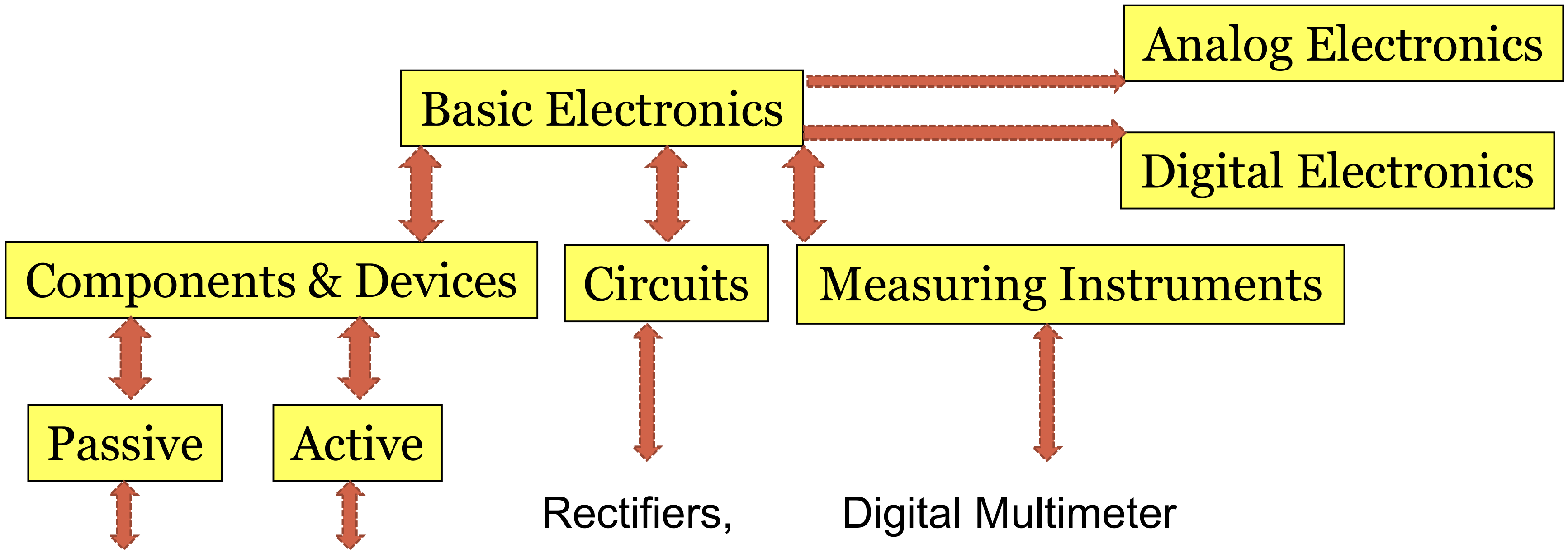
Introduction to Electronics



R
L
C

Transistor
OPAMPs

Rectifiers,
Clipper,
Clamper
Amplifiers
Filters
Oscillators

Digital Multimeter
Oscilloscopes
Function Generators

Prerequisites:

- Some basic understanding of general principles of electricity and magnetism

Books

1.	Electronic Devices and Circuit Theory	Robert L. Boylestad and Louis Nashelsky, Pearson Education
2.	Electronic Instrumentation	H.S. Kalsi, Tata McGraw-Hill Publishing Company Limited

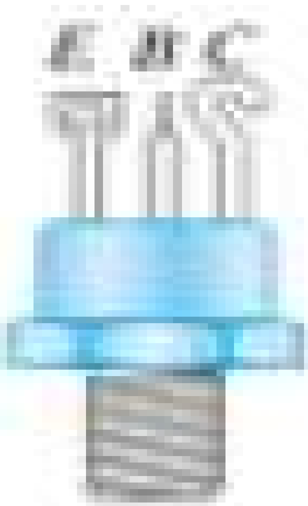
input signal i/p

o/p

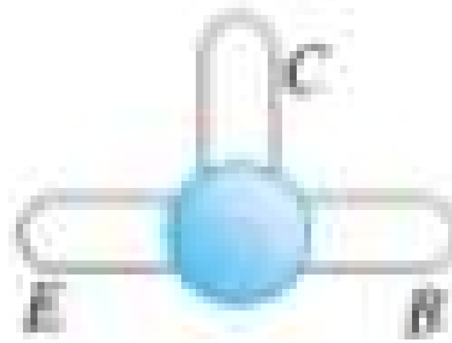
Transistor DC Biasing

#LECTURE -1

- INTRODUCTION
- FIXED BIASING METHOD
- EMITTER STABILIZED BIASING METHOD
- VOLTAGE DIVIDER BIASING METHOD
- FEEDBACK RESISTOR BIASING METHOD


E B C


White
dot

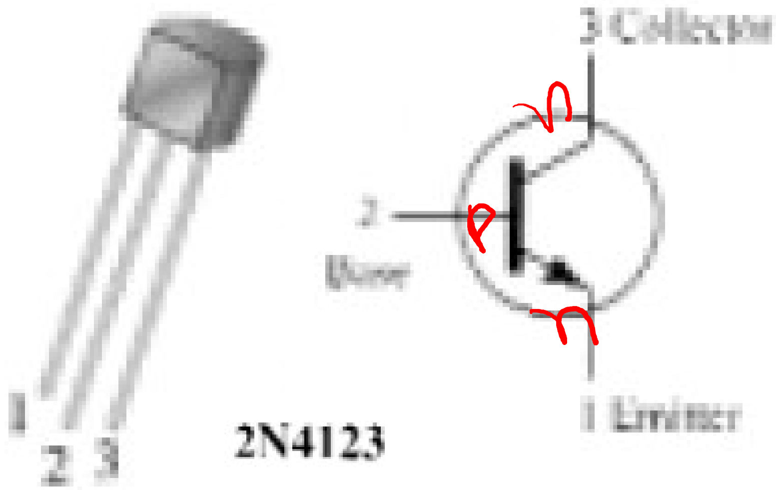

C
E
B


E
B
C


E B C

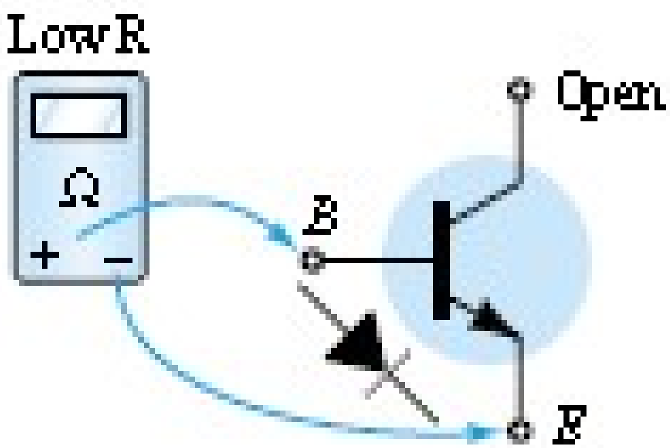

C
E

$I_E = I_B + I_C$

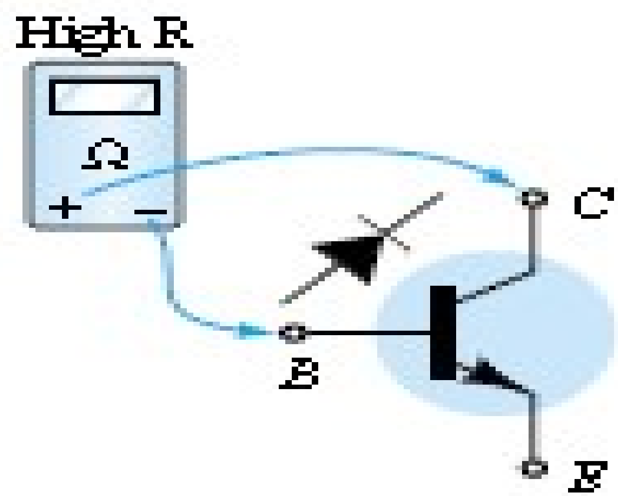


Fairchild Semiconductor

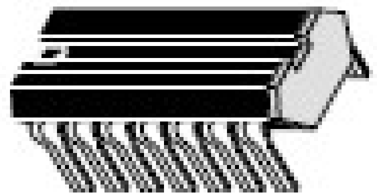
$$I_{CEO} \leq I_C \leq I_{C_{max}}$$
$$V_{CE_{sat}} \leq V_{CE} \leq V_{CE_{max}}$$
$$V_{CE} I_C \leq P_{C_{max}}$$

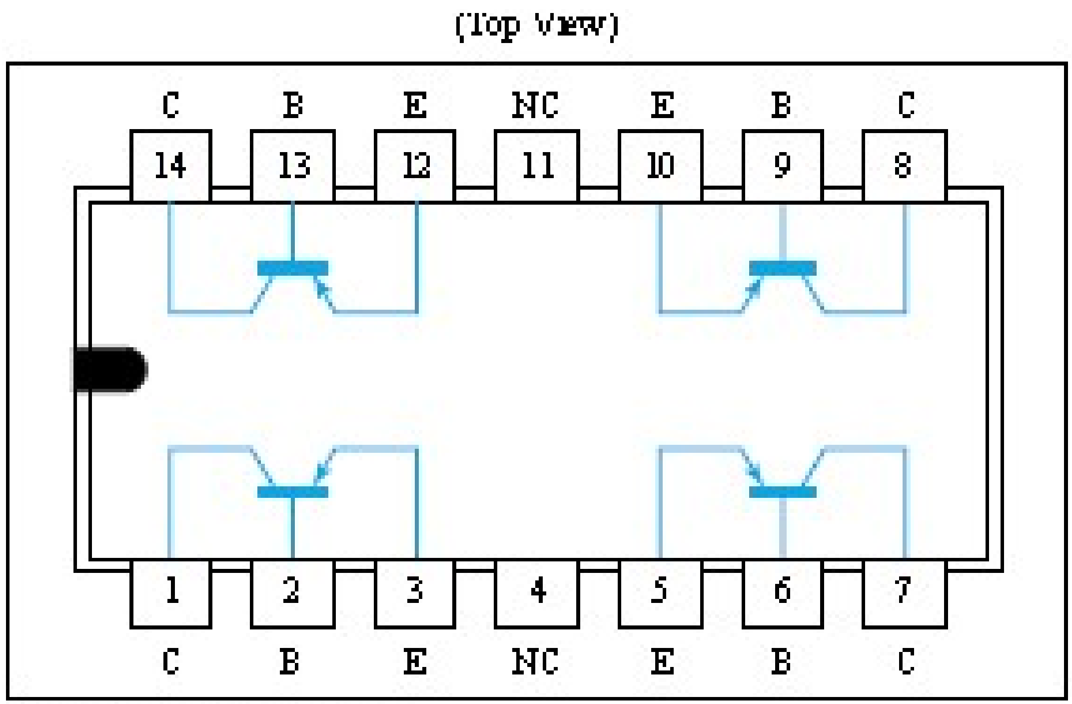


Checking the forward-biased base-to-emitter junction of an npn transistor



Checking the reverse-biased base-to collector junction of an npn transistor.





NC – No internal connection

Type Q2T2905 Texas Instruments quad *pnp silicon transistors*

Dr. Shockley [C] [UK]-1910, PhD, Harvard [1936]

Dr. Bardeen B [L] [Wisconsin]-1908, PhD Princeton, 1936

Dr. Brattain [C] [China]-1902, PhD University of Minnesota, 1928

All shared the Nobel Prize in 1956 for this contribution

INTRODUCTION

- Technology:
    - Vacuum tube type
    - Solid state type
- Vacuum Diode [1904]: Two electrodes-anode and cathode: by J A Fleming
- Triode: [1906]: Three electrodes: anode, cathode, control grid by L D Forest
- Tetrode [1920]: A, C, control grid, screen grid
- Pentode [1926]: A, C, control grid, screen grid, suppressor grid by Holst, Bernhard
- Production rose from about 1 million tubes in 1922 to about 100 million in 1937
- On December 23, 1947, however, the electronics industry was to experience the advent of a completely new direction of interest and development.
- It was on the afternoon of this day that Dr. S. William Shockley, Walter H. Brattain, and John Bardeen demonstrated the amplifying action of the first transistor at the Bell Telephone Laboratories.

Advantages of Solid State Technology over Tube Technology

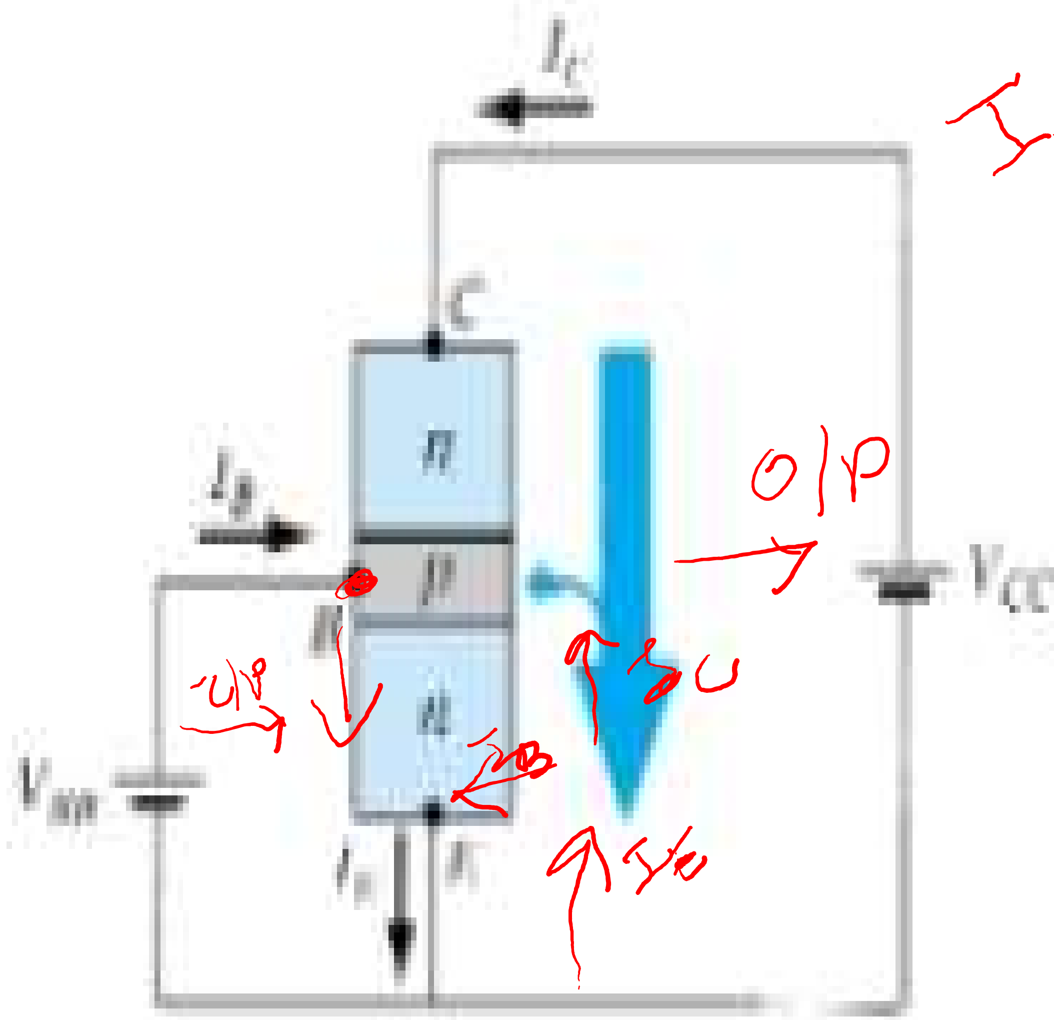
- Smaller and lightweight
- No heater requirement or heater loss;
- More efficient since less power was absorbed by the device itself;
- Instantly available for use,
- Requiring no warm-up period [eliminating delay)
- can be manufactured as a single integrated circuit;
- low operating voltages compatible with batteries of only a few cells;
- inherent reliability and very long life;
- providing design flexibility, not possible with vacuum tubes
- very low sensitivity to mechanical shock and vibration,
- not susceptible to breakage of a glass envelope, leakage, and other physical damage.

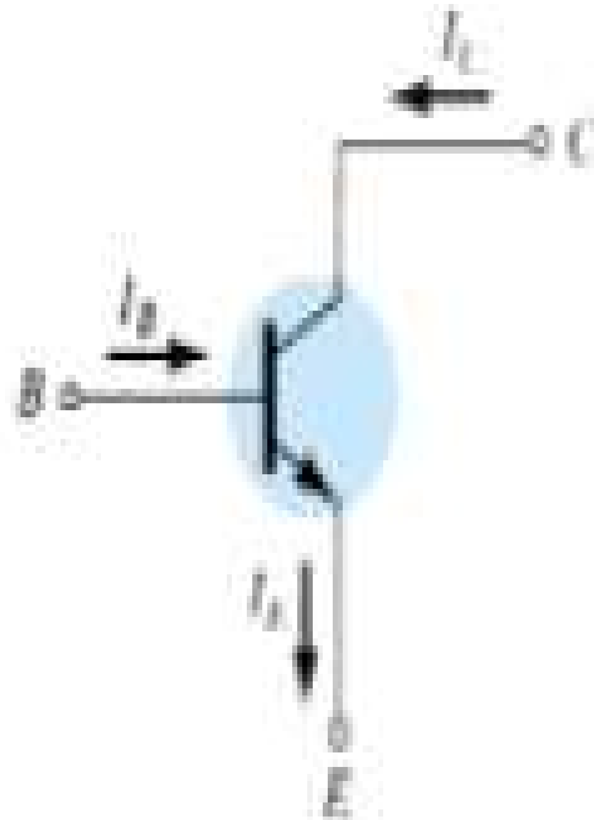
Types: Transistors are categorized by

- **Semiconductor material**: Ge (first used in 1947), Si (first used in 1954), GaAs (1966), SiC (1997), the alloy silicon-germanium (1989), the allotrope of carbon graphene
- **Structure**: BJT, FET: IGFET (MOSFET),
- **Electrical polarity** (positive and negative): n–p–n, p–n–p (BJTs), n-channel, p-channel (FETs);
- **Maximum power rating**: low, medium, high;
- **Maximum operating frequency**: low, medium, high, radio (RF), microwave frequency.
- **Application**: switch, amplifiers;
- **Physical packaging**: through-hole metal, through-hole plastic, surface mount, ball grid array, power modules
- **Amplification factor** : h_{FE}, β or g_m (transconductance).

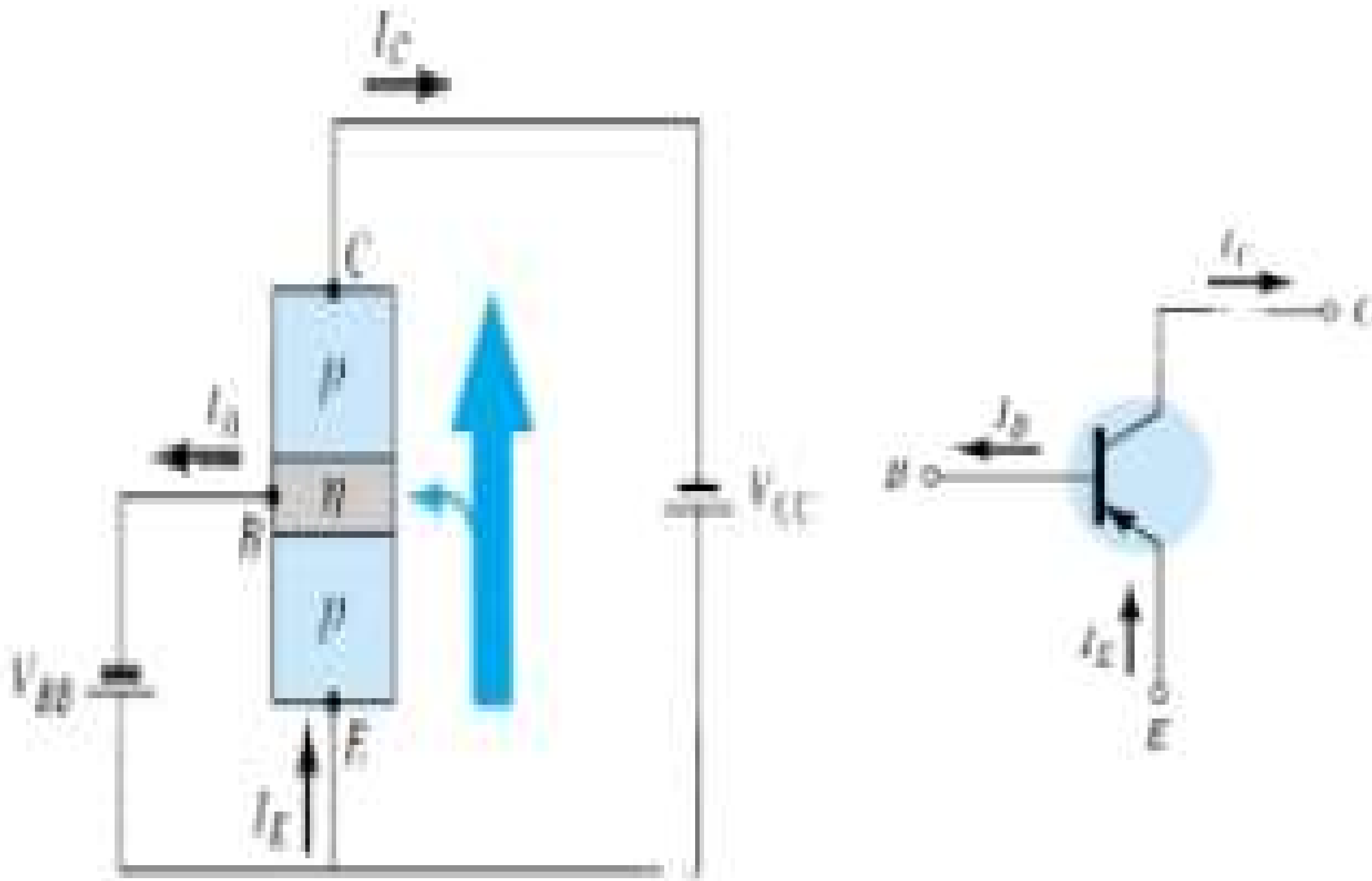
Configurations: CE

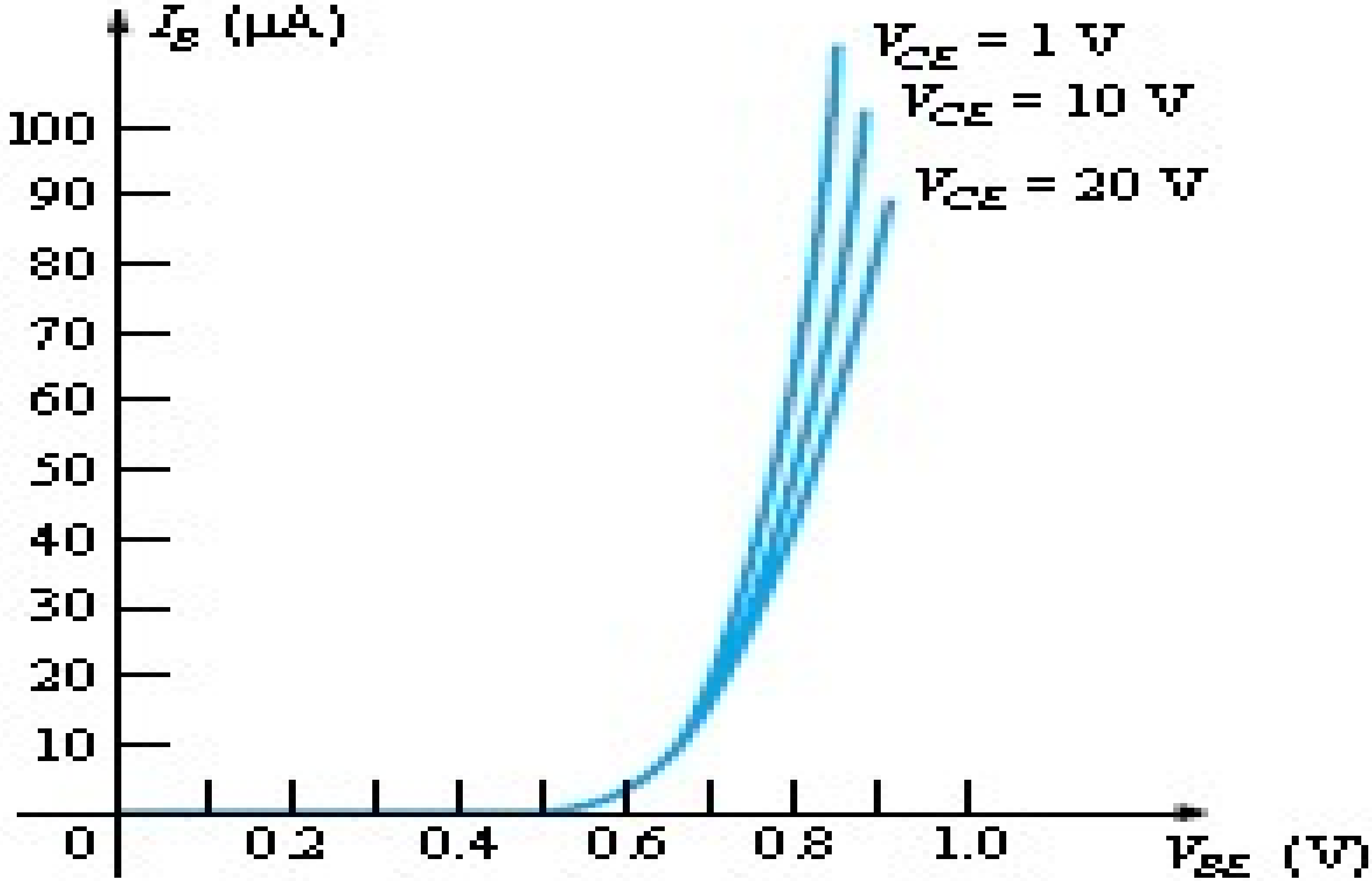
$I_E = I_B + I_C$



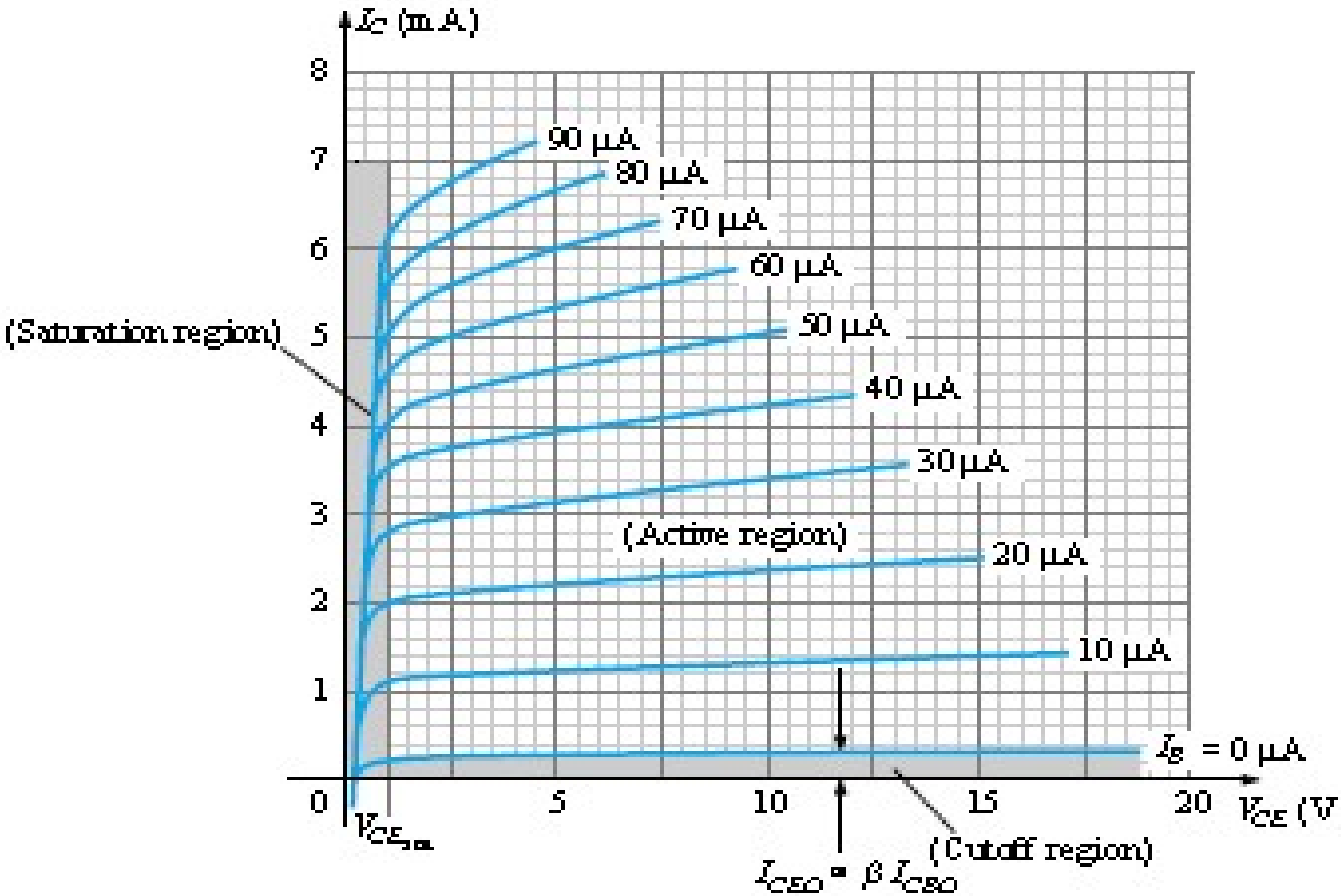


$I_E = I_B + I_C$





Input or driving point characteristics for a CE silicon transistor amplifier



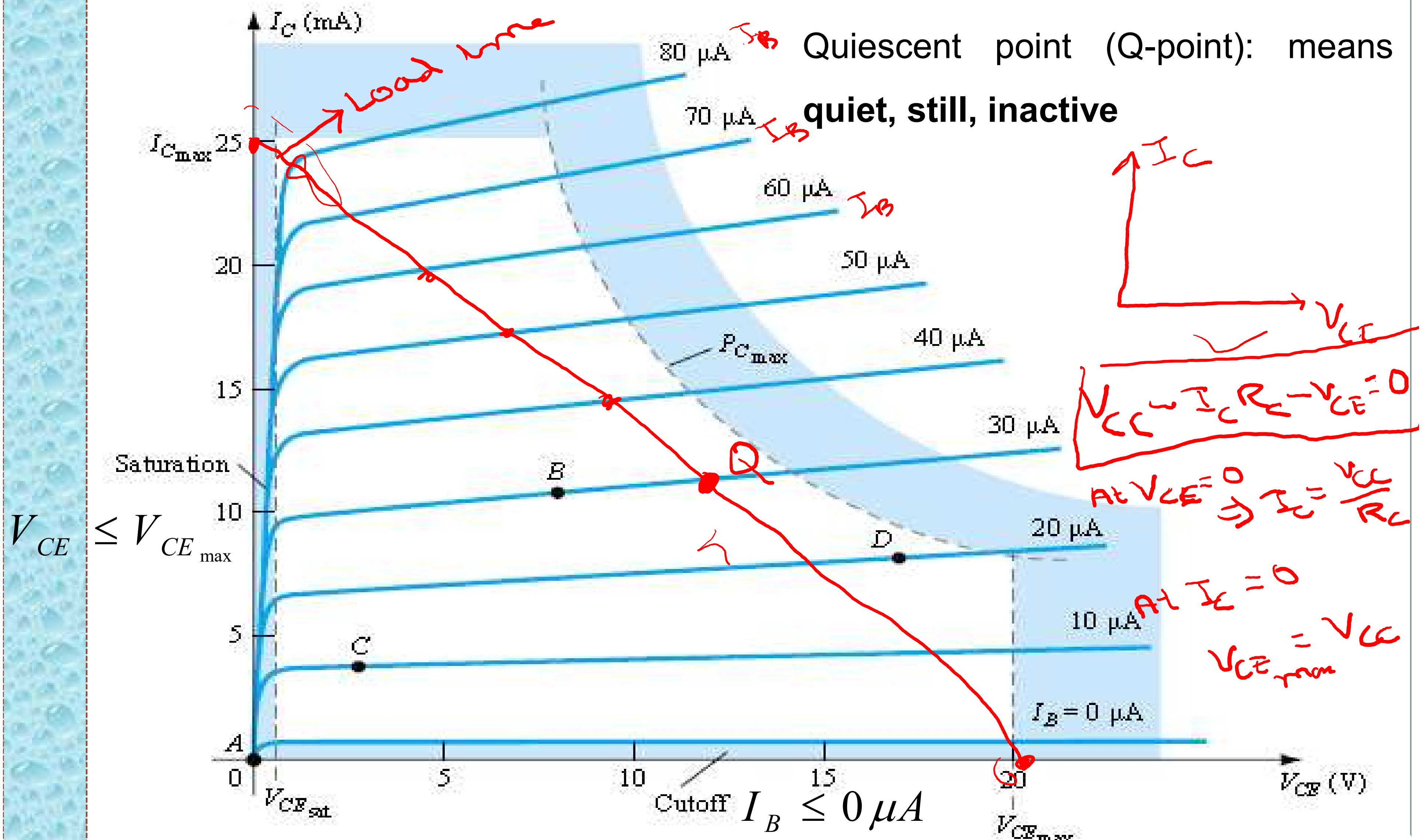
Output or collector characteristics for a **CE** amplifier

$$\beta_{dc} = \frac{I_C}{I_B}$$

$$\beta_{ac} = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE} = \text{constant}}$$

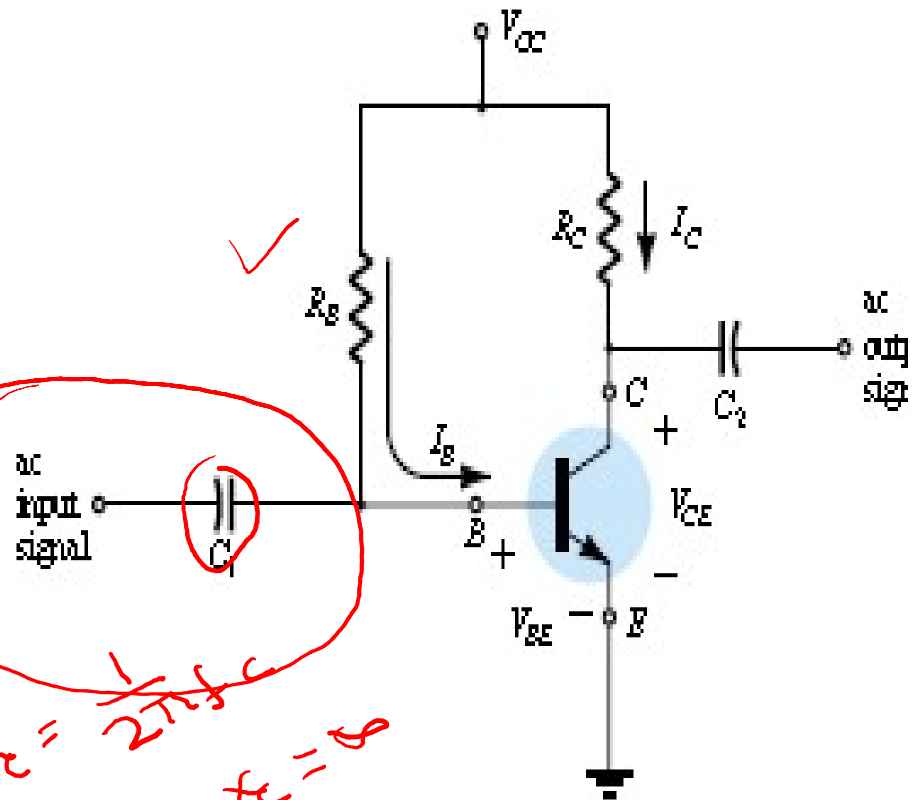
INTRODUCTION: Operating Point

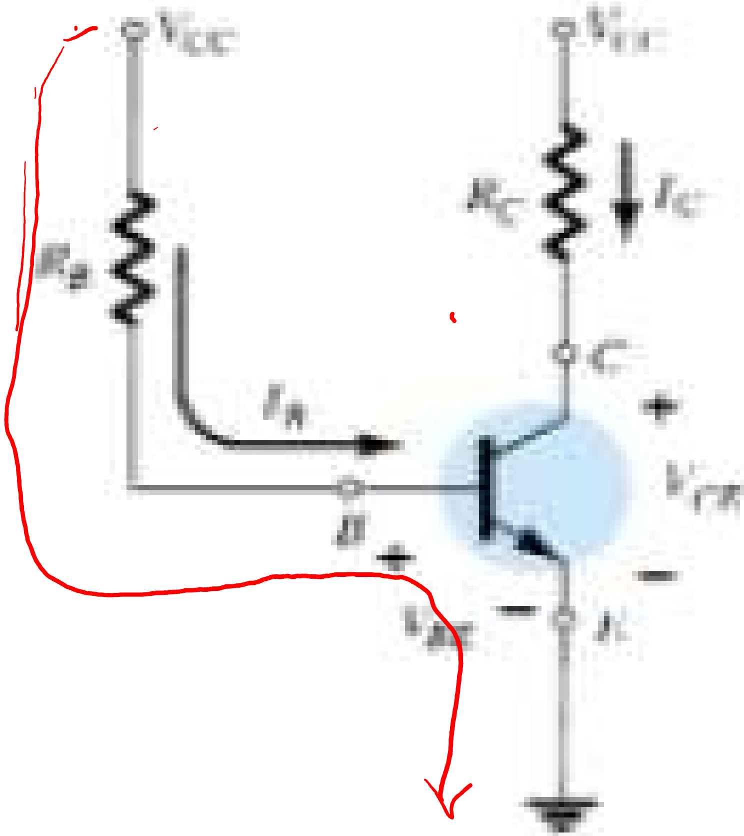
Quiescent point (Q-point): means **quiet, still, inactive**



Various operating points within the limits of operation of a transistor

Base Resister Method





$X_C = \frac{1}{2\pi f C}$

$f = 0$, $X_C = \infty$

$I_B = I_C/\beta$

V_o

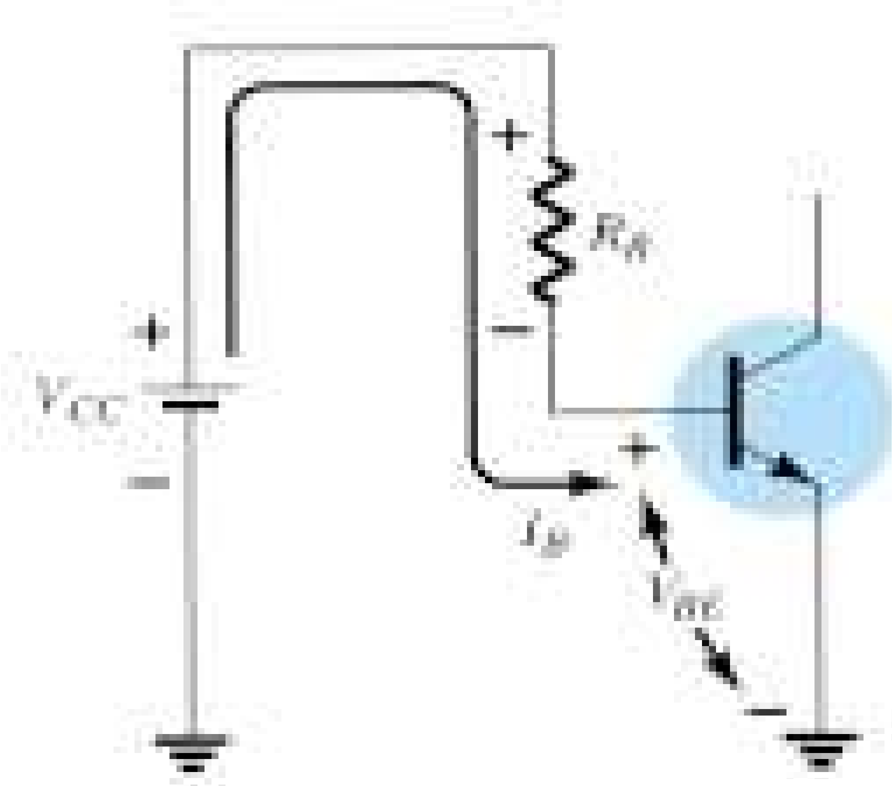
I_{CQ}

V_{CEQ}

V_{CC} is connected directly to R_B and R_C

A high resistance R_B is connected base and V_{CC}.

Forward Bias of Base–Emitter



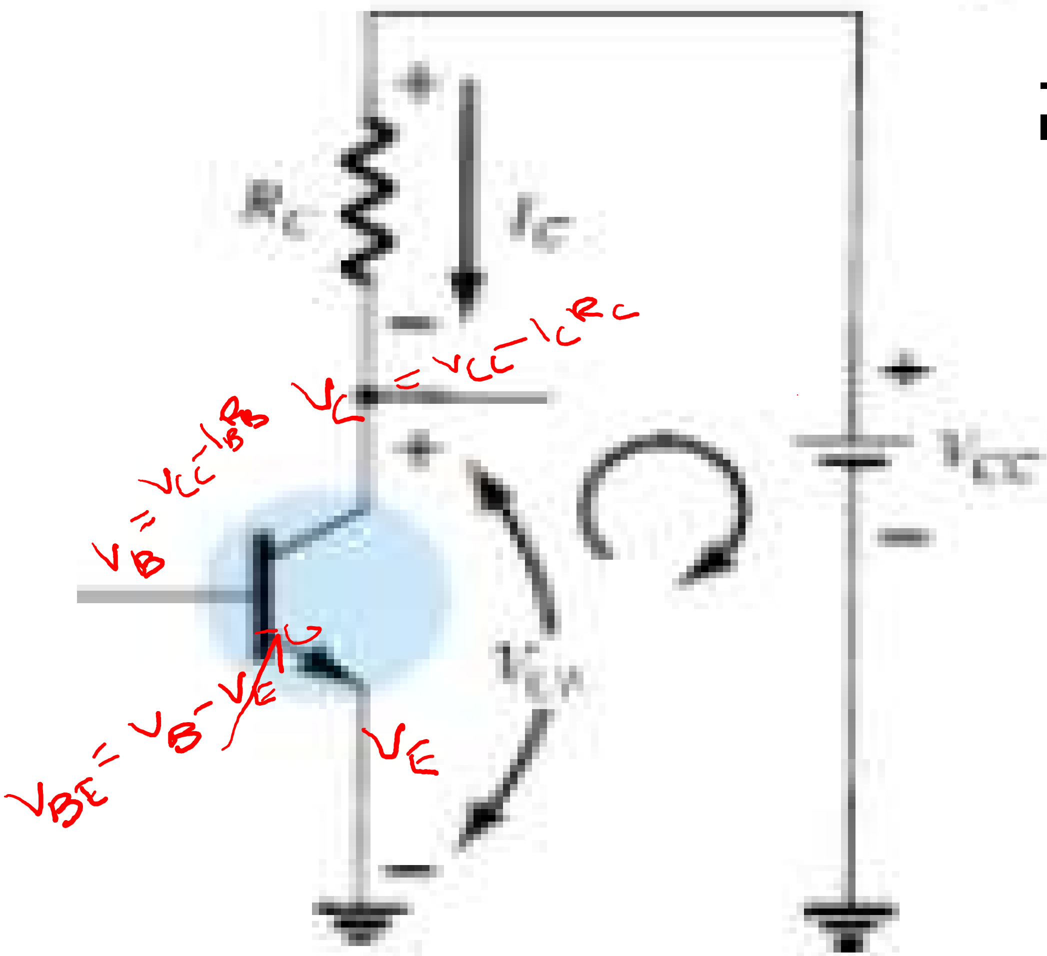
Base–Emitter Loop

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

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

Forward Bias of Collector - Emitter

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

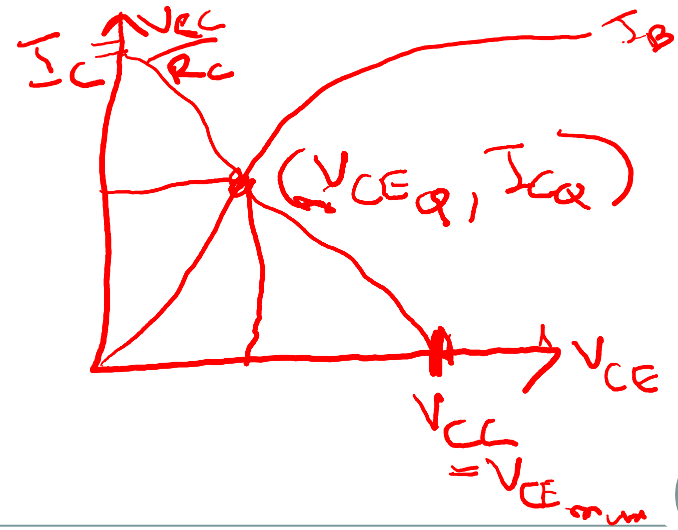


Collector–Emitter Loop

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

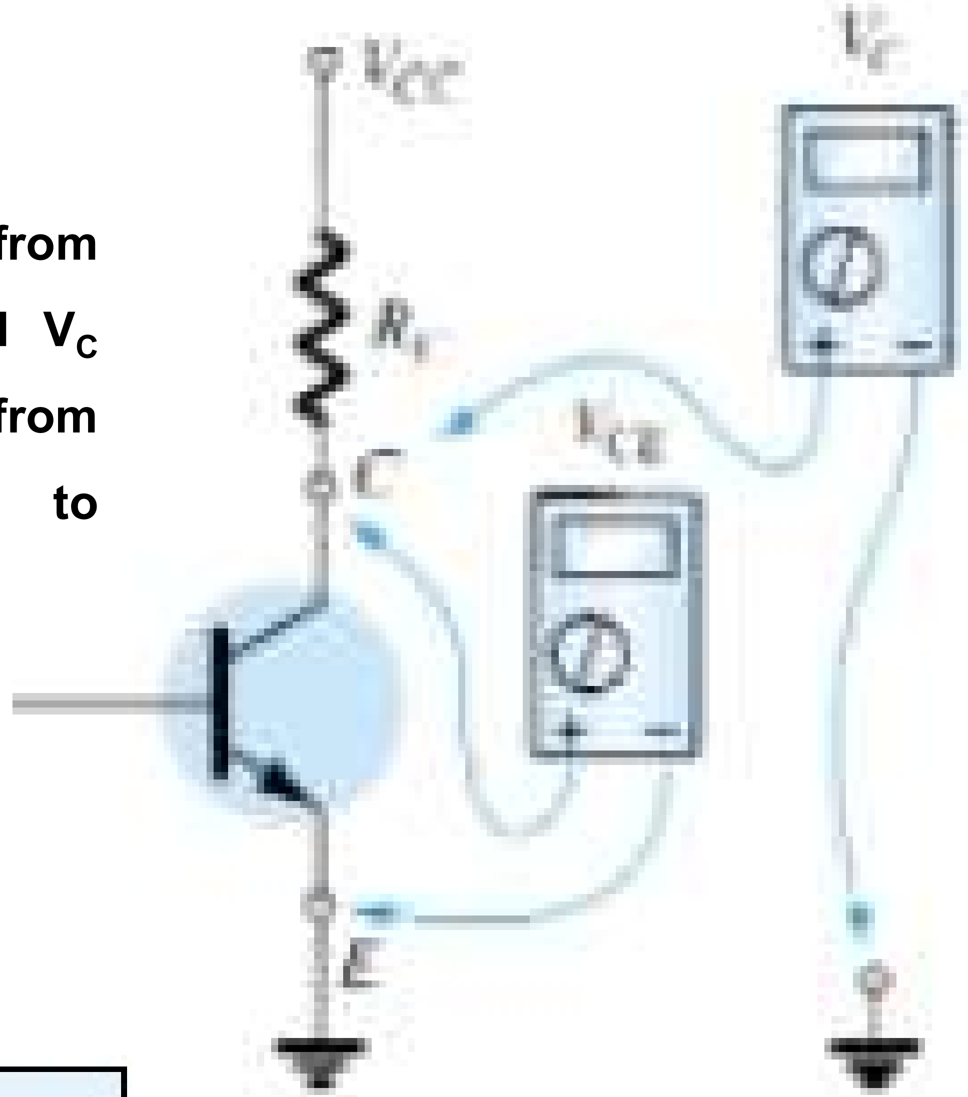
$$\boxed{V_{CE} = V_{CC} - I_C R_C}$$

$$\boxed{I_C = \beta I_B}$$



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

where V_{CE} is the voltage from collector to emitter and V_C and V_E are the voltages from collector and emitter to ground respectively

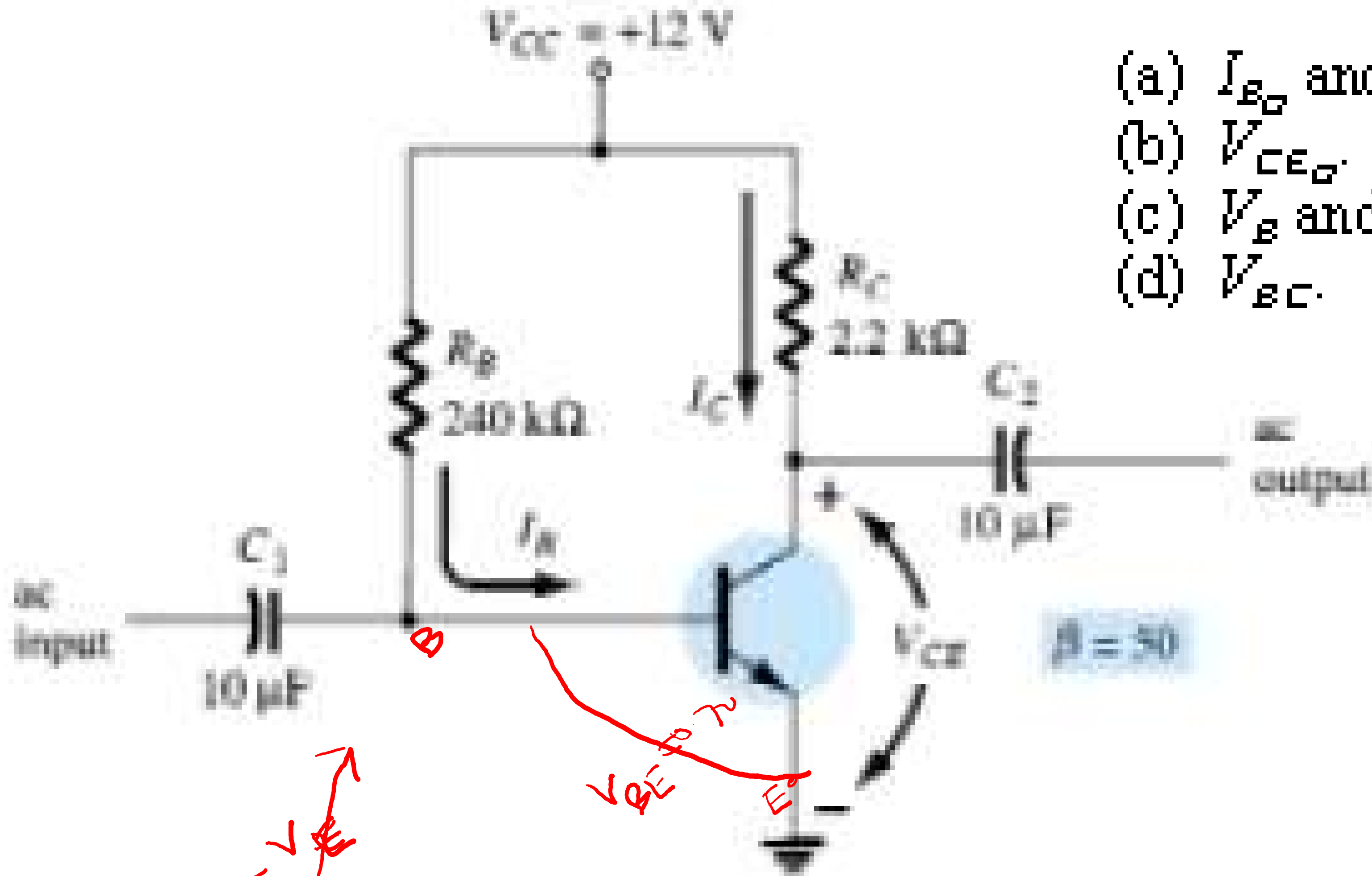


since V_E = 0 V

$$V_{CE} = V_C$$

$$V_{BE} = V_B - V_E$$

$$V_{BE} = V_B$$



(a) I_{B_Q} and I_{C_Q}.
(b) V_{CE_Q}.
(c) V_B and V_C.
(d) V_{BC}.

$V_{BE} = V_B - V_E$

$V_B = V_{BE}$

$$I_{B_Q} = \frac{V_{CC} - V_{BE}}{R_B} = \frac{12\text{ V} - 0.7\text{ V}}{240\text{ k}\Omega} = \mathbf{47.08\ \mu A}$$

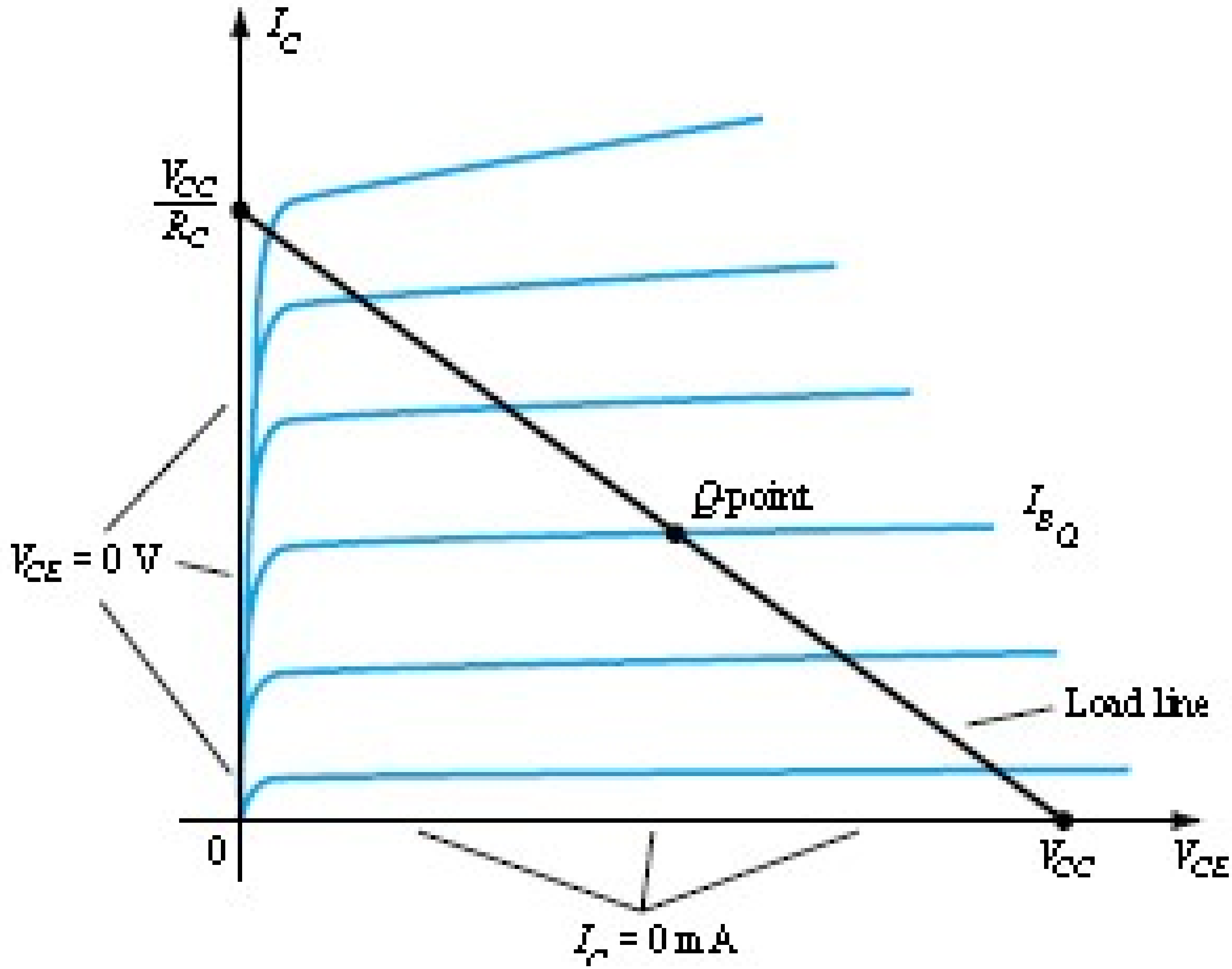
$$I_{C_Q} = \beta I_{B_Q} = (50)(47.08\ \mu\text{A}) = \mathbf{2.35\ mA}$$

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

$$= 12\text{ V} - (2.35\text{ mA})(2.2\text{ k}\Omega) = \mathbf{6.83\ V}$$

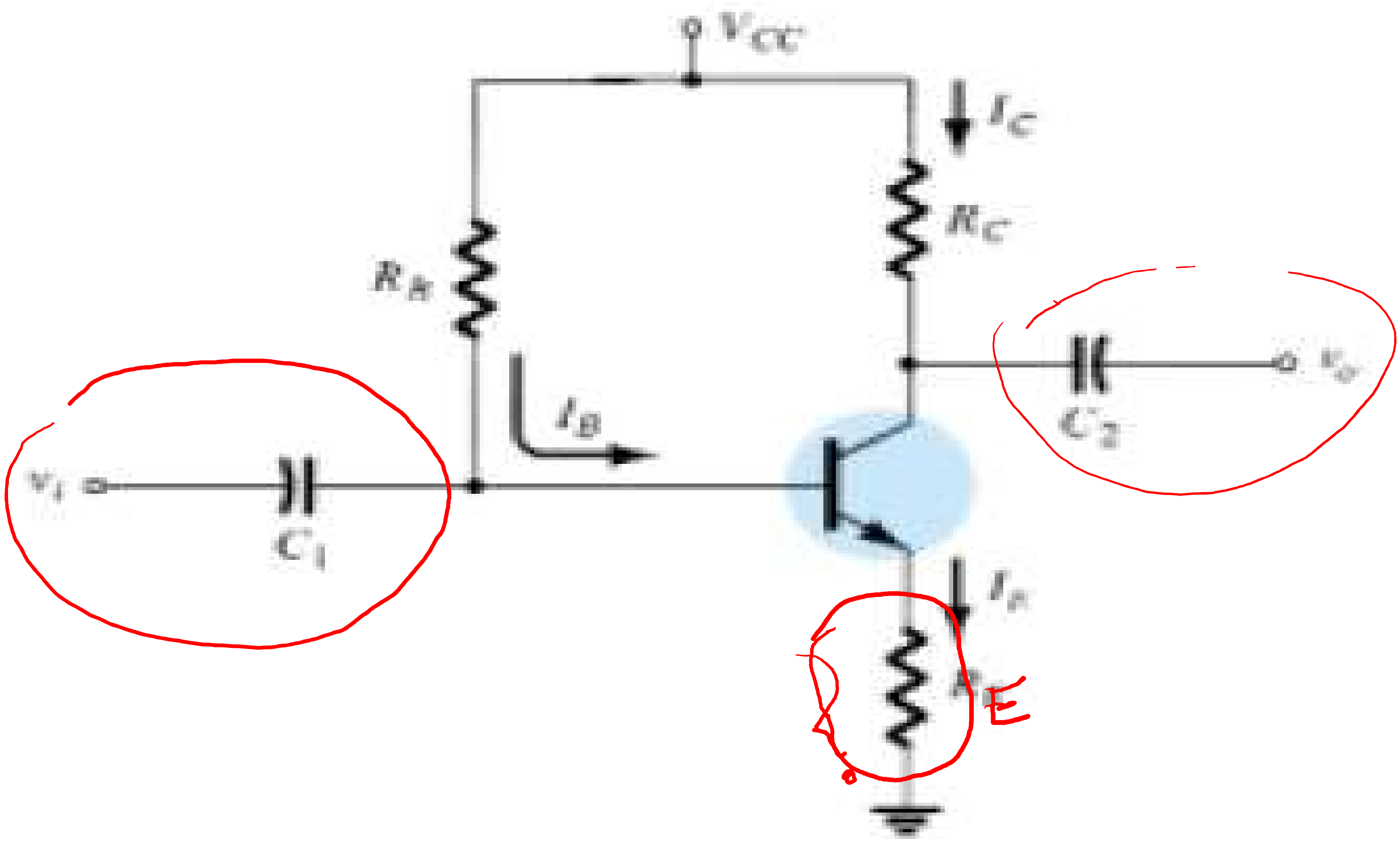
$$V_B = V_{BE} = \mathbf{0.7\ V} \qquad V_C = V_{CE} = \mathbf{6.83\ V}$$

$$V_{BC} = V_B - V_C = 0.7\text{ V} - 6.83\text{ V} = \mathbf{-6.13\ V}$$



I_C
$\frac{V_{CC}}{R_C}$
Q-point
I_{B_Q}
$V_{CE} = 0$ V
Load line
0
V_{CC}
V_{CE}
$I_C = 0$ mA

Emitter Stabilized Bias Method

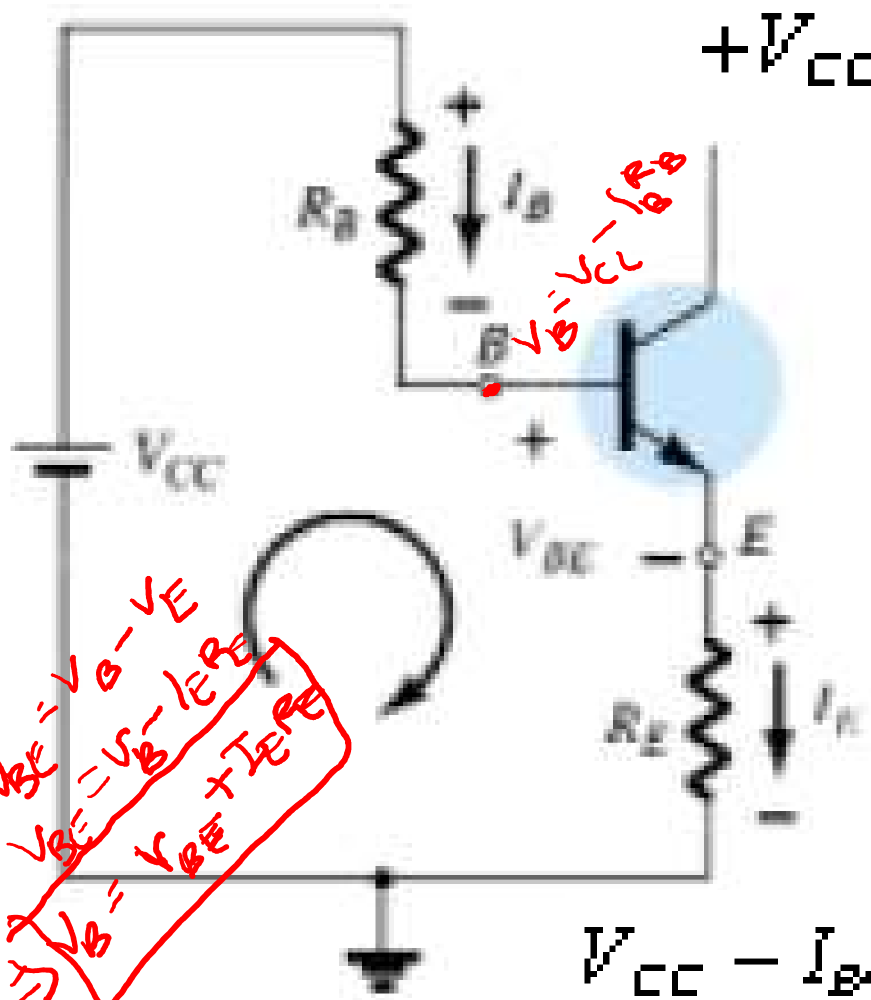


To improve the stability level over that of the fixed-bias configuration

A emitter resistor R_E is connected between Emitter and Ground.

Base–Emitter loop → I_B

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



$V_B = V_{CC} - I_B R_B$

$V_{BE} = V_B - V_E$

$V_{BE} = V_B - I_E R_E$

$\Rightarrow V_B = V_{BE} + I_E R_E$

Base–Emitter Loop

$$V_{CC} - I_B R_B - V_{BE} - (\beta + 1) I_B R_E = 0$$

$I_B + I_C = I_E = (\beta + 1) I_B$ → BJB

$S \simeq \dfrac{\partial I_C}{\partial I_{CO}}$ $\quad S \propto \dfrac{1}{I_{CO}}$ $\quad I_B = \dfrac{V}{R}$

$$-I_B(R_B + (\beta + 1)R_E) + V_{CC} - V_{BE} = 0$$

$$I_B(R_B + (\beta + 1)R_E) - V_{CC} + V_{BE} = 0$$

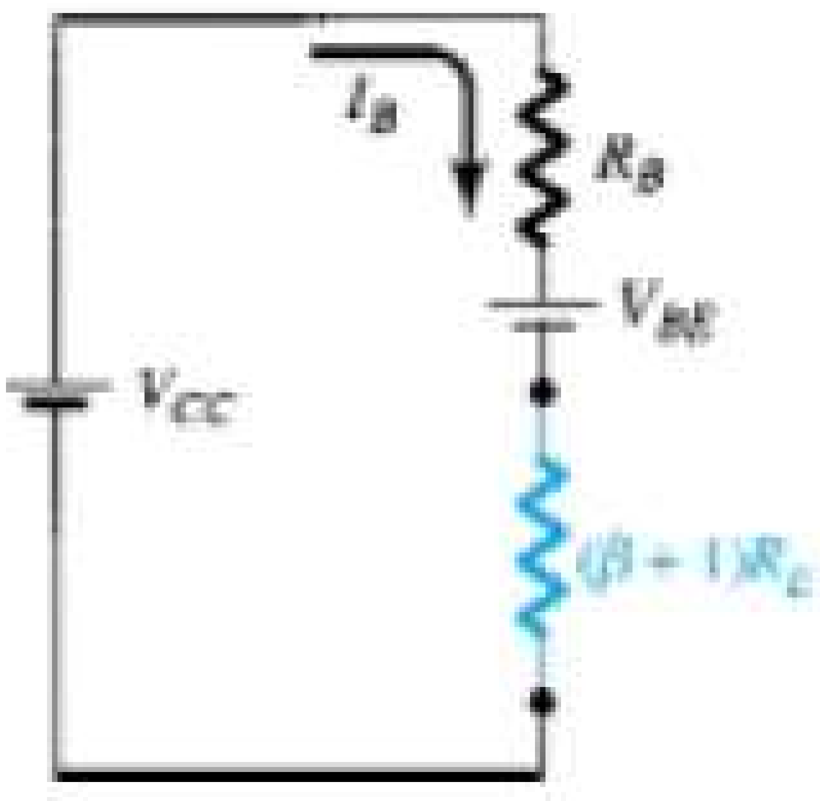
$$I_B(R_B + (\beta + 1)R_E) = V_{CC} - V_{BE}$$

solving for I_B gives

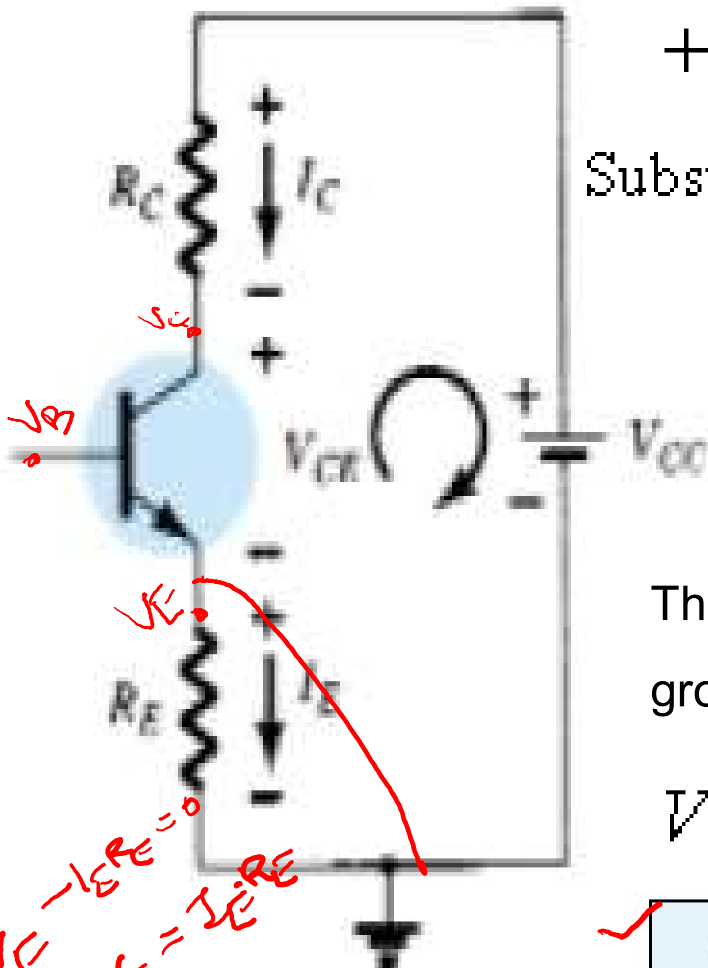
$$\boxed{I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E}}$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E}$$

Network derived from Eq.



Collector–Emitter loop



$V_E - I_E R_E = 0$

$\Rightarrow V_E = I_E R_E$

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

Substituting $I_E \cong I_C$ and grouping terms gives

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

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

The voltage V_E is the voltage from emitter to ground is determined by $\boxed{V_E = I_E R_E}$

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

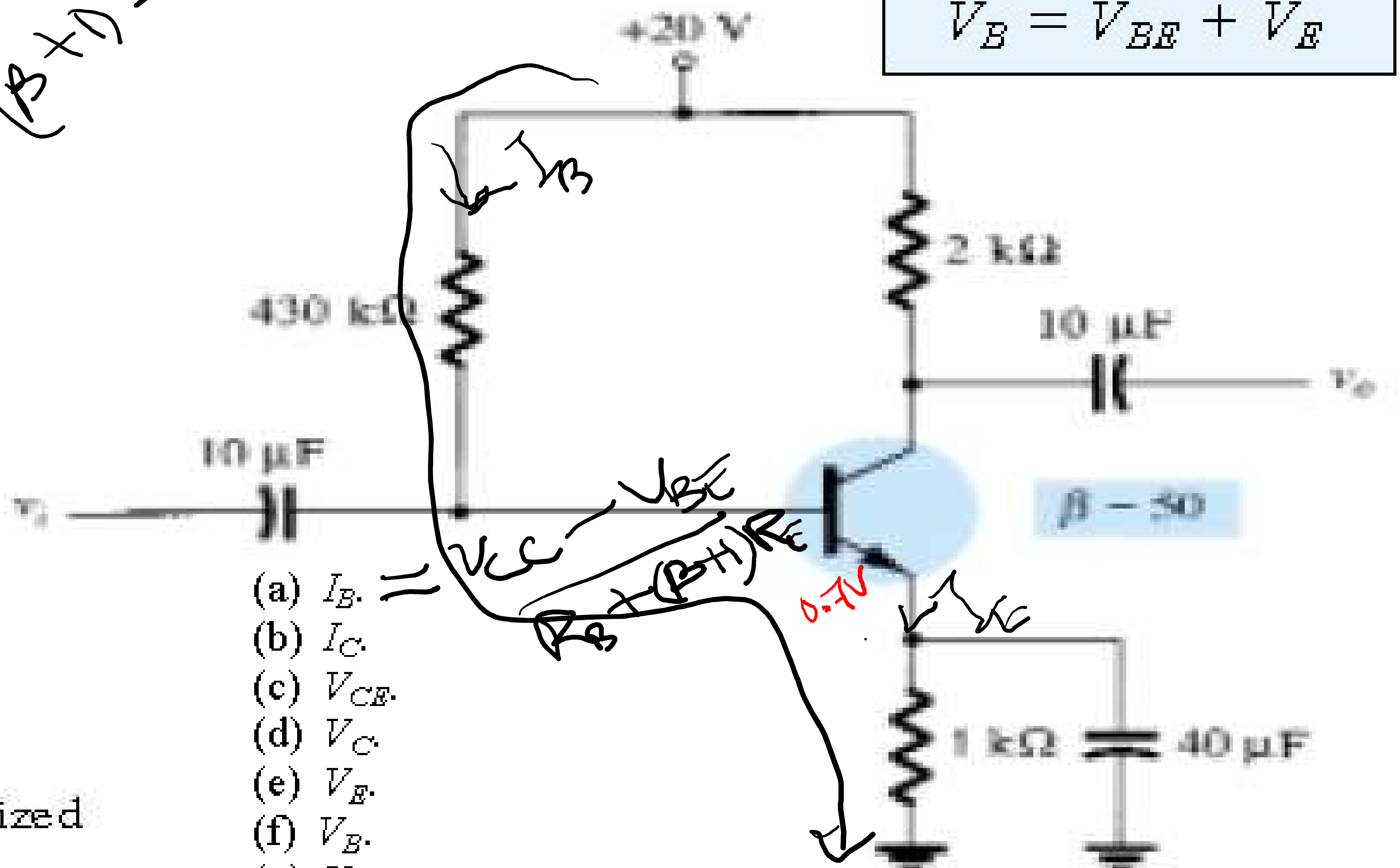
$$\boxed{V_C = V_{CE} + V_E} = V_{CC} - I_C R_C$$

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

The voltage at the base with respect to ground

$$V_B = V_{CC} - I_B R_B$$

$$V_B = V_{BE} + V_E$$



$I_E = (\beta+1) I_B$

I_B

V_{BE}

V_E

0.7V

(a) I_B. $= \dfrac{V_{CC} - V_{BE}}{R_B + (\beta+1) R_E}$

(b) I_C.

(c) V_{CE}.

(d) V_C.

(e) V_E.

(f) V_B.

(g) V_{BC}.

ized

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E} = \frac{20\text{ V} - 0.7\text{ V}}{430\text{ k}\Omega + (51)(1\text{ k}\Omega)} = \frac{19.3\text{ V}}{481\text{ k}\Omega} = \mathbf{40.1\ \mu A}$$

$$I_C = \beta I_B = (50)(40.1\ \mu\text{A}) \cong \mathbf{2.01\ mA}$$

$$V_{CE} = V_{CC} - I_C(R_C + R_E) = 20\text{ V} - (2.01\text{ mA})(2\text{ k}\Omega + 1\text{ k}\Omega)$$

$$= 20\text{ V} - 6.03\text{ V} = \mathbf{13.97\ V}$$

$$V_C = V_{CC} - I_C R_C = 20\text{ V} - (2.01\text{ mA})(2\text{ k}\Omega)$$

$$= 20\text{ V} - 4.02\text{ V} = \mathbf{15.98\ V}$$

$$V_E = V_C - V_{CE} = 15.98\text{ V} - 13.97\text{ V} = \mathbf{2.01\ V}$$

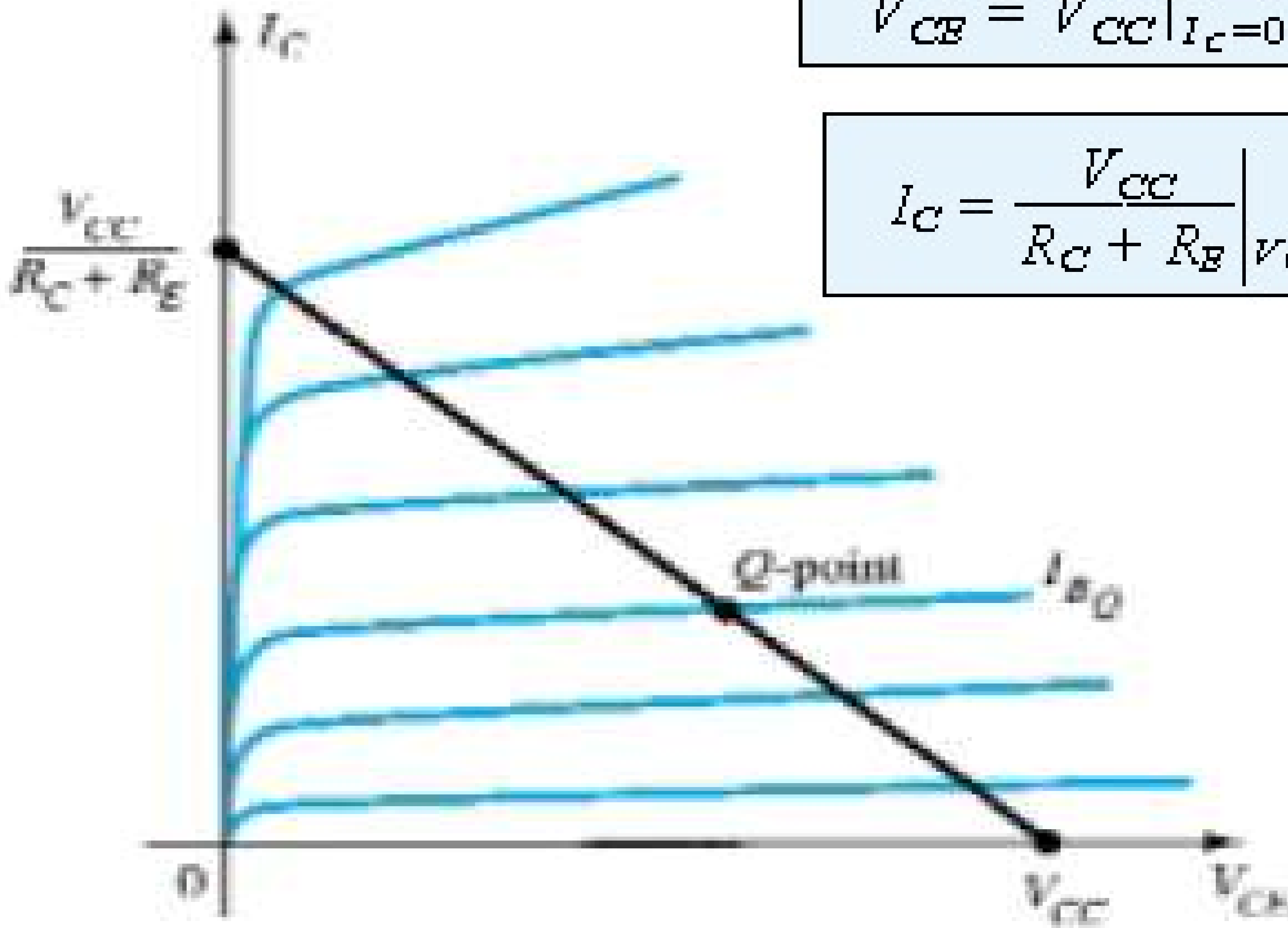
$$V_E = I_E R_E \cong I_C R_E = (2.01\text{ mA})(1\text{ k}\Omega) = \mathbf{2.01\ V}$$

$$V_B = V_{BE} + V_E \quad = 0.7\ \text{V} + 2.01\ \text{V} = \mathbf{2.71\ V}$$

$$V_{BC} = V_B - V_C \ = 2.71\ \text{V} - 15.98\ \text{V}$$

$$= \mathbf{-13.27\ V} \quad \text{(reverse-biased as required)}$$

Load-Line Analysis



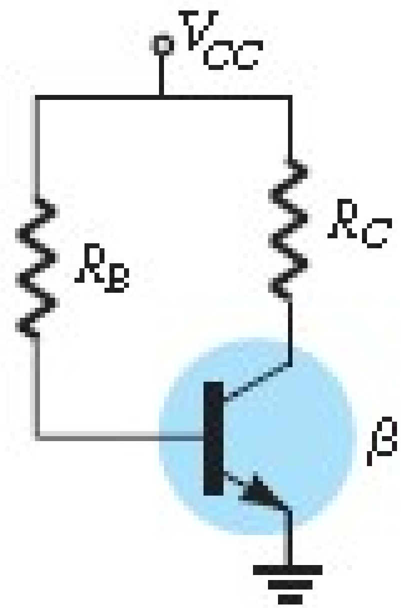
$$V_{CE} = V_{CC}\big|_{I_C = 0\ \text{mA}}$$

$$I_C = \frac{V_{CC}}{R_C + R_E}\bigg|_{V_{CE} = 0\ \text{V}}$$

Transistor DC Biasing

Summary

Fixed-bias

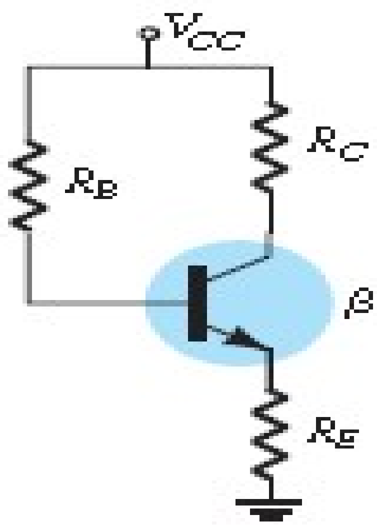


$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

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

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

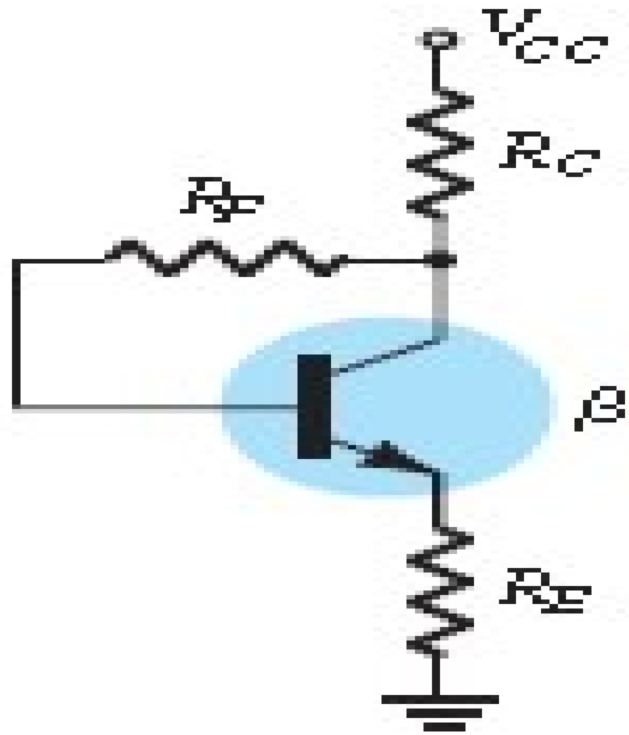
Emitter-bias



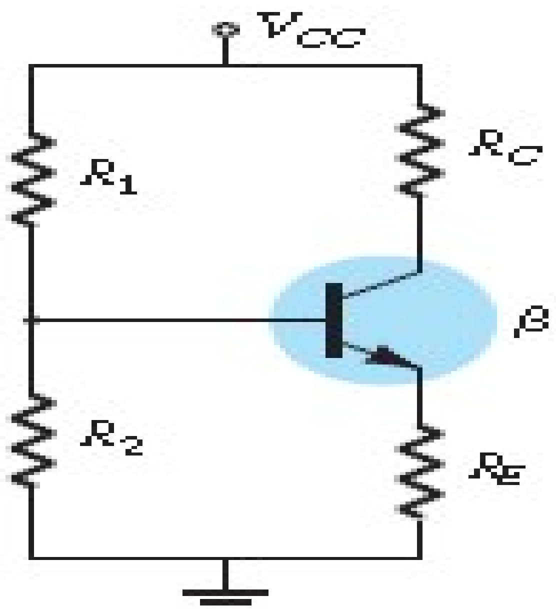
$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E}$$

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

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



Voltage divider-bias-Approx



$$V_B = \frac{R_2 V_{CC}}{R_1 + R_2}, \; V_E = V_B - V_{BE}$$

$$I_E = \frac{V_E}{R_E}, \; I_B = \frac{I_E}{\beta + 1}$$

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

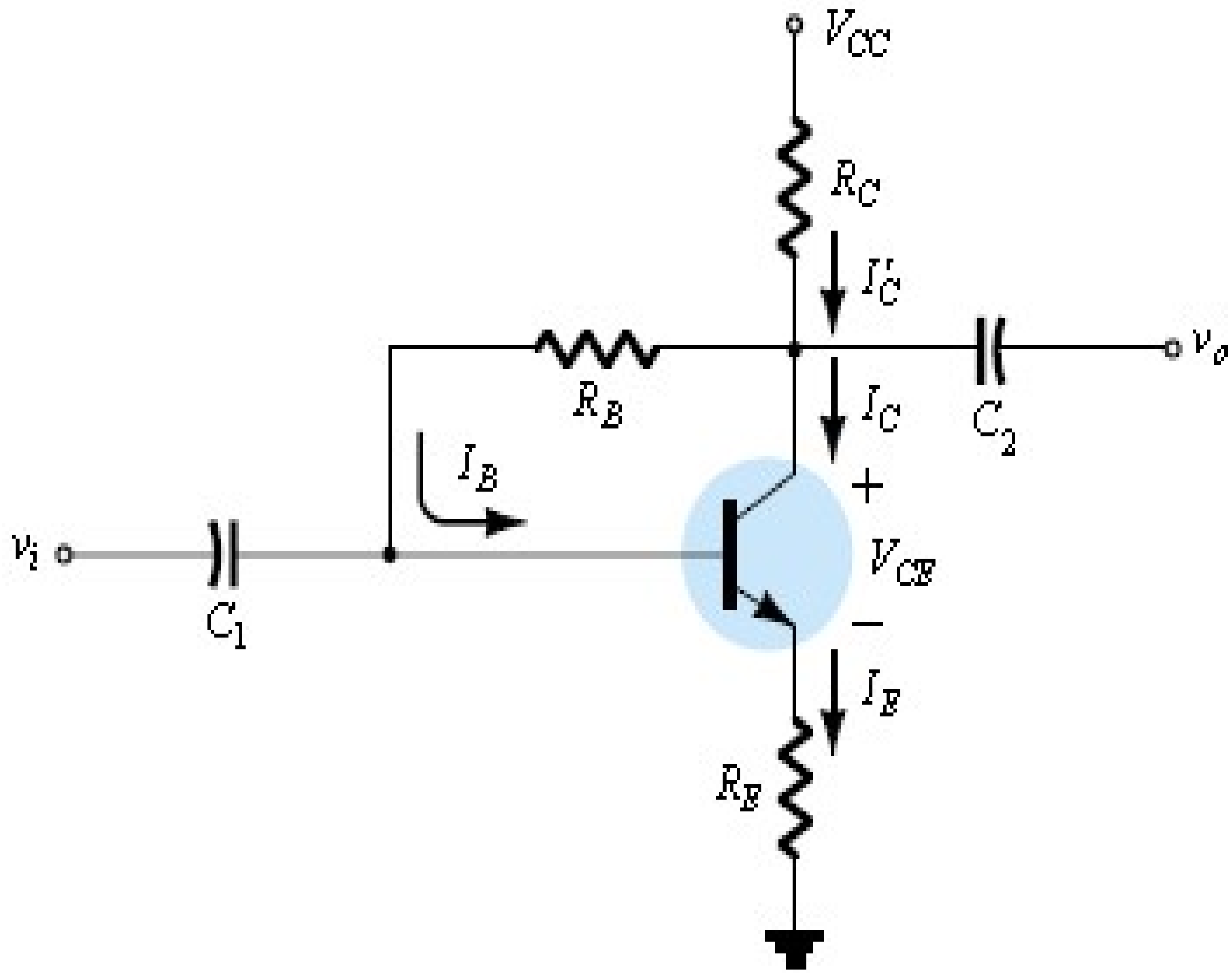
$$R_{Th} = R_1 \| R_2, \; E_{Th} = \frac{R_2 V_{CC}}{R_1 + R_2}$$

$$I_B = \frac{E_{Th} - V_{BE}}{R_{Th} + (\beta + 1) R_E}$$

$$I_C = \beta I_B, \; I_E = (\beta + 1) I_B$$

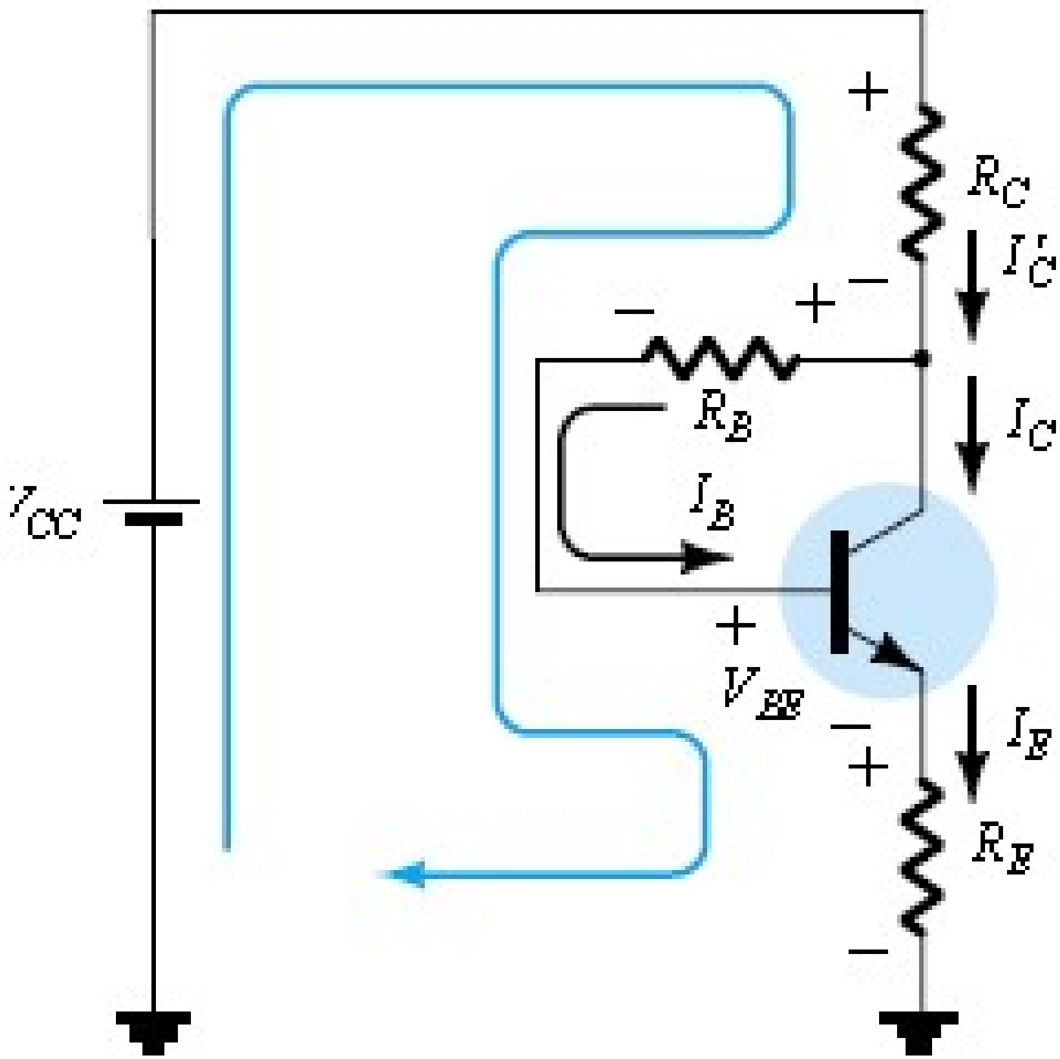
$$V_{CE} = V_{CC} - I_C (R_C + R_E)$$

DC Bias with Voltage Feedback Bias Method



To improve the stability.

Base–Emitter loop



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

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

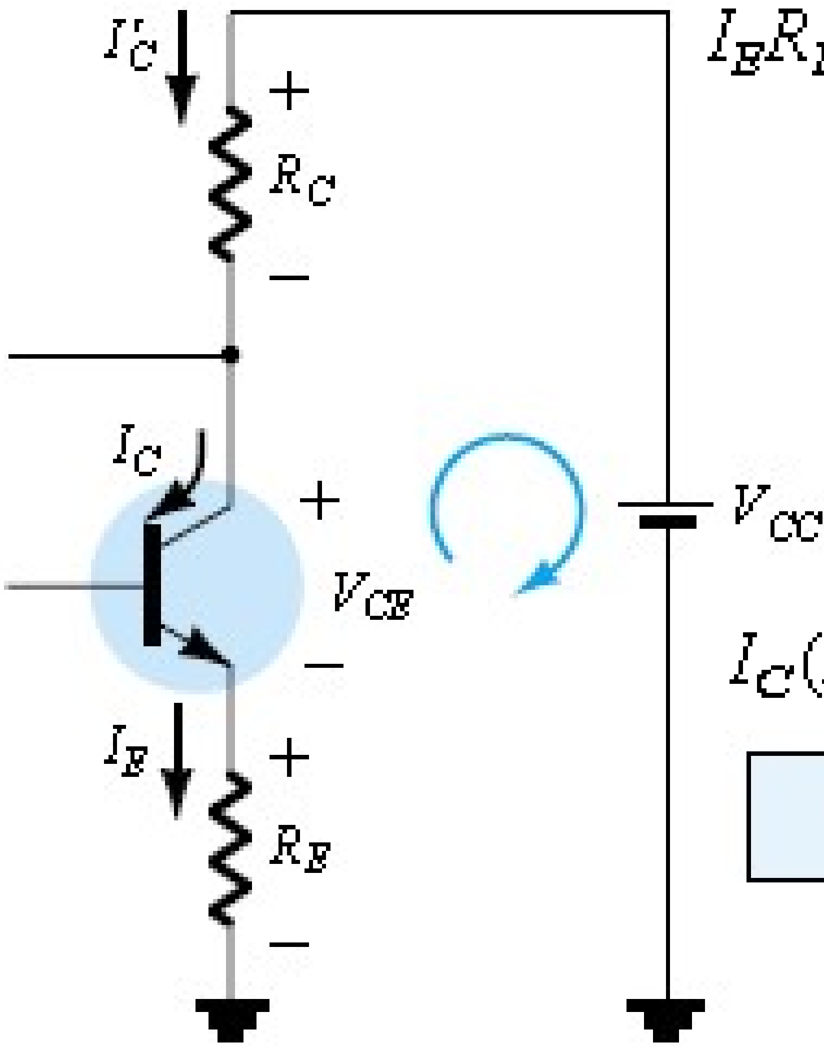
Substituting $I'_C \cong I_C = \beta I_B$ and $I_E \cong I_C$

$$V_{CC} - \beta I_B R_C - I_B R_B - V_{BE} - \beta I_B R_E = 0$$

$$V_{CC} - V_{BE} - \beta I_B (R_C + R_E) - I_B R_B = 0$$

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

Collector–Emitter loop

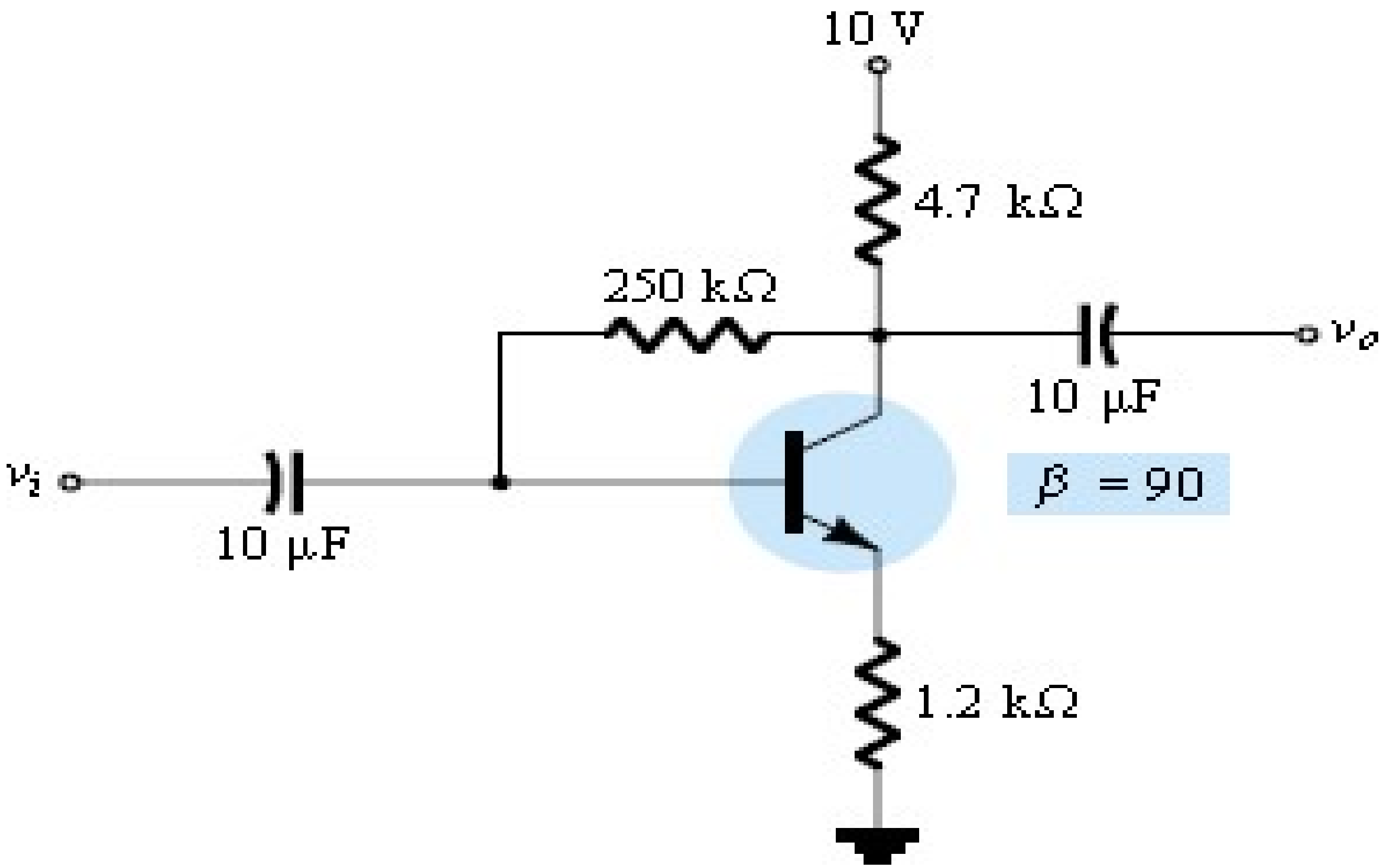


$$I_E R_E + V_{CE} + I'_C R_C - V_{CC} = 0$$

Since $I'_C \cong I_C$ and $I_E \cong I_C$,

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

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



Determine the quiescent levels of I_{C_Q} and V_{CE_Q} for the network

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \beta(R_C + R_E)} = \frac{10\text{ V} - 0.7\text{ V}}{250\text{ k}\Omega + (90)(4.7\text{ k}\Omega + 1.2\text{ k}\Omega)}$$

$$= \frac{9.3\text{ V}}{250\text{ k}\Omega + 531\text{ k}\Omega} = 11.91\ \mu\text{A}$$

$$I_{C_Q} = \beta I_B = (90)(11.91\ \mu\text{A}) = \mathbf{1.07\ mA}$$

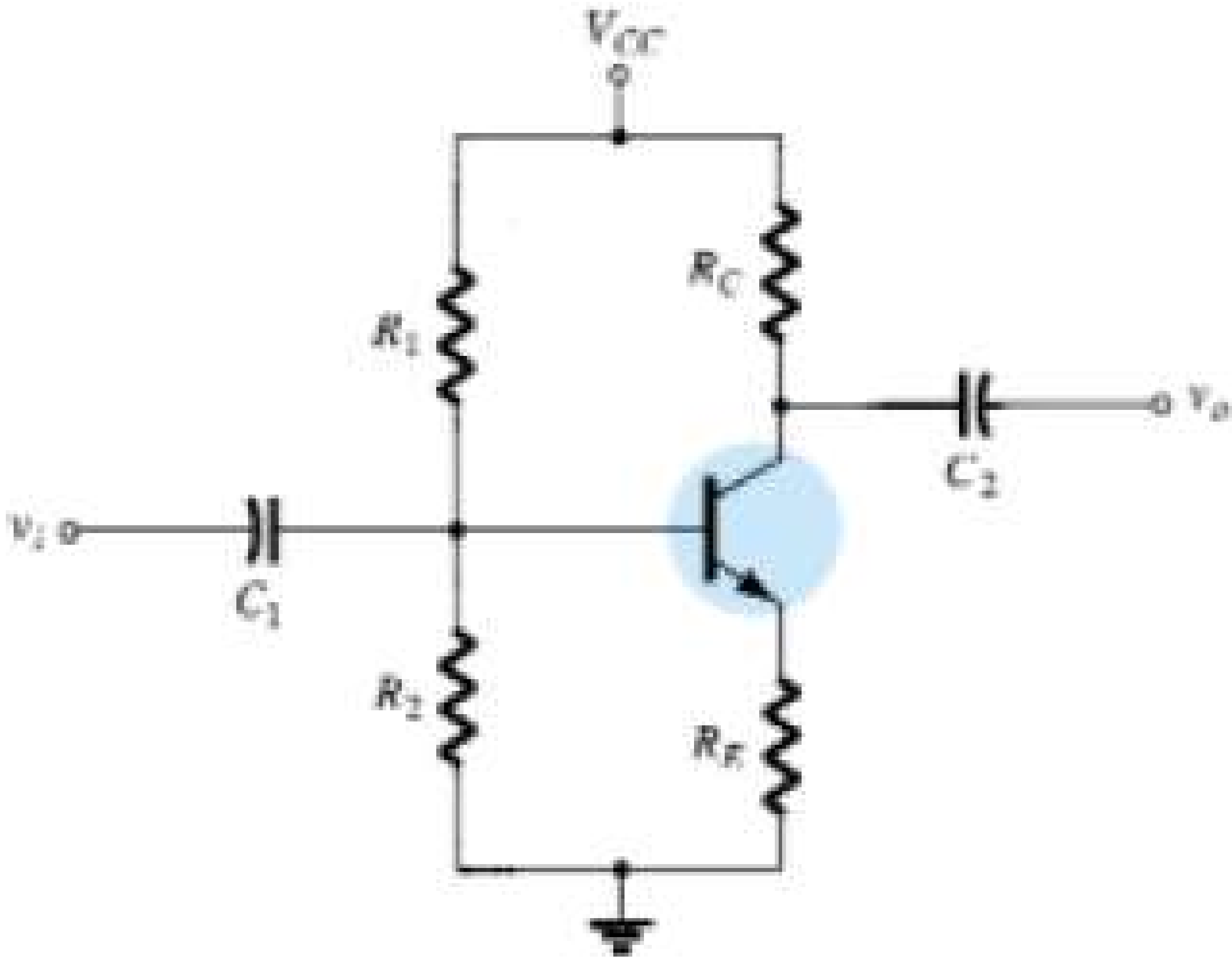
$$V_{CE_Q} = V_{CC} - I_C(R_C + R_E)$$

$$= 10\text{ V} - (1.07\text{ mA})(4.7\text{ k}\Omega + 1.2\text{ k}\Omega)$$

$$= 10\text{ V} - 6.31\text{ V}$$

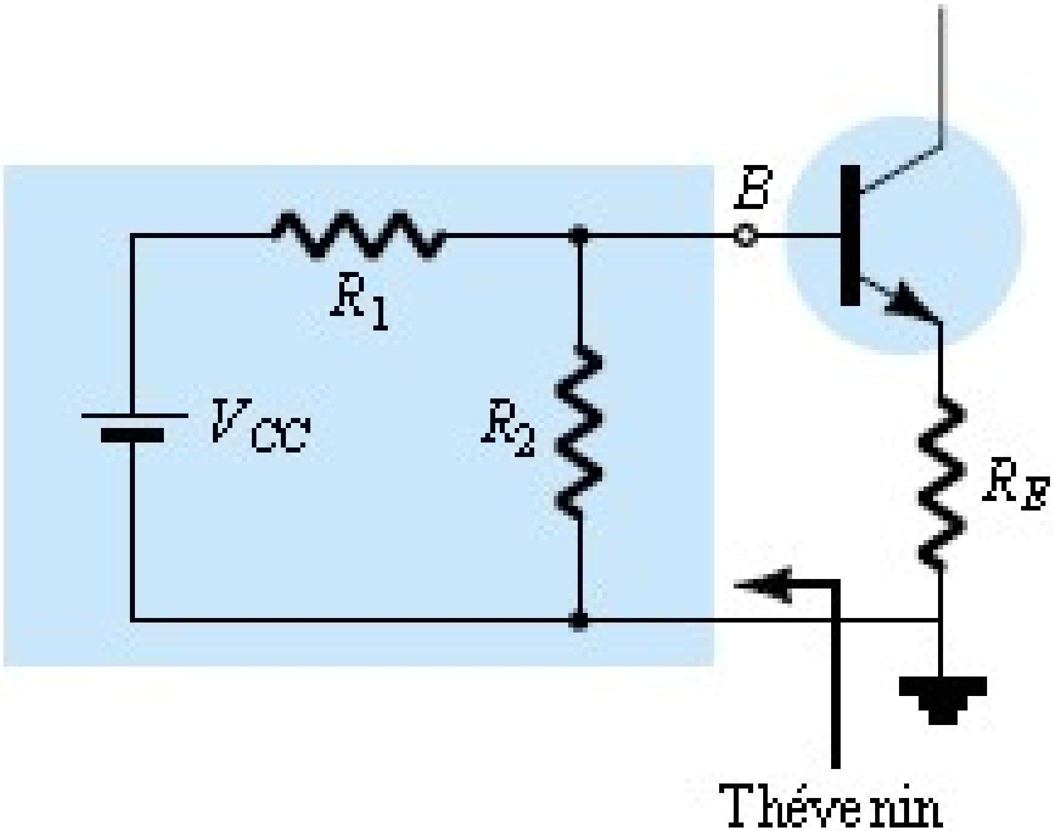
$$= \mathbf{3.69\ V}$$

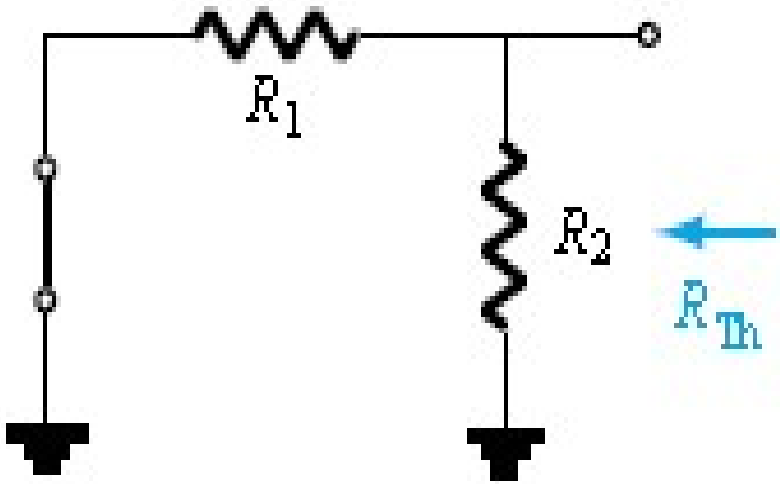
Voltage Divider Bias Method

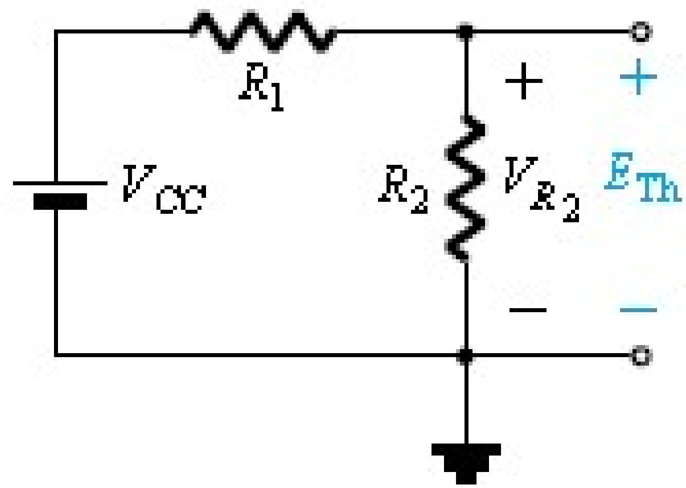


To improve the stability.

Base–Emitter loop





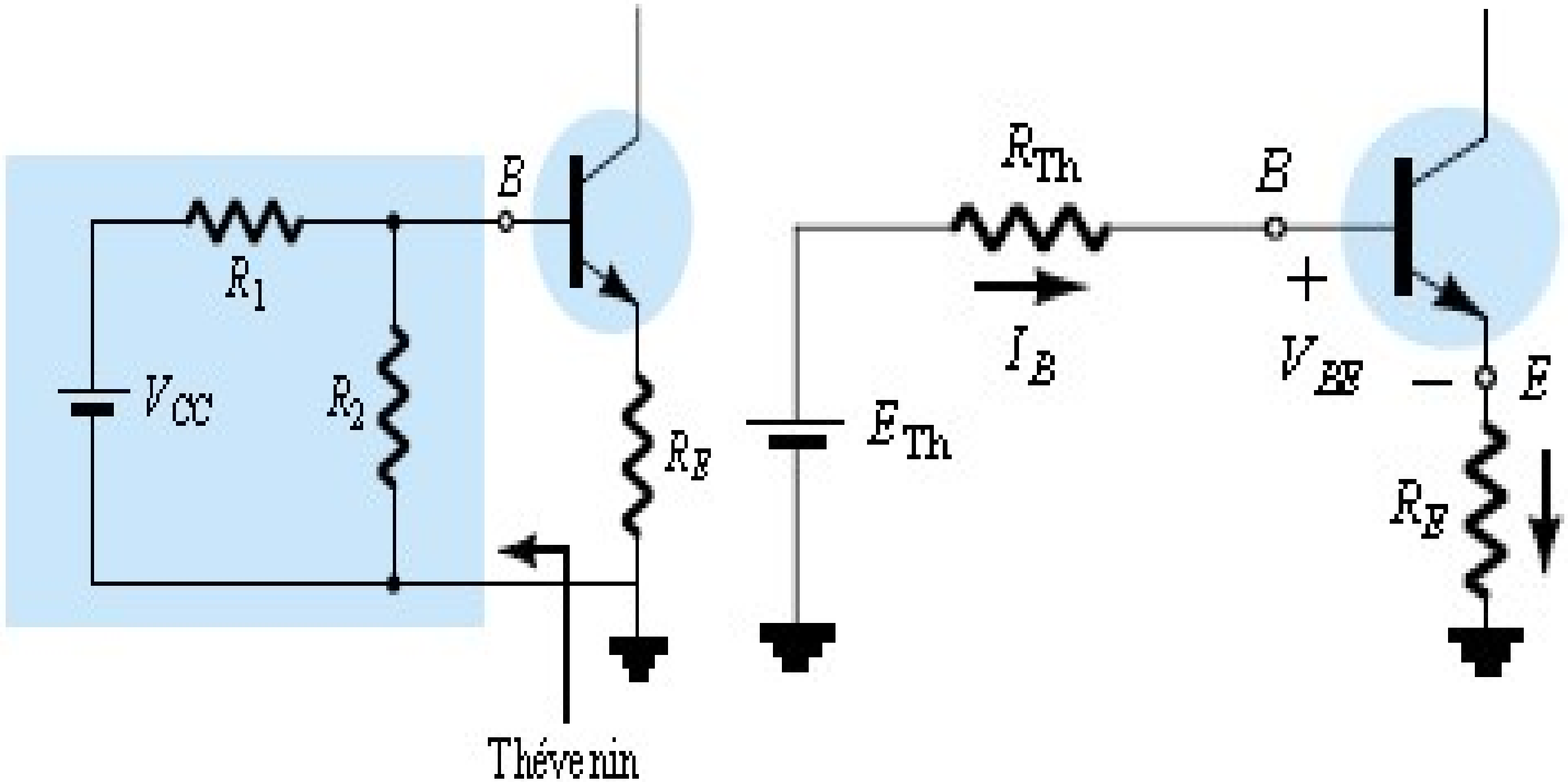


The voltage source is replaced by a short-circuit equivalent

$$R_{Th} = R_1 \| R_2$$

The voltage source VCC is returned to the network and the open-circuit Thévenin voltage

$$E_{Th} = V_{R_2} = \frac{R_2 V_{CC}}{R_1 + R_2}$$

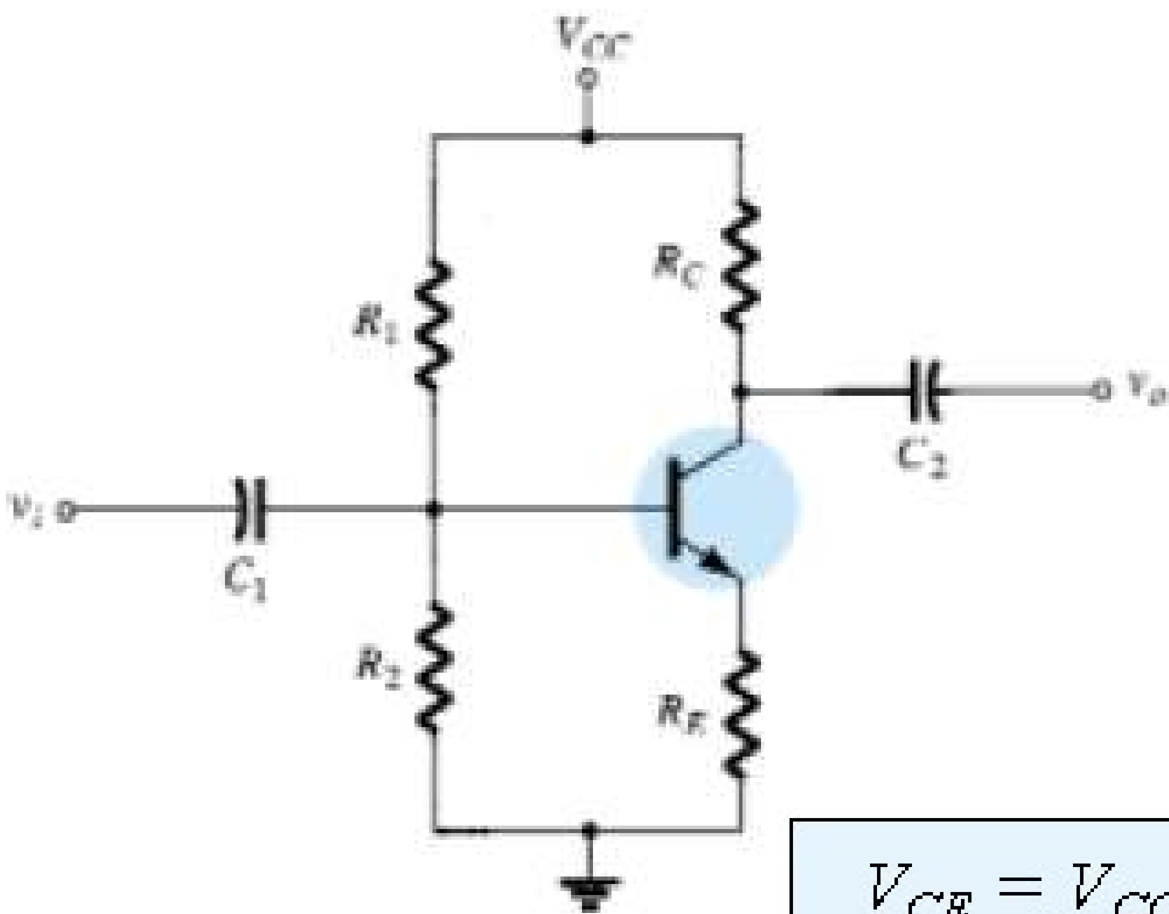


$$E_{\text{Th}} - I_B R_{\text{Th}} - V_{BE} - I_E R_E = 0$$

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

$$I_B = \frac{E_{\text{Th}} - V_{BE}}{R_{\text{Th}} + (\beta + 1)R_E}$$

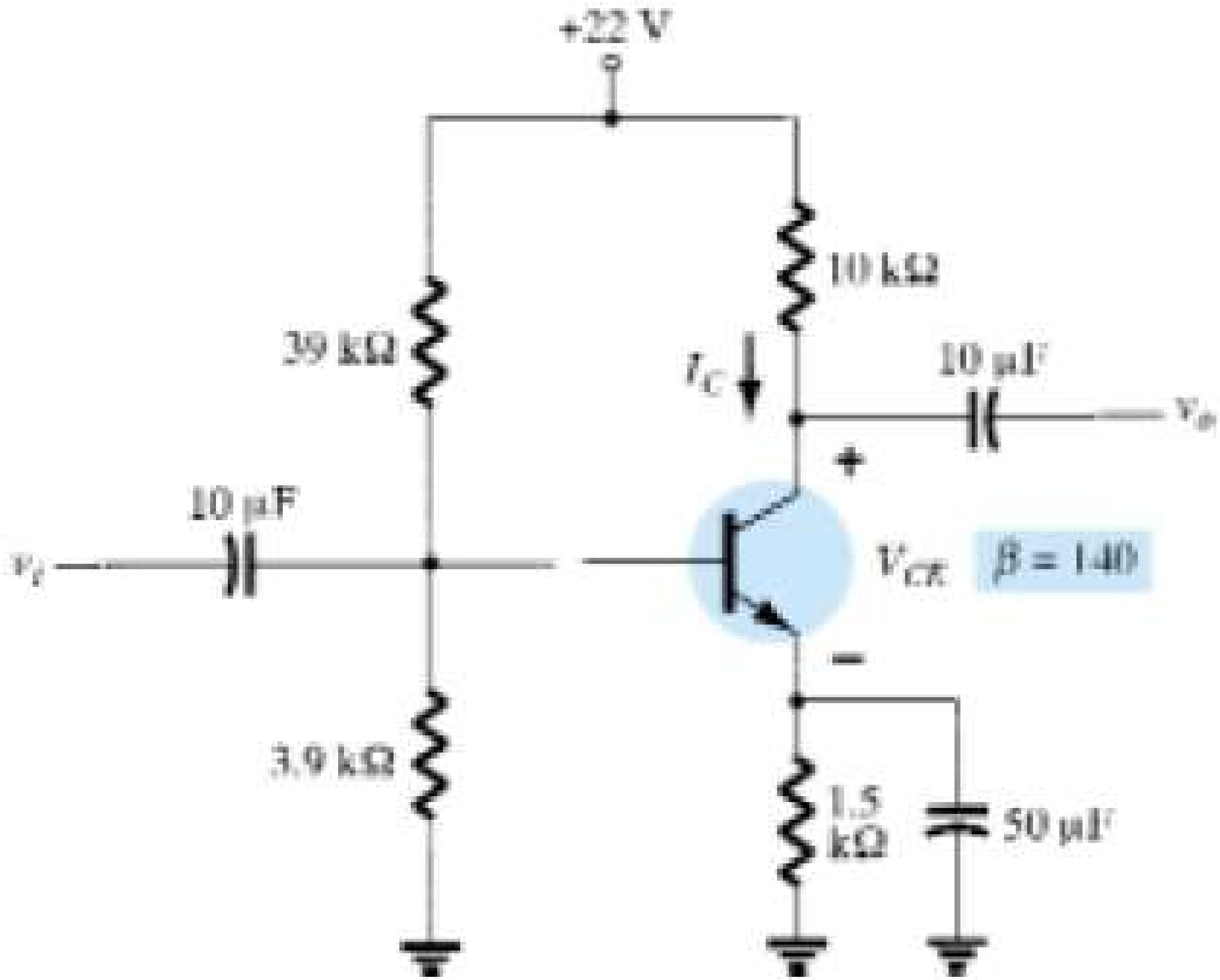
Collector–Emitter loop



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

The approximate approach can be applied with a high degree of accuracy

$$\beta R_E \geq 10R_2$$



Determine the dc bias voltage V_{CE} and the current I_C

$$R_{\text{Th}} = R_1 \| R_2 \quad = \frac{(39\ \text{k}\Omega)(3.9\ \text{k}\Omega)}{39\ \text{k}\Omega + 3.9\ \text{k}\Omega} = \mathbf{3.55\ k\Omega}$$

$$E_{\text{Th}} = \frac{R_2 V_{CC}}{R_1 + R_2} = \frac{(3.9\ \text{k}\Omega)(22\ \text{V})}{39\ \text{k}\Omega + 3.9\ \text{k}\Omega} = 2\ V$$

$$I_B = \frac{E_{\text{Th}} - V_{BE}}{R_{\text{Th}} + (\beta + 1)R_E} = \frac{2\ \text{V} - 0.7\ \text{V}}{3.55\ \text{k}\Omega + (141)(1.5\ \text{k}\Omega)}$$

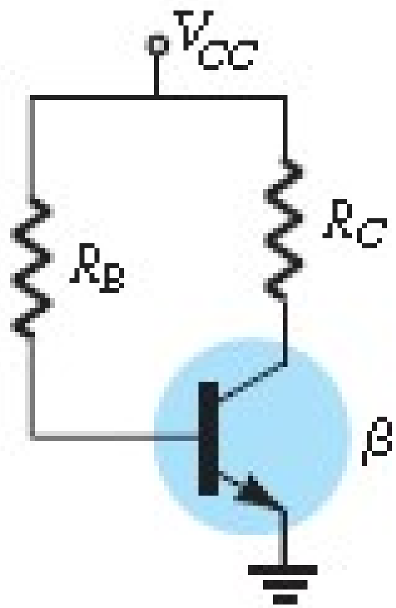
$$= \frac{1.3\ \text{V}}{3.55\ \text{k}\Omega + 211.5\ \text{k}\Omega} = 6.05\ \mu A$$

$$I_C = \beta I_B = (140)(6.05\ \mu\text{A}) = \mathbf{0.85\ mA}$$

$$V_{CE} = V_{CC} - I_C(R_C + R_E) = 22\ \text{V} - (0.85\ \text{mA})(10\ \text{k}\Omega + 1.5\ \text{k}\Omega)$$

$$= 22\ \text{V} - 9.78\ \text{V} = \mathbf{12.22\ V}$$

Summary

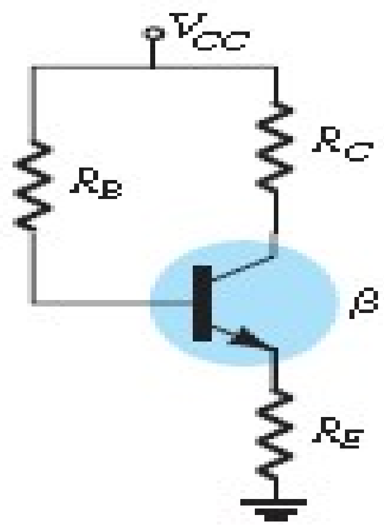


Fixed-bias

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

$$I_C = \beta I_B, \; I_E = (\beta + 1) I_B$$

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

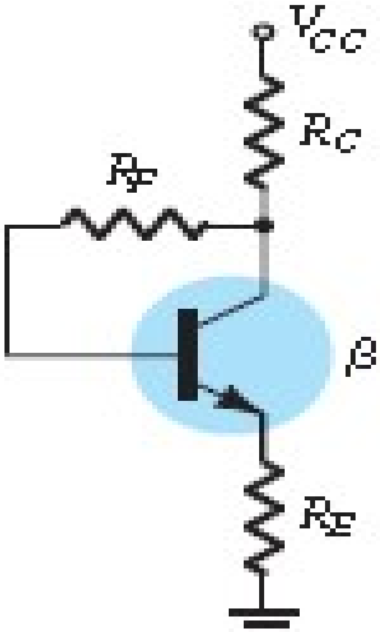


Emitter-bias

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1) R_E}$$

$$I_C = \beta I_B, \; I_E = (\beta + 1) I_B$$

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



Collector feedback-bias

$$I_B = \frac{V_{CC} - V_{BE}}{R_F + \beta(R_C + R_E)}$$

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

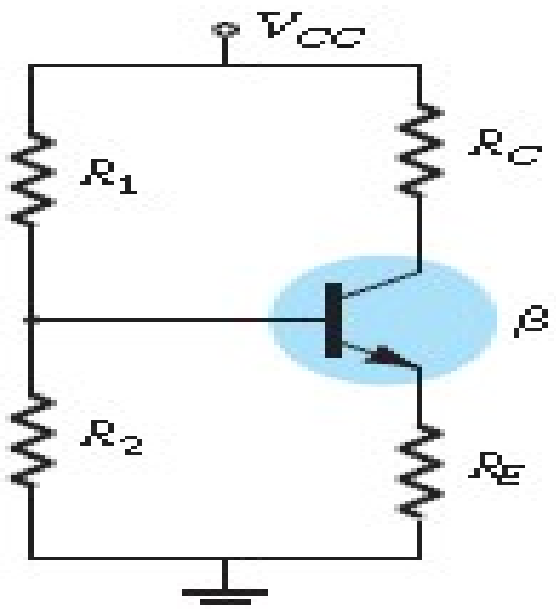
$$V_{CE} = V_{CC} - I_C(R_C + R_E)$$

Voltage divider-bias-Approx

$$V_B = \frac{R_2 V_{CC}}{R_1 + R_2}, V_E = V_B - V_{BE}$$

$$I_E = \frac{V_E}{R_E}, I_B = \frac{I_E}{\beta + 1}$$

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



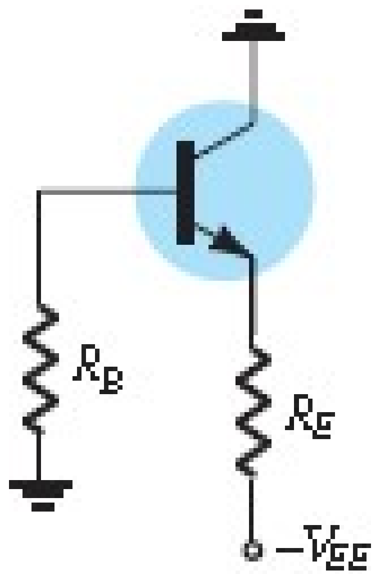
$$R_{Th} = R_1 \| R_2, E_{Th} = \frac{R_2 V_{CC}}{R_1 + R_2}$$

$$I_B = \frac{E_{Th} - V_{BE}}{R_{Th} + (\beta + 1)R_E}$$

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

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

Emitter Follower



$$I_B = \frac{V_{EE} - V_{BE}}{R_B + (\beta + 1)R_E}$$

$$I_C = \beta I_B, \; I_E = (\beta + 1)I_B$$

$$V_{CE} = V_{EE} - I_E R_E$$

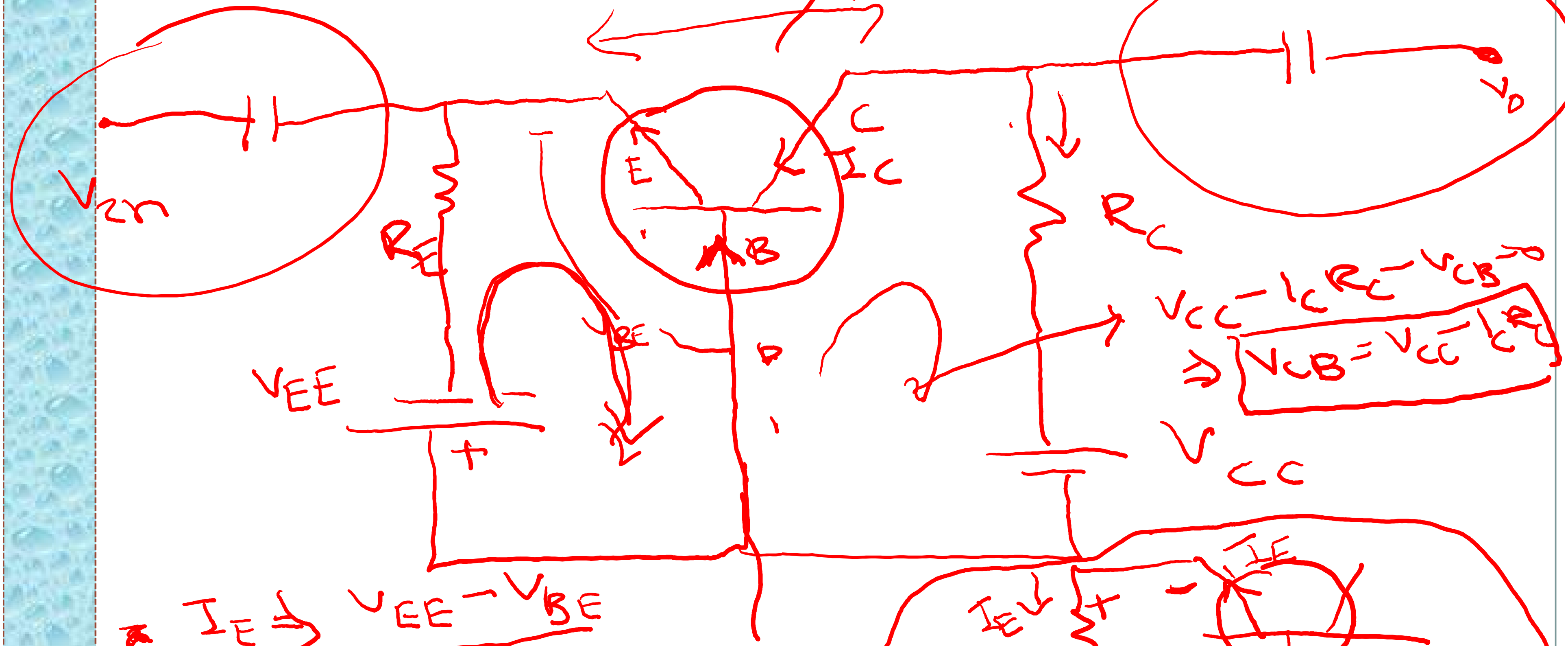
The configuration is not the only one where the output can be taken off the emitter terminal.

The previous sections introduced configurations in which the output voltage is typically taken off the collector terminal of the BJT.

Example:

CB Configuration

$\boxed{I_E = I_B + I_C}$



$V_{CC} - I_C R_C - V_{CB} = 0$

$\Rightarrow \boxed{V_{CB} = V_{CC} - I_C R_C}$

$I_E \Rightarrow \frac{V_{EE} - V_{BE}}{R_E}$

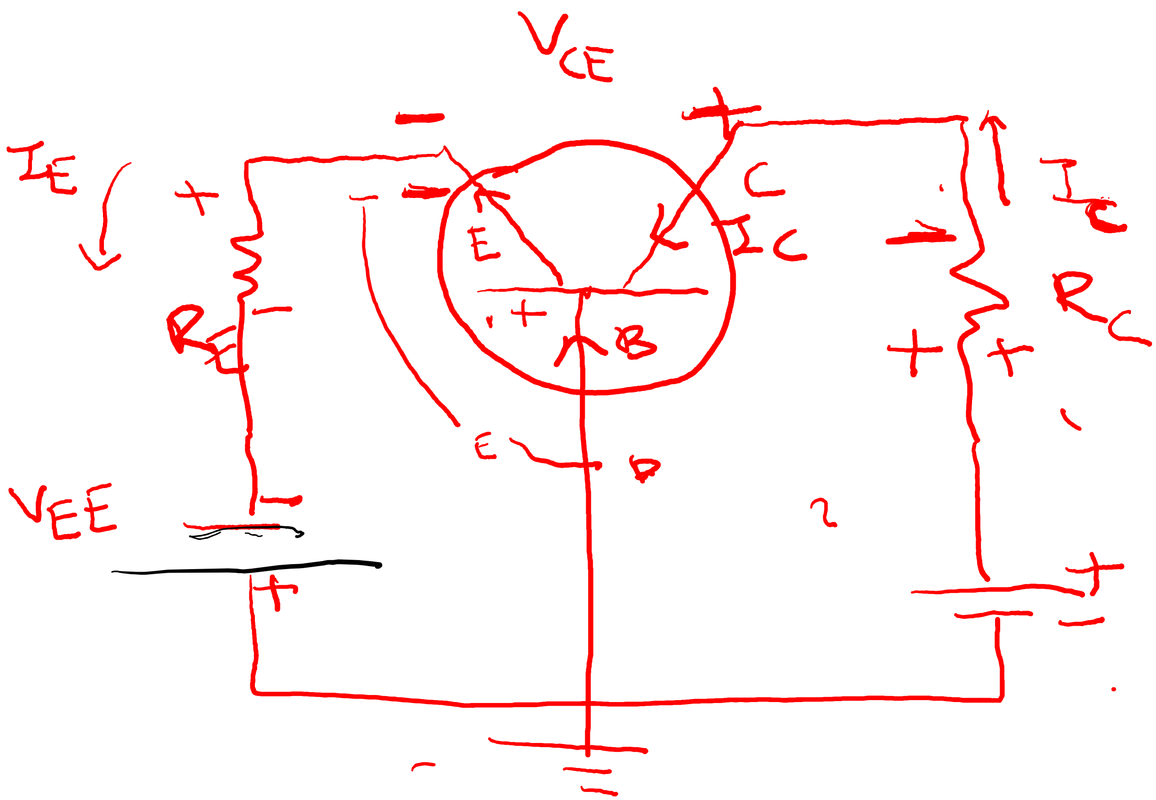
$V_{EE} - I_E R_E - V_{BE} = 0$

$\Rightarrow I_C \cong I_E$

$-V_{EE} + I_E R_E + V_{BE} = 0$

$V_{EE} - I_E R_E - V_{BE} = 0$

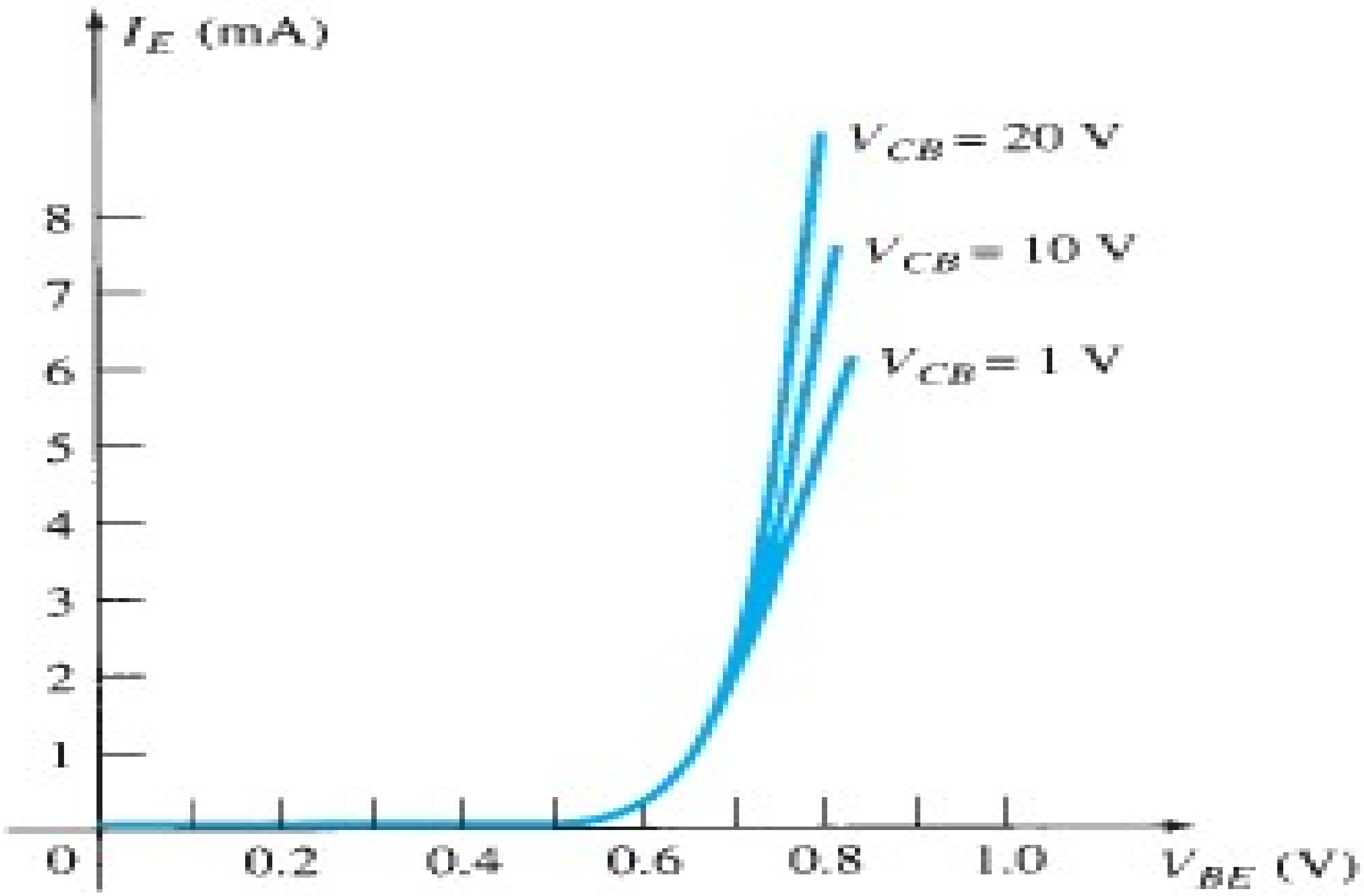
$\Rightarrow I_E = \frac{V_{EE} - V_{BE}}{R_E}$



Applying KVL to the entire outside network

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

$$\Rightarrow \boxed{V_{CE} = V_{EE} + V_{CC} - I_E R_E - I_C R_C}$$



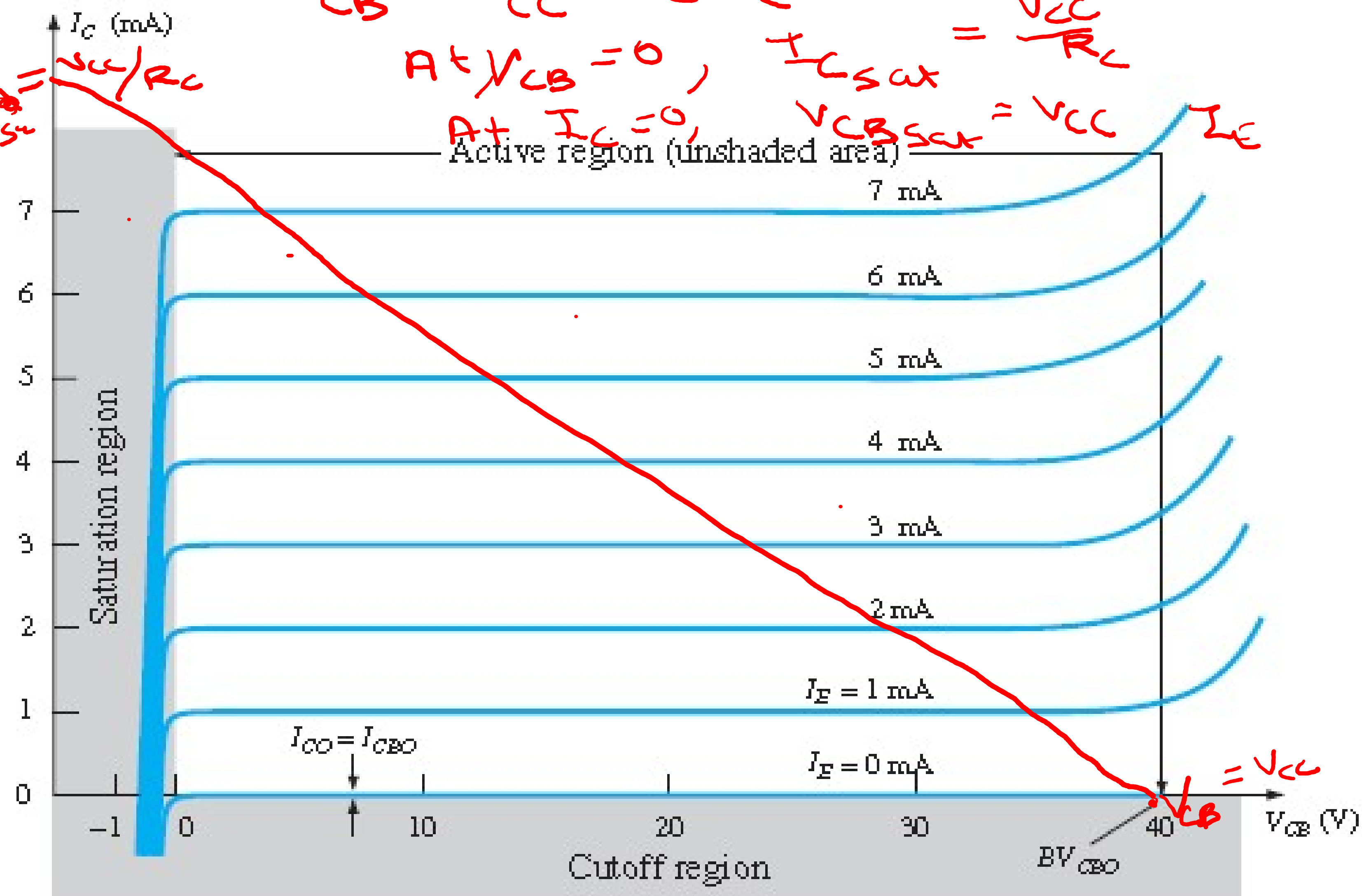
Input or driving point characteristics for a common-base silicon transistor amplifier

Emitter i/p a $V_{CE} = V_{EE} + V_{CC} - I_C R_C - I_E R_E$

O/P Loop $V_{CB} = V_{CC} - I_C R_C$

At $V_{CB} = 0$, $I_{Csat} = \frac{V_{CC}}{R_C}$

At $I_C = 0$, $V_{CBsat} = V_{CC}$



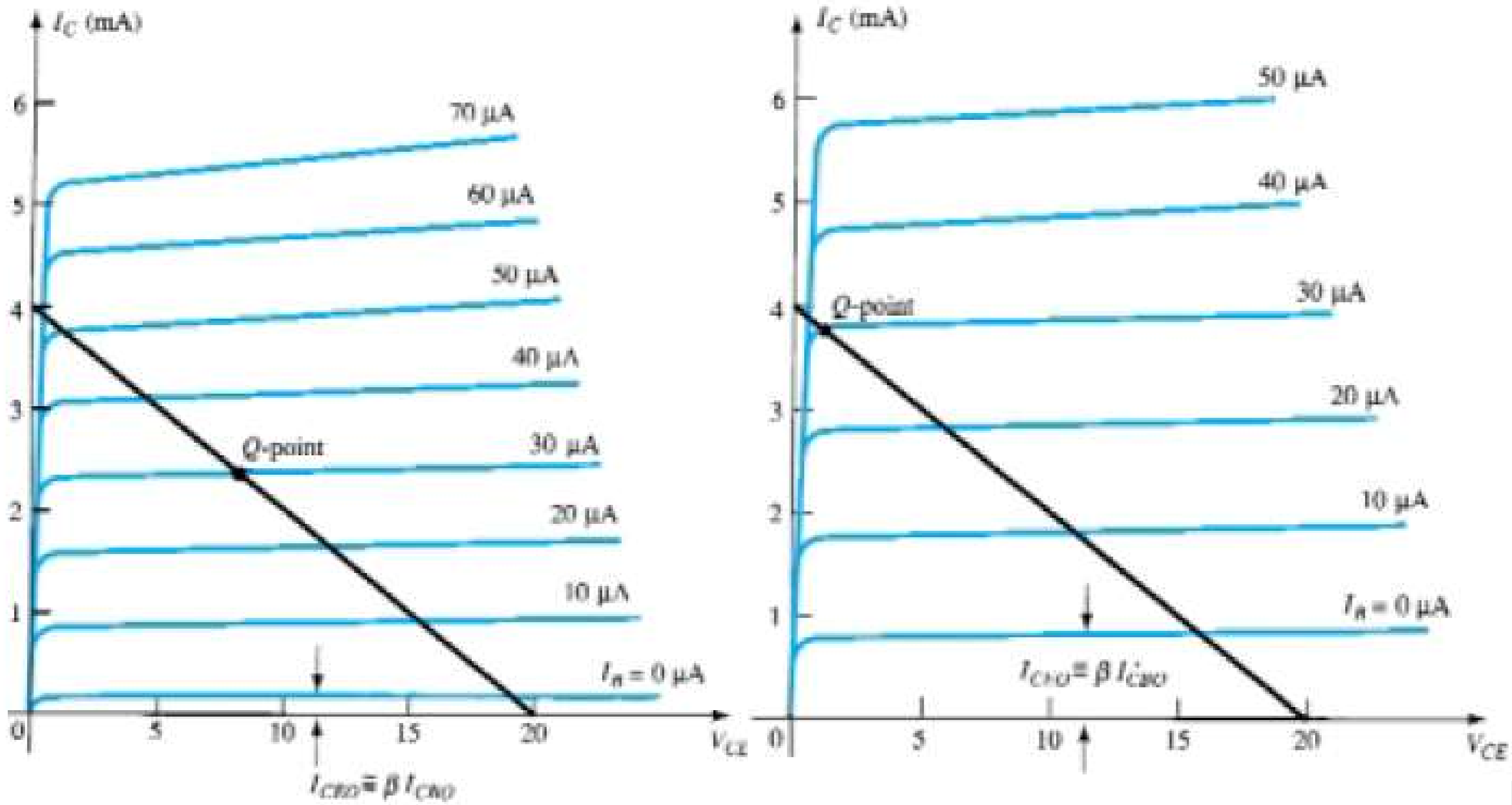
Output or collector characteristics for a common-base transistor amplifier

Bias Stabilization

- The stability of a system is a measure of the sensitivity of a network to variations in its parameters.
- In any amplifier employing a transistor the collector current (I_C) is sensitive to each of the following parameters:
  - increases with increase in temperature
  - V_{BE}: decreases about 7.5 mV per degree Celsius (°C) increase in temperature
  - I_{CO} (reverse saturation current): doubles in value for every 10°C increase in temperature

TABLE 4.1 Variation of Silicon Transistor Parameters with Temperature

T (°C)	I_{CO} (nA)	β	V_{BE}(V)
−65	0.2×10^{-3}	20	0.85
25	0.1	50	0.65
100	20	80	0.48
175	3.3×10^{3}	120	0.3



Shift in dc bias point (Q-point) due to change in temperature: (a) 25°C; (b) 100°C.

Stability Factors: $S(I_{CO})$, $S(V_{BE})$, and $S(\beta)$

$$S(I_{CO}) = \frac{\Delta I_C}{\Delta I_{CO}}$$

$$S(V_{BE}) = \frac{\Delta I_C}{\Delta V_{BE}}$$

$$S(\beta) = \frac{\Delta I_C}{\Delta \beta}$$

For the **emitter-bias configuration**, an analysis of the network will result in

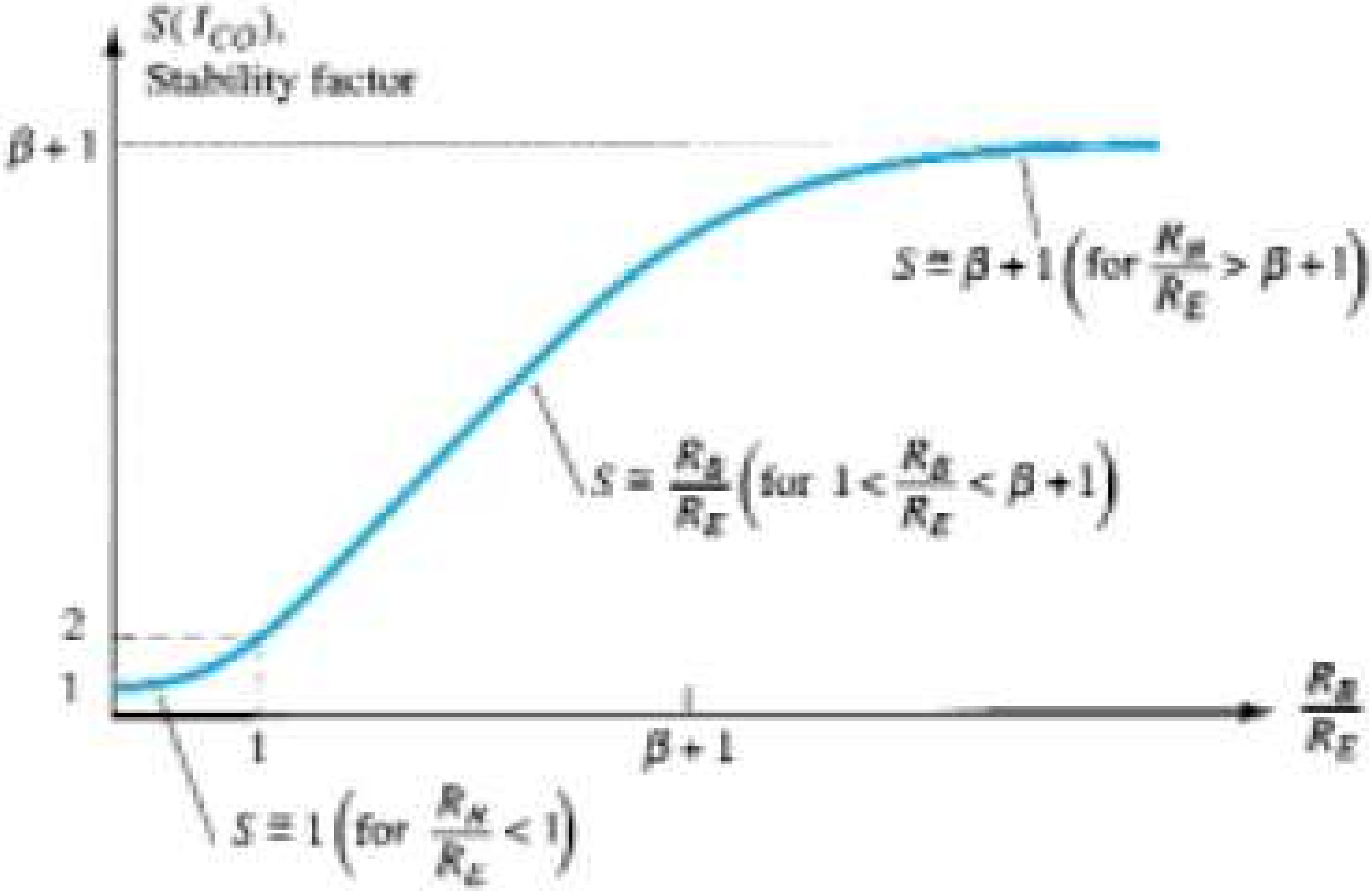
$$S(I_{CO}) = (\beta + 1)\frac{1 + R_B/R_E}{(\beta + 1) + R_B/R_E}$$

For $R_B/R_E \gg (\beta + 1)$, $$S(I_{CO}) = \beta + 1$$

For $R_B/R_E \ll 1$, $$S(I_{CO}) = (\beta + 1)\frac{1}{(\beta + 1)} = \rightarrow 1$$

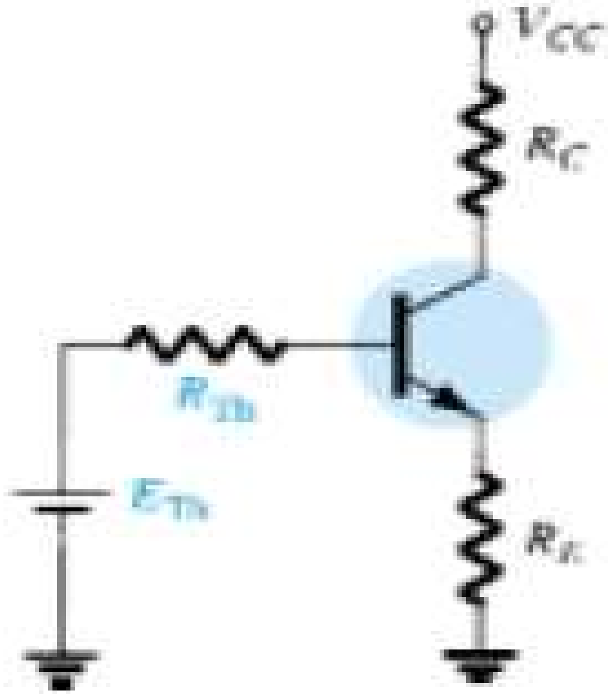
For the range where R_B/R_E ranges between 1 and $(\beta + 1)$, $$S(I_{CO}) \cong \frac{R_B}{R_E}$$

Stability Factors: Emitter Bias Configuration



Variation of stability factor $S(I_{CO})$ with the R_B / R_E for the emitter-bias configuration.

Stability Factors: **Voltage Divider Bias Configuration**



For the voltage divider-bias configuration, R_{Th} can be much less than the corresponding R_B of the emitter-bias configuration and still have an effective design.

$$R_E > R_{Th} \Rightarrow \frac{R_{Th}}{R_E} < 1$$

$R_1 || R_2$

$$S(I_{CO}) = (\beta + 1)\frac{1 + R_{Th}/R_E}{(\beta + 1) + R_{Th}/R_E}$$

Stability Factors: **Fixed Bias Configuration**

For the fixed-bias configuration, if we multiply the top and bottom of Equation for $S(I_{CO})$ by R_E and then plug in $R_E = 0$, the following equation will result

$$S(I_{CO}) = (\beta + 1)\frac{1 + R_B/R_E}{(\beta + 1) + R_B/R_E}$$

- The result is a configuration with
  - a poor stability factor and
  - a high sensitivity to variations in I_{CO}.