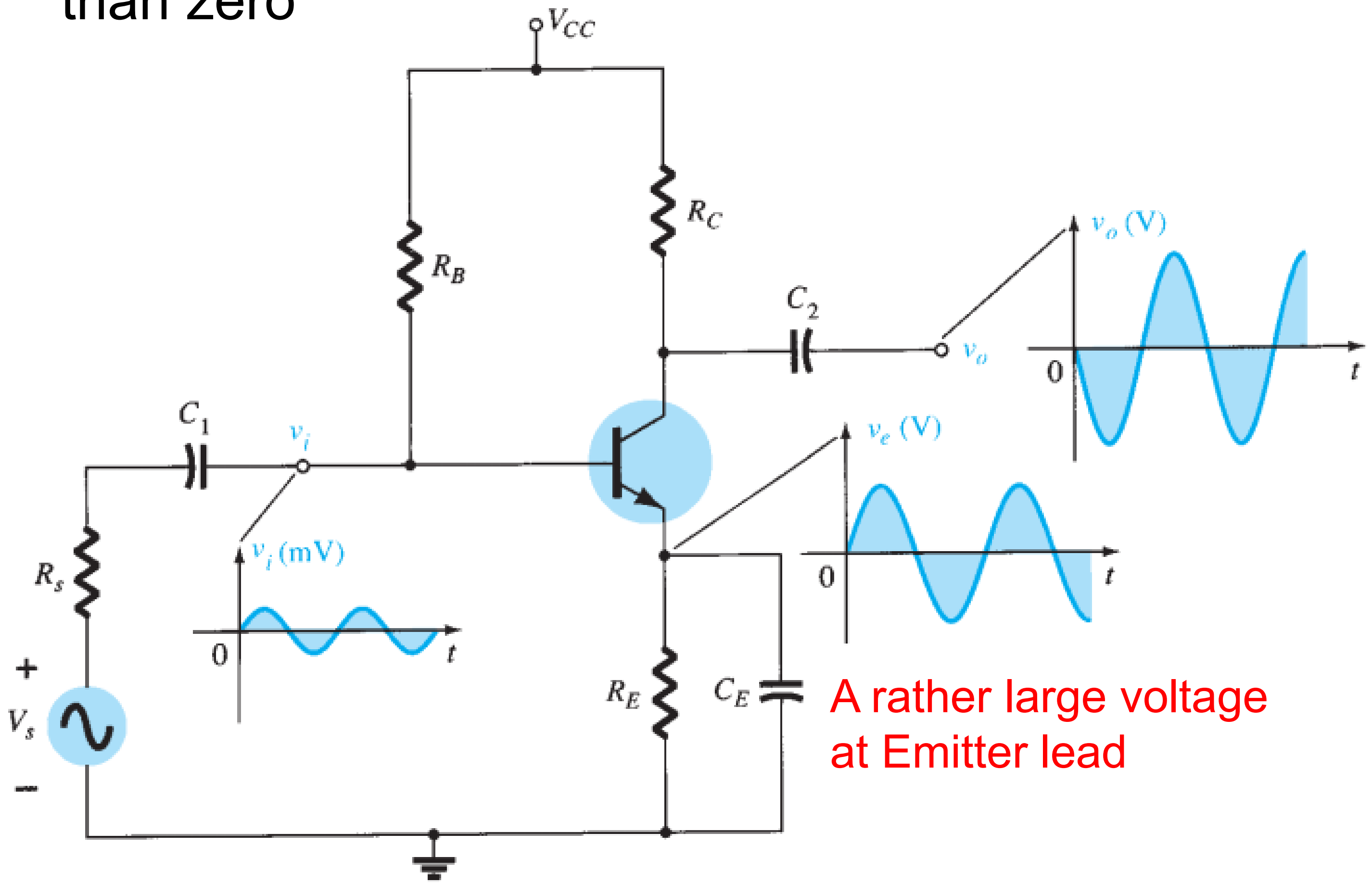
- Case 1: The output voltage is lower than the expectation



5. DC biasing vs AC performance

5.2. Trouble shooting

- Measure the voltage at Emitter lead, it is greater than zero

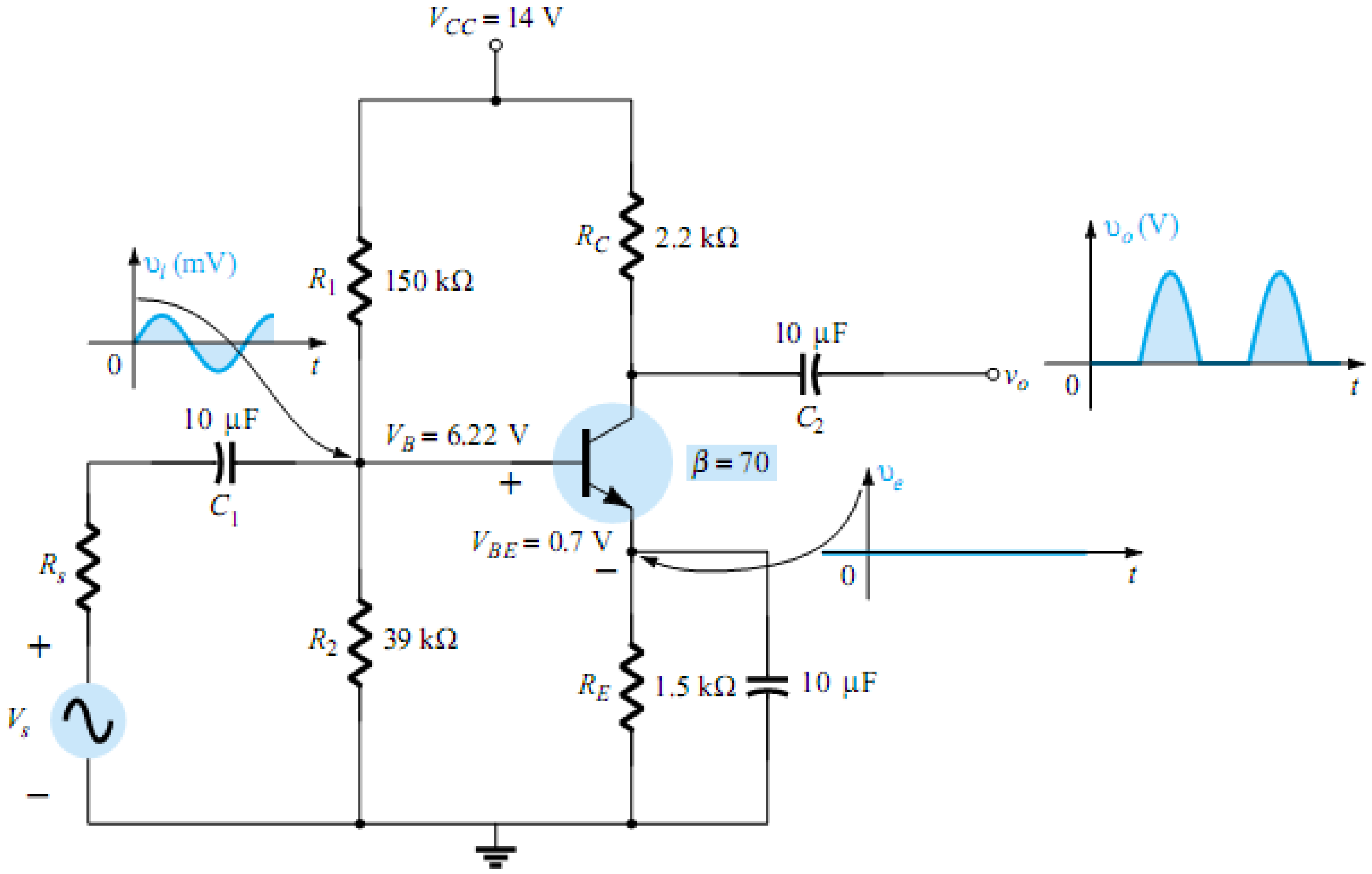


A rather large voltage at Emitter lead

5. DC biasing vs AC performance

5.2. Trouble shooting

- Case 2: The output voltage is only half-cycle



5. DC biasing vs AC performance

5.3. Notes on design process of an amplifier

- Consider the DC operating point in relationship with
  - ✓Saturation level – Max rating of I_C
  - ✓Cutoff level – Max rating of V_{CE}
- Concern of the limiting power of BJT devices
- Concern of DC stability, and íts affects on AC gain, impedance

Summary

1. DC level condition for BJT working in amplifier mode is the BE junction in forward-biasing and the BC junction in reverse-biasing. Note on the saturation current and the cut-off condition.

2. AC equivalent circuits of BJT vary with the DC level condition (input resistor r_e) and the amplifier configuration (Common-Base, Common-Emitter, Common-Collector).

3. The AC parameters (input resistance, output resistance and voltage/current gain) of Common-Base, Common-Emitter, Common-Collector networks reflect the role of each configuration.

4. The interaction of DC level condition and AC parameters directs several trade-offs in circuit design process.

Next lesson guide...

Lesson 3: FET signal-small amplifier

Reference

Electronics devices and Circuits theory – Robert Boylestad, Louis Nashelsky, Prentice Hall, 11th edition

Electronic principles – Albert Paul Malvino