Bipolar Junction Transistors

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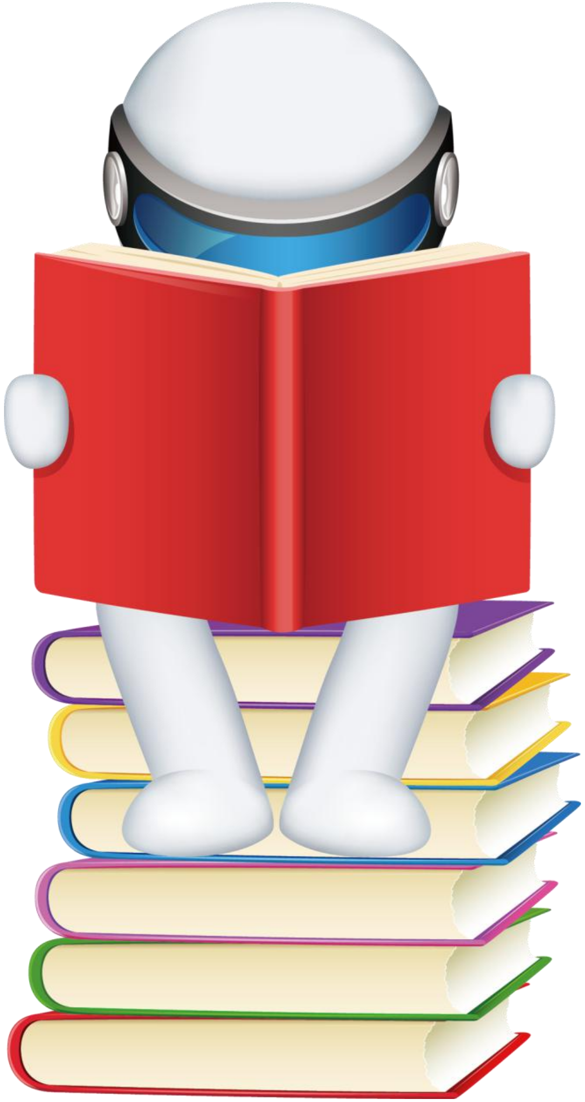
Outline

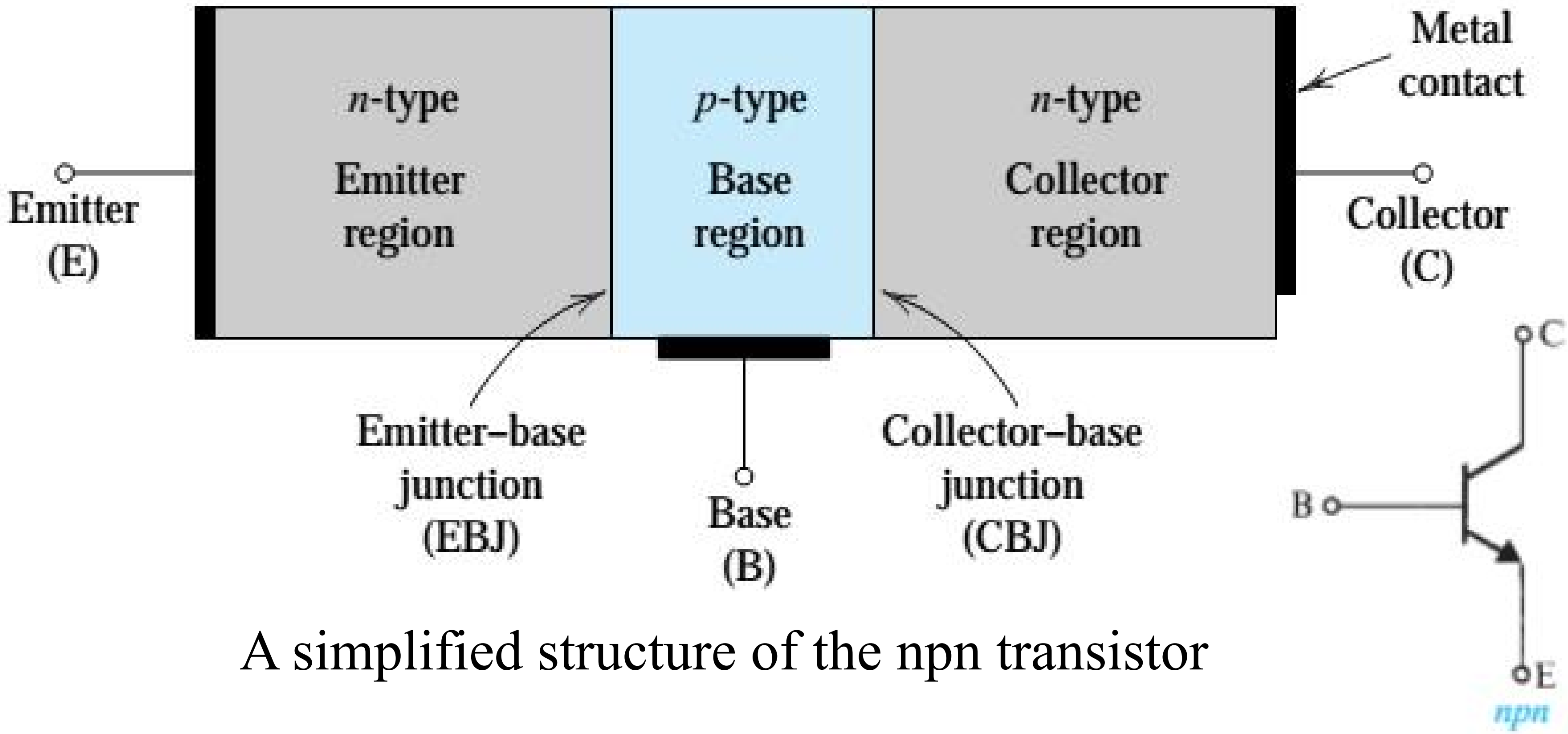
- Transistor Construction &Operation
- Analysis of Transistor Circuits at DC
- Basic BJT Amplifiers

Bipolar Junction Transistors

- Construction & Operation
- Circuit Symbols for BJTs
- Modes of Operation
- Basic Characteristic



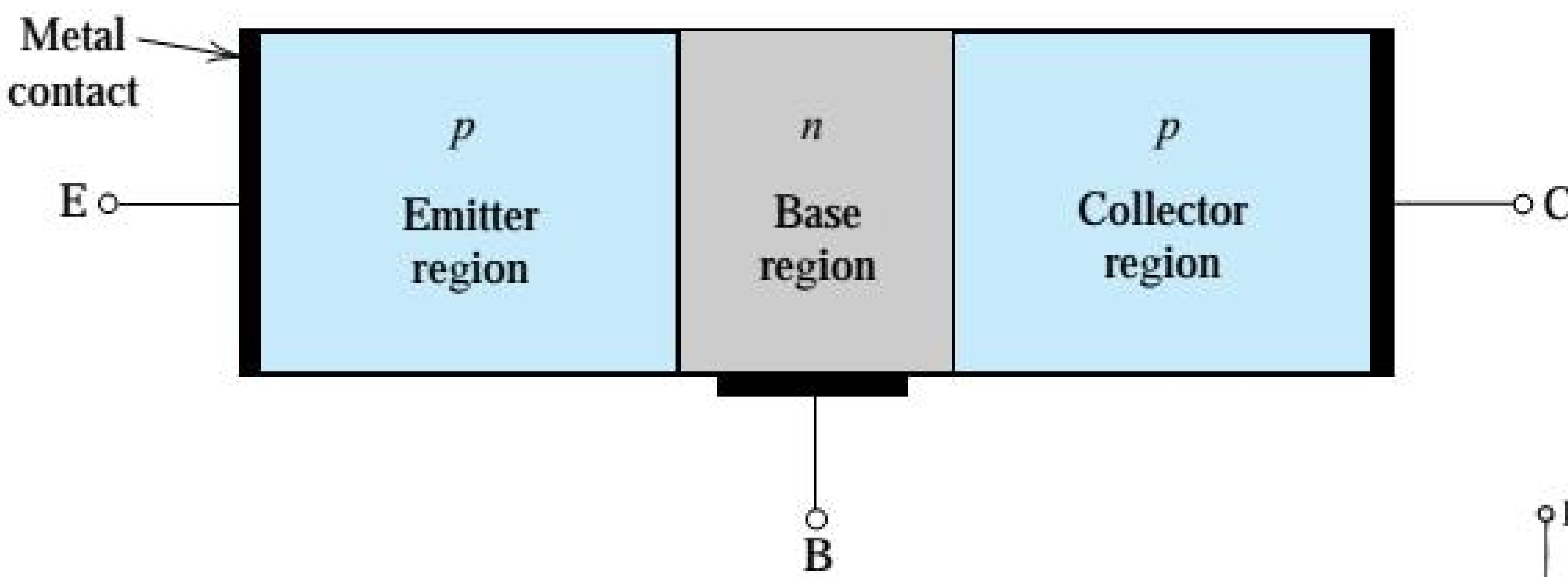
Construction



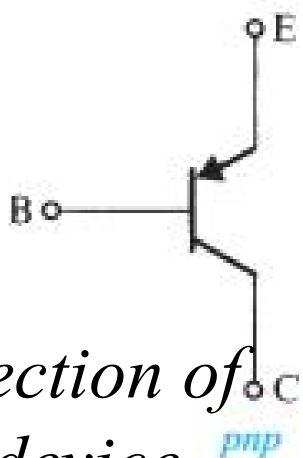
A simplified structure of the npn transistor

- *The arrow in the graphic symbol defines the direction of emitter current (conventional flow) through the device.*

Construction

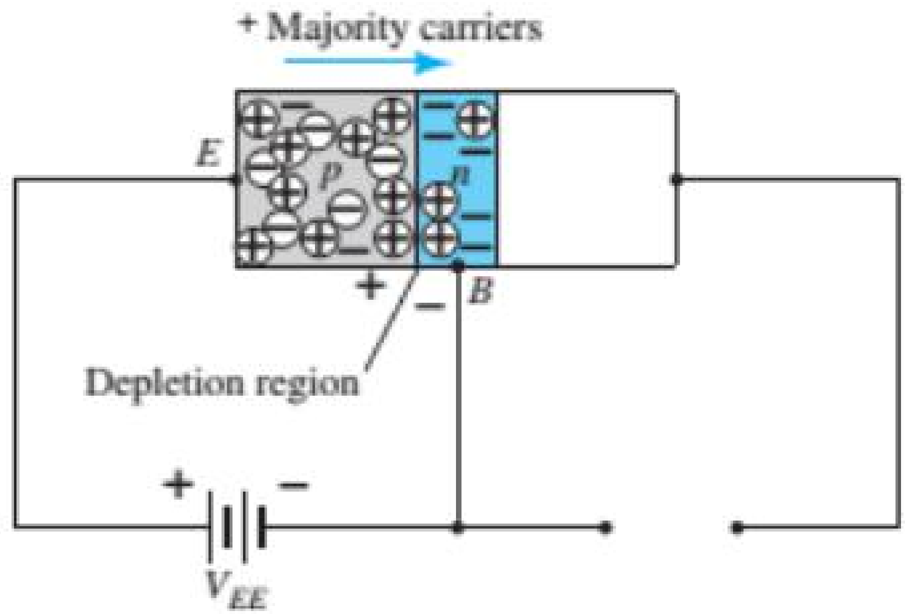


A simplified structure of the npn transistor



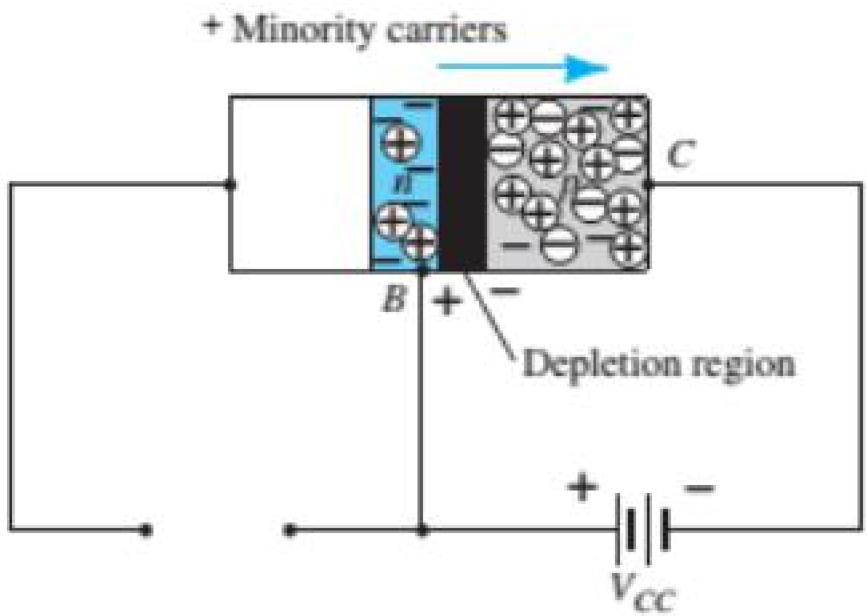
♥ *The arrow in the graphic symbol defines the direction of emitter current (conventional flow) through the device.*

Operation



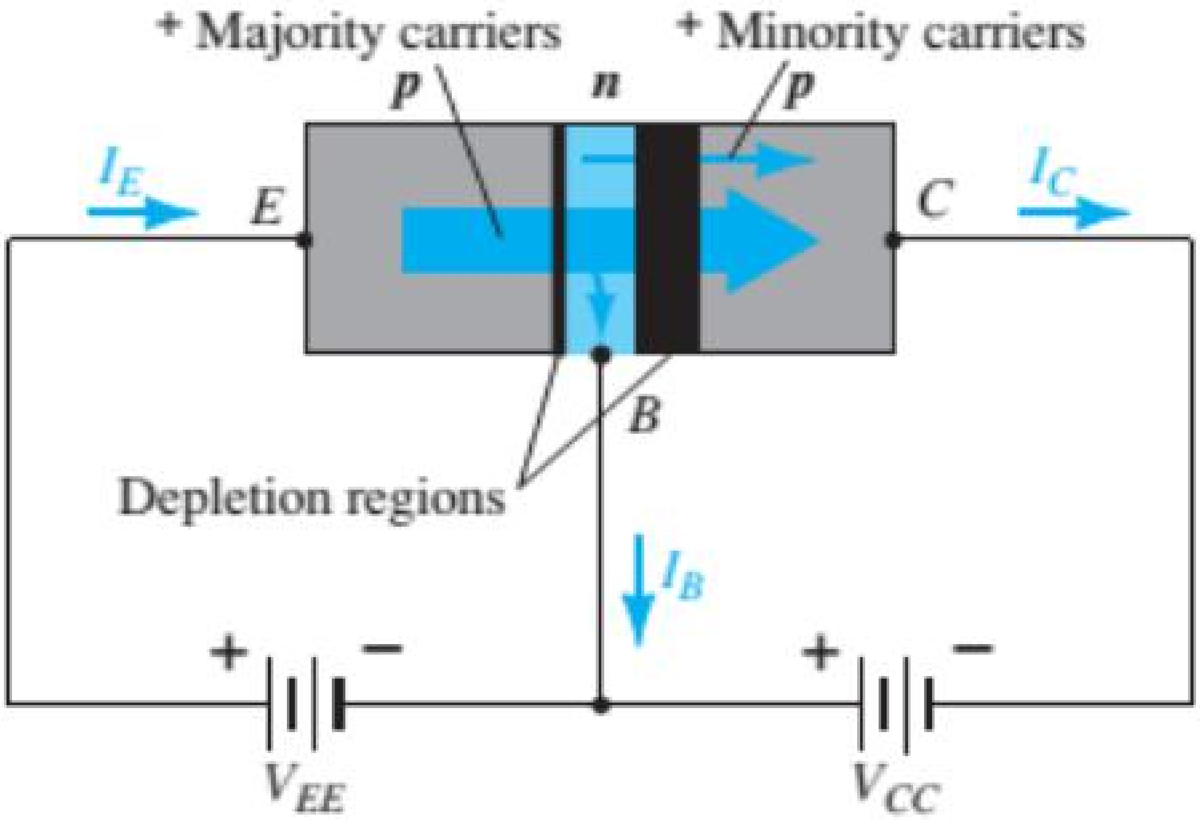
- A large number of majority carriers will diffuse across the forward-biased EBJ into the n-type material.
- A very small number of these carriers will take this path of high resistance to the base terminal.

Operation



- The larger number of these majority carriers will diffuse across the reverse-biased CBJ in the p-type material connected to the collector terminal.(There has been an injection of minority carriers into the n-type base region material.)

Operation



+ Majority carriers
+ Minority carriers
p
n
p
I_E
E
C
I_C
B
Depletion regions
I_B
+
−
+
−
V_{EE}
V_{CC}

Operation

Kirchhoff's Current Law

$$I_E = I_C + I_B$$ ★ 重要

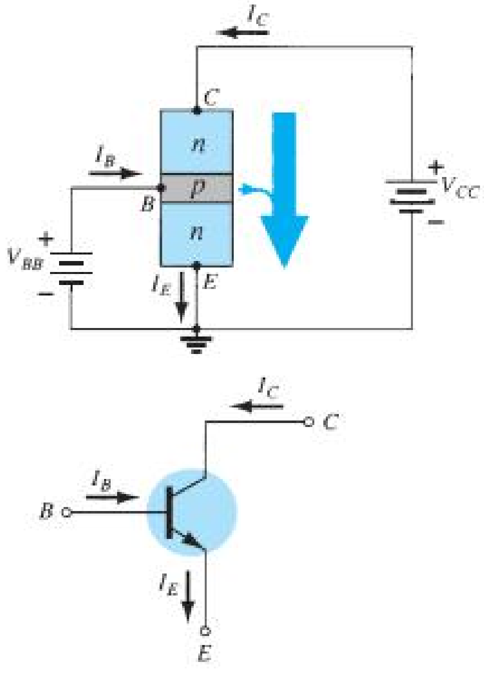
$$I_C = I_{C_{majority}} + I_{CO_{minority}}$$

Leakage current: is temperature sensitive and must be examined carefully when applications of wide temperature if not considered properly.

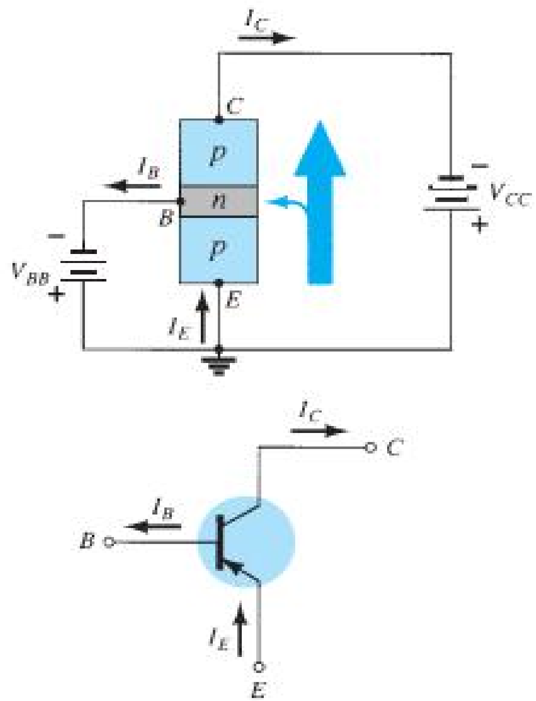
Transistor Circuit Configurations

	Input terminal	Common terminal	Output terminal
Common-Base (CB)	Emitter	Base	Collector
Common-Emitter (CE)	Base	Emitter	Collector
Common-Collector (CC)	Base	Collector	Emitter

Common-Emitter Configuration



(a)



The common-emitter terminology is derived from the fact that the emitter is common to both the input and output sides of the configuration. In addition, the emitter is usually the terminal closed to, or at, ground potential.

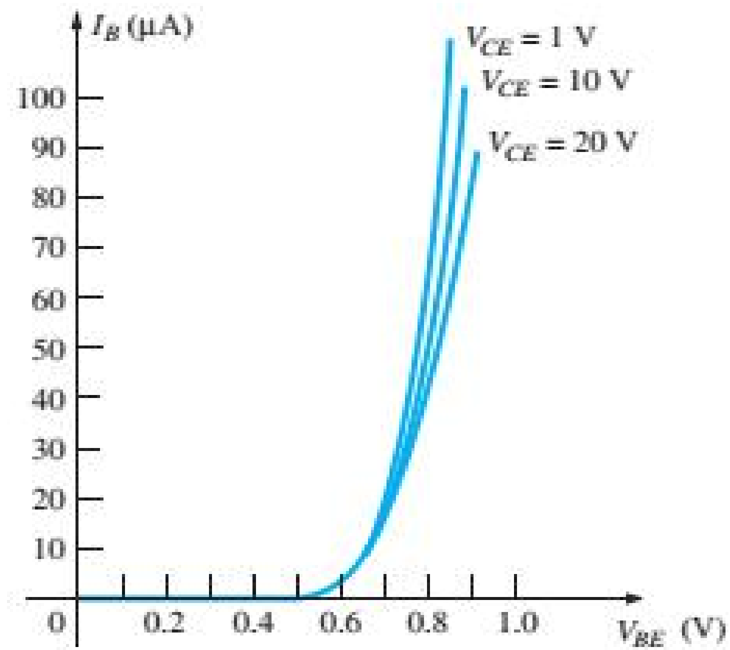
Common-Emitter Configuration

- The arrow in the graphic symbol defines the direction of emitter current (conventional flow) through the device.
- Note in each case that $\mathbf{I_E = I_C + I_B}$.
- Note also that the applied biasing(voltage sources) are such as to establish current in the direction indicated for each branch.
- To fully describe the behavior of a three-terminal device such as the common-emitter amplifiers requires two sets of characteristics----*input characteristics* and *output characteristics*.

Common-Emitter Configuration

- The input characteristics are a plot of the input current (I_B) versus the input voltage (V_{BE})for a range of values of output voltage (I_C).

- Once a transistor is in the "on" state, the base-to-emitter voltage will be assumed to be the following:$V_{BE} = 0.7V$

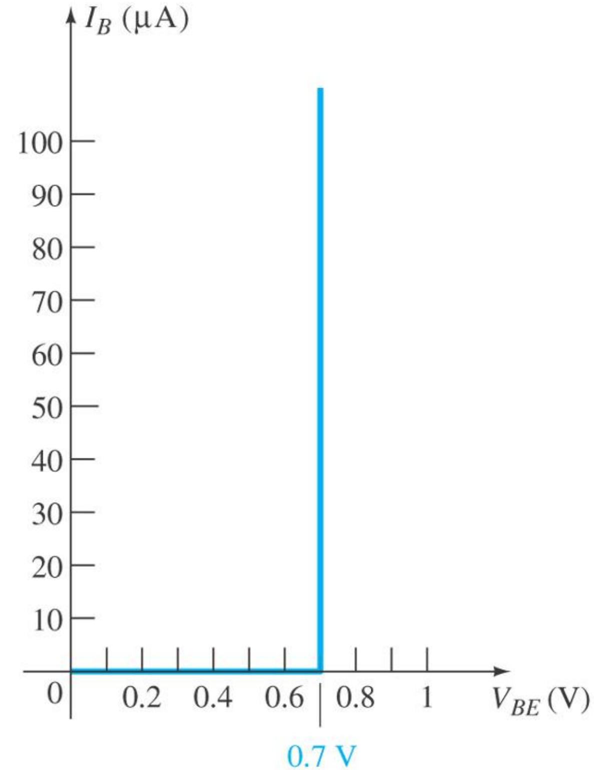


(b)

Common-Emitter Configuration

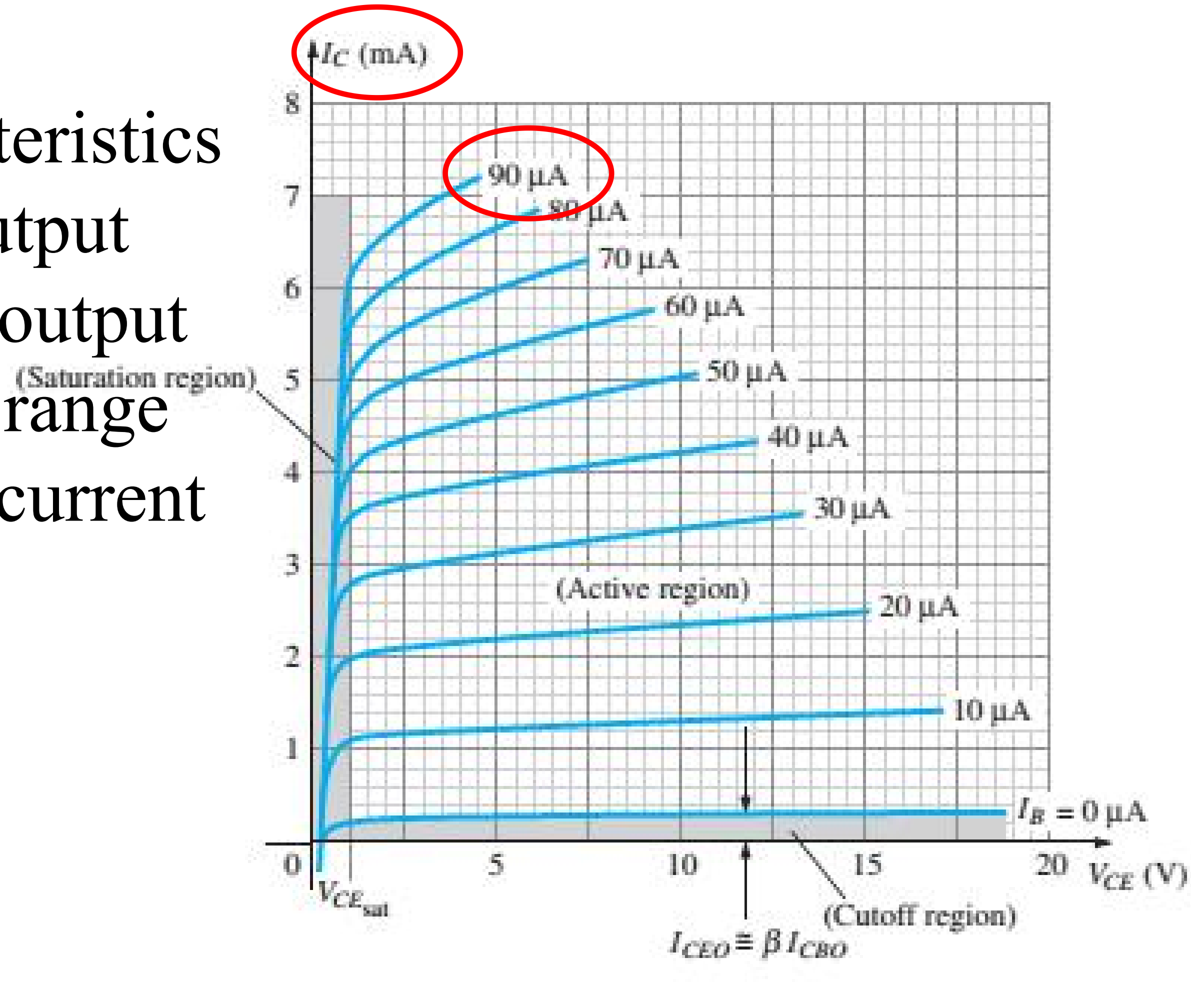
- The input characteristics are a plot of the input current (I_B) versus the input voltage (V_{BE})for a range of values of output voltage (I_C).

- Once a transistor is in the "on" state, the base-to-emitter voltage will be assumed to be the following: $V_{BE} = 0.7V$



Common-Emitter Configuration

- The output characteristics are a plot of the output current(I_C) versus output voltage(V_{CE}) for a range of values of input current (I_B).



(a)

Common-Emitter Configuration

Note:

- The output set of characteristics has three basic regions of interest: the ***active***, ***cutoff***, and ***saturation*** regions.

- *In the **active region** the base-emiter junction is forward-biased, whereas the collector-base junction is reverse-biased.*
- *In the cutoff region the base-emitter and collector-base junctions of a transistor are both reverse-biased.*
- *In the saturation region the base-emitter and collector-base junctions are forward-biased.*

Common-Emitter Configuration

Note:

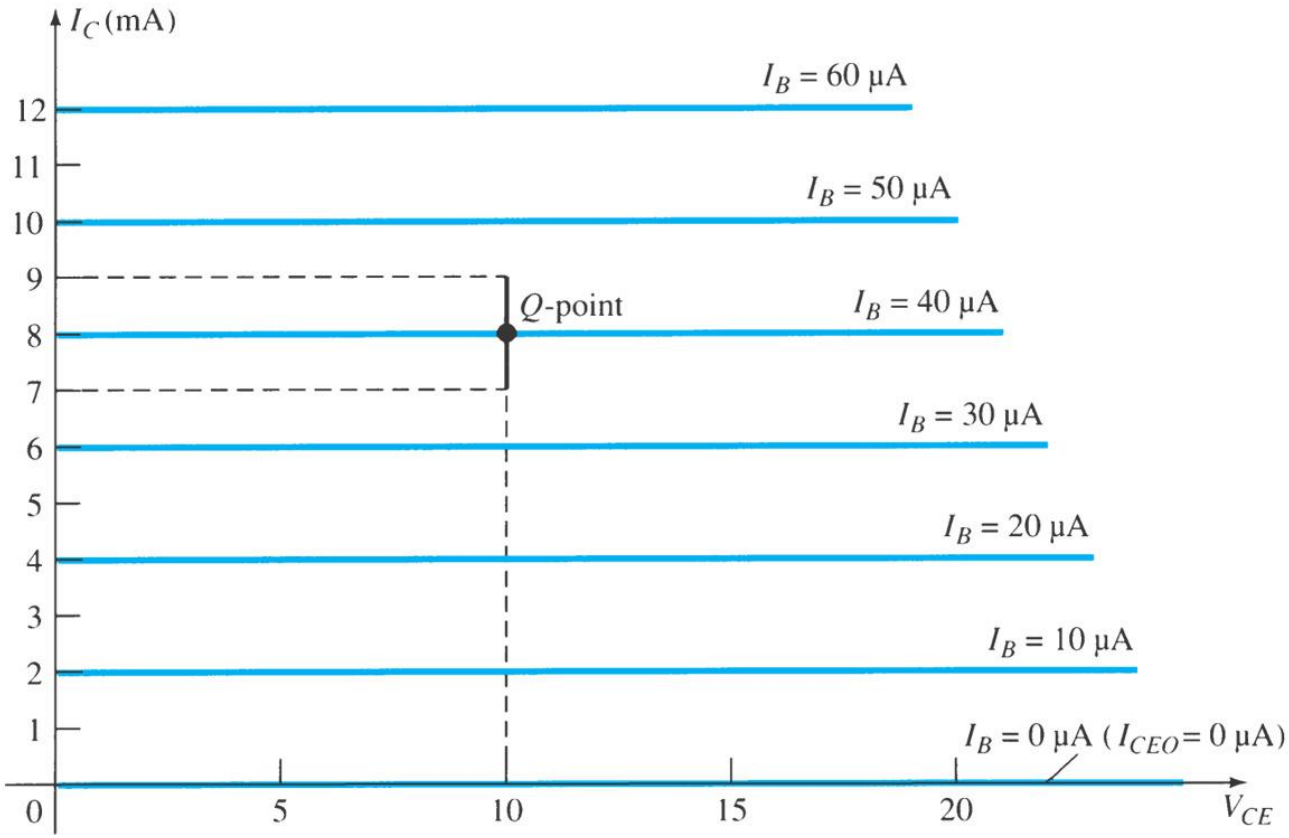
- The magnitude of I_B is in microamperes, compared to milliamperes of I_C.
- The active region for the CE configuration has the greatest linearity, that is ,the region in which the curves for I_B are nearly straight and equally spaced.
- The result shows that for a transistor in the "on" or active region the base-to-emitter voltage is 0.7V.
- Common-emitter current gain:$\beta = \frac{I_C}{I_B}$

Beta(β)

In the DC mode the levels of I_C and I_B are related by a quantity call *beta*:

For ac situations an ac beta is defined as:

Although not exactly equal, the levels of β_{dc} and β_{ac} are usually reasonably close and are often used interchangeably.



Characteristics in which β_{ac} is the same everywhere and $\beta_{ac} = \beta_{dc}$

Alpha(α)

Alpha (α) relates the DC currents I_C and I_E :

Ideally: a = 1
In reality: a is between 0.9 and 0.998

Alpha (α) in the AC mode:

Relationship between amplification factors β and α

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

Relationship Between Currents

$$I_C = \beta I_B \qquad I_E = (\beta + 1) I_B$$

Beta is a particularly important parameter because it provides a direct link between current levels of the input and output circuits for a common-emitter configuration.

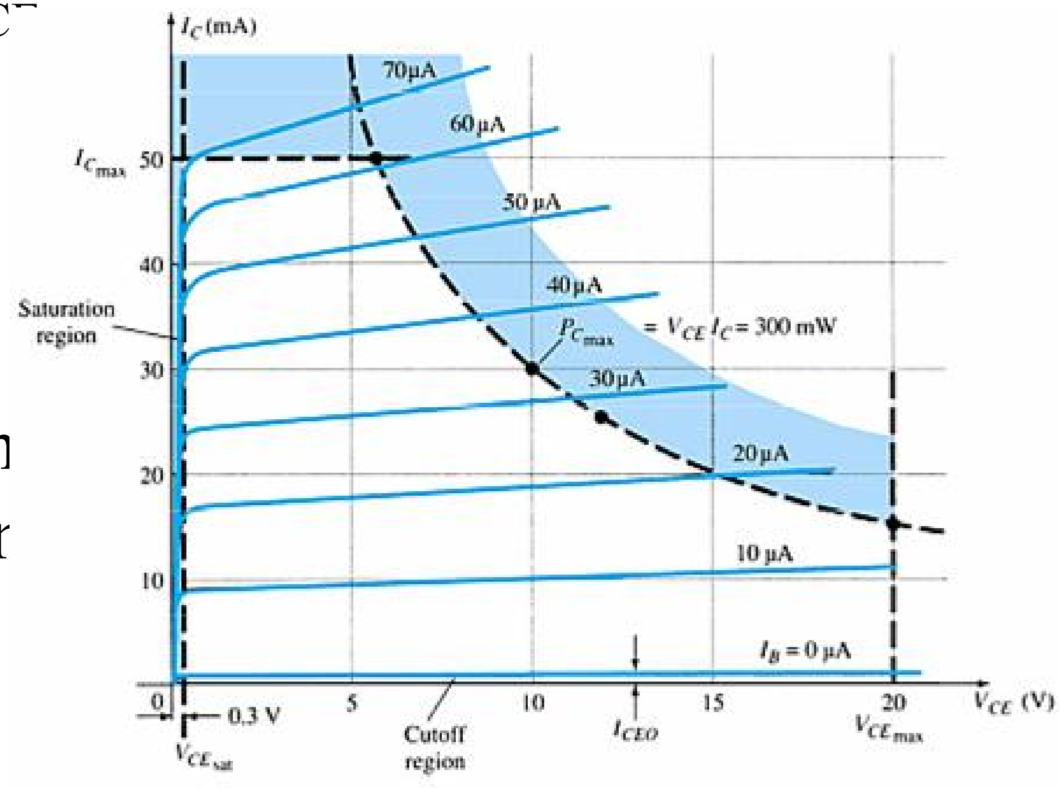
Limitations of Operation

V_{CE} is at maximum and I_C is at minimum ($I_{Cmin} = I_{CEO}$) in the cutoff region.

Common-emitter:

I_C is at maximum and V_{CE} is at minimum ($V_{CE\,min} = V_{CEsat} = V_{CEO}$) in the saturation region.

The transistor operates in the active region between saturation and cutoff.



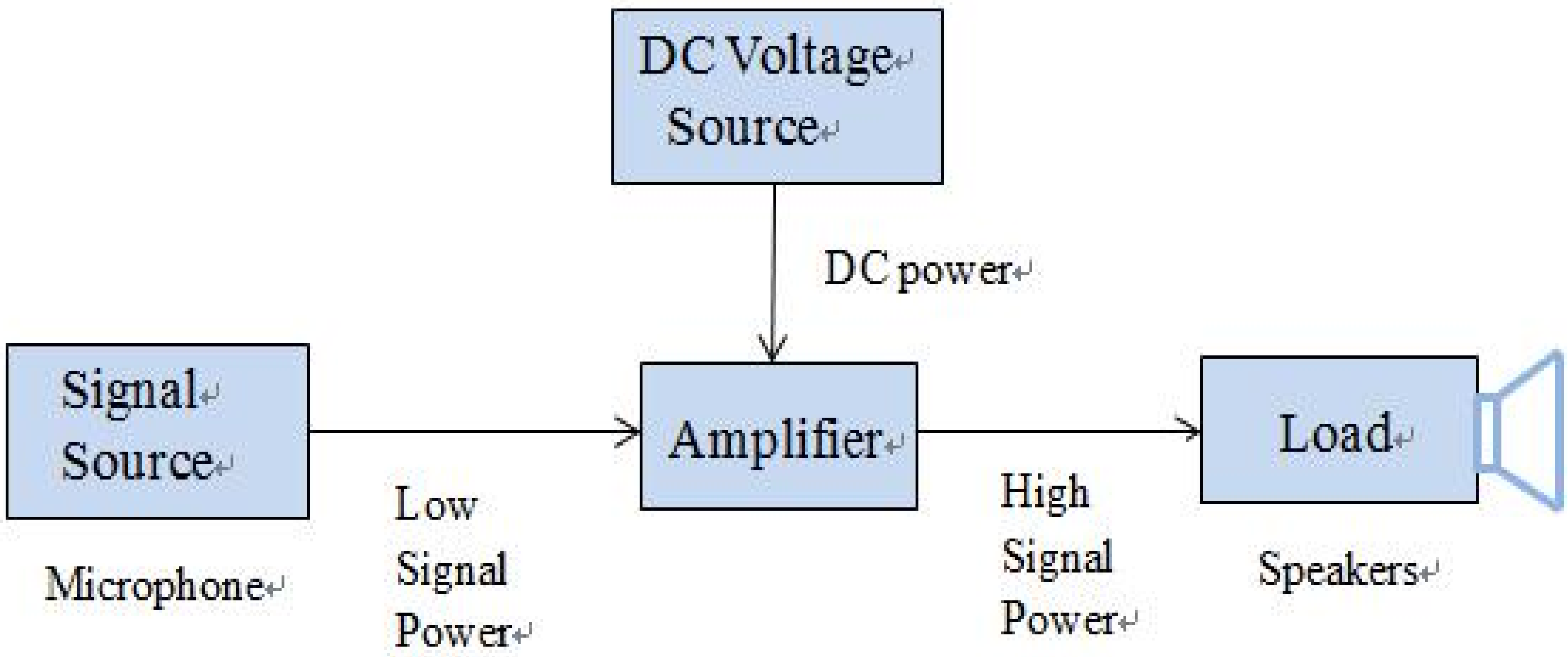
Summary

- **Key Information**
  - **Transistor construction and operation**
    - **Current relationship**
  - **Three Basic Configurations:**
    - **CE**
    - **CB**
    - **CC**
  - **Characteristics of CE, CB and CC configuration**
  - **Transistor Operation Regions**
    - **Active region**
    - **Cutoff region**
    - **Saturation region**
- **Application Key Notes**
  - **Limits of Operation**

Current Relationships ★ 重要

Current relationships in the active region	
$I_E = I_C + I_B$	$I_C = \beta I_B$
$I_E = (1 + \beta) I_B$	$I_C = \alpha I_E = (\frac{\beta}{1+\beta}) I_E$
$\alpha = \frac{\beta}{1+\beta}$	$\beta = \frac{\alpha}{1-\alpha}$

BJT Circuits Analysis



The improved output ac power level is the result of a transfer of energy from the applied dc supplies.

BJT Circuits Analysis

The analysis or design of a transistor amplifier requires a knowledge of both the dc and the ac response of the system.

- DC Analysis of BJT Circuits
- AC Analysis of BJT Circuits

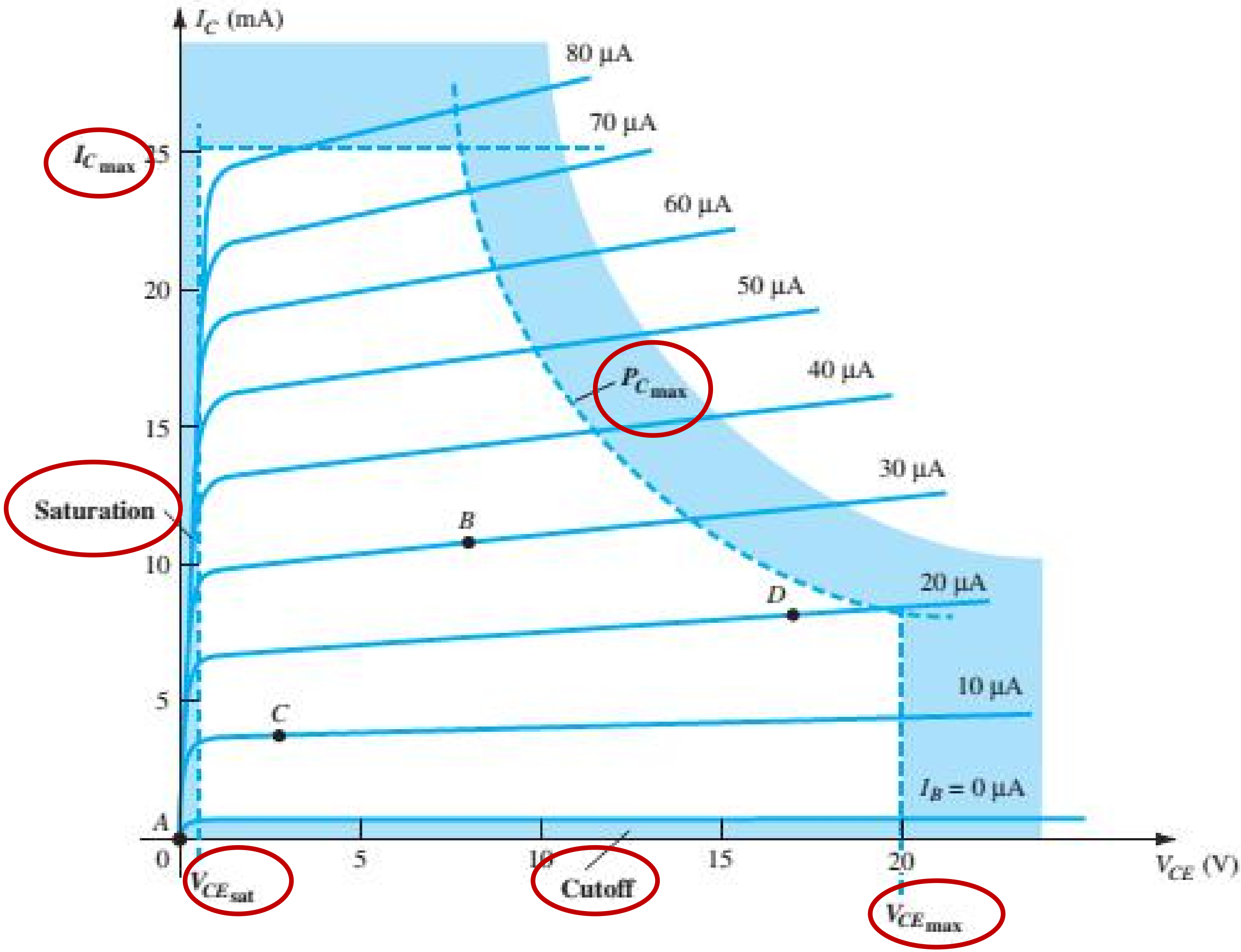
Fortunately, the ***superposition theorem*** *is applicable and the investigation of the dc conditions can be totally separated from the ac response.*

Operating Point

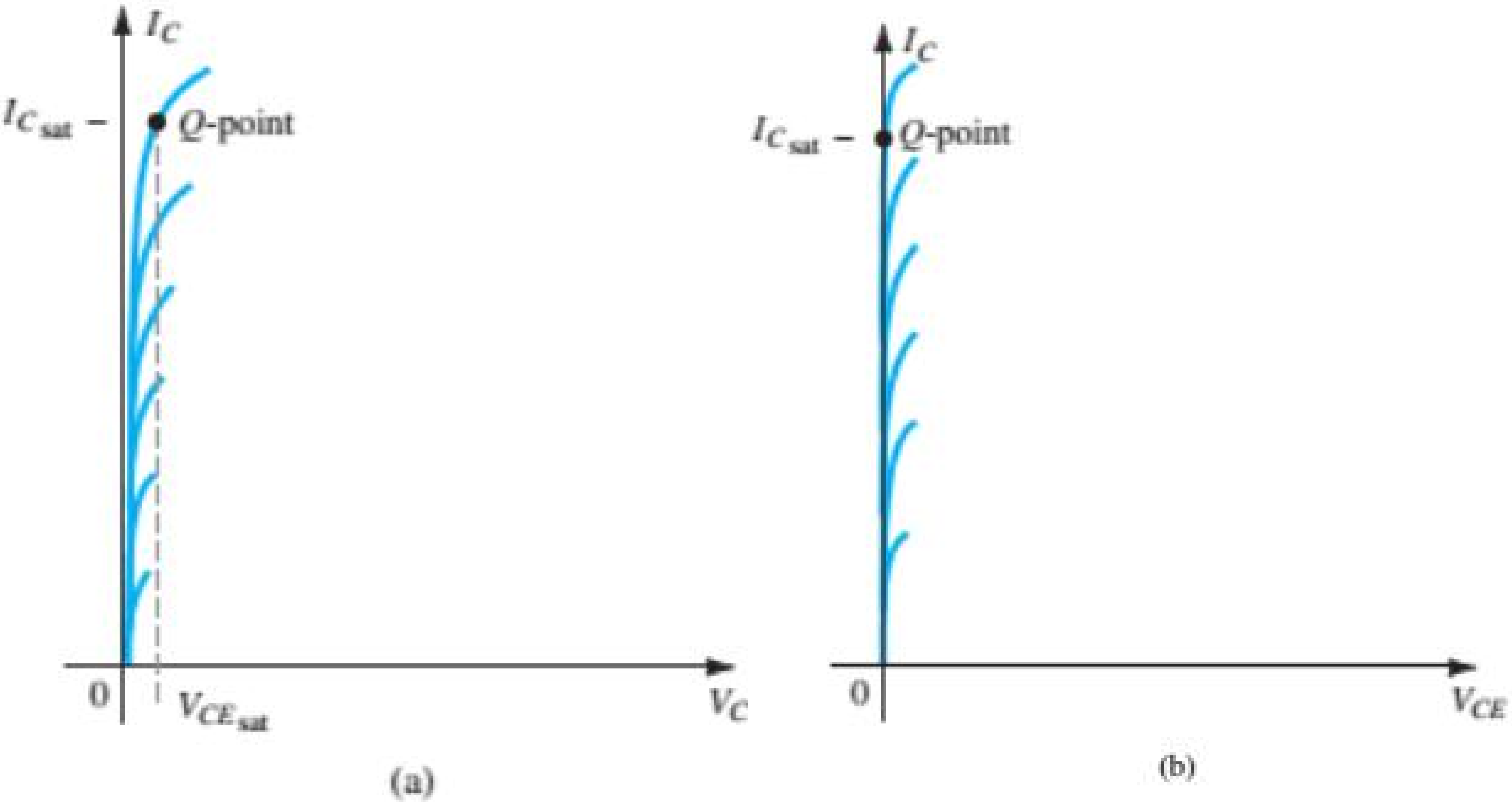
- *For transistor amplifiers the resulting dc current and voltage establish an* ***operating point*** *on the characteristics that define the region that will be employed for amplification of the applied signal. It is also called the* ***quiescent point*** *(**Q-point**).*

Why should we consider the DC analysis firstly?

Operating Point



Transistor Saturation



Saturation regions: (a)actual; (b) approximate

DC Analysis of BJT Circuits

Analysis Method

- The capacitors can be replaced by an open-circuit equivalent.(The reactance of a capacitor for dc is$X_C = 1/2\pi f C = \infty\Omega$)
- The AC supplies can be replaced by a zero-potential equivalent(short circuit).

Important basic relationships for a transistor

$$V_{BE} = 0.7V \qquad I_E = (1+\beta)I_B \cong I_C \qquad I_C = \beta I_B$$

DC Analysis of BJT Circuits

Fixed-Bias Circuit

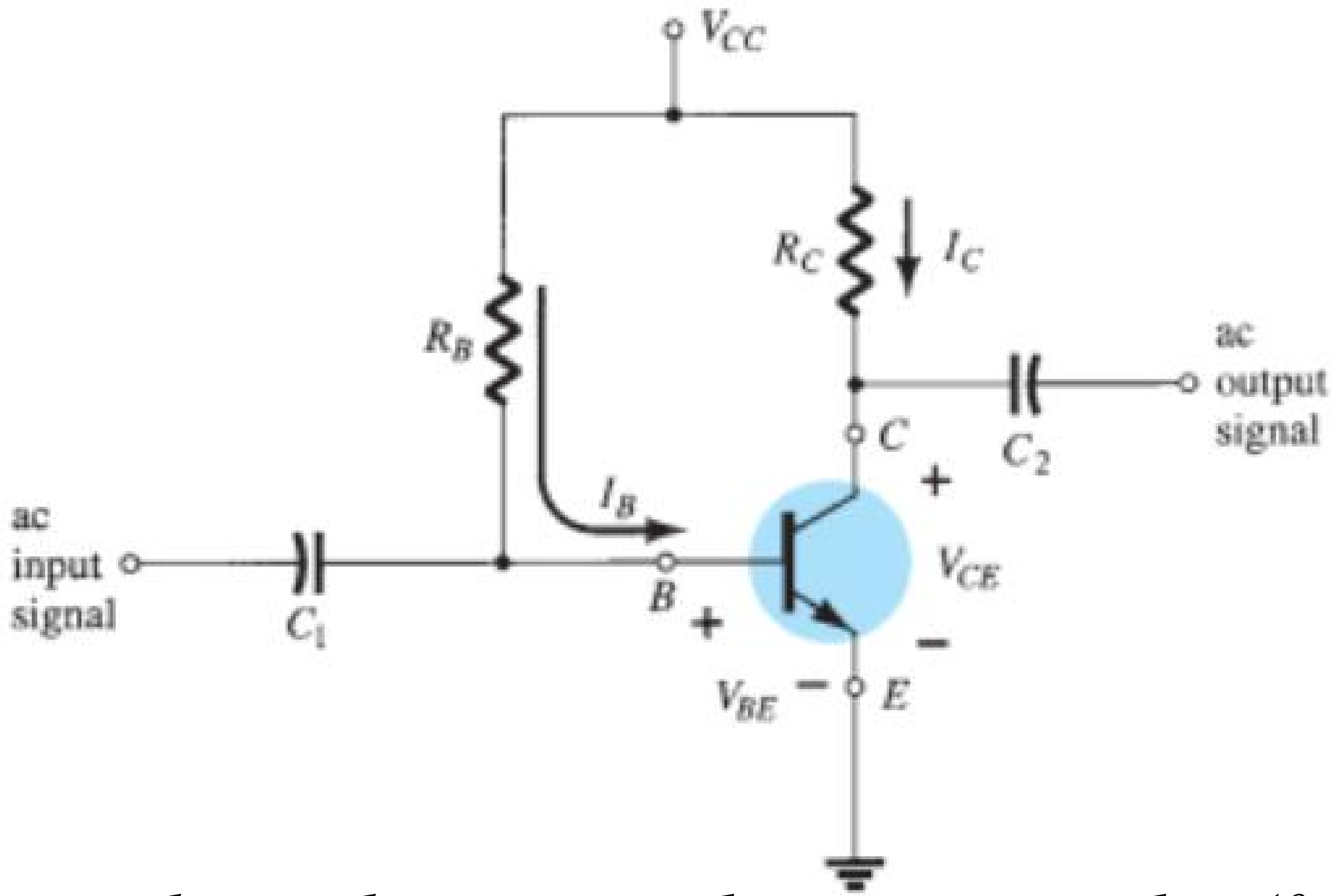
Emitter Bias

Voltage-Divider Bias

DC Bias with Voltage Feedback*

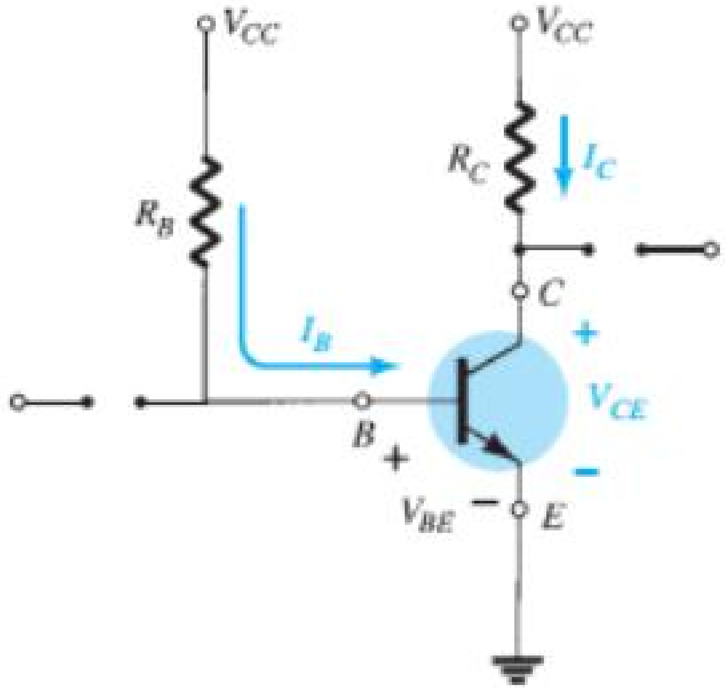
Miscellaneous Bias Configurations*

Fixed-Bias Circuit

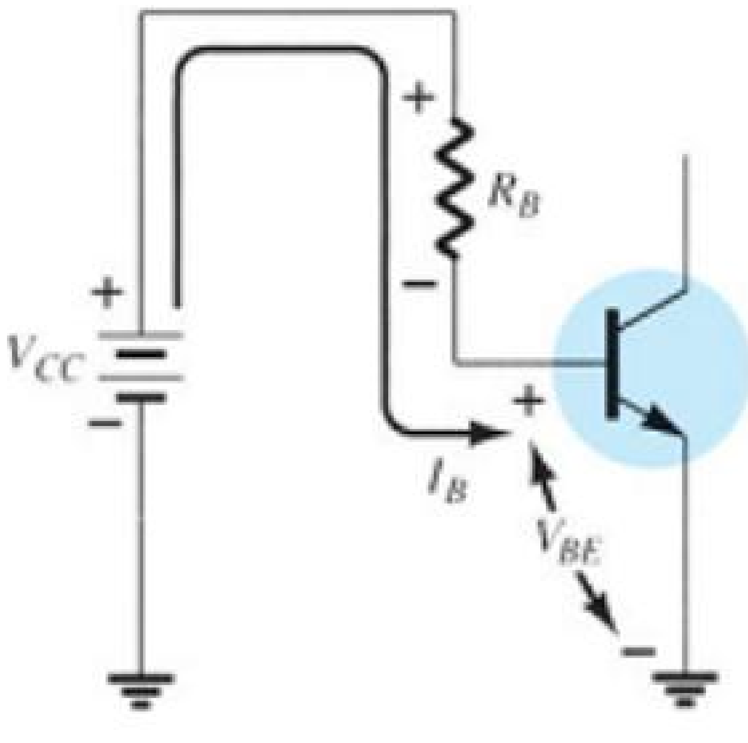


The dc supply can be separated into two supplies(for analysis purposes only) to permit a separation of input and output circuits.

Fixed-Bias Circuit



Fixed-Bias Circuit



DC equivalent

Base-emitter loop

Kirchhoff's voltage law:

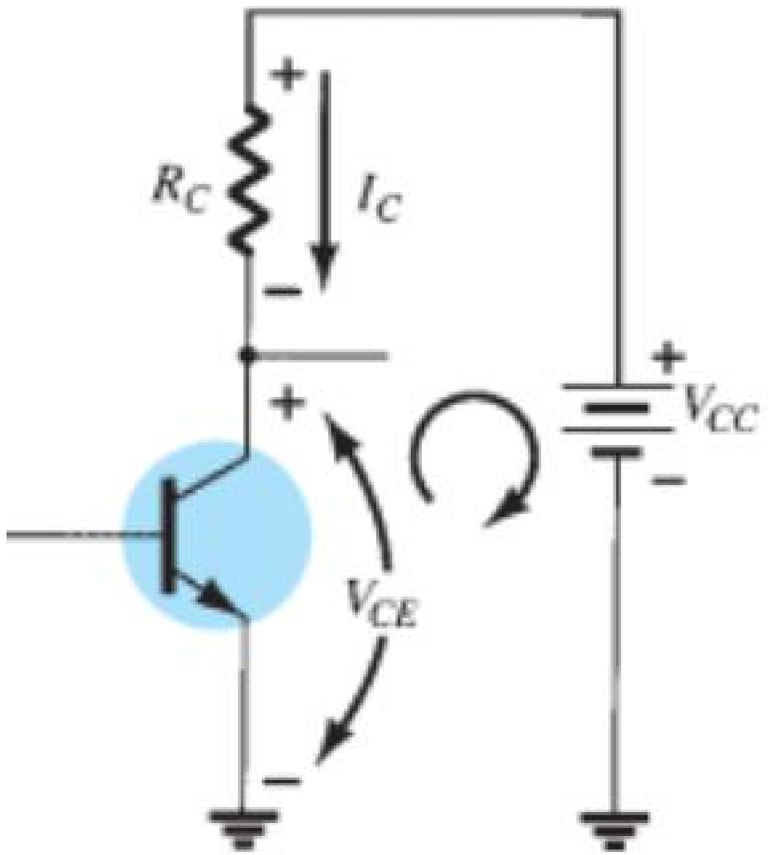
$$V_{CC} - I_B R_B - V_{EE} = 0$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

Sketching the DC equivalent is the first step for DC analysis:

1. Replacing the capacitor with an open-circuit equivalent.
2. Replacing the inductor with a short-circuit equivalent.
3. DC supply can be separated for analysis purpose only

Fixed-Bias Circuit



Kirchhoff's voltage law:

$$V_{CE} + I_C R_C - V_{CC} = 0$$

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

$$V_{CE} = V_C - V_E$$

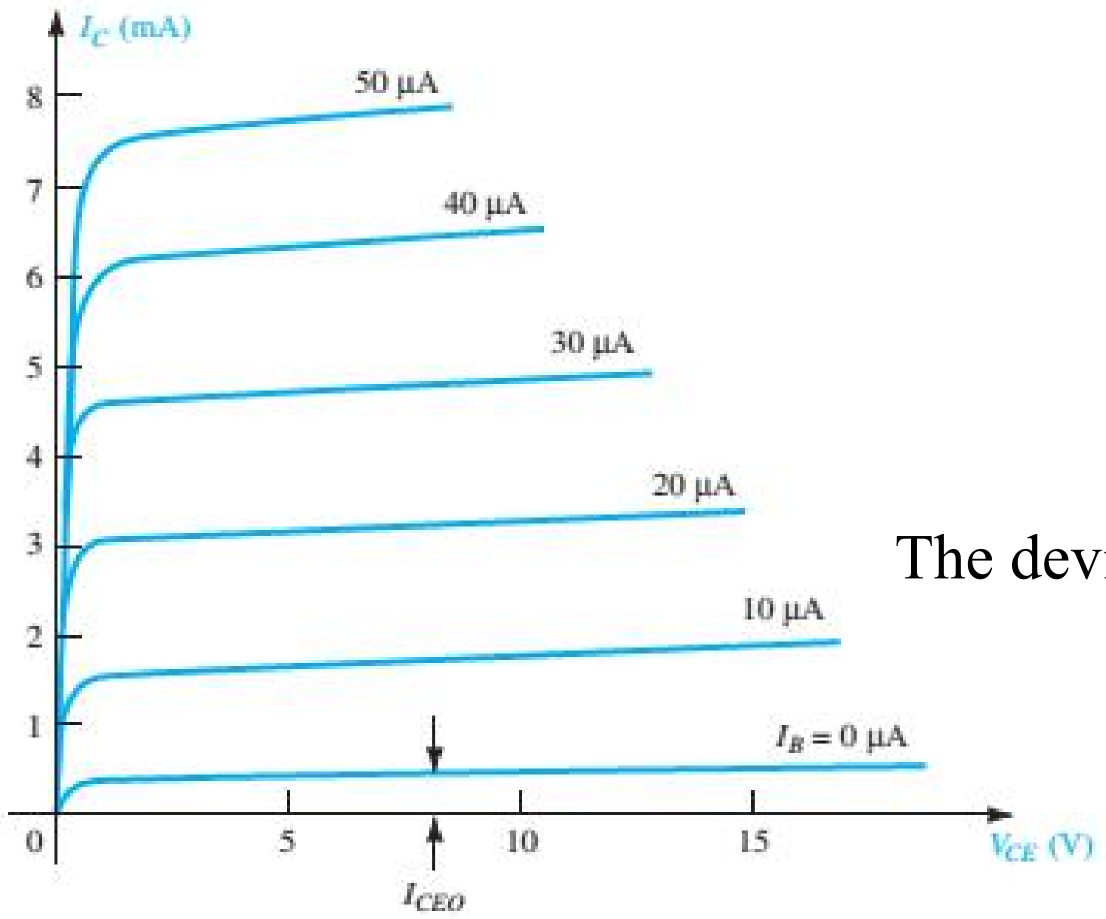
If $V_E=0$

$$V_{CE} = V_C$$

Example 4.1

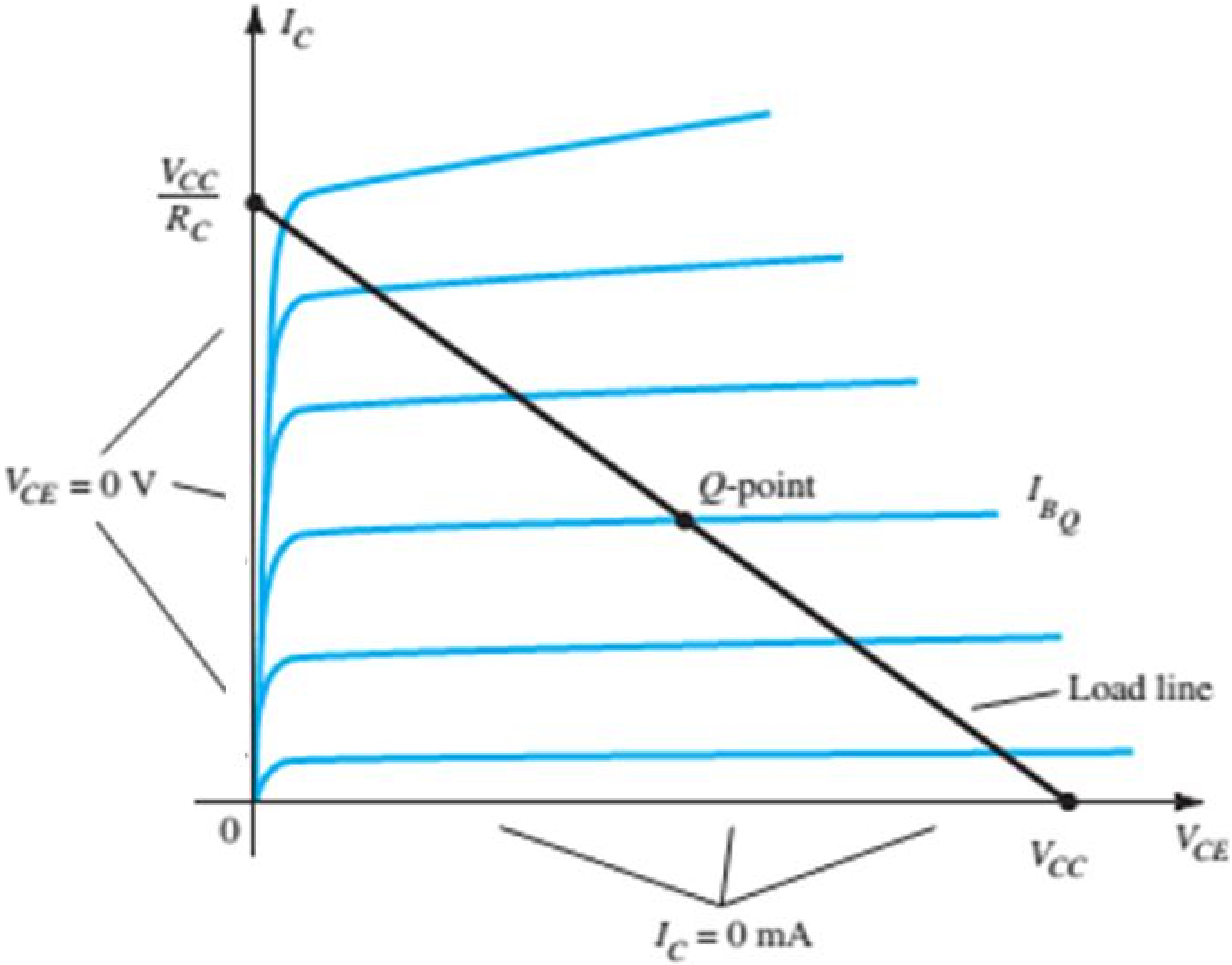
Load-Line Analysis

Output Equation: $V_{CE} = V_{CC} - I_C R_C$

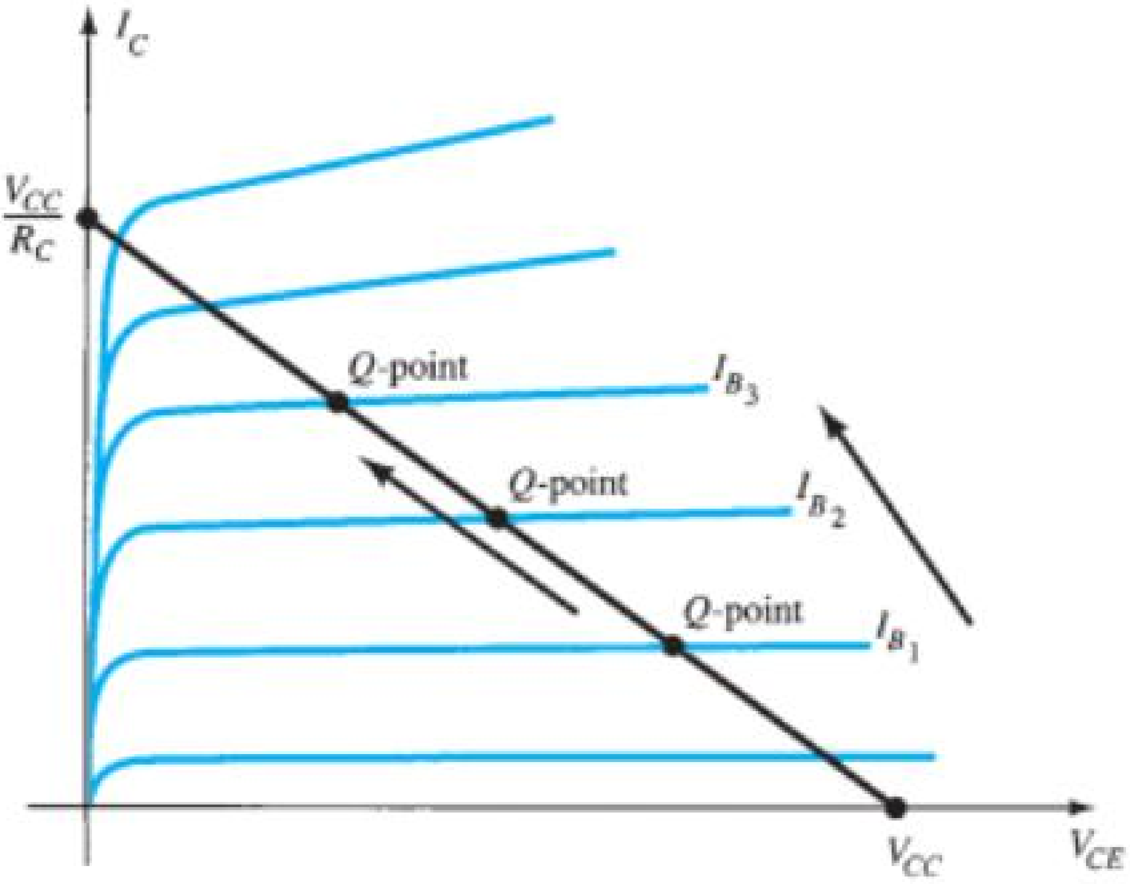


The device characteristics

Load-Line Analysis

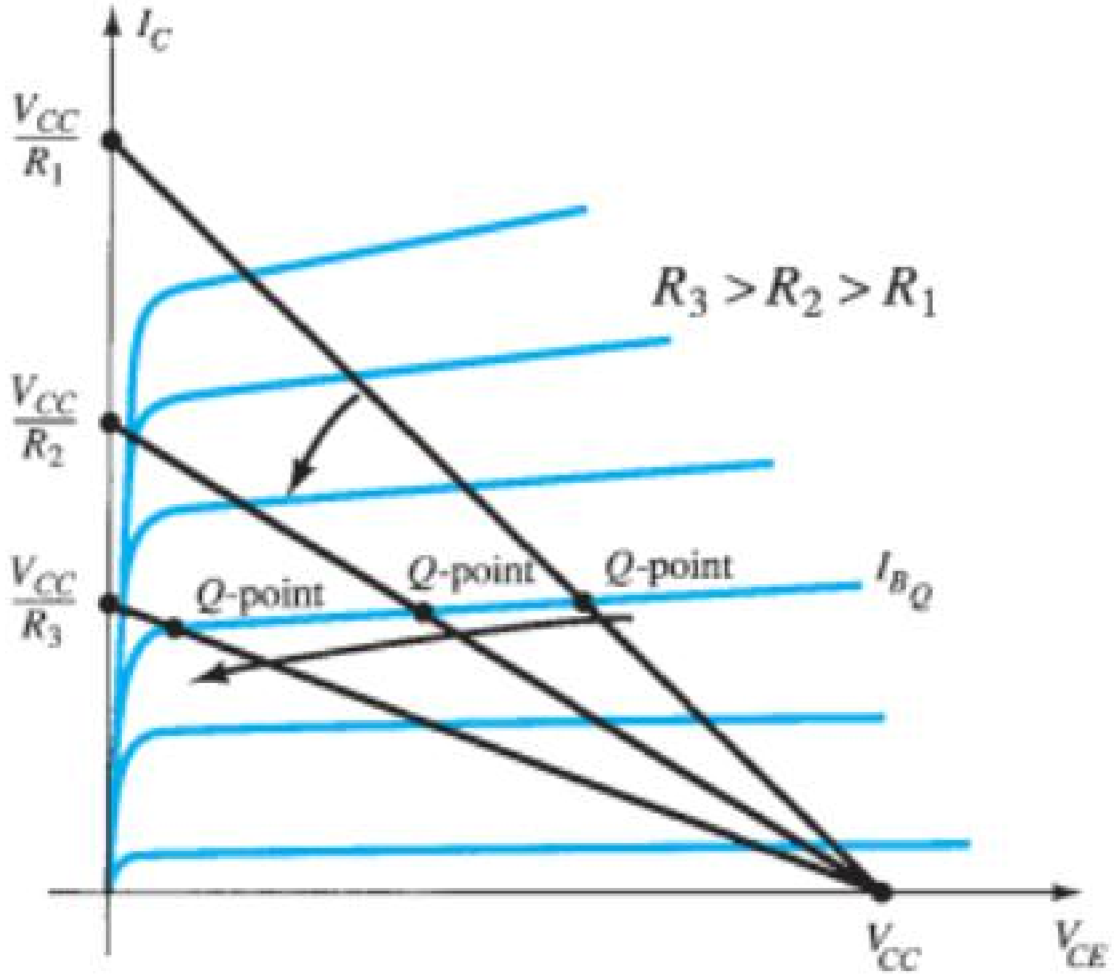


Load-Line Analysis



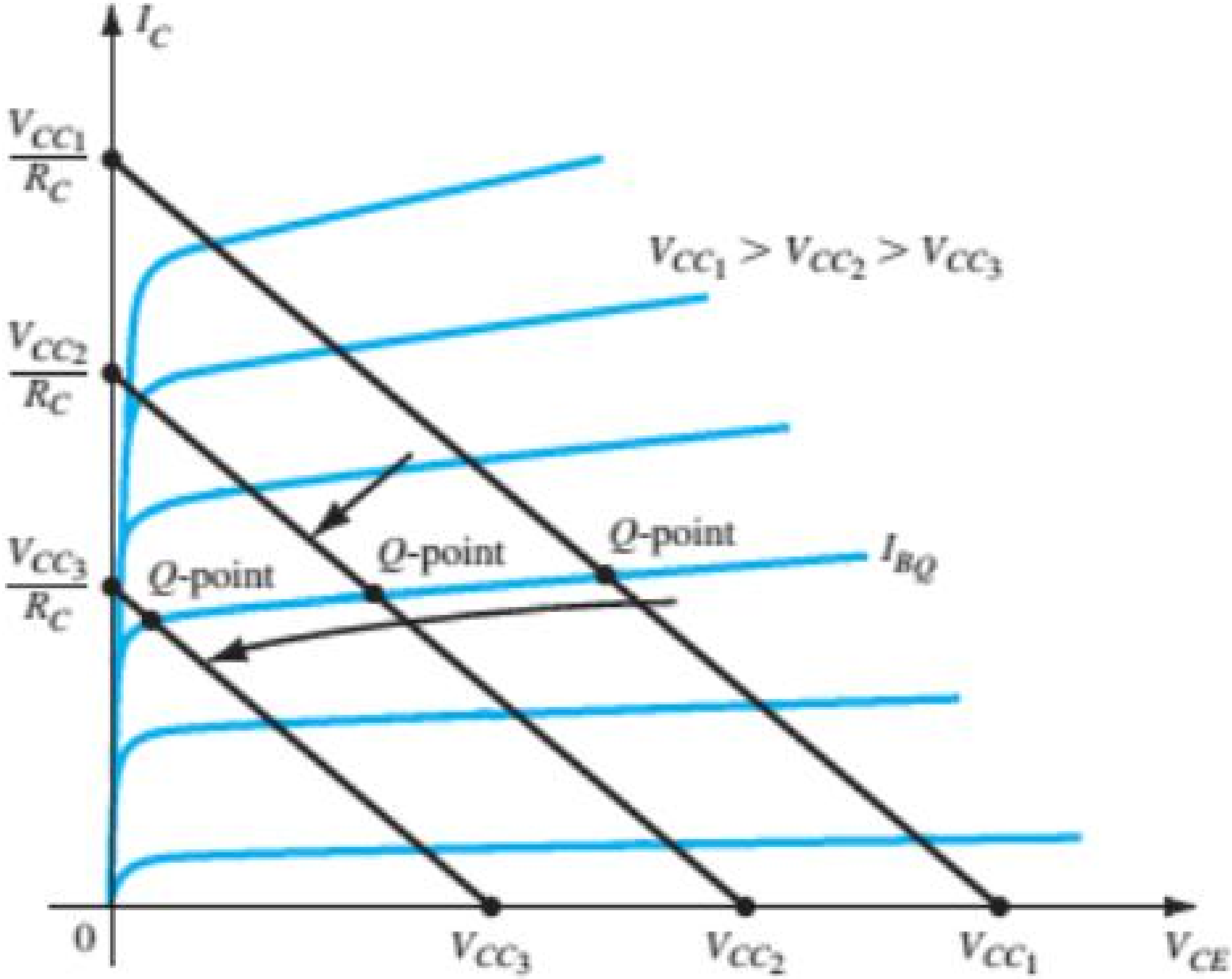
Movement of the Q-point with increasing level of I_B

Load-Line Analysis



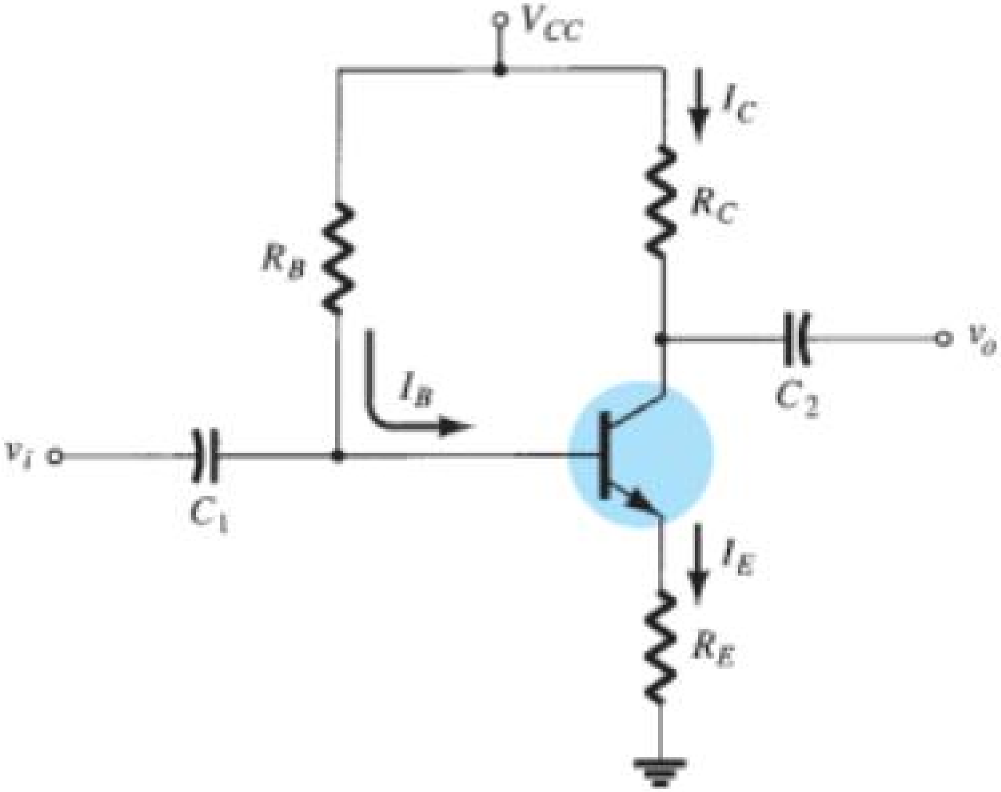
Effect of an increasing level of R_C on the load line and the Q-point

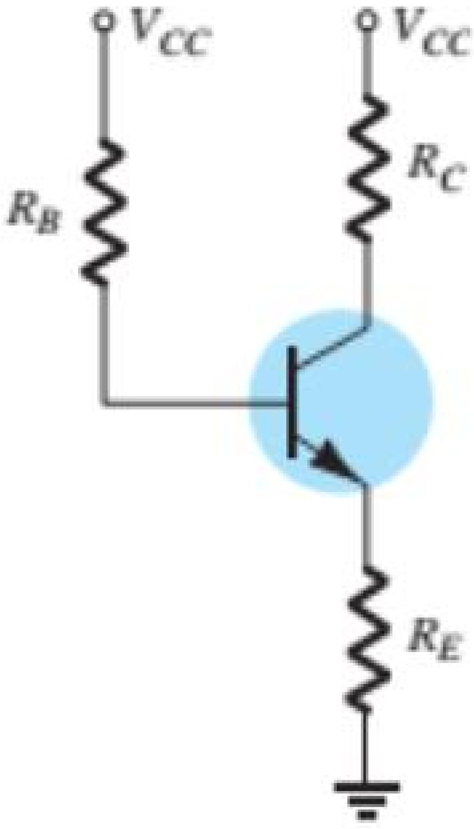
Load-Line Analysis



Effect of lower values of V_{CC} on the load line and the Q-point

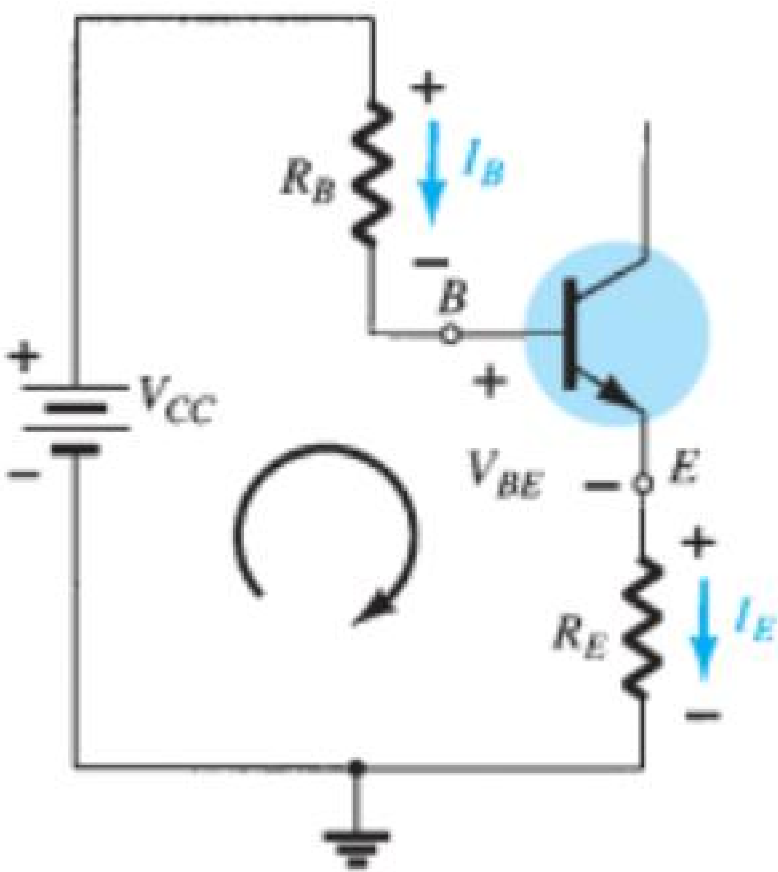
Emitter Bias



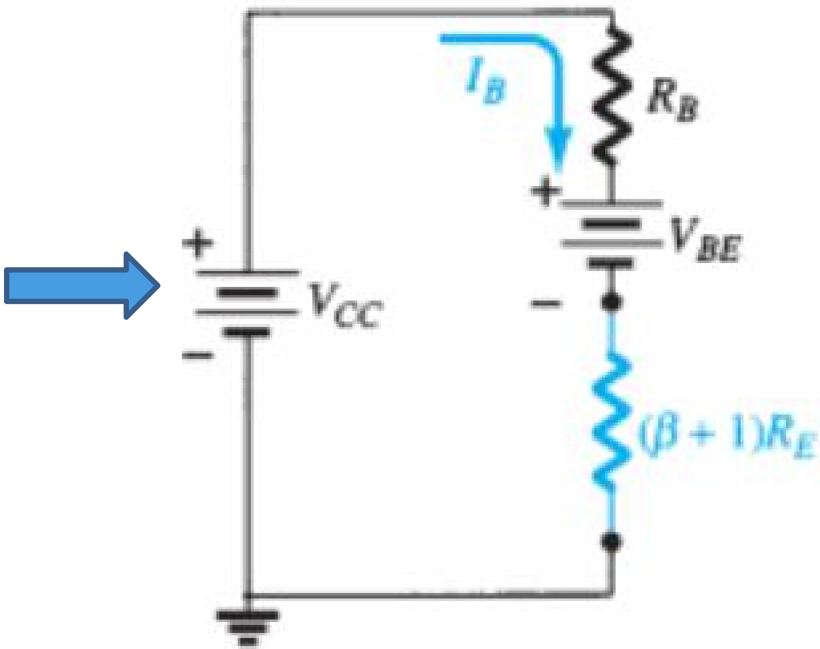


DC equivalent

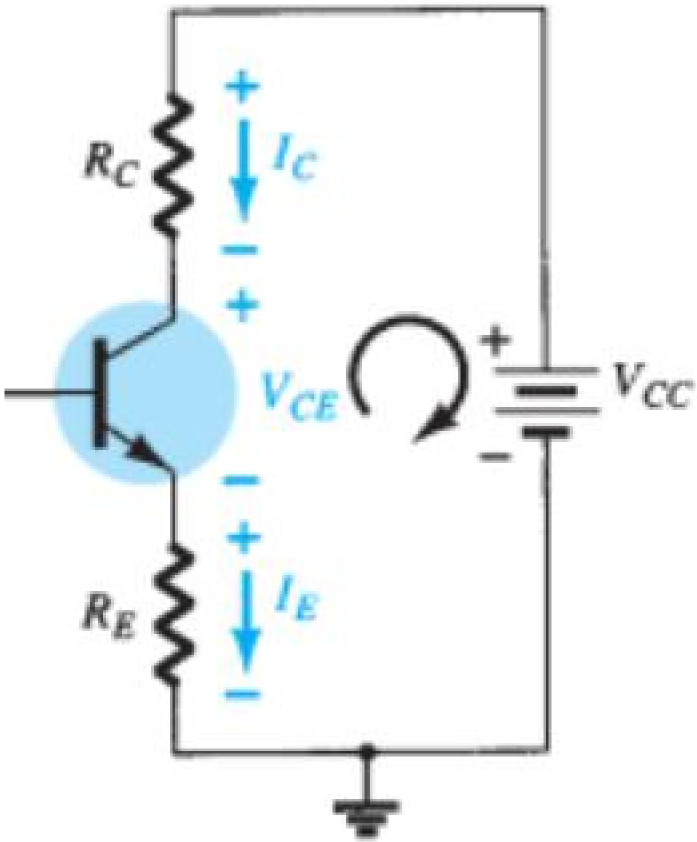
Emitter Bias



Base-emitter Loop



Emitter Bias



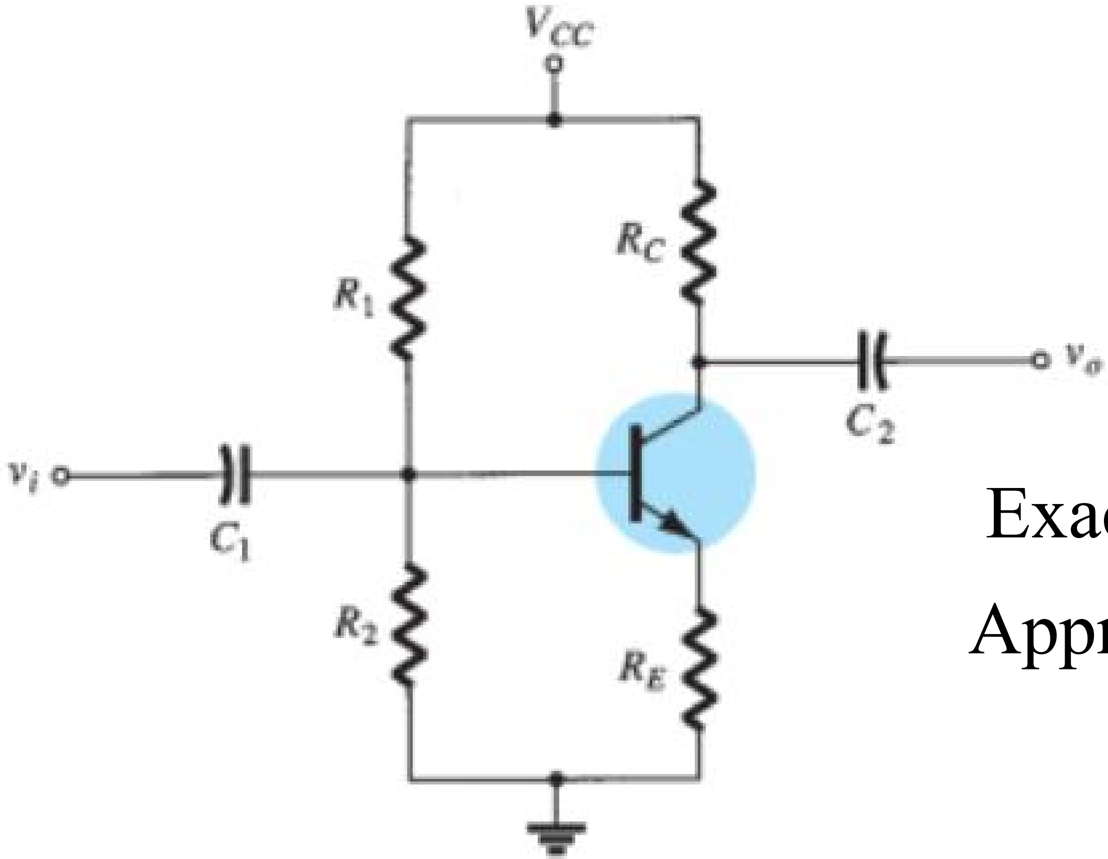
Collector-emitter Loop

Example 4.4

Example 4.5

Improved bias stability

Voltage-Divider Bias



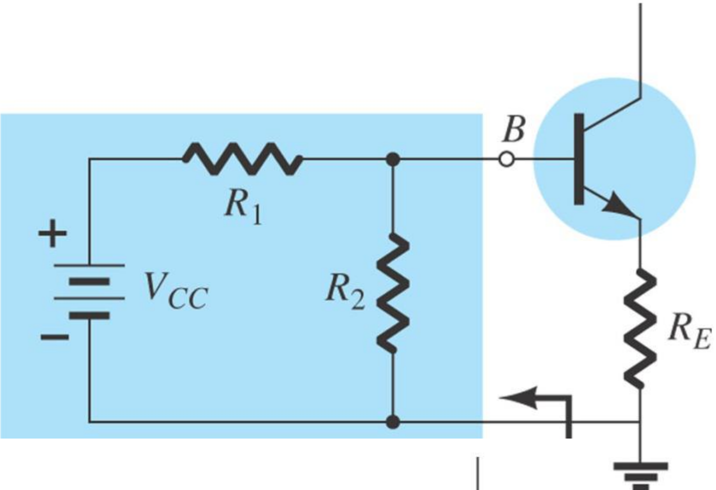
Exact Analysis

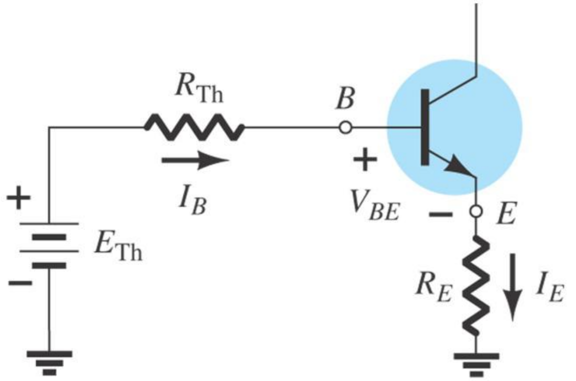
Approximate Analysis

Exact Analysis

This is a very stable bias circuit.

The currents and voltages are almost independent of variations in β.



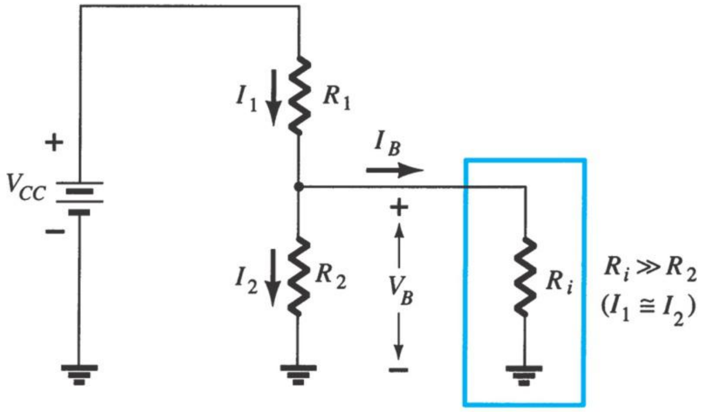


Approximate Analysis

Where $I_B << I_1$ and I_2 and $I_1 \cong I_2$:

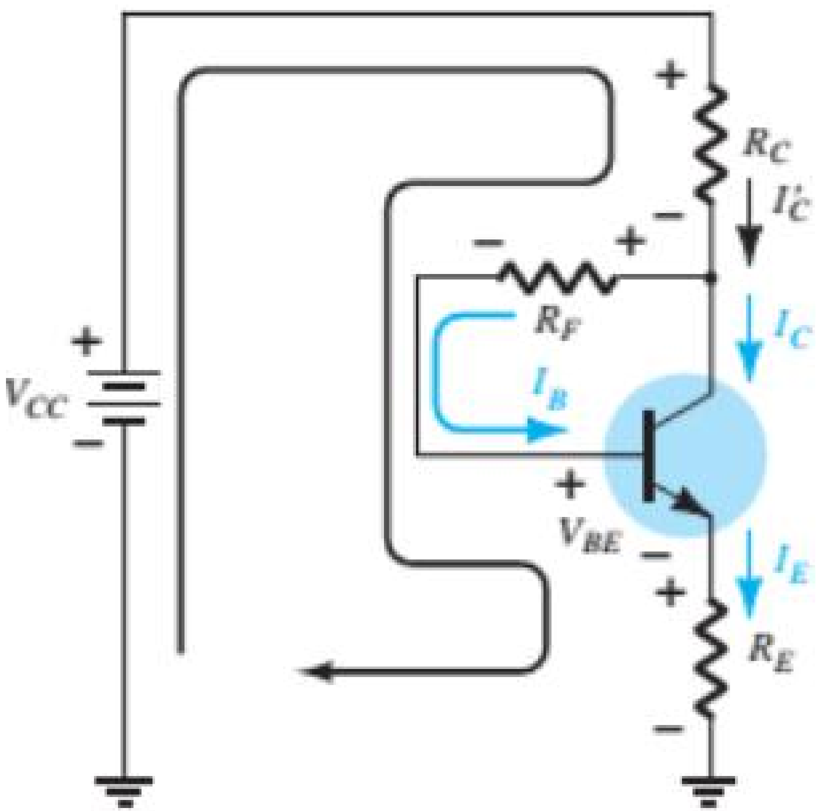
Where $\beta R_E > 10R_2$:

From Kirchhoff's voltage law:



DC Bias with Voltage Feedback

DC Bias with Voltage Feedback



Base-Emitter Loop

From Kirchhoff's voltage law:

Where $I_B << I_C$:

Knowing $I_C = \beta I_B$ and $I_E \cong I_C$, the loop equation becomes:

Solving for I_B:

DC Bias with Voltage Feedback

Collector-Emitter Loop

Applying Kirchoff's voltage law:

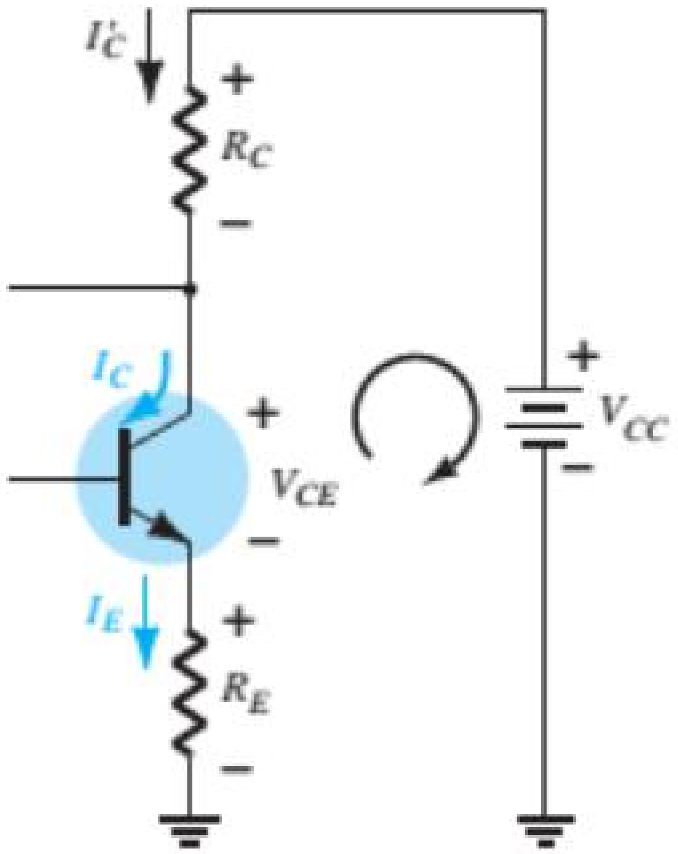
$$I_E R_E + V_{CE} + I_C' R_C - V_{CC} = 0$$

Since $I_C' \cong I_C$ and $I_C = \beta I_B$:

$$I_C(R_C + R_E) + V_{CE} - V_{CC} = 0$$

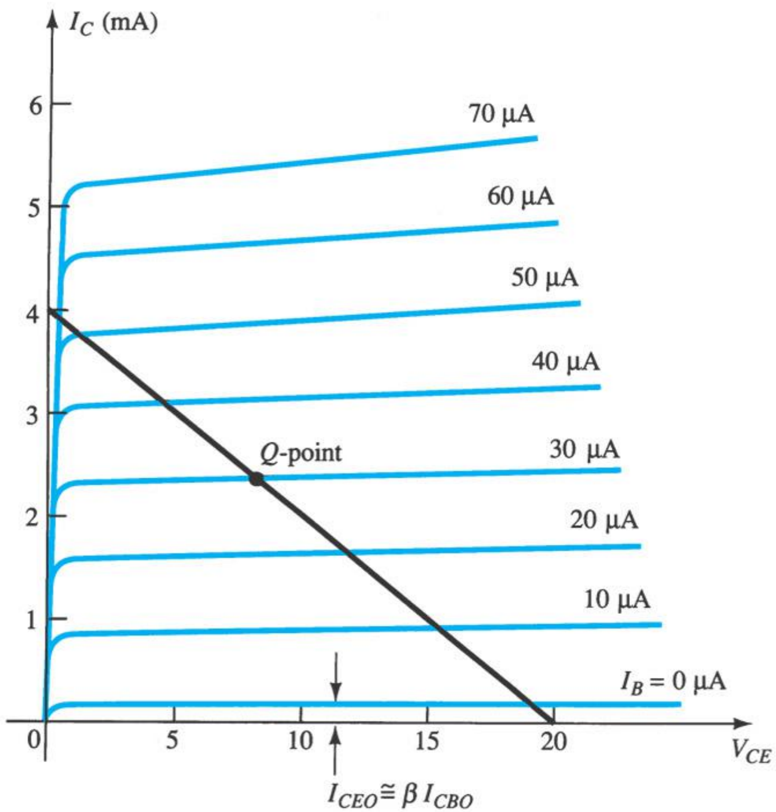
Solving for V_{CE}:

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



Bias Stabilization

- I_C is sensitive to β , temperature, V_{BE}, and I_{CO}



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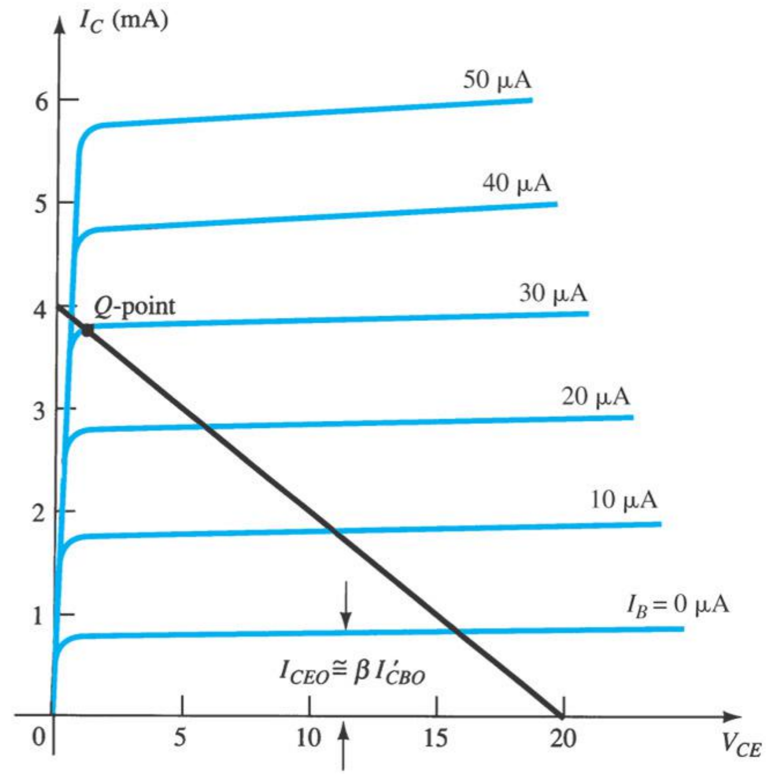
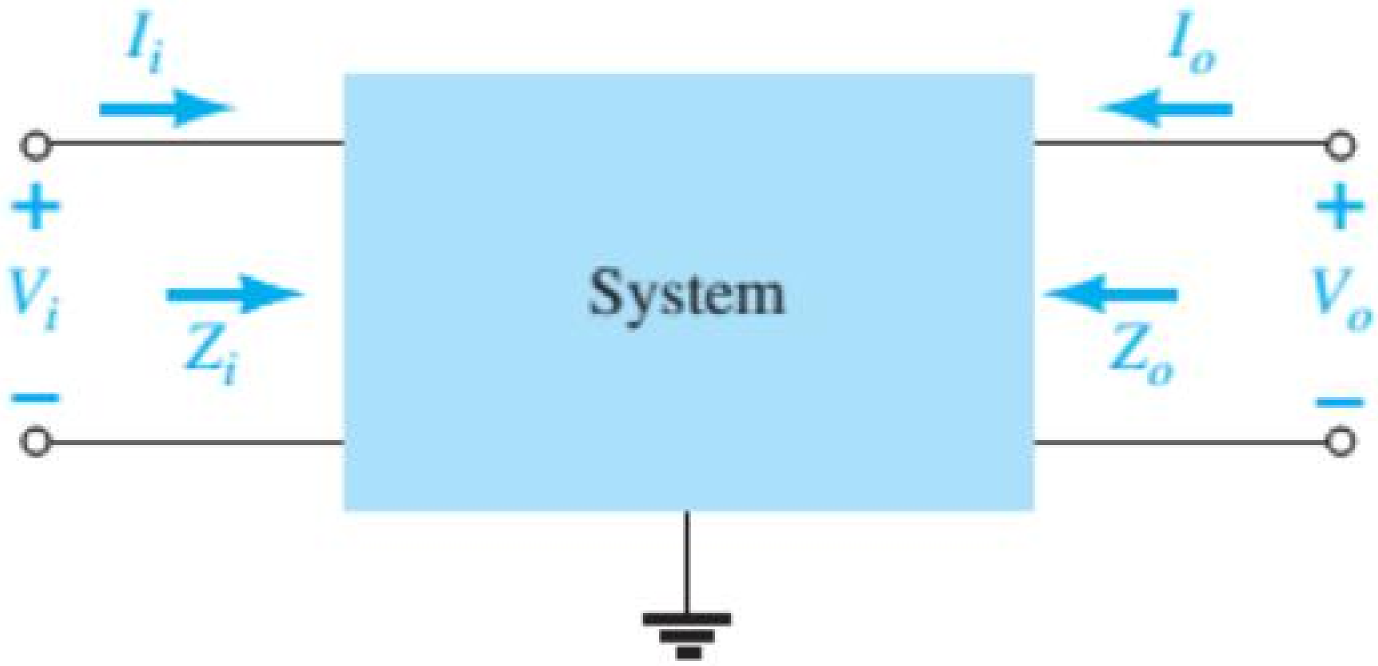


(b)

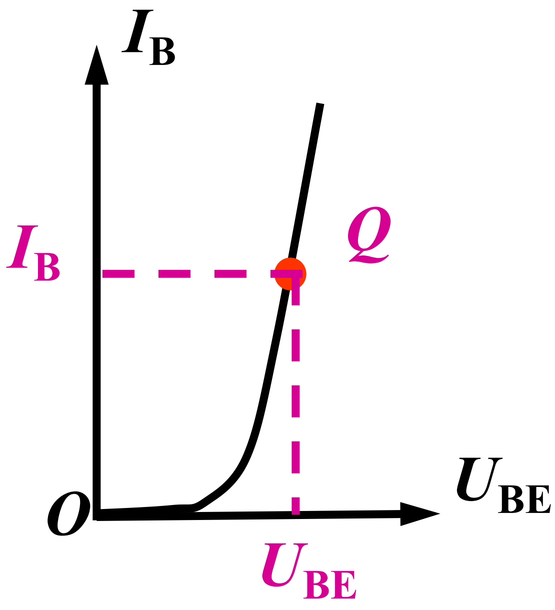
BJT AC Analysis

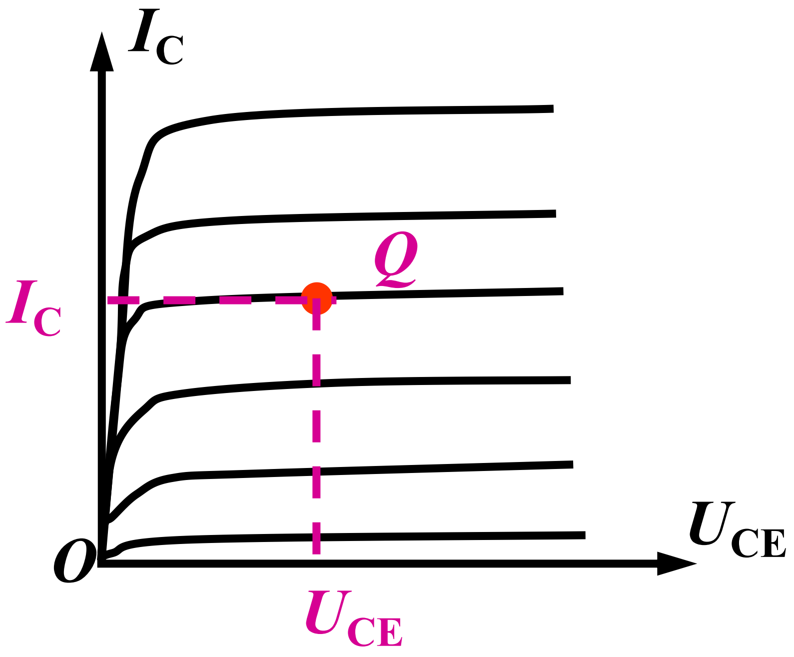
The factor missing from the discussion above that permits an ac power output greater than the input ac power is the applied dc power. It is the principal contributor to the total output power even though part of it is dissipated by the device and resistive elements. In other words, there is an "exchange" of dc power to the ac domain that permits establishing a higher output ac power.

BJT AC Analysis



BJT AC Analysis





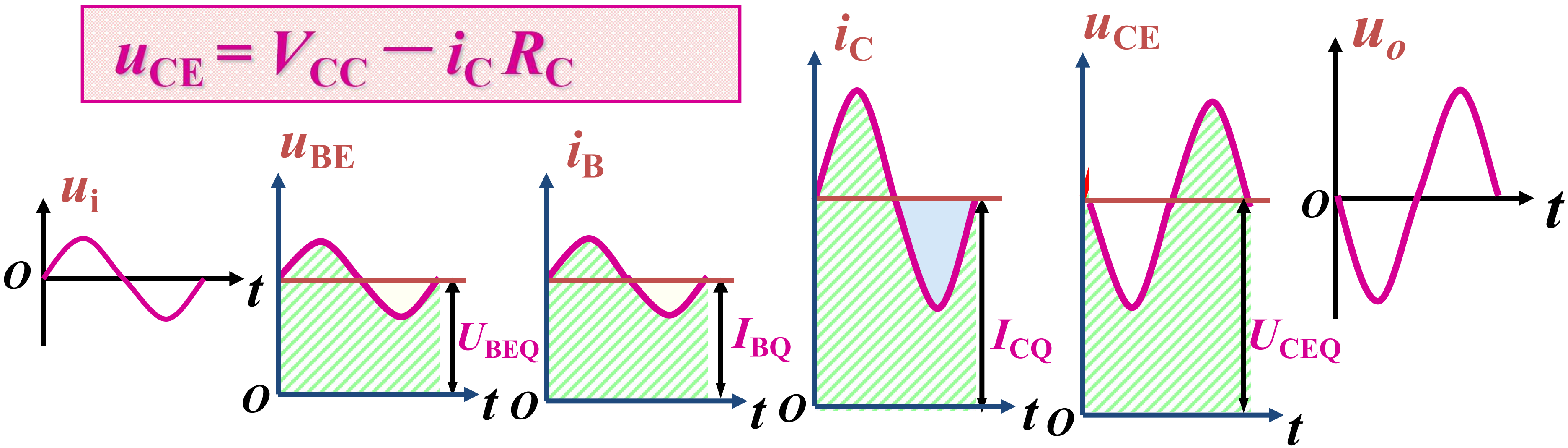
BJT AC Analysis

$$u_o \neq 0$$

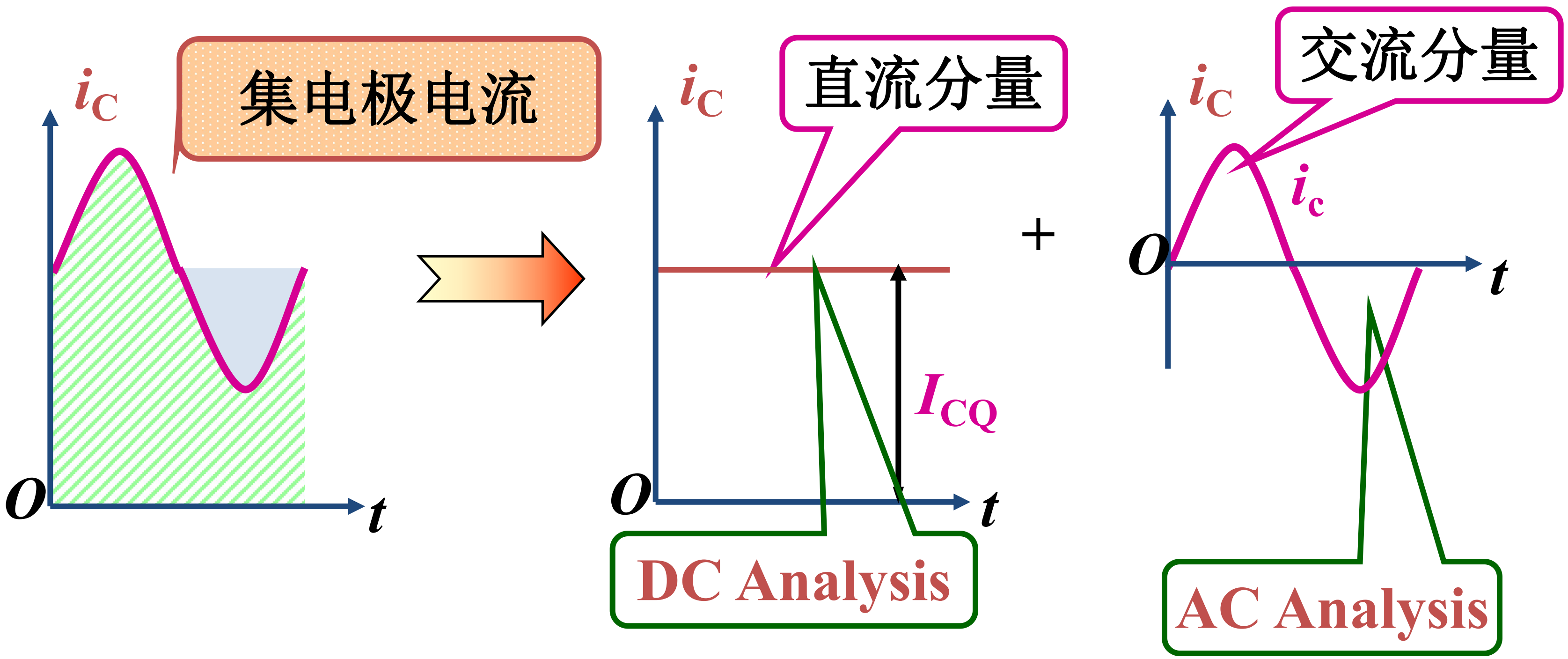
$$u_{BE} = U_{BEQ} + u_i$$

$$u_{CE} = U_{CEQ} + u_o$$

$$u_{CE} = V_{CC} - i_C R_C$$

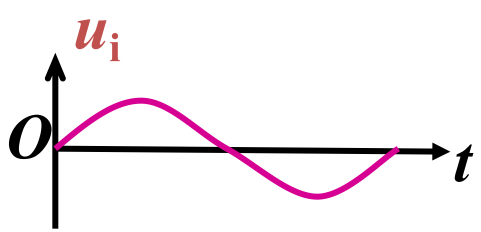


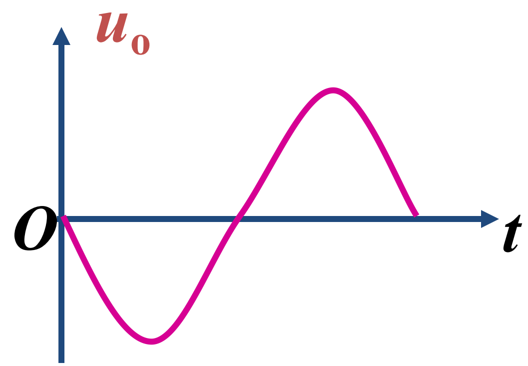
BJT AC Analysis



BJT AC Analysis

- 若参数选取得当，输出电压可比输入电压大，即电路具有电压放大作用。





- 输出电压与输入电压在相位上相差180°，即共发射极电路具有反相作用。

BJT AC Analysis

In other words, one can make a complete dc analysis of a system before considering the ac response. Once the dc analysis is complete, the ac response can be determined using a completely ac analysis. It happens, however, that one of the components appearing in the ac analysis of BJT networks will be determined by the dc conditions, so there is still an important link between the two types of analysis.

AC Equivalent Circuit

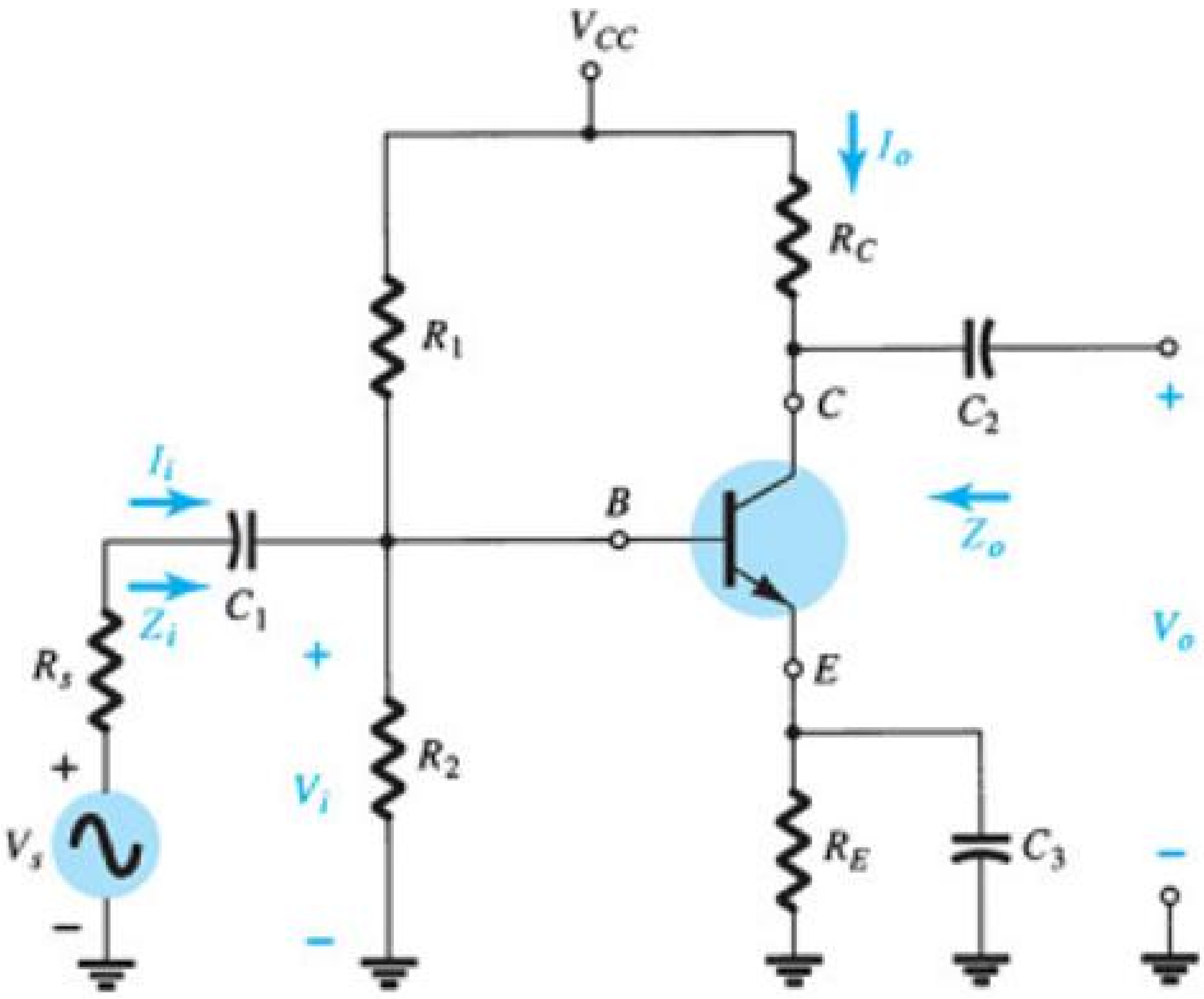
1. Setting all dc sources to zero and replacing them by a short-circuit equivalent.

2. Replacing all capacitors by a short-circuit equivalent.

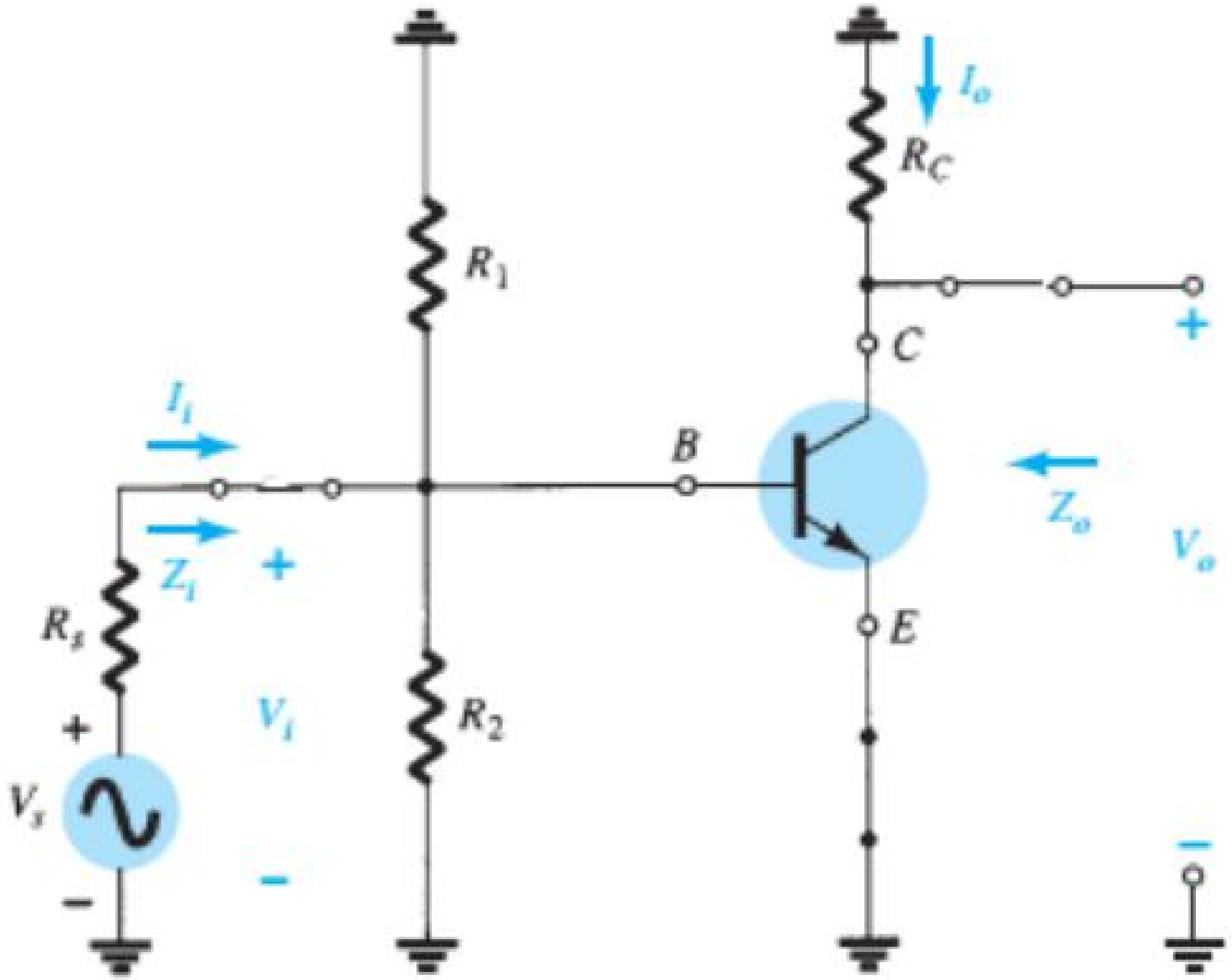
3. Removing all elements bypassed by the short-circuit equivalents introduced by steps 1 and 2.

4. Redrawing the network in a more convenient and logical form.

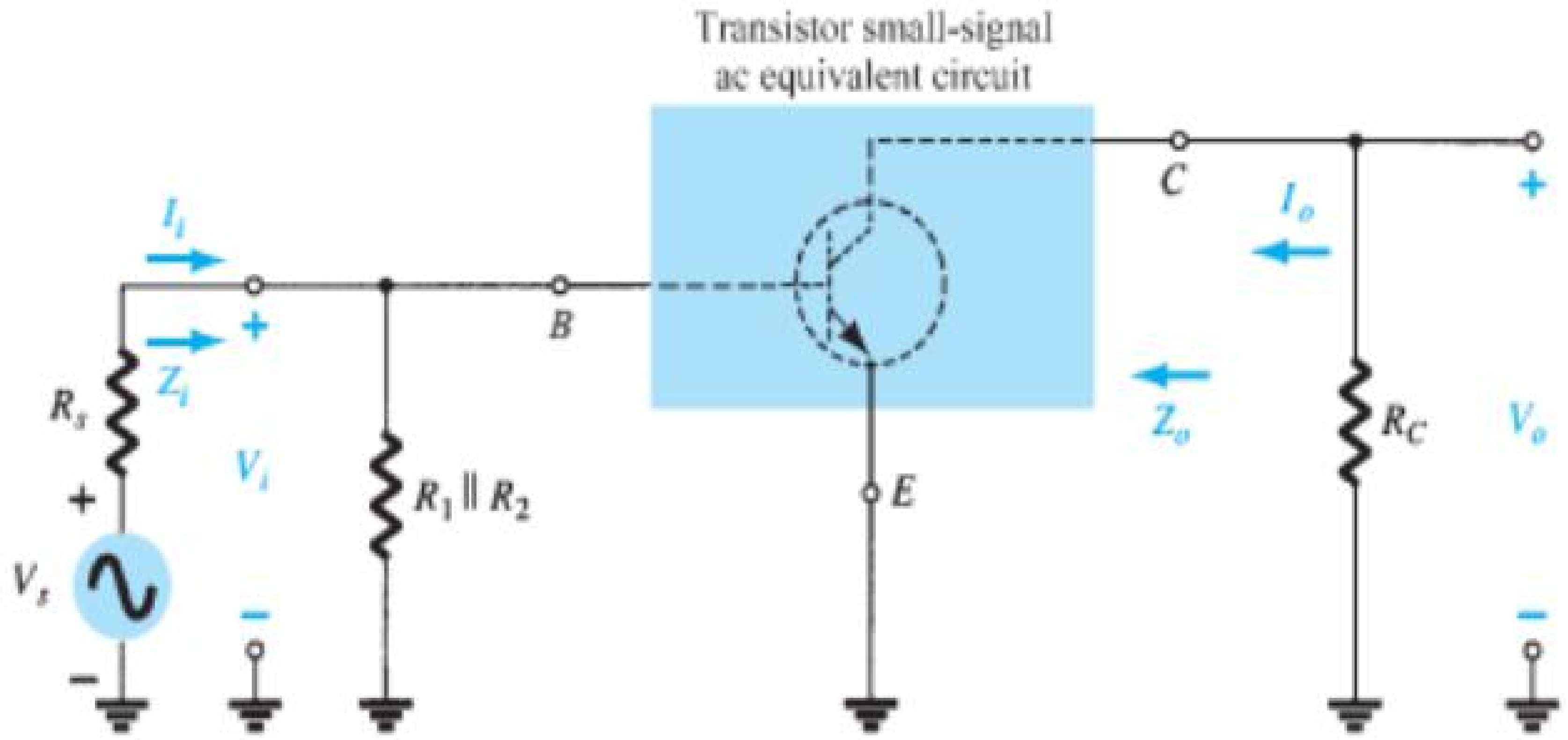
BJT AC Analysis



BJT AC Analysis



BJT AC Analysis

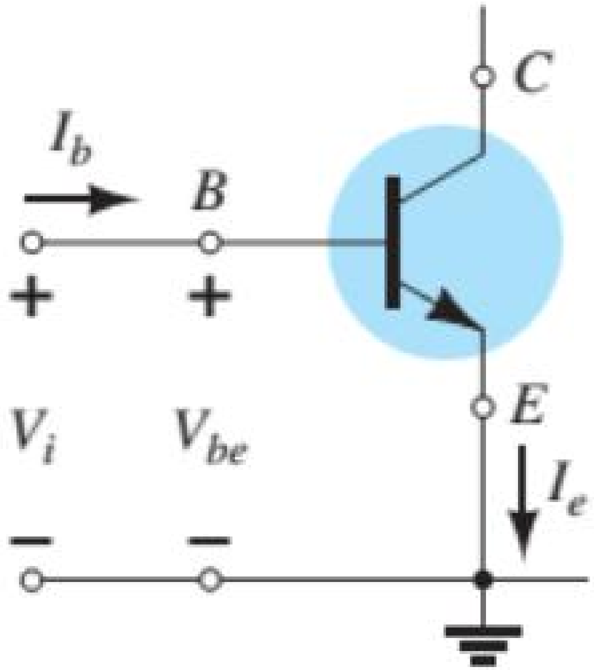


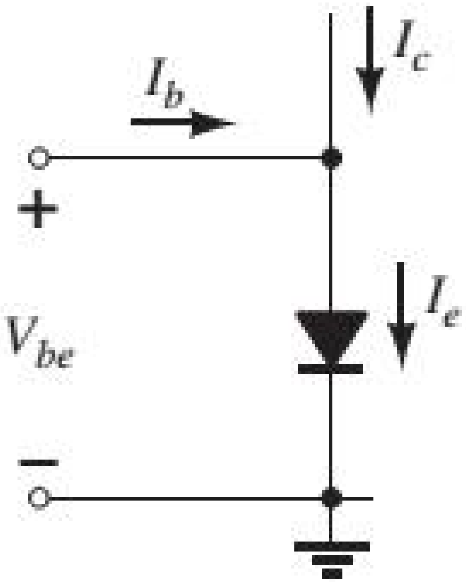
BJT Transistor Modeling

A model is a combination of circuit elements, properly chosen, that best approximates the actual behavior of a semiconductor device under specific operating conditions.

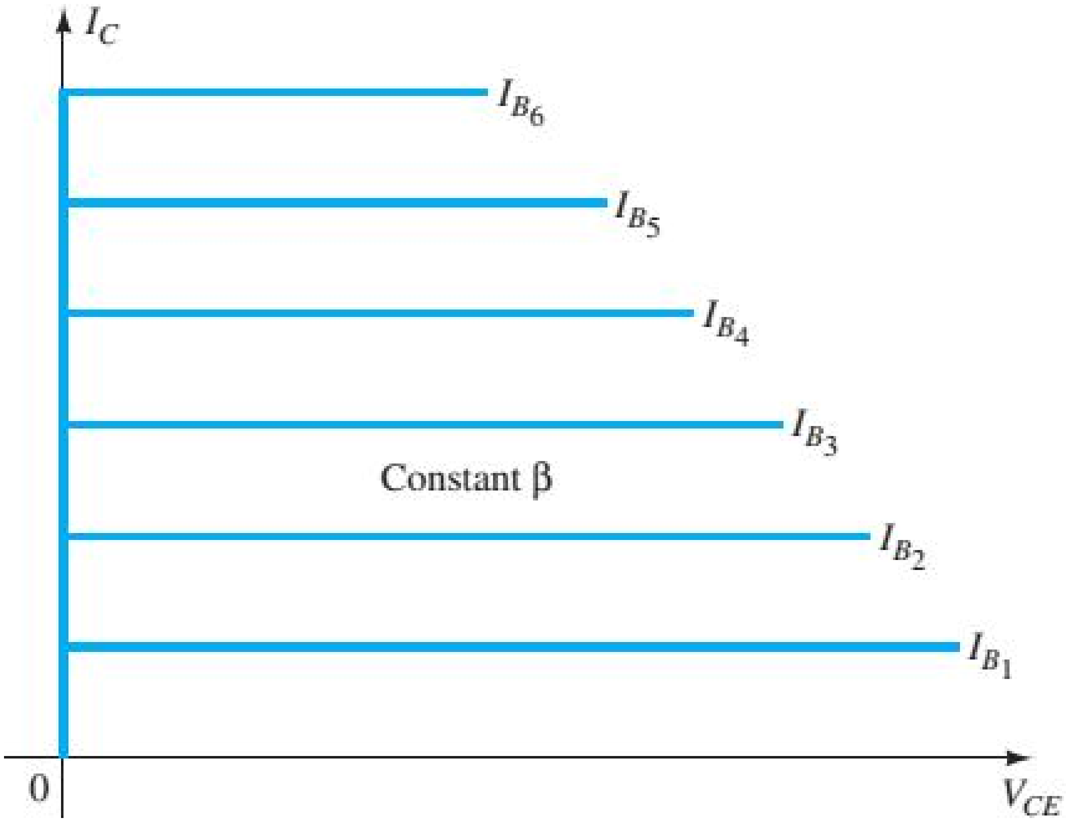
- The r_e model ❤
- The hybrid π model
- The hybrid equivalent model

Common-Emitter Configuration

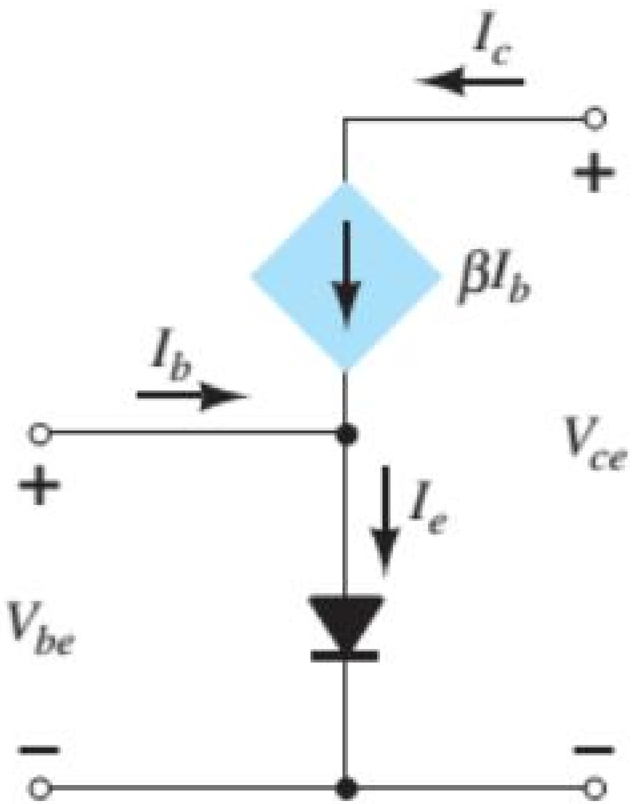




The r_e model

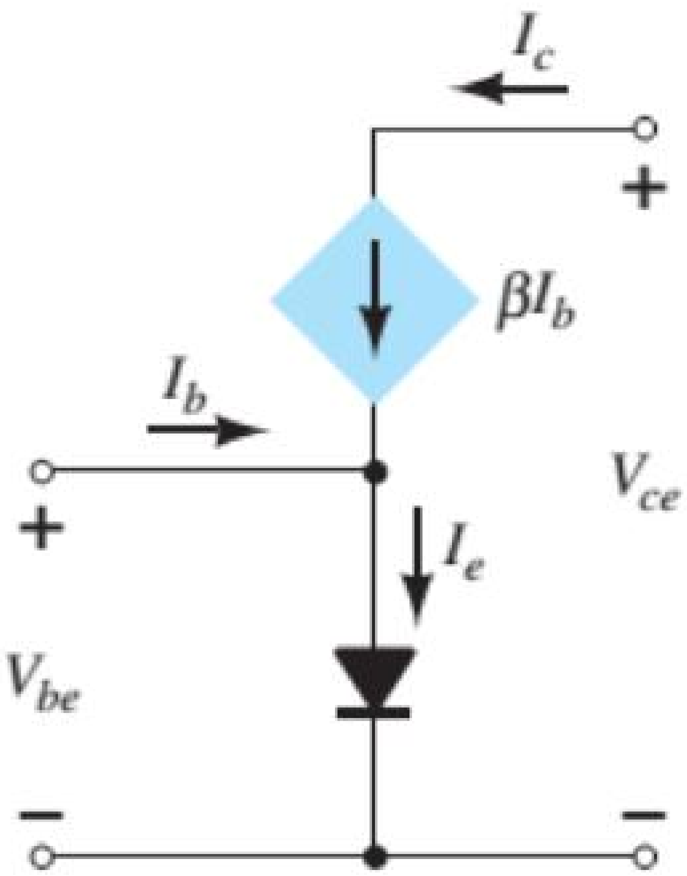


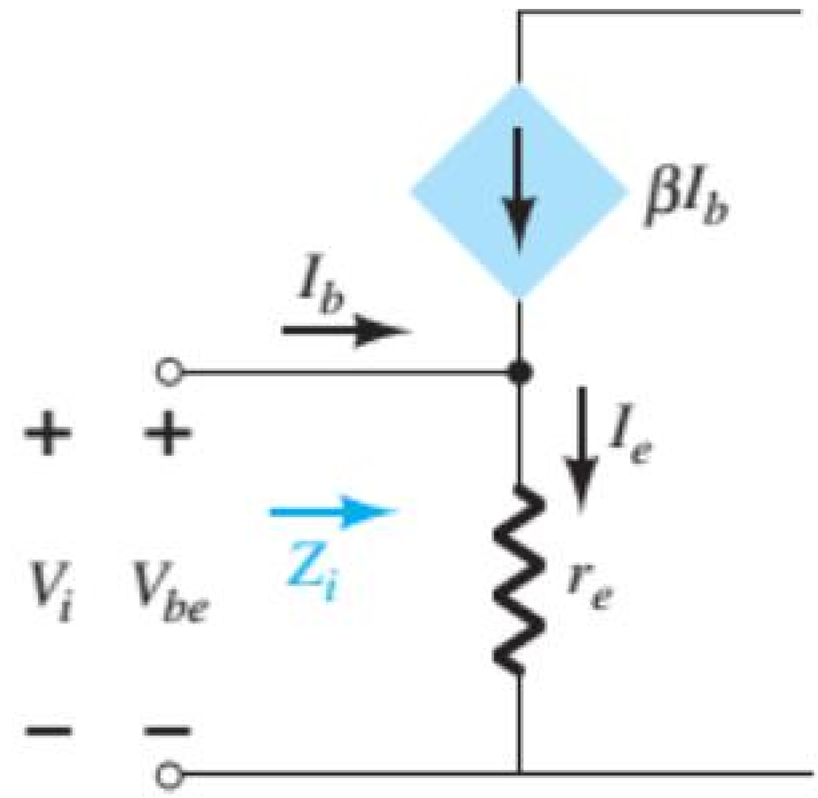
I_C
I_{B_6}
I_{B_5}
I_{B_4}
I_{B_3}
Constant β
I_{B_2}
I_{B_1}
0
V_{CE}



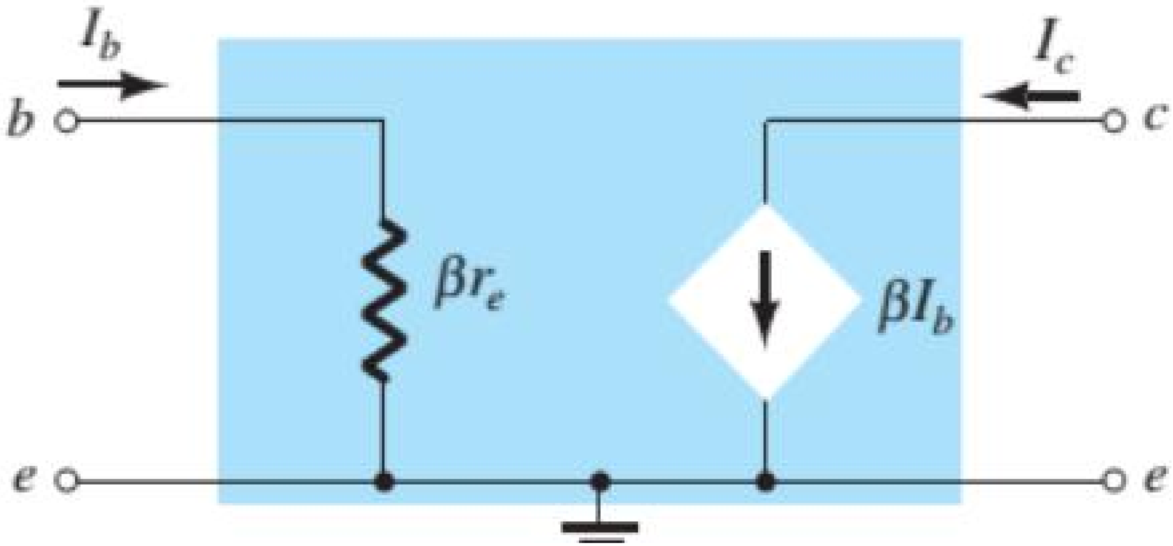
I_c
+
βI_b
I_b
V_{ce}
+
I_e
V_{be}
–
–

The r_e model





The r_e model

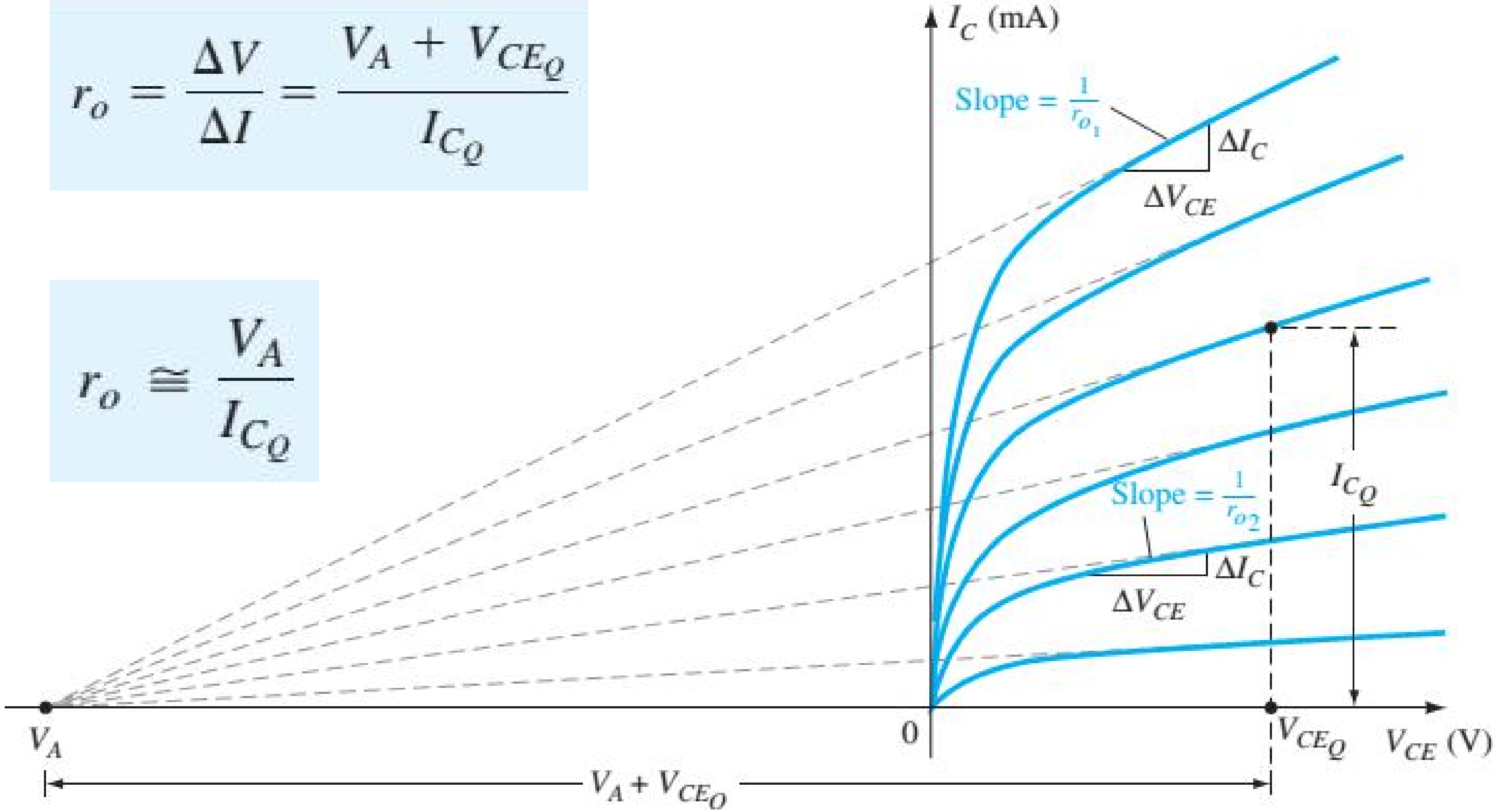


Improved BJT equivalent circuit

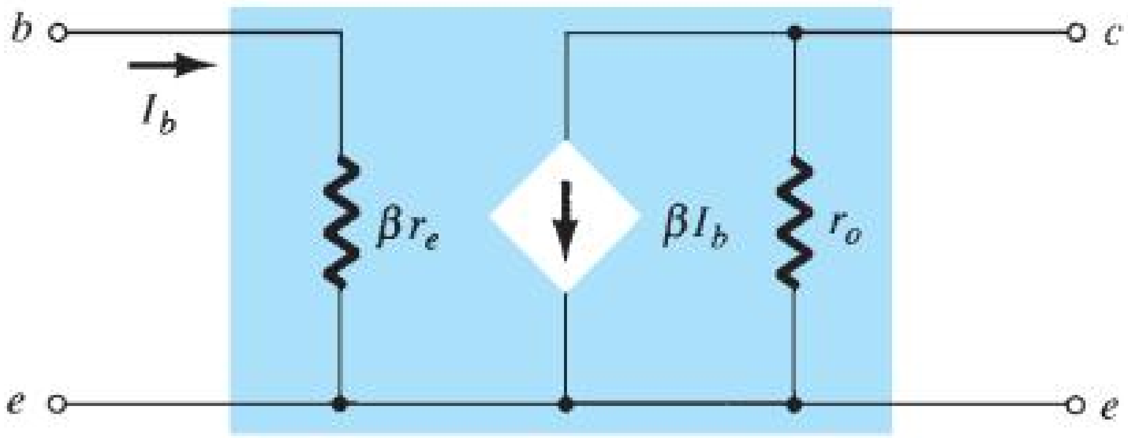
The r_e model

$$r_o = \frac{\Delta V}{\Delta I} = \frac{V_A + V_{CE_Q}}{I_{C_Q}}$$

$$r_o \cong \frac{V_A}{I_{C_Q}}$$

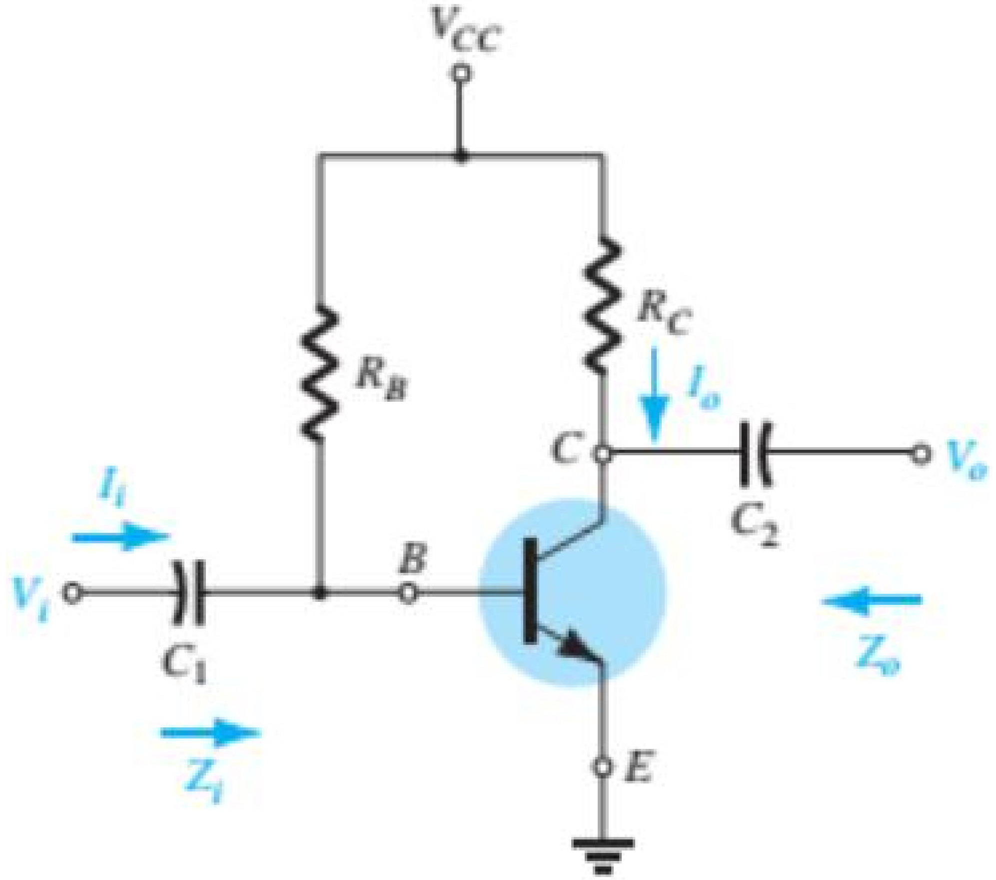


The r_e model



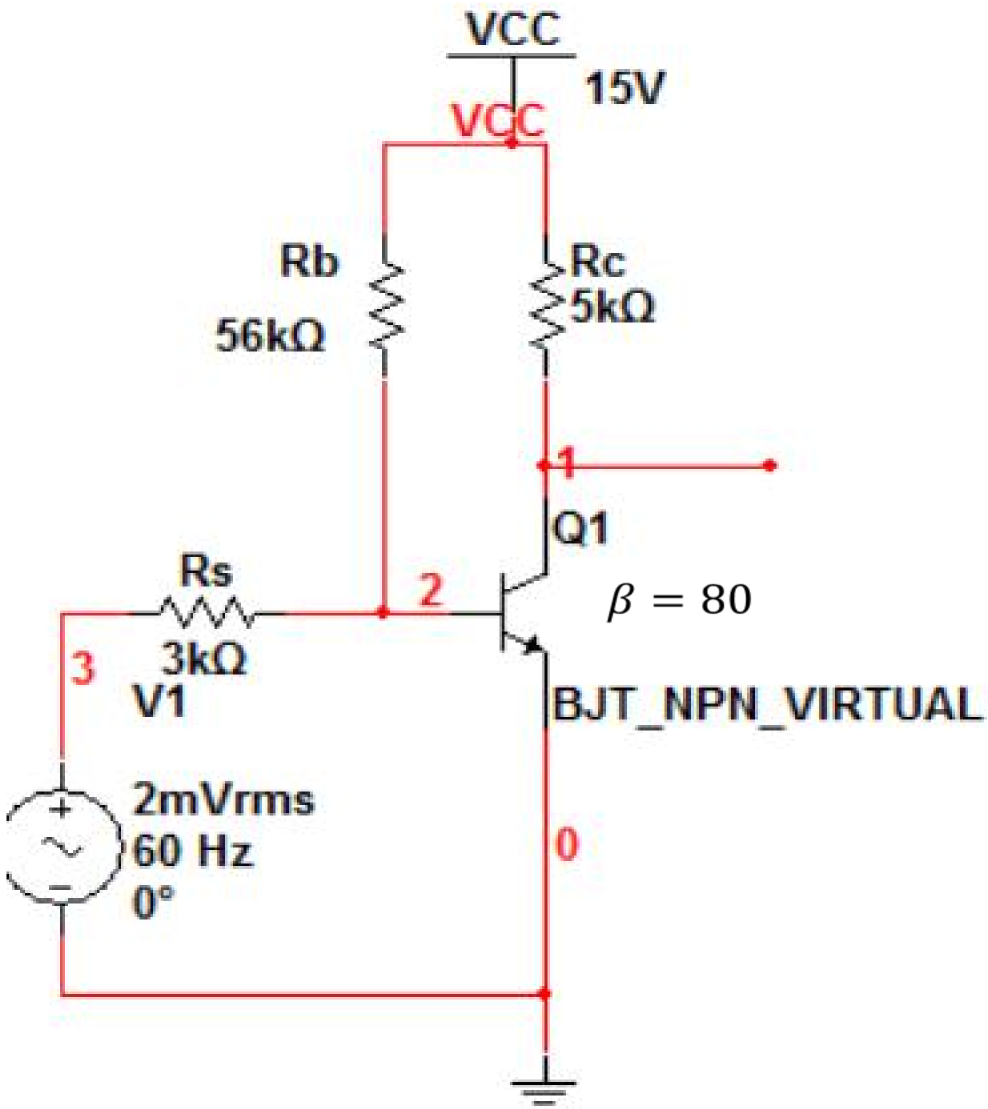
r_e model for the common-emitter transistor configuration including effects of r_o

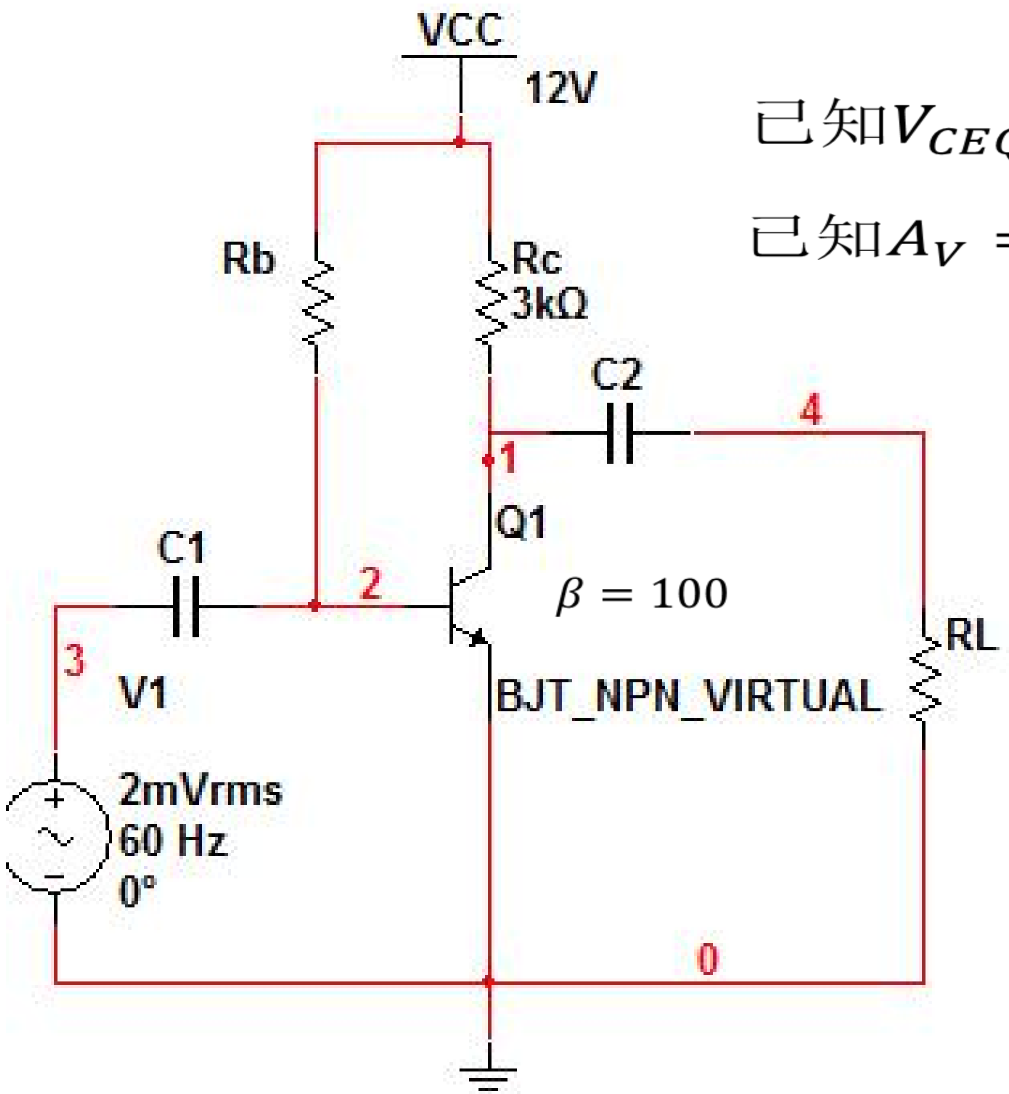
CE FIXED-BIAS CONFIGURATION



Example 5.4

Problem

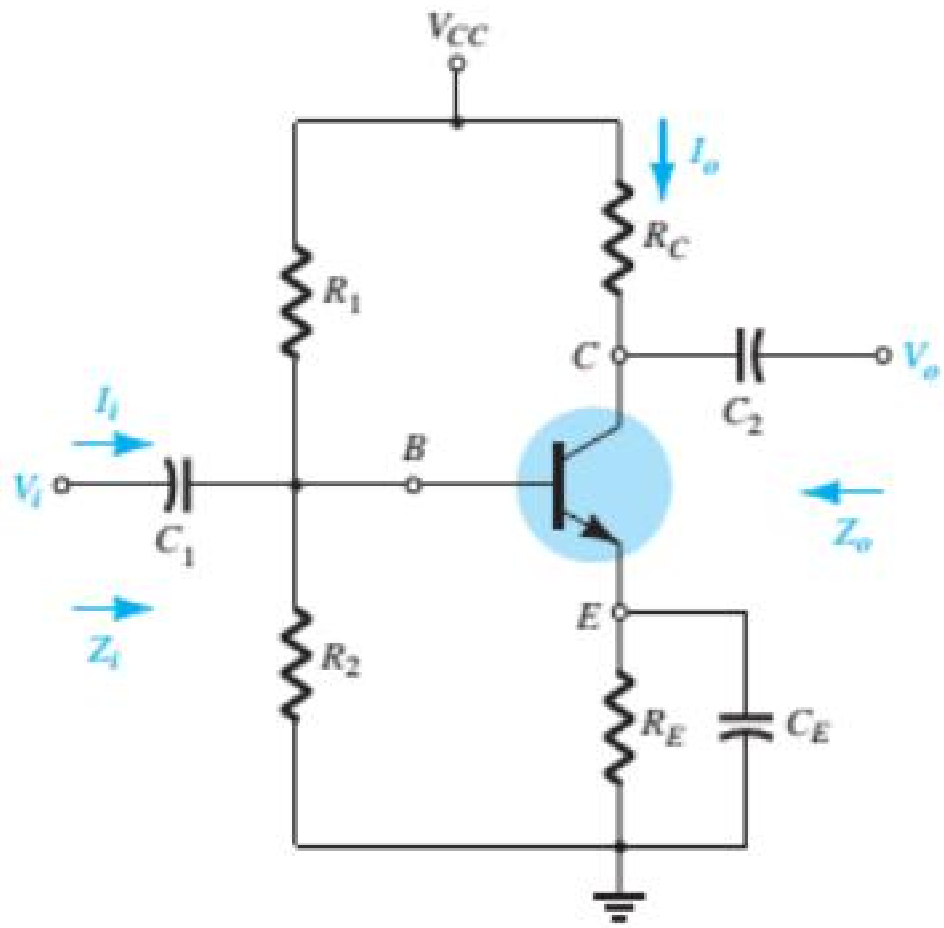

VCC
15V
VCC
Rb
56kΩ
Rc
5kΩ
1
Q1
Rs
3kΩ
2
β = 80
3
V1
BJT_NPN_VIRTUAL
2mVrms
60 Hz
0°
0



已知$V_{CEQ}=6V$,估算R_b约为多少？

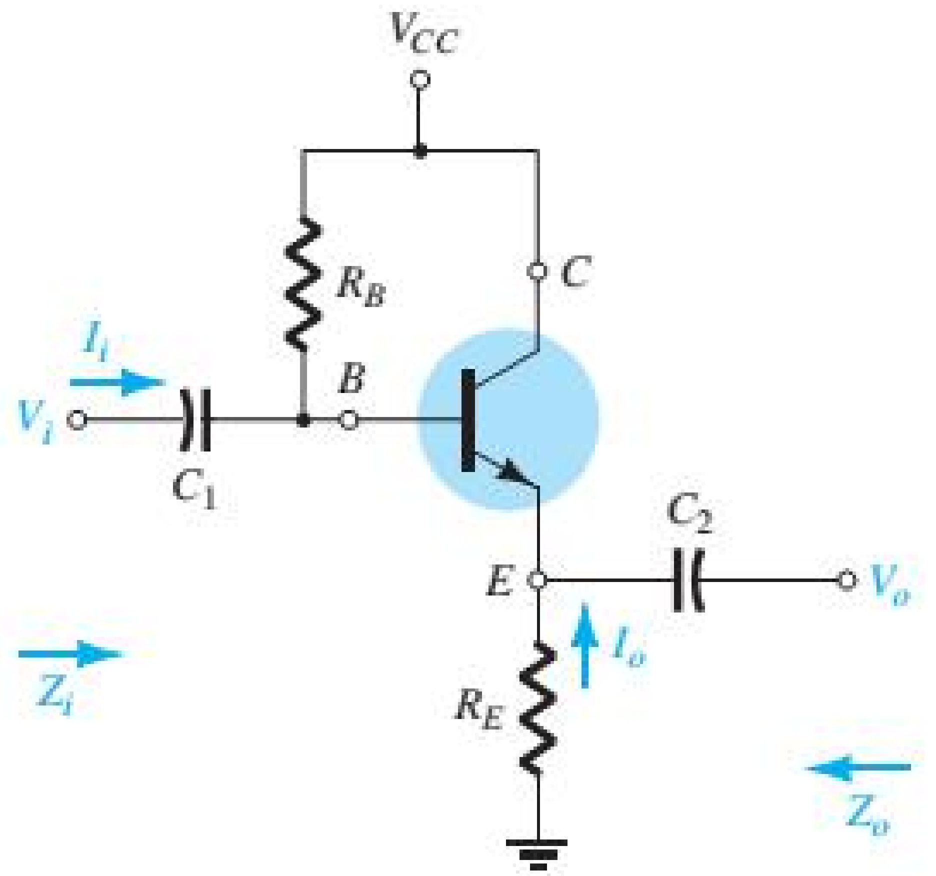
已知$A_V=100$,估算R_L约为多少？

Voltage-Divider Bias

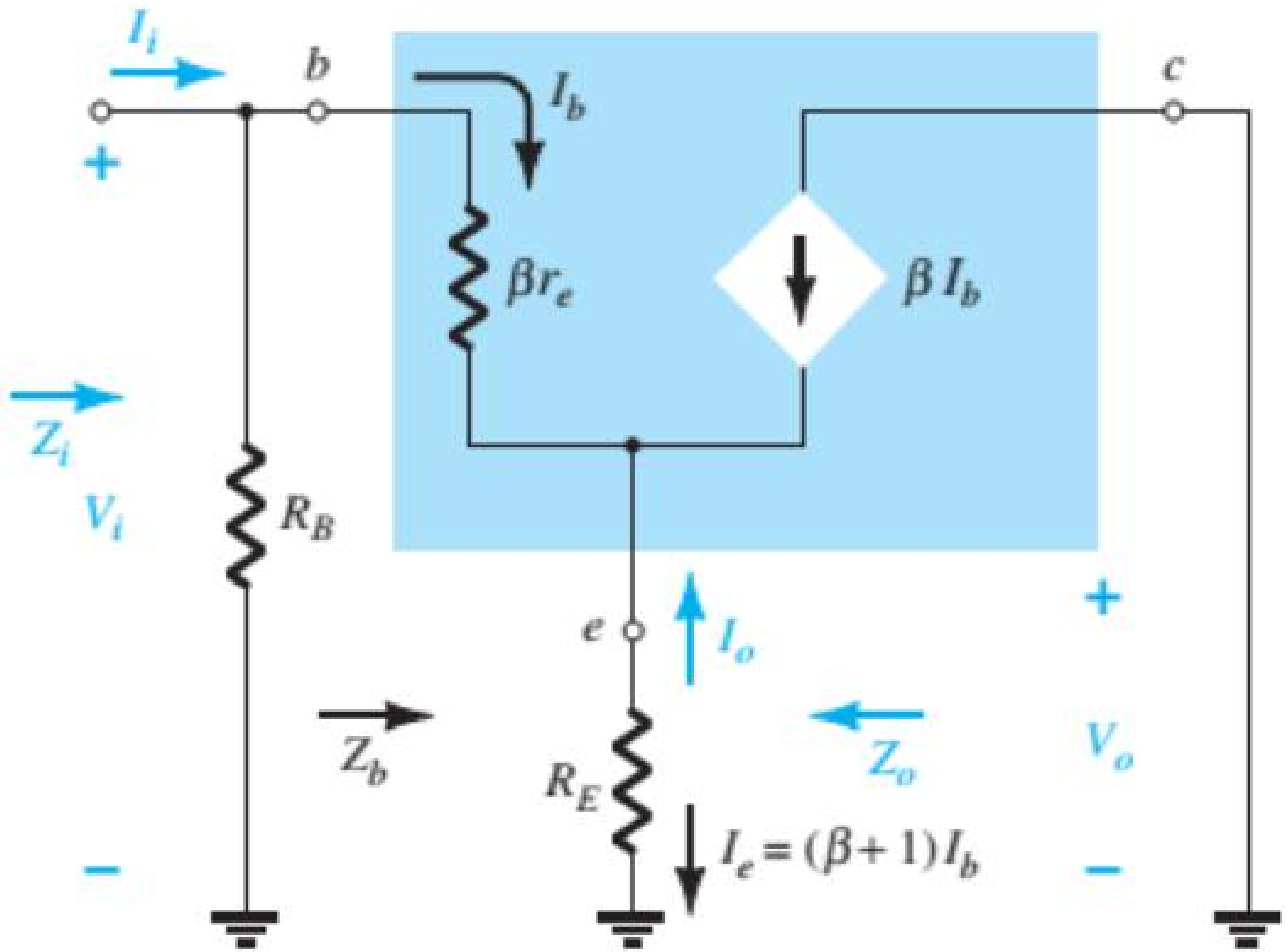


Example 5.5

Emitter-Follower Configuration



Emitter-Follower Configuration

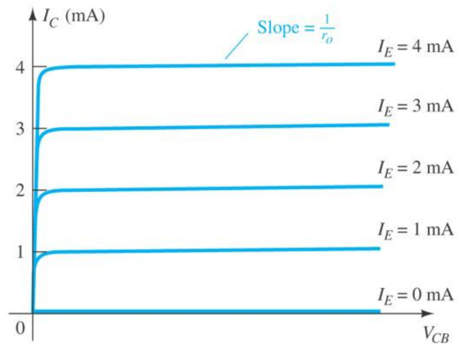


[Example]

Common-Base Configuration

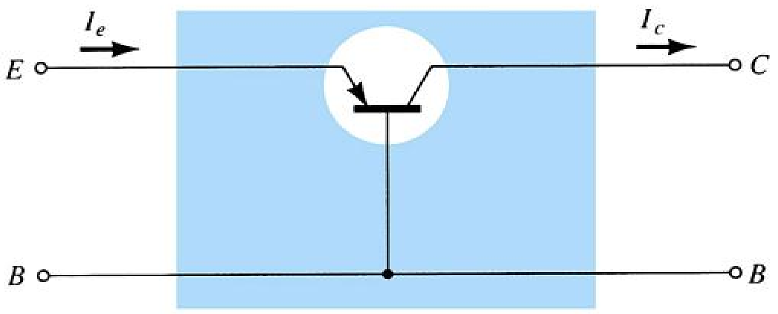
Input impedance: Low

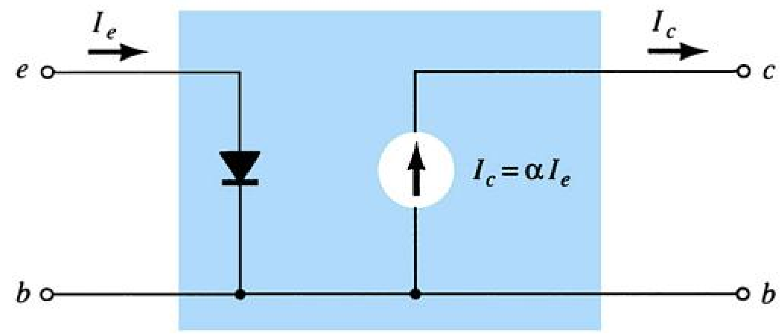
Output impedance: High



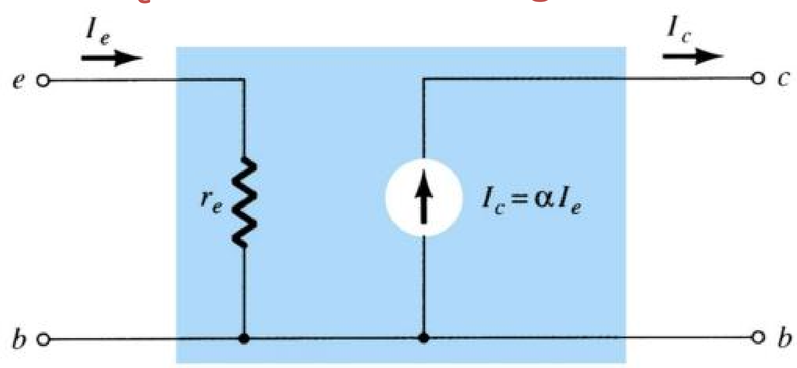
Voltage gain: voltage amplification

Current gain: No current amplification



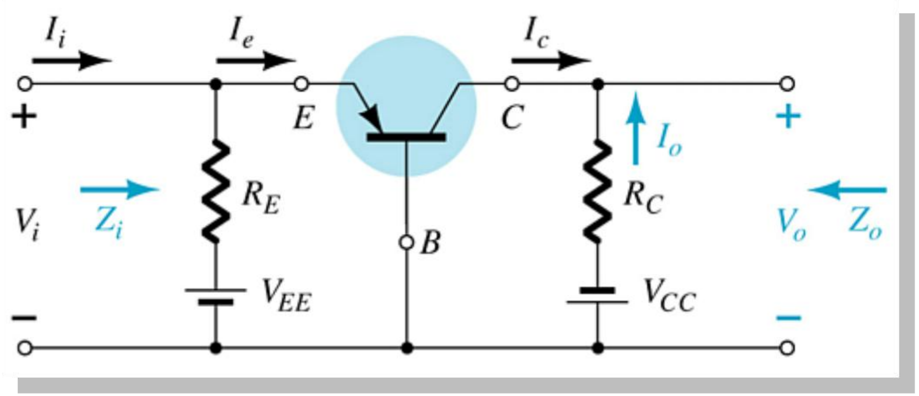


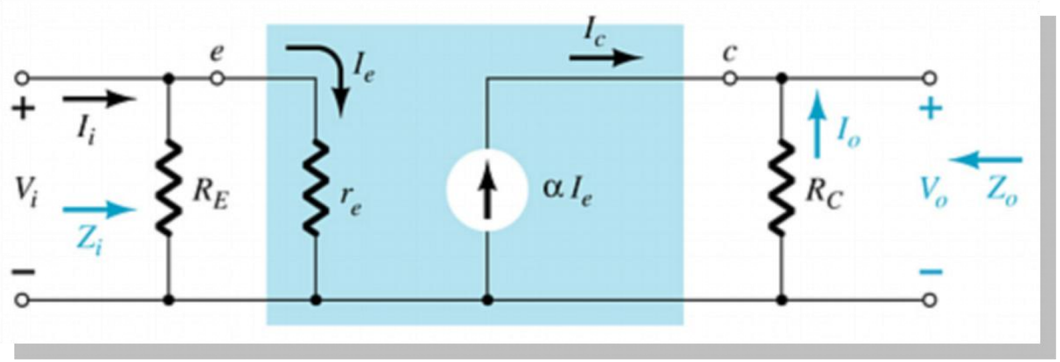
r_e model for CB configuration



Common-Base Configuration

- The input is applied to the emitter.
- The output is taken from the collector.
- Low input impedance.
- High output impedance.
- Current gain less than unity.
- Very high voltage gain.
- No phase shift between input and output.





Input impedance:

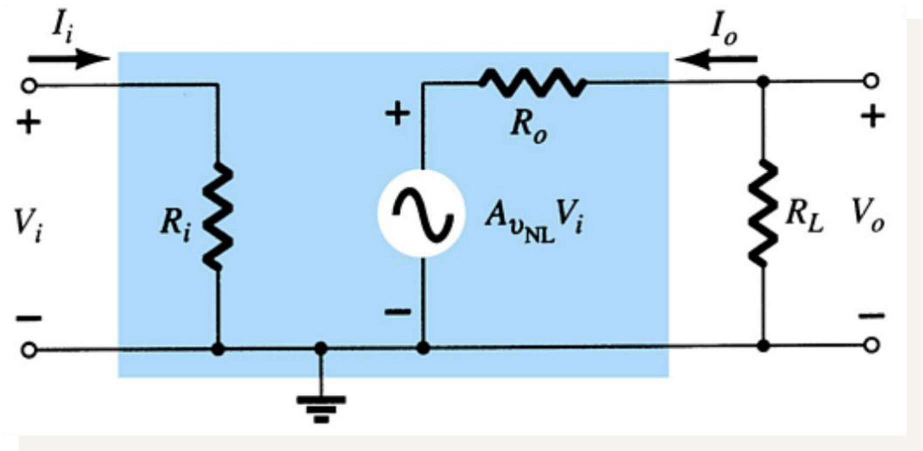
Voltage gain:

Current gain:

Output impedance:

Effect of Load Impedance on Gain

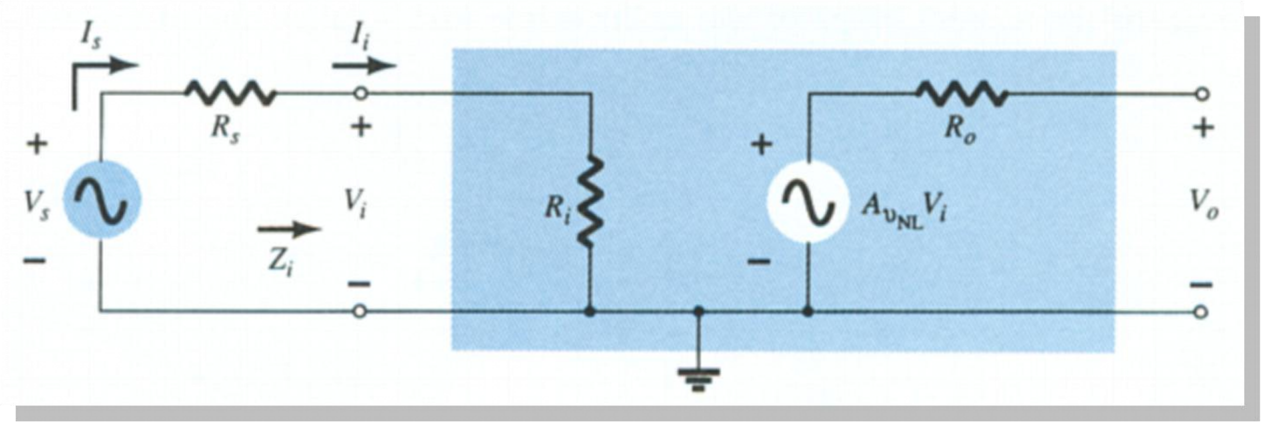
This model can be applied to any current- or voltage-controlled amplifier.



Adding a load reduces the gain of the amplifier:

Effect of Source Impedance on ain

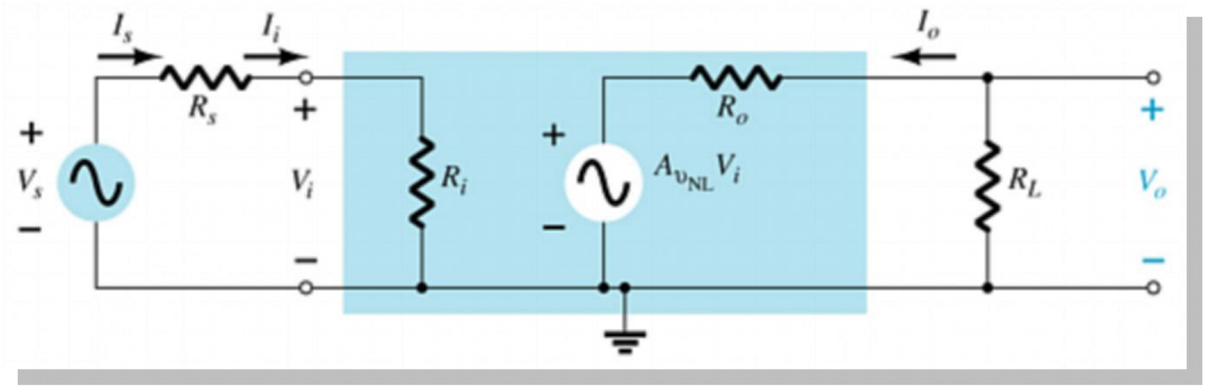
The fraction of applied signal that reaches the input of the amplifier is:



The internal resistance of the signal source reduces the overall gain:

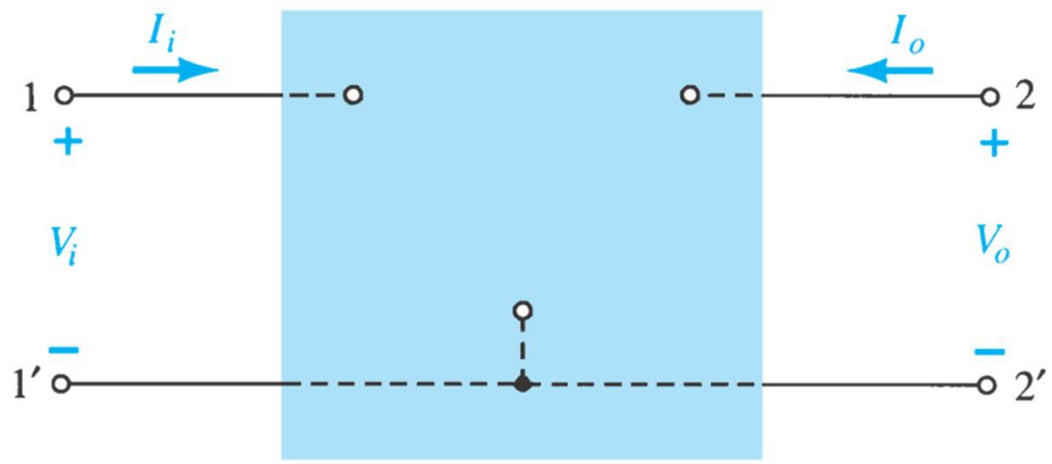
Combined Effects of R_S and R_L on Voltage Gain

Effects of R_L:



Effects of R_L and R_S:

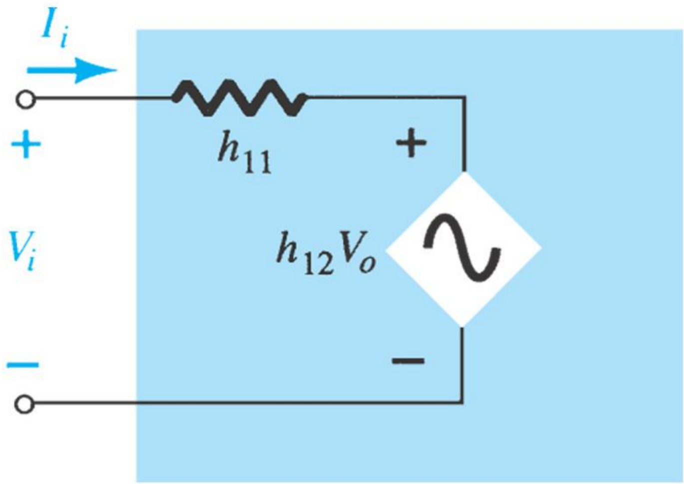
The Hybrid Equivalent Model

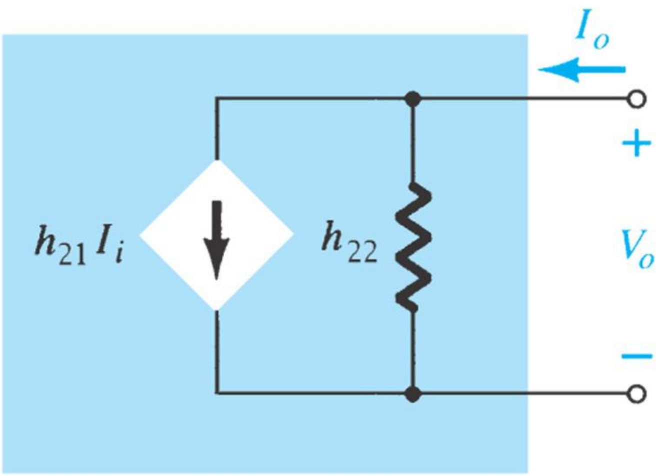


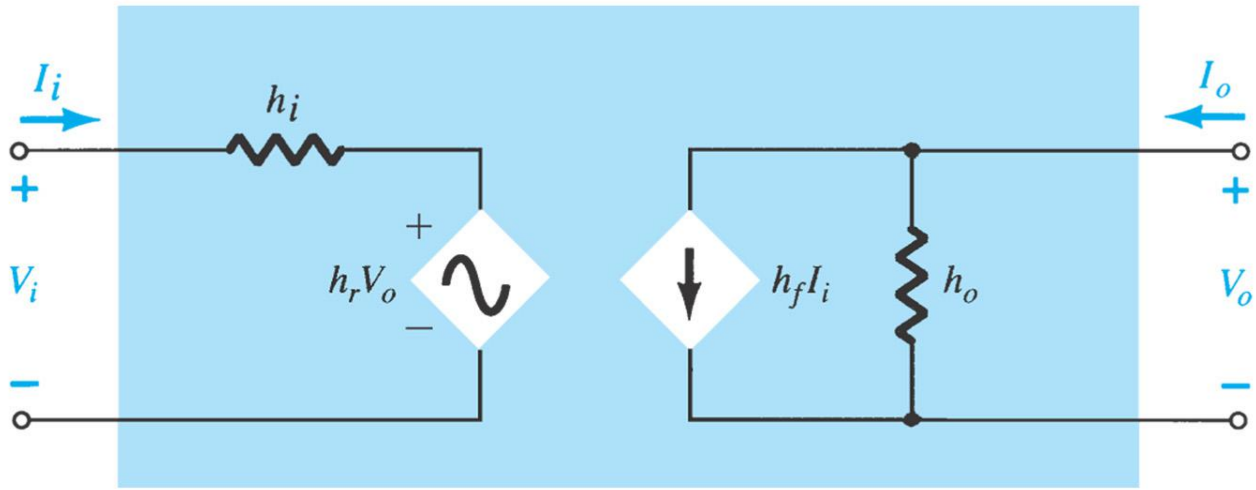
$$V_i = h_{11} I_i + h_{12} V_o$$

$$I_o = h_{21} I_i + h_{22} V_o$$

The Hybrid Equivalent Model





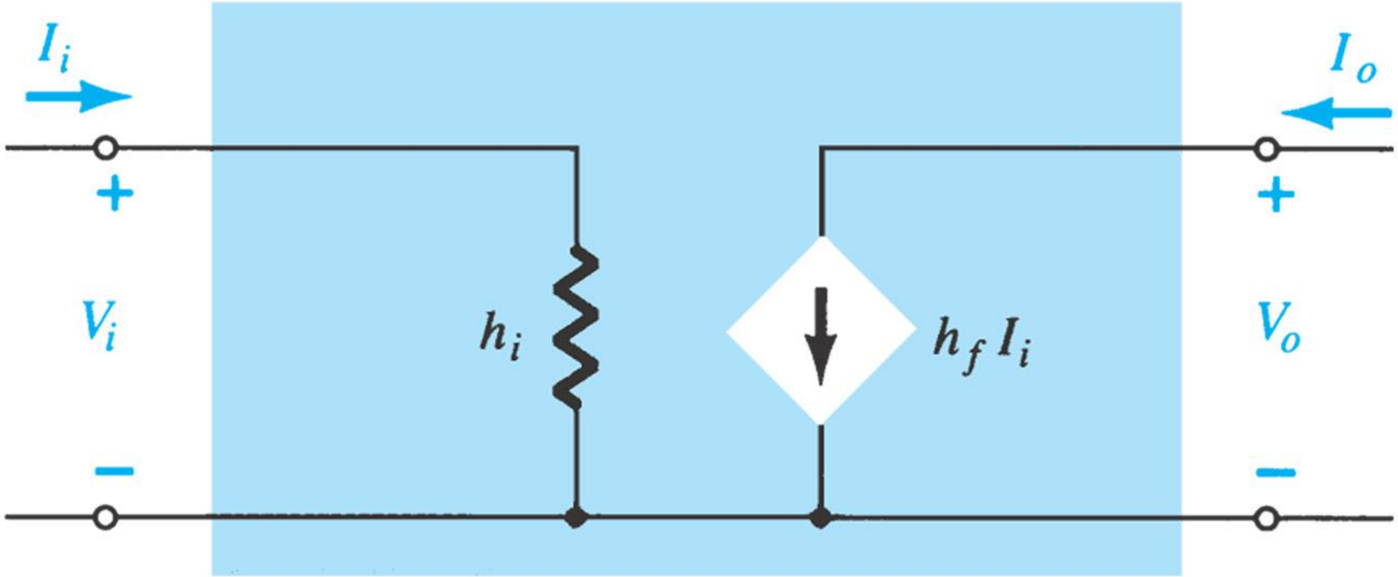


h_i = input resistance

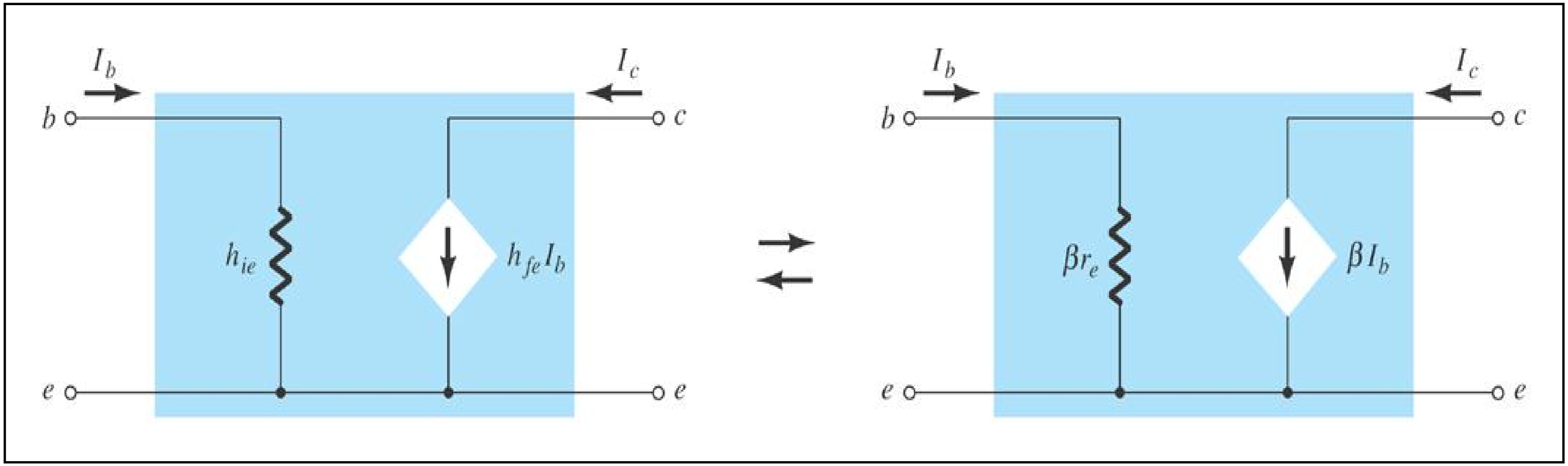
h_r = reverse transfer voltage ratio $(V_i/V_o) \cong 0$

h_f = forward transfer current ratio (I_o/I_i)

h_o = output conductance



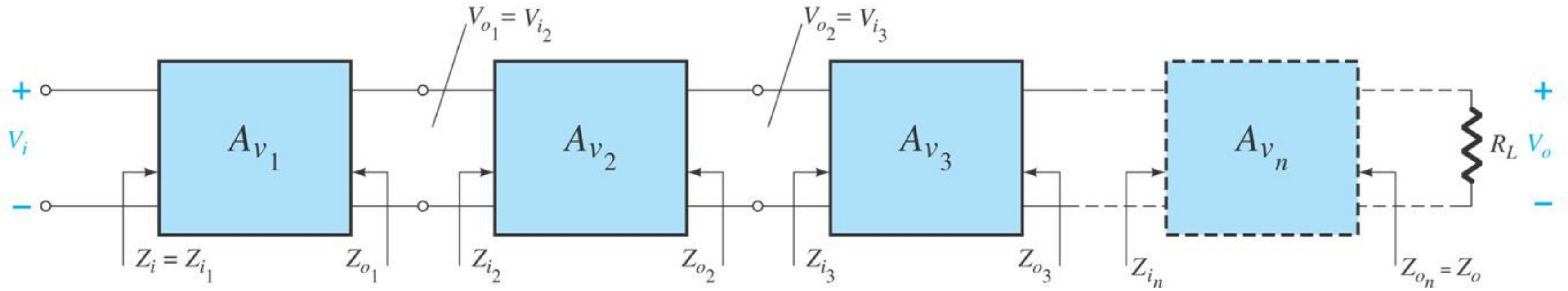
h_i = input resistance
h_f = forward transfer current ratio (I_o/I_i)



I_b
I_c
b
c
h_{ie}
$h_{fe}I_b$
e
e
I_b
I_c
b
c
βr_e
βI_b
e
e

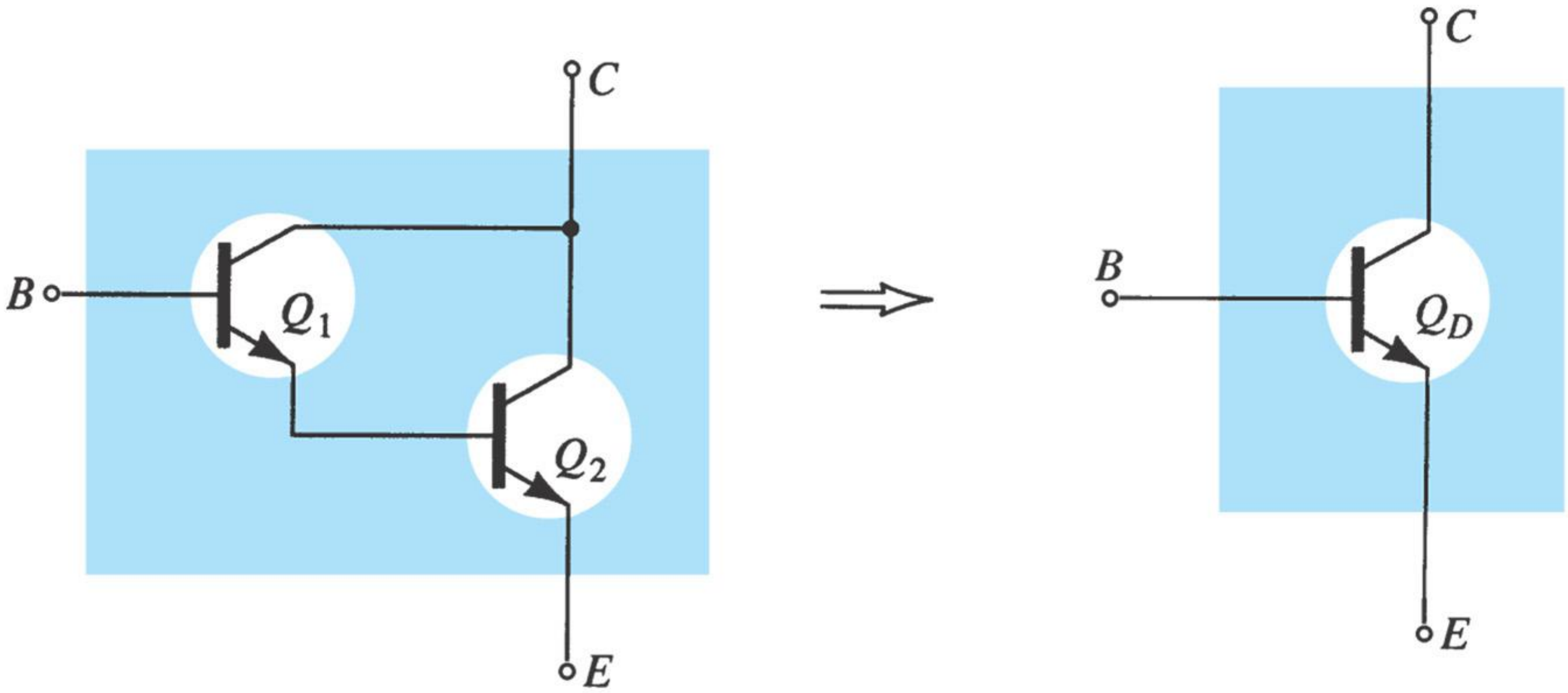
Cascaded Systems

- **The output of one amplifier is the input to the next amplifier**
- **The overall voltage gain is determined by the product of gains of the individual stages**
- **The DC bias circuits are isolated from each other by the coupling capacitors**
- **The DC calculations are independent of the cascading**
- **The AC calculations for gain and impedance are interdependent**



are loaded gains

Darlington Connection



Feedback Pair