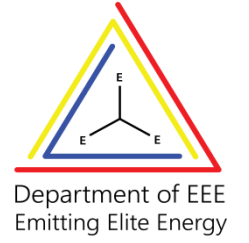




A T M E

College of Engineering



Emitting Elite Energy

Analog Electronic Circuits BEE303

Text Books and Reference Books

1. **“Electronic devices and circuit theory”**, Robert L Boylestad and Louis Nashelsky, Pearson, 11th Edition 2015.
2. **“Electronic devices and circuits”**, Millman and Halkias, McGraw Hill, 4th Edition 2015.
3. **“Electronic devices and circuits”**, David A Bell, Oxford University Press, 5th edition 2008.
4. **“Microelectronics circuits analysis and design”**, Muhammad Rashid, 2nd Edition 2014.
5. **“A Textbook of Electrical technology, Electronic devices and circuits”** by B.L.Theraja and A.K.Theraja, 2013.
6. **“Fundamentals of analog circuits”**, Thomas L Floyd, 2nd Edition 2012.
7. **“Analog Electronic Circuits”**, U B Mahadevaswamy.

Basic Concepts

Conductors

It is an object or a type of material that allows flow of charge (electrical current) in one or more directions.

Examples: **Copper wire, Aluminium Wire**

Insulators:

It is a material in which the electron does not flow freely. Insulators does not conduct.

Examples: **Glass, Porcelain, Paper, Rubber etc.**

Semiconductors:

A semiconductor material has an electrical conductivity value falling between that of a conductor and an insulator.

Examples: **Silicon, Germanium, Gallium Arsenide**

Semiconductor Devices

Diode

Bipolar Junction Transistor (BJT)

Field Effect Transistor (FET)

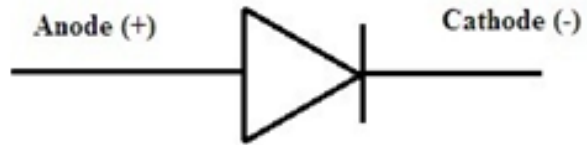
Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

Thyristors

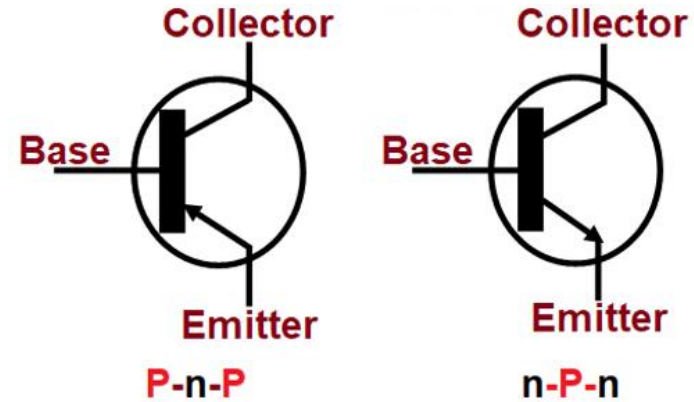
Insulated Gate Bipolar Junction Transistor (IGBT)

Semiconductor Devices

Diode



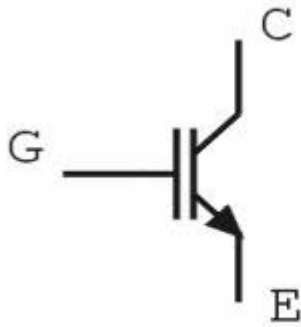
Bipolar Junction Transistor (BJT)



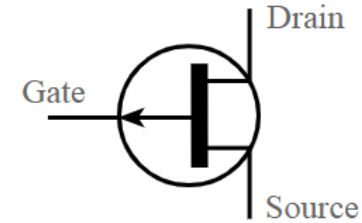
BJT Junctions	Operating Regions	Function
Collector-Base Junction	Cut-off region	OFF Switch
Base-Emitter Junction	Active region	Amplifier
	Saturation region	ON Switch

Semiconductor Devices

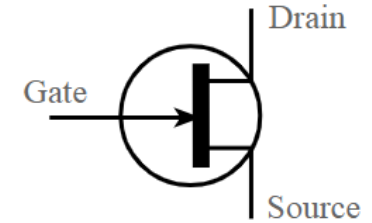
Insulated Gate Bipolar Transistor (IGBT)



Field Effect Transistor (FET)

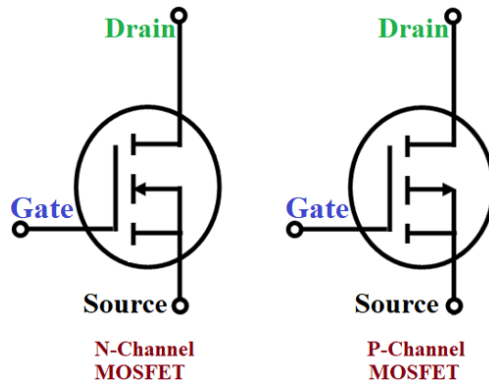


P-Channel



N-Channel

Metal Oxide Semiconductor Field Effect Transistor (MOSFET)



N-Channel
MOSFET

P-Channel
MOSFET

Important Terminologies

Gain (A): Ratio of output function to the input function.

Voltage Gain(A_v): It is defined as ratio of output voltage to the input voltage.

Current Gain (A_I): It is defined as ratio of output current to the input current.

Amplifier: An amplifier or electronic amplifier is an electronic device that can increase the power of a signal (a time-varying voltage or current).

Oscillator: An electronic oscillator is an electronic circuit that produces a periodic, oscillating electronic signal, often a sine wave or a square wave.

Clipper Circuits or Limiters

The clipper circuits are used to **remove the certain portions of the waveform** above or below the certain levels, as per the requirement.

Classification of Clippers

```
graph TD; A[Classification of Clippers] --> B[Series Clippers]; A --> C[Shunt Clippers]; A --> D[Double Ended Clippers]; B --> B1[1. Series Negative Clippers]; B --> B2[2. Series Positive Clippers]; C --> C1[1. Shunt Negative Clippers]; C --> C2[2. Shunt Positive Clippers];
```

Series Clippers

1. Series Negative Clippers
2. Series Positive Clippers

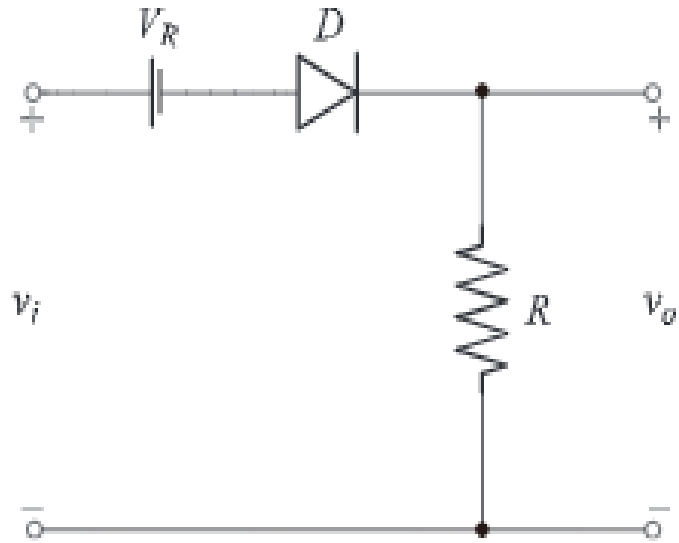
Shunt Clippers

1. Shunt Negative Clippers
2. Shunt Positive Clippers

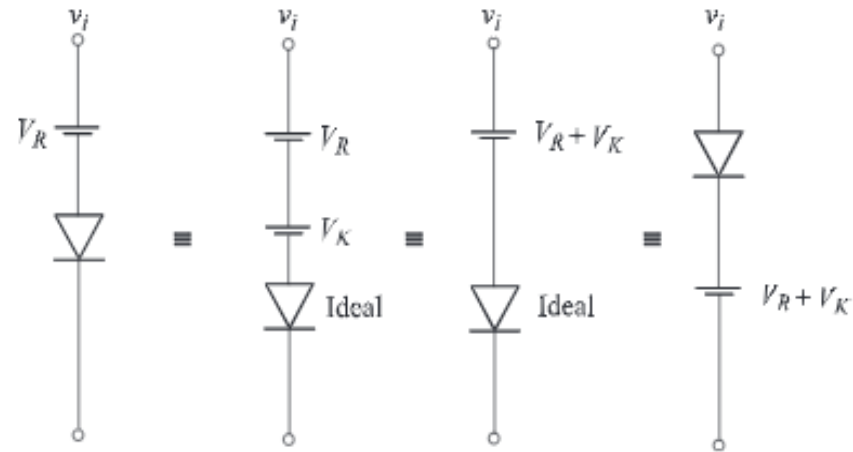
Double Ended Clippers

Series Negative Clippers

In series clippers the diode is connected in series with the load.



Circuit Diagram



Voltage on Diode Terminals

Series Negative Clippers

The diode conducts (ON) for

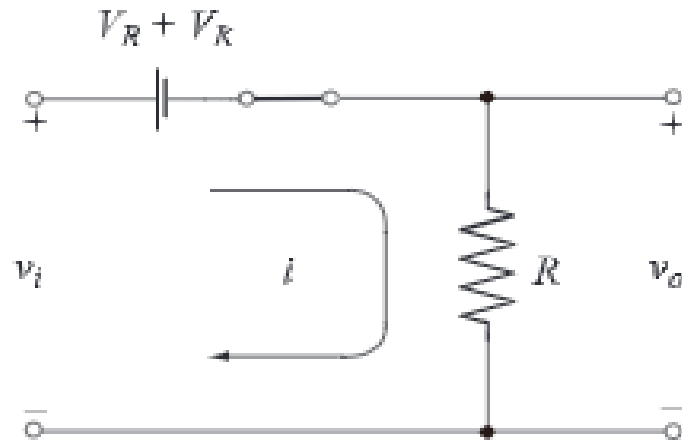
$$v_I \geq V_R + V_K$$

Where,

v_I = Input voltage

V_R = Reference voltage

V_K = Voltage drop across diode



Diode ON Condition

Apply KVL to the circuit, we get;

$$v_i - [V_R + V_K] - v_o = 0$$

$$v_o = v_i - [V_R + V_K] \text{ for } v_I \geq V_R + V_K$$

$$\text{when } v_i = v_m, v_o = v_m - [V_R + V_K]$$

Since $V_R + V_K$ is constant

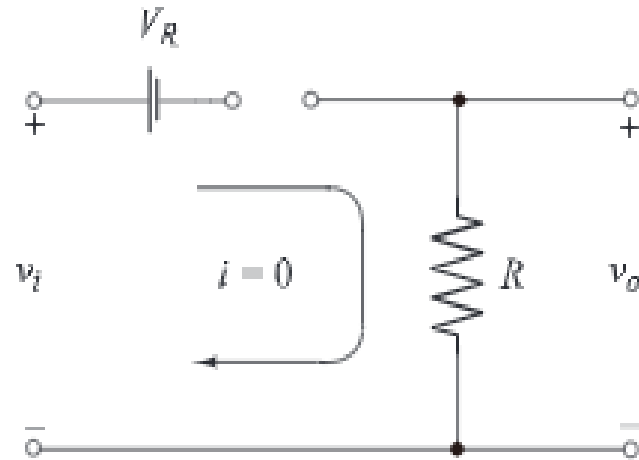
$$\Delta v_o = \Delta v_i$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 1$$

Series Negative Clippers

The diode is in OFF condition for

$$v_i \leq V_R + V_K$$

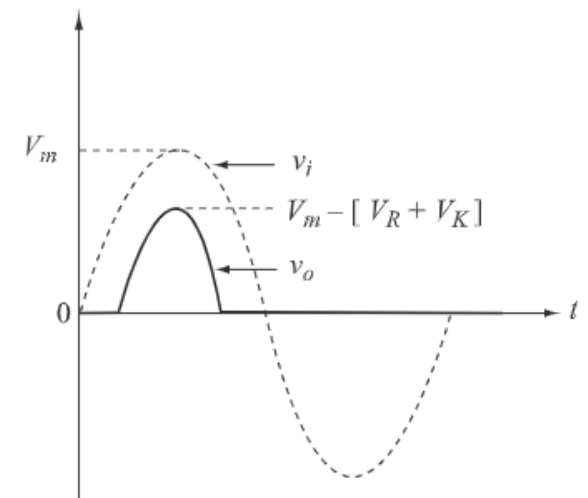
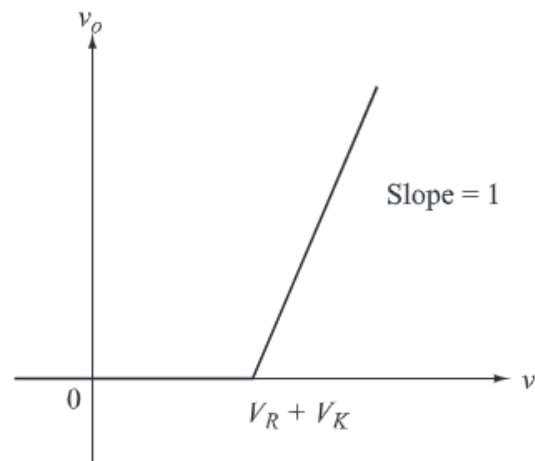


Diode OFF Condition

Apply KVL to the circuit, we get;

$$v_o = iR = 0$$

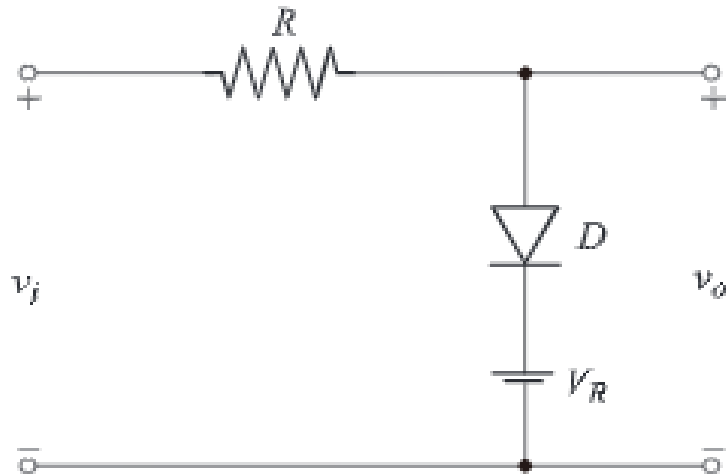
$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 0$$



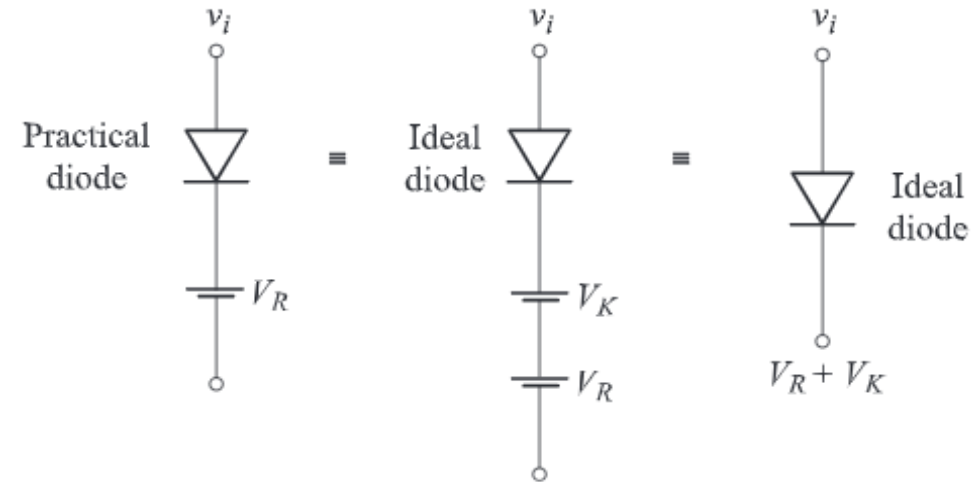
Transfer Characteristics and Output voltage Waveform

Shunt Positive Clippers

In shunt clippers the diode is connected in parallel with the load.



Circuit Diagram



Voltage on Diode Terminals

Shunt Positive Clippers

The diode conducts (ON) for

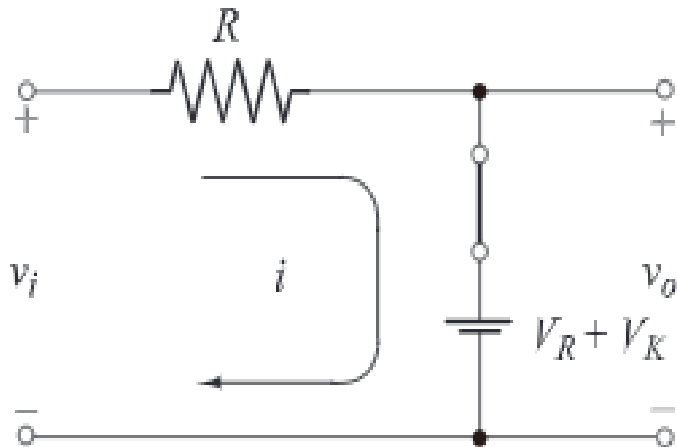
$$v_I \geq V_R + V_K$$

Where,

v_I = Input voltage

V_R = Reference voltage

V_K = Voltage drop across diode



Diode ON Condition

Apply KVL to the circuit, we get;

$$v_O = V_R + V_K \text{ for } v_I \geq V_R + V_K$$

Since $V_R + V_K$ is constant

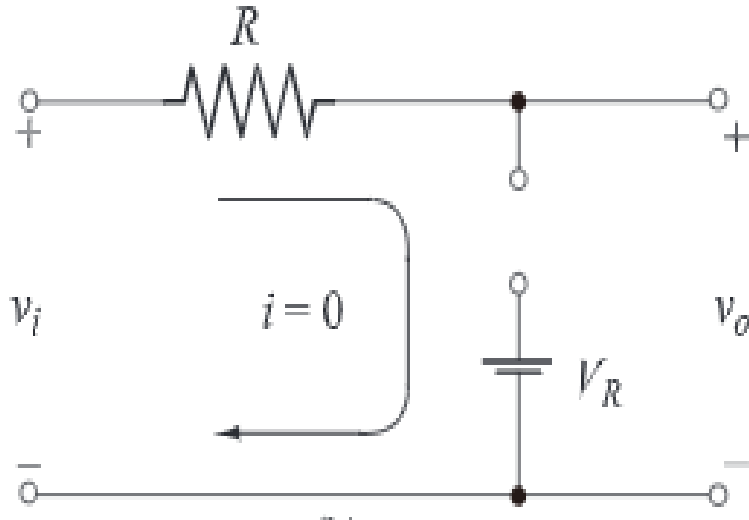
$$\Delta v_o = 0$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 0$$

Shunt Positive Clippers

The diode is in OFF condition for

$$v_i \leq V_R + V_K$$



Diode OFF Condition

Apply KVL to the circuit, we get;

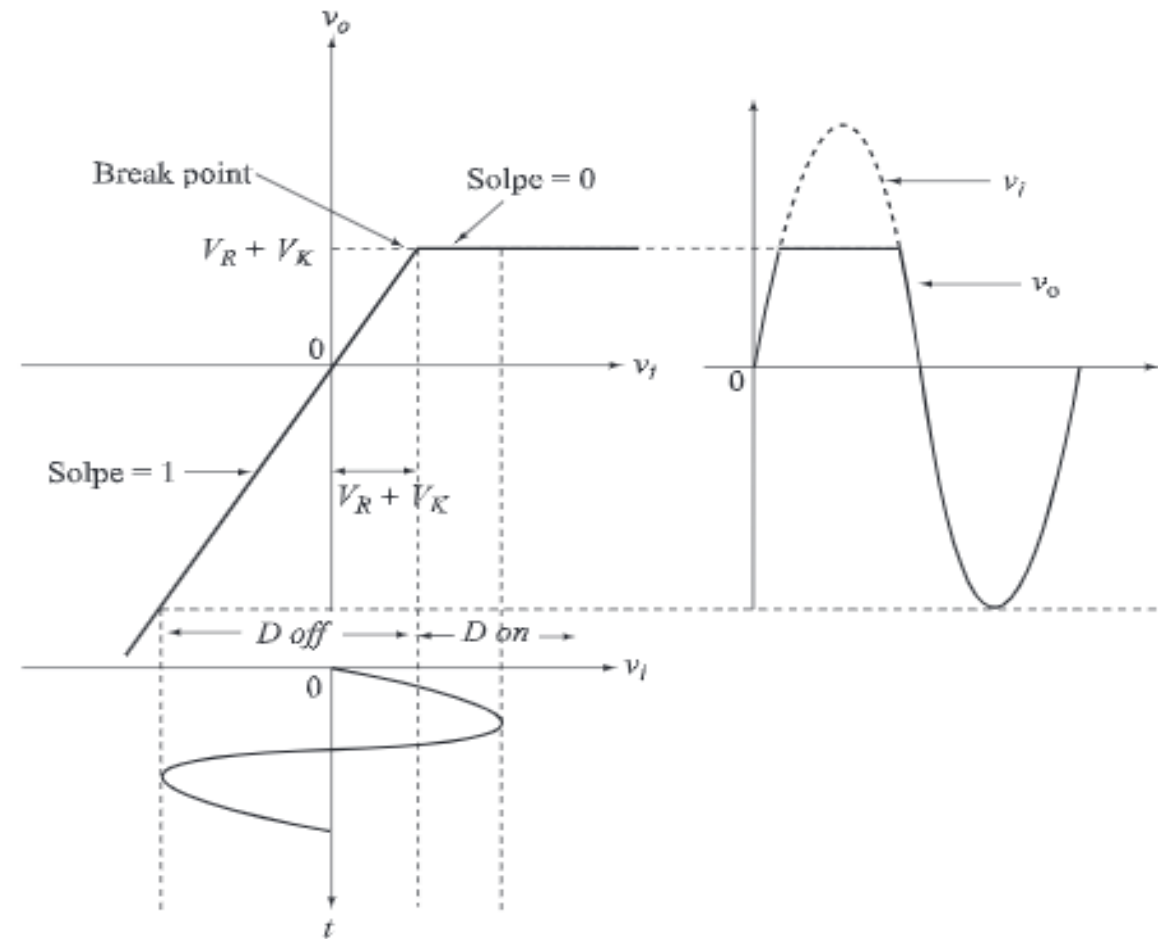
$$v_i - iR - v_o = 0$$

$$v_o = v_i, \text{ for } v_i \leq V_R + V_K$$

$$\Delta v_o = \Delta v_i$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 1$$

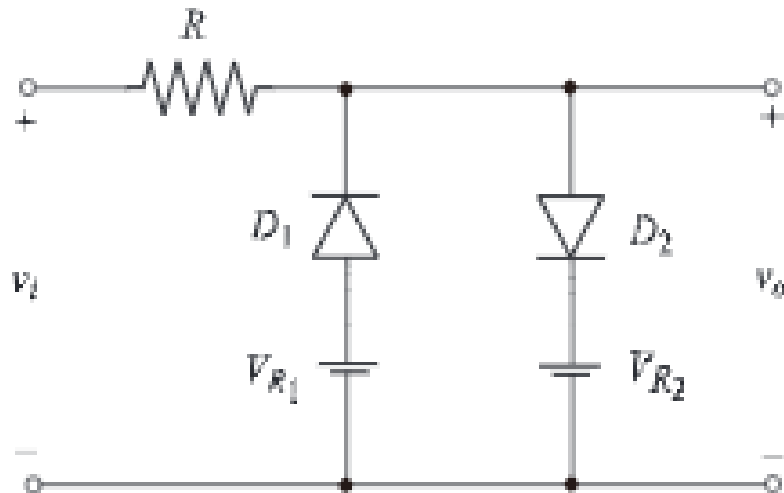
Shunt Positive Clippers



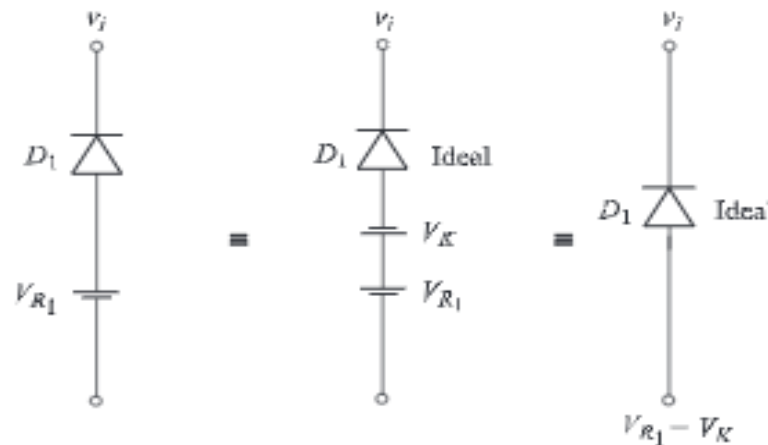
Transfer Characteristics and Output voltage Waveform

Double Ended Clippers

Two shunt clippers can be combined to obtain clipping at two independent levels.



Circuit Diagram



Voltage on Diode (D_1) Terminals

Note:

V_{R1} and V_{R2} are positive
 V_{R1} forward biases D_1
 V_{R2} reverse biases D_2
 $V_{R2} > V_{R1}$

Double Ended Clippers

The diode D_1 conducts (ON) for

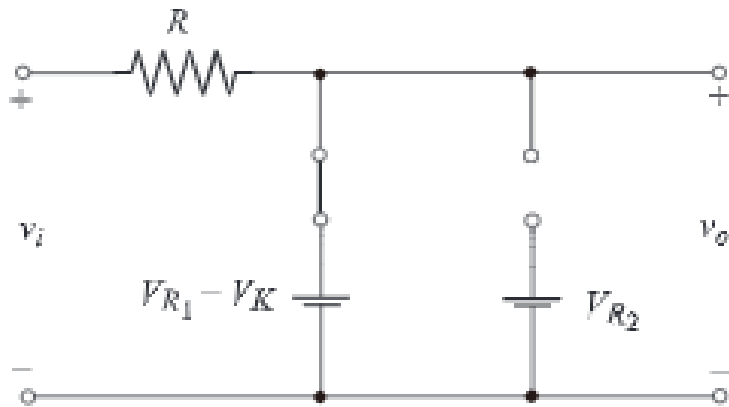
$$v_I \leq V_{R1} - V_K$$

Where,

v_I = Input voltage

V_{R1} = Reference voltage

V_K = Voltage drop across diode



Diode D_1 ON Condition

Apply KVL to the circuit, we get;

$$v_o = V_{R1} - V_K \quad \text{for } v_I \leq V_{R1} - V_K$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 0$$

Double Ended Clippers

The diode D_2 conducts (ON) for

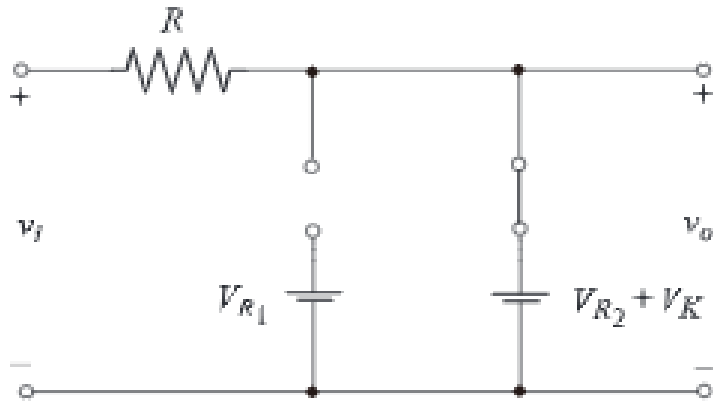
$$v_I \geq V_{R2} + V_K$$

Where,

v_I = Input voltage

V_{R2} = Reference voltage

V_K = Voltage drop across diode



Diode D_2 ON Condition

Apply KVL to the circuit, we get;

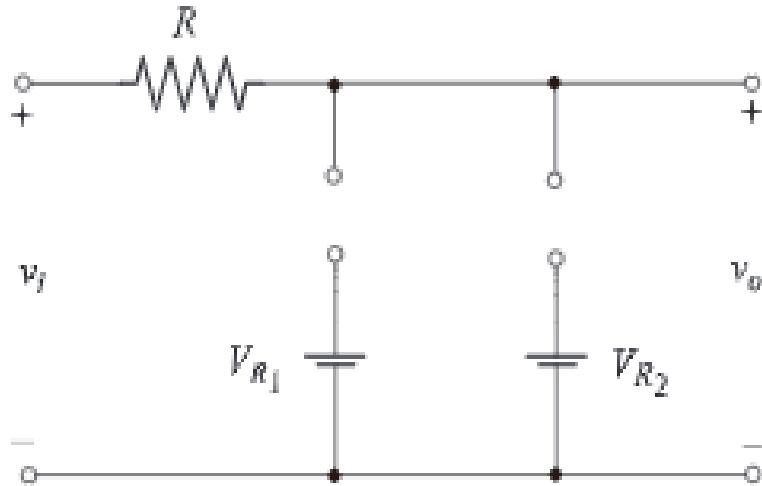
$$v_o = V_{R2} + V_K \text{ for } v_I \geq V_{R2} + V_K$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 0$$

Double Ended Clippers

For $(V_{R1} - V_K) < v_i < (V_{R2} + V_K)$

D_1 & D_2 are in OFF condition



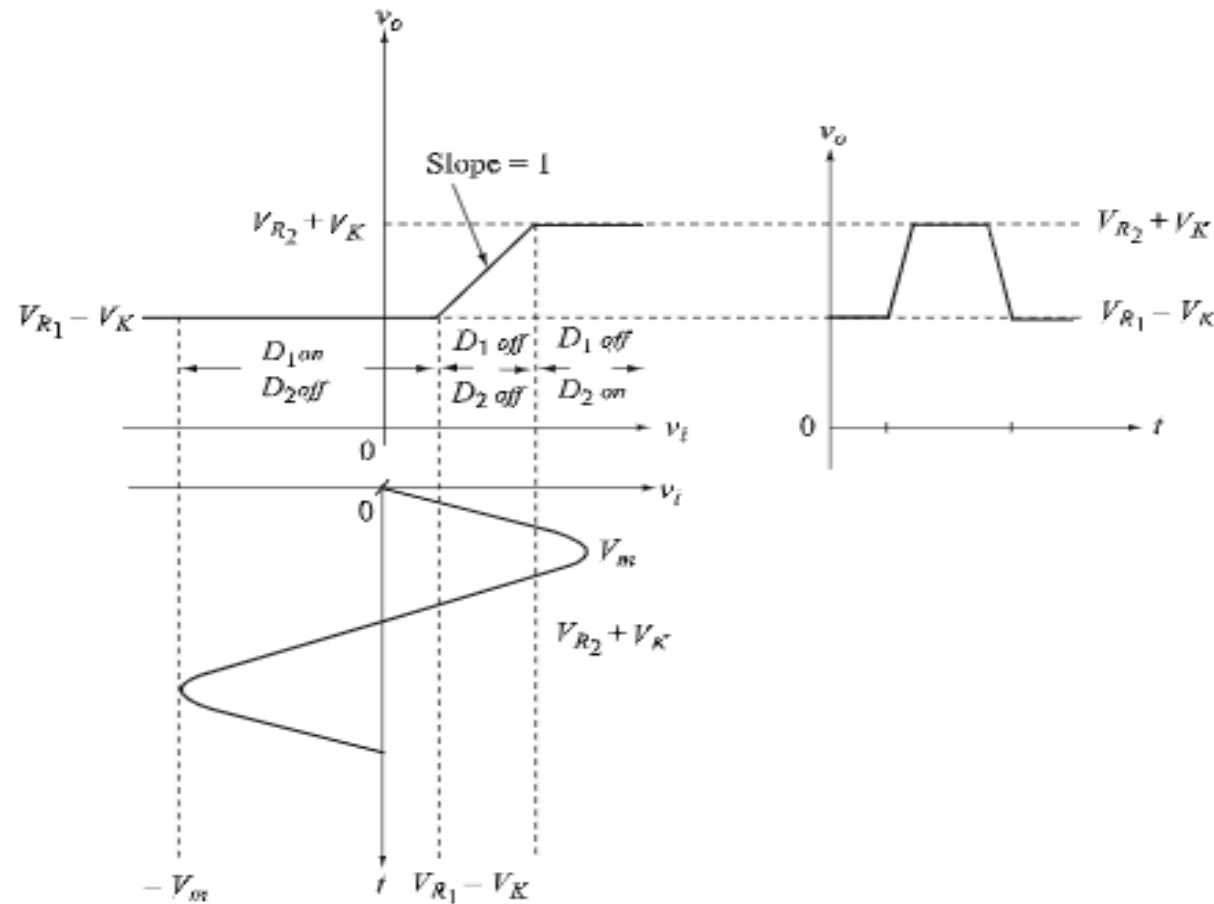
Diode D_1 & D_2 OFF Condition

Apply KVL to the circuit, we get;

$$v_o = v_i$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 1$$

Double Ended Clippers



Transfer Characteristics and Output voltage Waveform

Clamper Circuits

Clamping circuits are **used to add dc level to the input signal**. Clamping circuits are also called as **dc inserters or dc restorers**.

Classification of Clampers

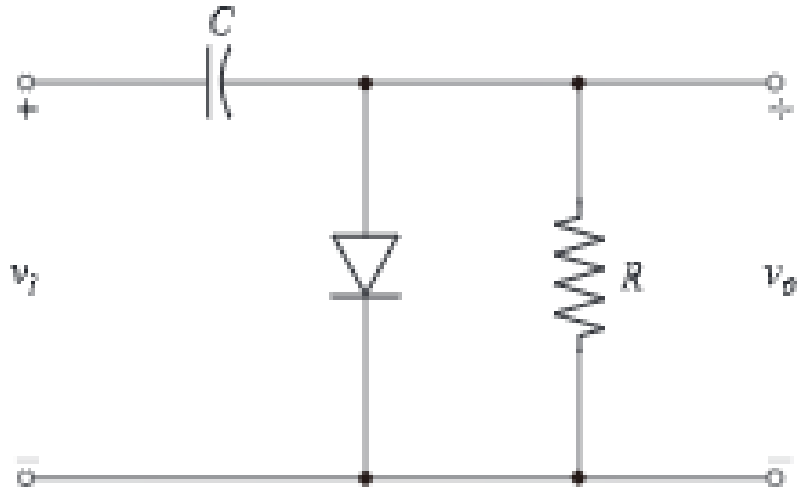
1. Positive Clampers
2. Negative Clampers

Assumptions

1. The time constant $\tau = RC$ is designed to **very large** by selecting large values of **R** and **C**.

Negative Clamper Circuits

A simple negative clamper circuit is used to add a **negative level to the ac output**.



Circuit Diagram

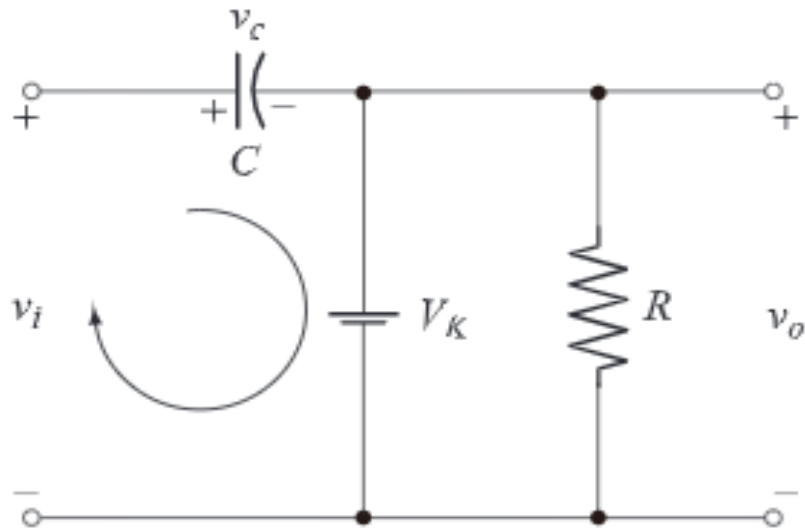
- The diode conducts during **positive half cycle**.
- The capacitor gets charged to a voltage level of **V_M** .
- The charging time constant is **$\tau_f = r_f C$** .

Where,

r_f = diode internal resistance

C = Capacitor

Negative Clamper Circuits



Diode ON condition

Apply KVL to the circuit, we get;

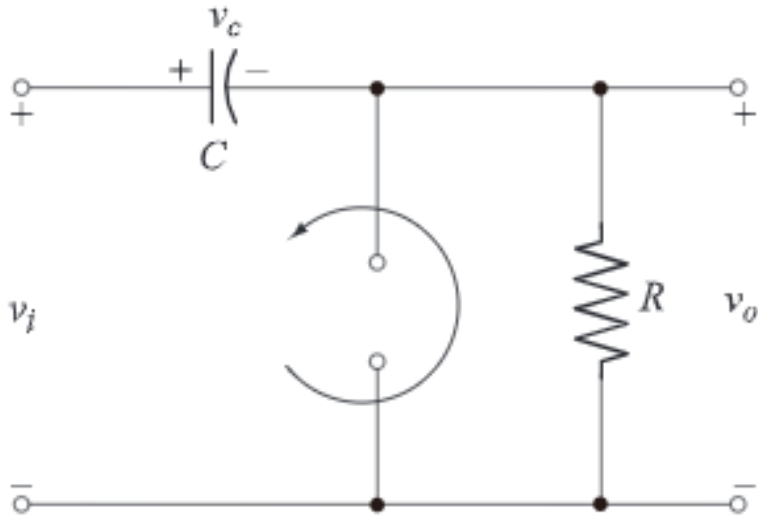
$$v_i - v_c - V_K = 0$$

$$v_c = V_K - v_i$$

When $v_i = V_M$;

$$v_c = V_K - V_M$$

Negative Clamper Circuits



Diode in OFF condition

- The diode is in OFF condition during negative **half cycle**.
- The capacitor gets discharged into R .
- The charging time constant is $\tau = RC$.

Apply the KVL for the circuit we get;

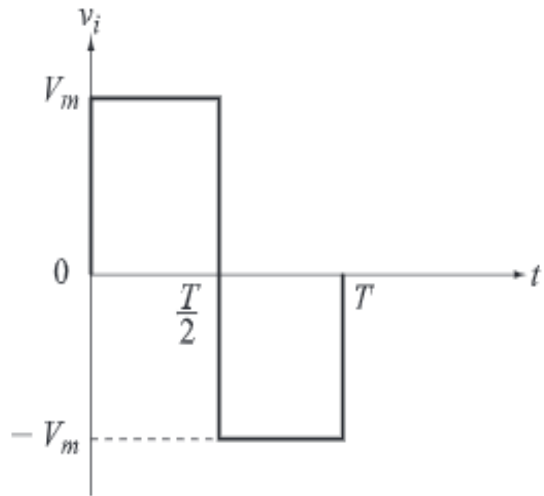
$$v_i - v_c - v_o = 0$$

$$v_o = v_i - v_c$$

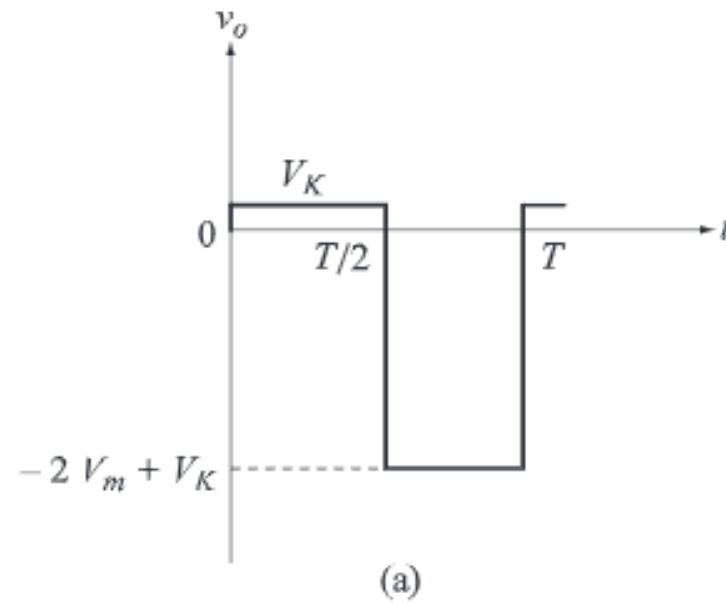
When $v_c = V_M - V_K$;

$$v_o = v_i - [V_M - V_K]$$

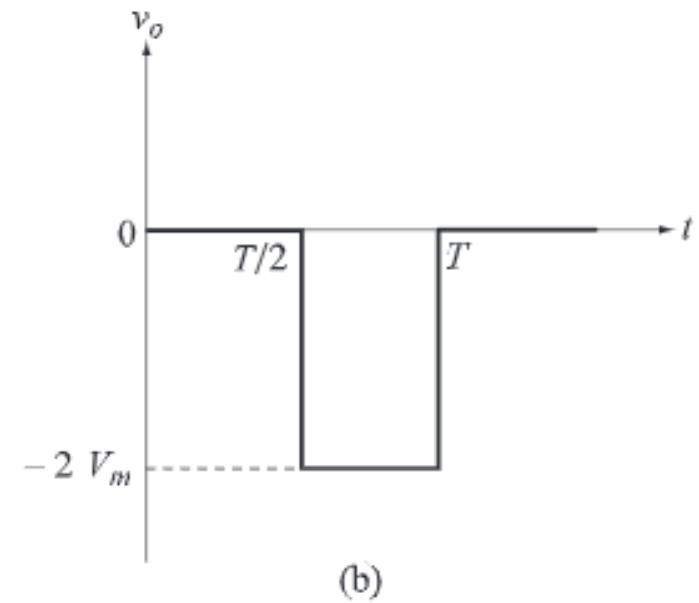
Negative Clamper Circuits



Input Signal



Output waveform for Practical diode



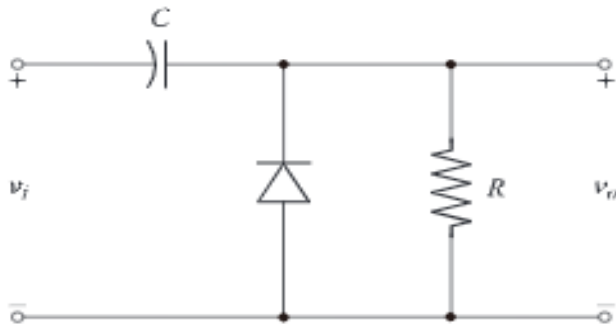
Output waveform for Ideal diode

Negative Clamper Circuits

<i>Input voltage level v_i</i>	<i>Output voltage level</i>	
	<i>Practical diode</i> $v_o = v_i - [V_m - V_K]$	<i>Ideal diode</i> $v_o = v_i - V_m$
0	$-[V_m - V_K]$	$-V_m$
V_m	V_K	0
$-V_m$	$-2V_m + V_K$	$-2V_m$

Positive Clamper Circuits

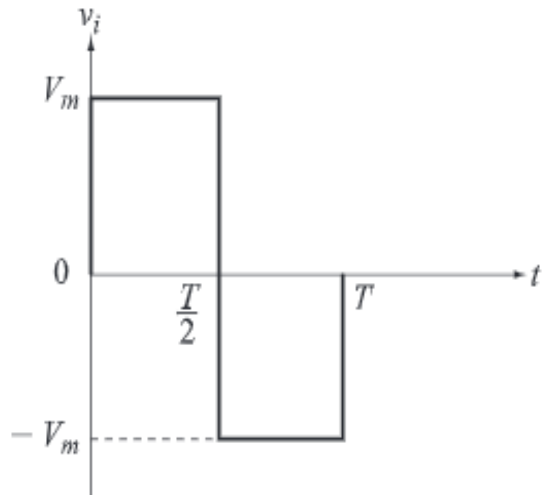
The positive clamper circuit adds the **positive dc level to the input signal**.



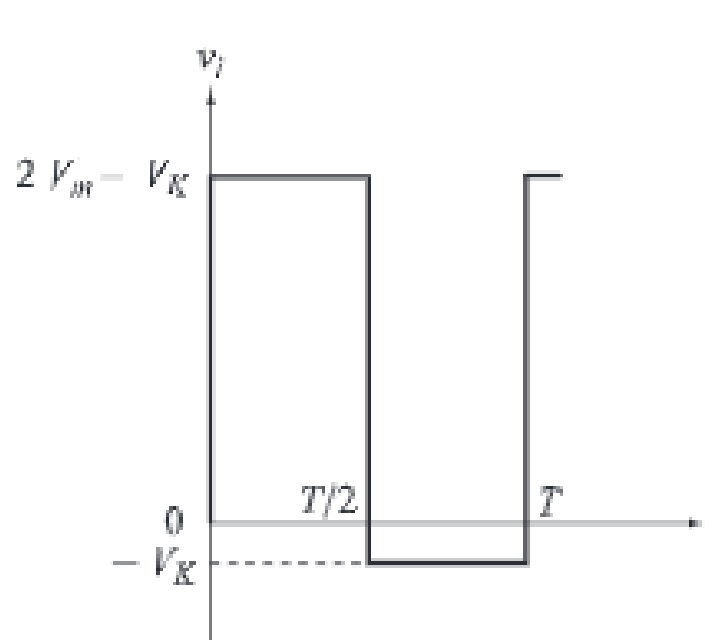
Circuit Diagram

- The diode conducts during **negative half cycle**.
 - The capacitor gets charged to a voltage level of **V_M** .
 - The charging time constant is **$\tau = RC$** .
-
- The diode is in OFF condition during positive **half cycle**.
 - The capacitor gets discharged into **R** .

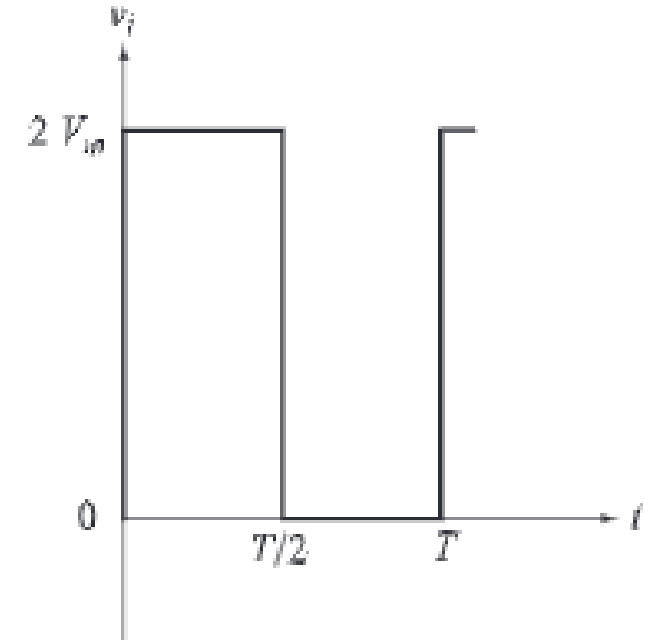
Positive Clamper Circuits



Input Signal



Output waveform for Practical diode



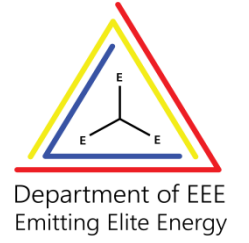
Output waveform for Ideal diode

Positive Clamper Circuits

<i>Input voltage level v_i</i>	<i>Output voltage level</i>	
	<i>Practical diode</i> $v_o = v_i + [V_m - V_K]$	<i>Ideal diode</i> $v_o = v_i + V_m$
0	$V_m - V_K$	V_m
V_m	$2V_m - V_K$	$2V_m$
$-V_m$	$-V_K$	0



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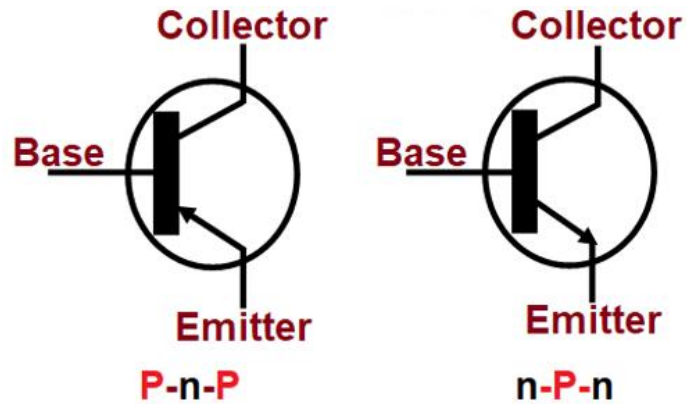


Department of EEE
Emitting Elite Energy

Transistor Biasing

Transistor Biasing

Bipolar Junction Transistor (BJT)



Junctions of Transistor

- ☐ Collector – Base Junction
- ☐ Base- Emitter Junction

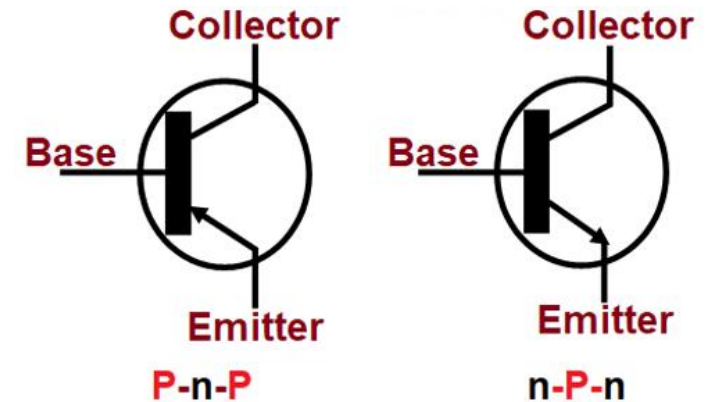
The biasing of a bipolar junction transistor is to establish the desired value of **collector to emitter voltage V_{CE} and Collector current I_C** .

The values of V_{CE} and I_C together are known as **operating point or quiescent point (Q-point)**

Transistor Biasing

Operating regions of BJT

Operating Regions	Emitter-Base Junction	Collector-Base Junction	Function
Cut-off region	Reverse Biased	Reverse Biased	OFF Switch
Active region	Forward Biased	Reverse Biased	Amplifier
Saturation region	Forward Biased	Forward Biased	ON Switch



Biasing Configurations of BJT

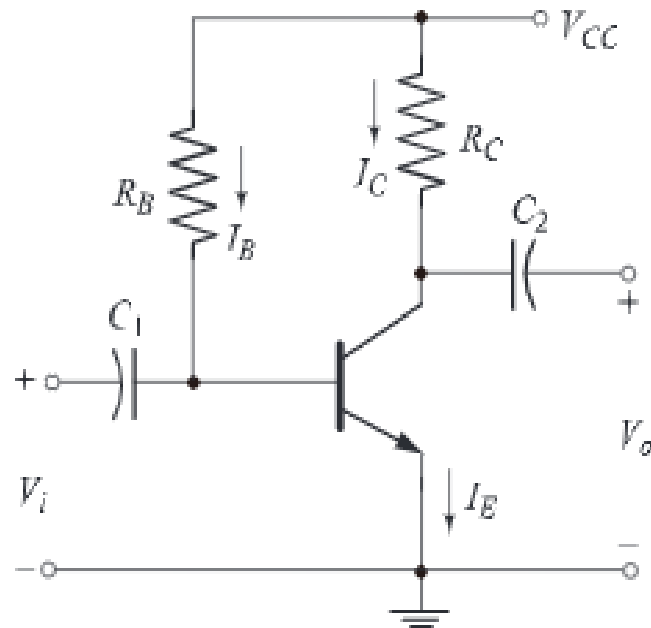
1. Fixed bias configuration
2. Emitter stabilized bias configuration
3. Voltage divider bias configuration

Parameters of BJT

1. Gain
2. Input Impedance
3. Output Impedance

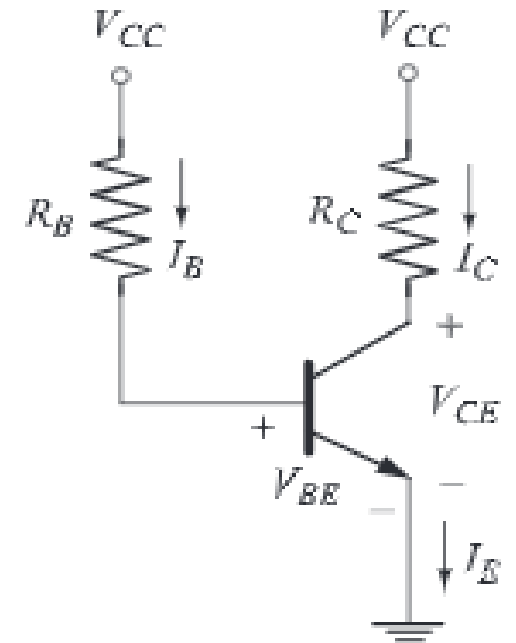
Fixed Bias Configuration

For the dc analysis we can replace capacitor with an **open circuit** (since capacitor blocks dc) because the reactance of capacitor is infinity



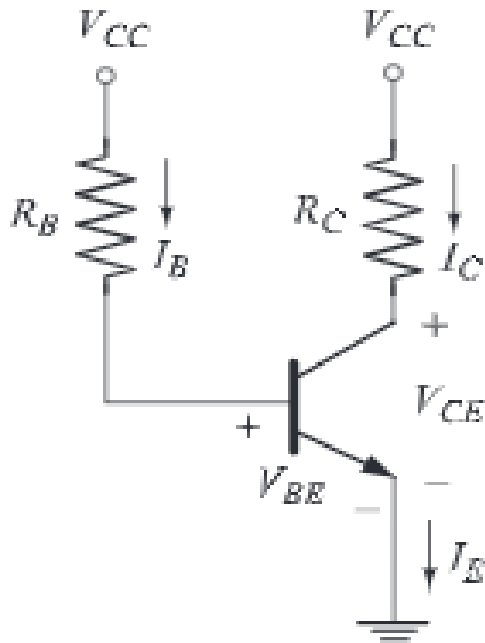
Circuit Diagram

C_1 & C_2 = Coupling Capacitors
 V_{CC} = Supply voltage
 R_B = Base Resistance
 R_C = Collector Resistance



DC equivalent circuit of fixed bias

Fixed Bias Configuration



DC equivalent circuit of fixed bias

Apply KVL to the base circuit we get;

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

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

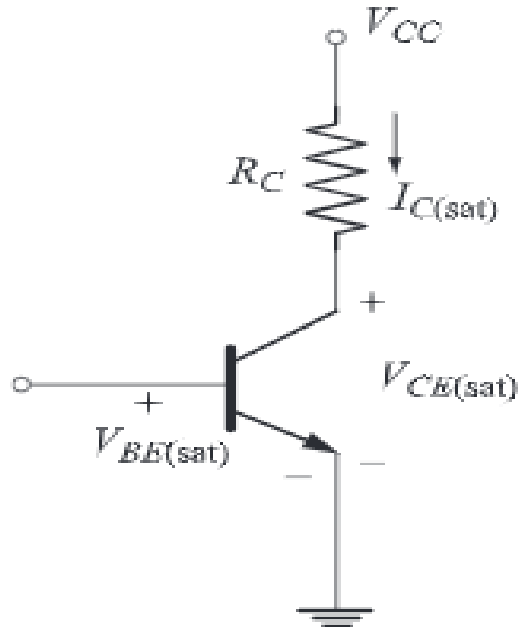
$$I_C = \beta I_B$$

Where, β = dc current gain

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

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

Fixed Bias Configuration



Transistor operating in Saturation region

Apply KVL to the base circuit we get;

$$V_{CC} - I_{C(sat)}R_C - V_{CE(sat)} = 0$$

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C}$$

But $V_{CE(sat)} \approx 0$

$$I_{C(sat)} \approx \frac{V_{CC}}{R_C}$$

Fixed Bias Configuration: Numericals

1. For the fixed bias circuit shown, assuming $V_{BE} = 0.7V$ and $\beta = 60$ find:

- Quiescent values of base and collector currents.
- Quiescent value of V_{CE} .
- Base-ground and collector-ground voltages.
- Base-collector voltage
- Quiescent values of I_C and V_{CE} for $\beta = 110$.

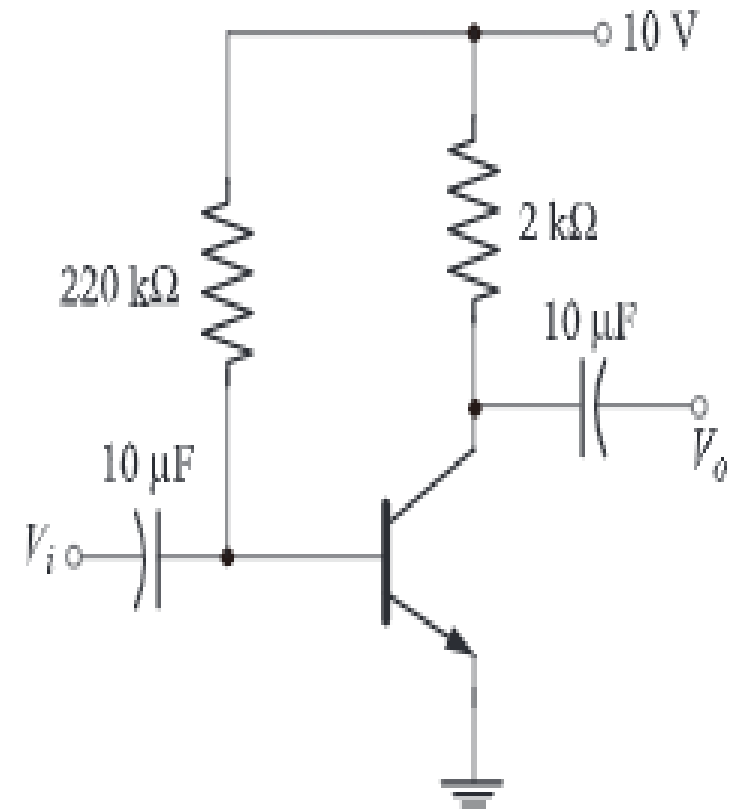
Given Data:

$$V_{CC} = 10V$$

$$R_B = 220k\Omega$$

$$R_C = 2k\Omega$$

$$C_1 = C_2 = 10\mu F$$



Circuit Diagram

Fixed Bias Configuration: Numericals

Coupling Capacitors acts as open circuit.

a. Quiescent values of base current and collector current.

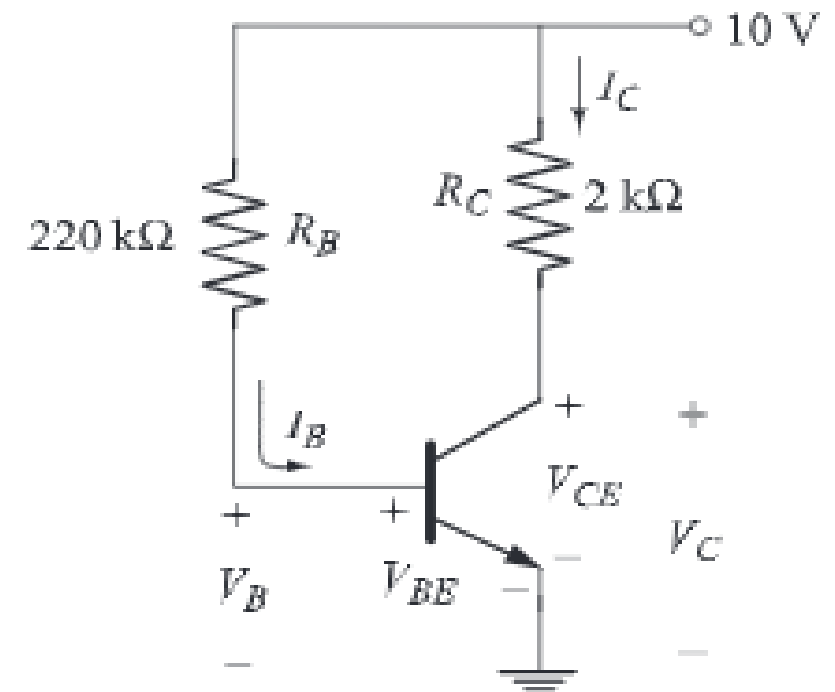
$$I_{BQ} = \frac{V_{CC} - V_{BE}}{R_B} = \frac{10\text{V} - 0.7\text{V}}{220\text{k}\Omega} = 42.27\text{ }\mu\text{A}$$

$$I_{CQ} = \beta I_{BQ} = 60 \times 42.27\text{ }\mu\text{A} = 2.54\text{ mA}$$

b. Quiescent value of V_{CE} .

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

$$V_{CEQ} = V_{CC} - I_{CQ} R_C = 10 - (2.54\text{ mA})(2\text{ k}\Omega) = 4.92\text{ V}$$



DC equivalent circuit of fixed bias

Fixed Bias Configuration: Numericals

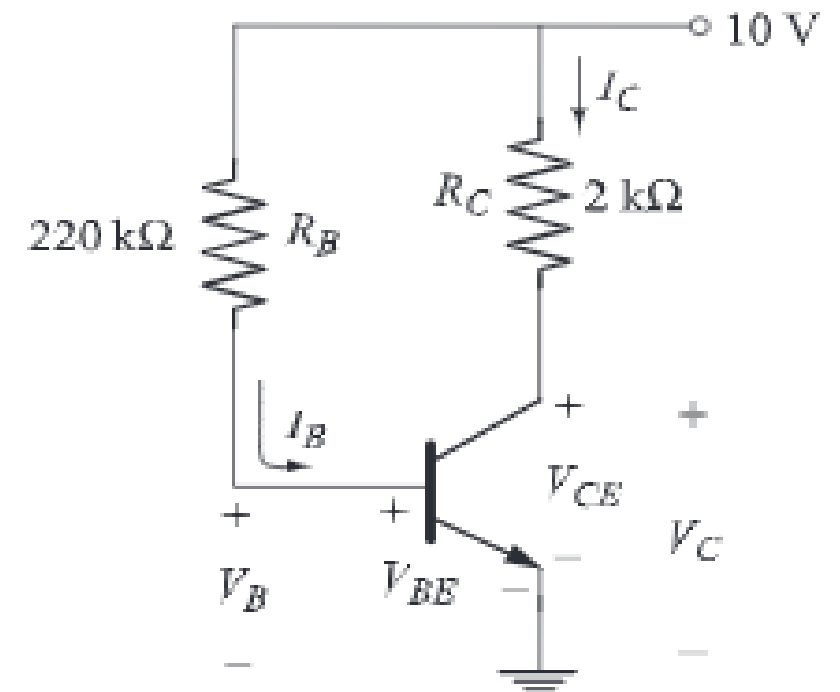
c. Base and collector voltages with respect to ground.

$$V_B = V_{BE} = 0.7 \text{ V}$$

$$V_C = V_{CE} = 4.92 \text{ V}$$

d. Base-collector voltage.

$$V_{BC} = V_B - V_C = 0.7 \text{ V} - 4.92 \text{ V} = -4.22 \text{ V}$$



DC equivalent circuit of fixed bias

Fixed Bias Configuration: Numericals

e. When $\beta = 110$.

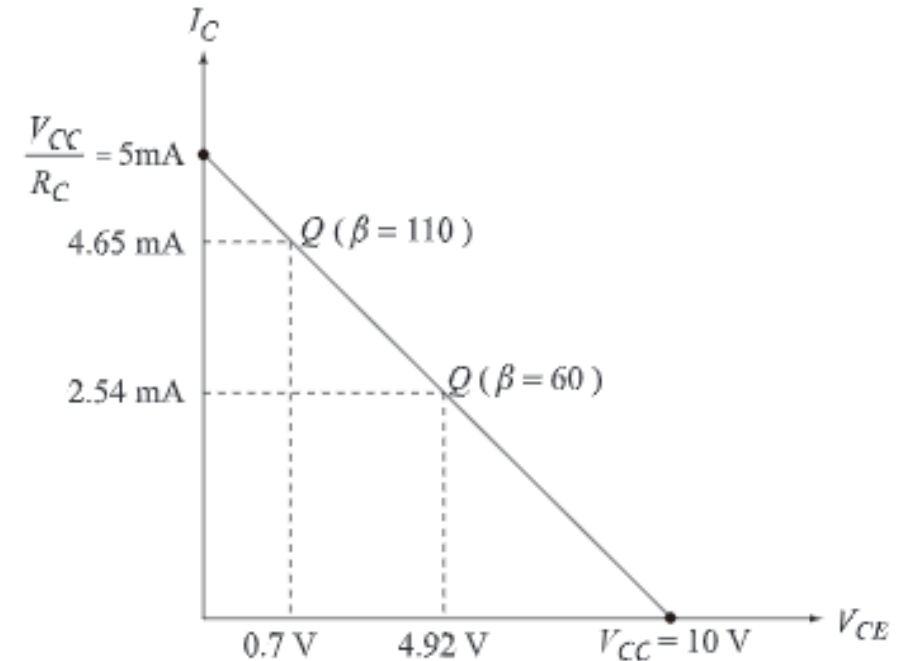
I_{BQ} is not affected by change in β .

$$I_{BQ} = 42.27 \mu\text{A} \quad [\text{as obtained in part (a)}]$$

$$I_{CQ} = \beta I_{BQ} = 110 \times 42.27 \mu\text{A} = 4.65 \text{ mA}$$

$$V_{CEQ} = V_{CC} - I_{CQ} R_C = 10 \text{ V} - (4.65 \text{ mA} \times 2 \text{ k}\Omega) = 0.7 \text{ V}$$

β	I_{BQ}	I_{CQ}	V_{CEQ}
60	$42.27 \mu\text{A}$	2.54 mA	4.92 V
110	$42.27 \mu\text{A}$	4.65 mA	0.7 V



Fixed Bias Configuration: Numericals

2. For the fixed bias circuit shown, find collector current, collector resistance, base resistance and V_{CE} . Assume $\beta = 80$ and $V_{BE} = 0.7V$

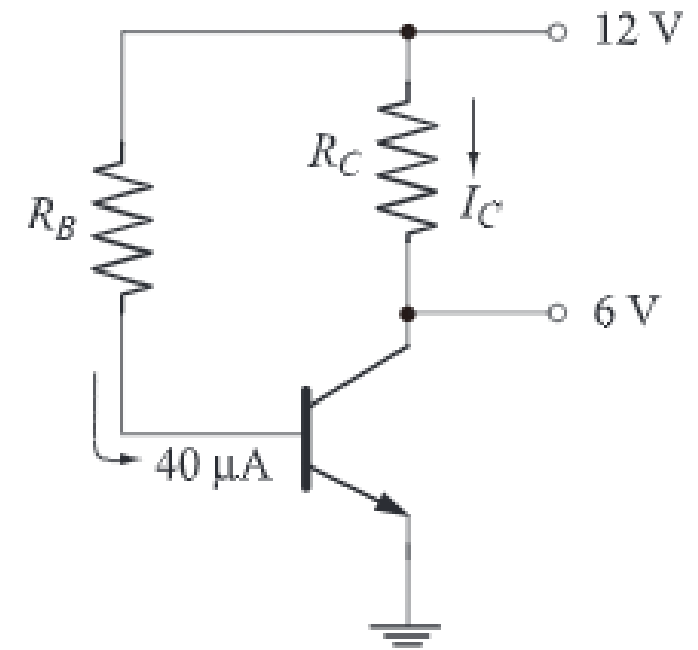
Given Data:

$V_{CC} = 12V$, $I_B = 40 \mu A$, $V_C = 6V$

a. Collector Current

$$I_C = \beta * I_B$$

$$I_C = (80) * (40 \mu A) = 3.2 \text{ mA}$$



Circuit Diagram

Fixed Bias Configuration: Numericals

Given Data:

$$V_{CC} = 12V, I_B = 40 \mu A, V_C = 6V = V_{CE}$$

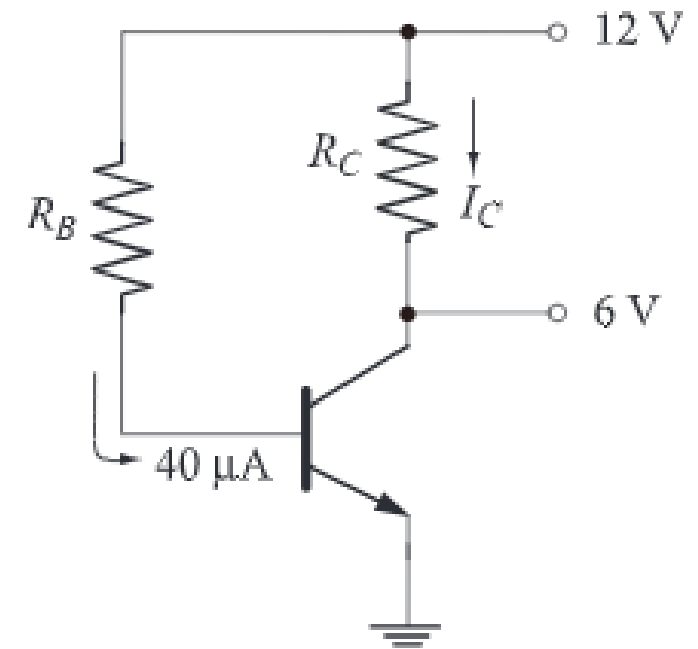
b. Collector Resistance

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

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

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

$$R_C = \frac{12 - 6}{3.2mA} = 1.875k\Omega$$



Circuit Diagram

Fixed Bias Configuration: Numericals

Given Data:

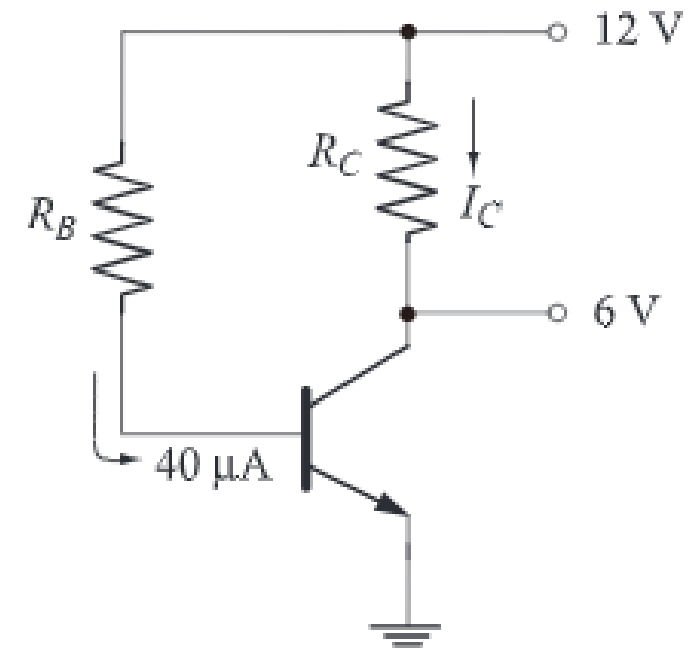
$$V_{CC} = 12V, I_B = 40 \mu A, V_C = 6V = V_{CE}$$

c. Base Resistance

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

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

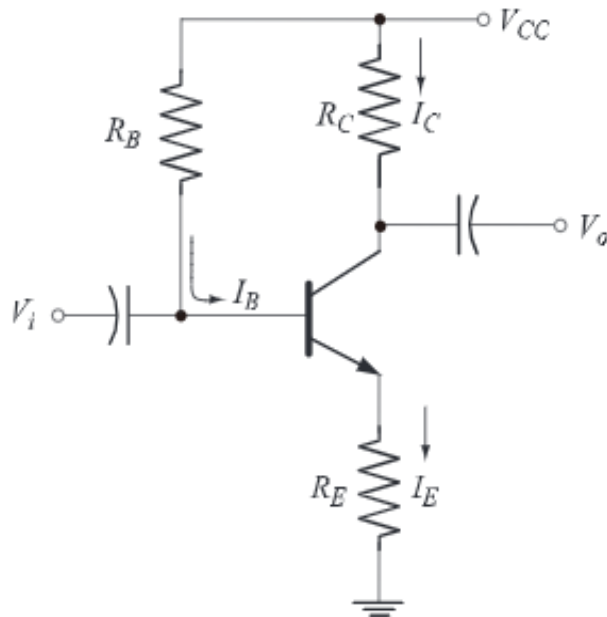
$$R_B = \frac{12 - 0.7}{40 \mu A} = 282.5 k\Omega$$



Circuit Diagram

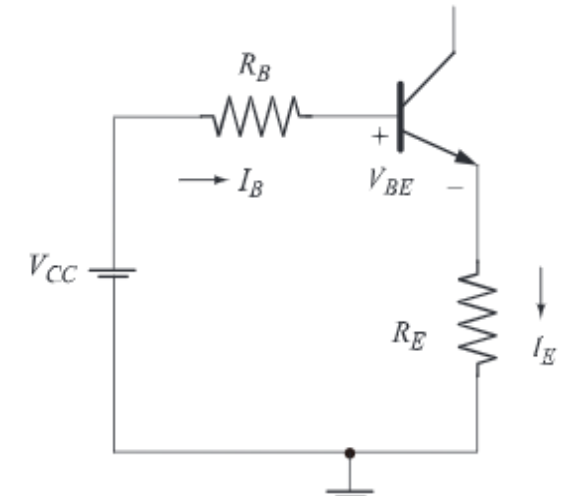
Emitter Stabilized Bias Configuration

For the dc analysis we can replace capacitor with an **open circuit** (since capacitor blocks dc) because the reactance of capacitor is infinity



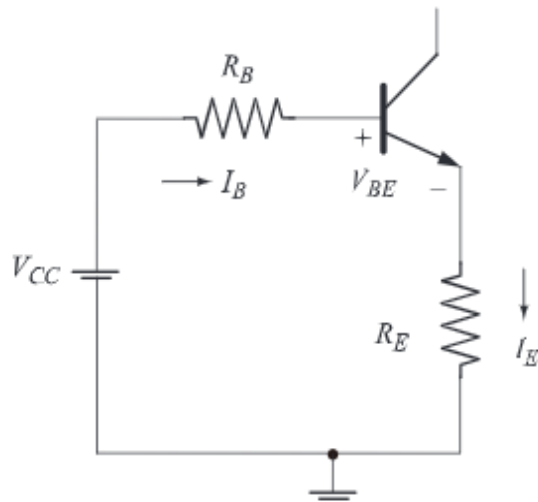
Circuit Diagram

C_1 & C_2 = Coupling Capacitors
 V_{CC} = Supply voltage
 R_B = Base Resistance
 R_C = Collector Resistance
 R_E = Emitter Resistance



Base-Emitter circuit

Emitter Stabilized Bias Configuration



Base-Emitter circuit

Apply KVL to the base circuit we get;

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

$$I_E = I_C + I_B$$

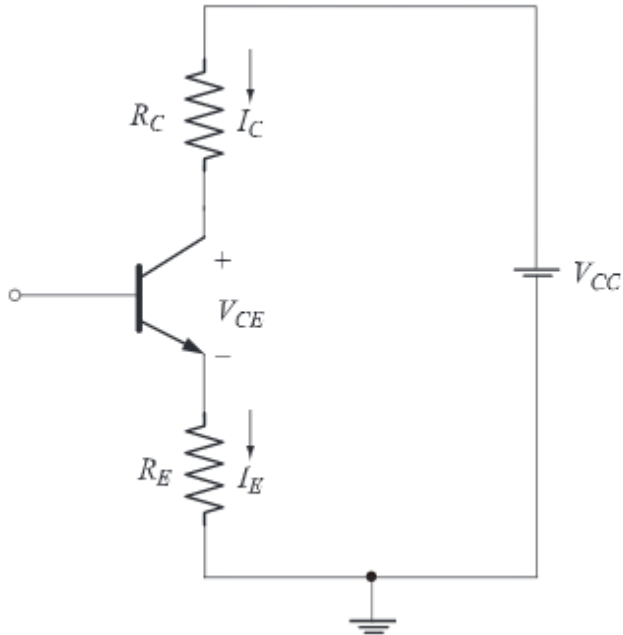
$$I_C = \beta I_B$$

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

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

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

Emitter Stabilized Bias Configuration



Collector-Emitter circuit

Apply KVL to the base circuit we get;

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

$$I_E = I_C$$

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

Voltage across emitter:

$$V_E = I_E R_E$$

$$V_C = V_{CE} + I_E R_E$$

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

Emitter Stabilized Bias Configuration

1. For the emitter-bias shown using silicon transistor with $V_{BE} = 0.7\text{ V}$ and $\beta = 60$, find;

- Base current and collector current
- Collector-Emitter voltage
- Collector, emitter and base voltages to ground
- Base-collector voltage

Given Data:

$$V_{CC} = 20\text{V}$$

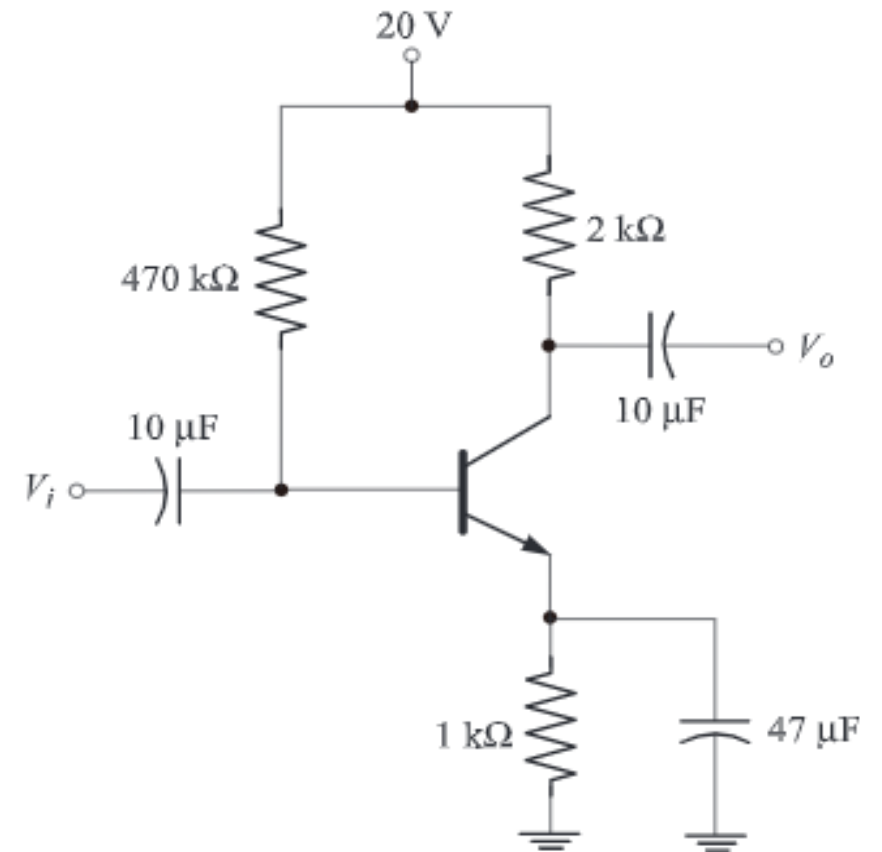
$$R_B = 470\text{k}\Omega$$

$$R_C = 2\text{k}\Omega$$

$$C_1 = C_2 = 10\mu\text{F}$$

$$R_E = 1\text{k}\Omega$$

$$C_E = 47\mu\text{F}$$



Circuit Diagram

Emitter Stabilized Bias Configuration

For the dc analysis we can replace capacitor with an **open circuit (since capacitor blocks dc)** because the reactance of capacitor is infinity

Given Data:

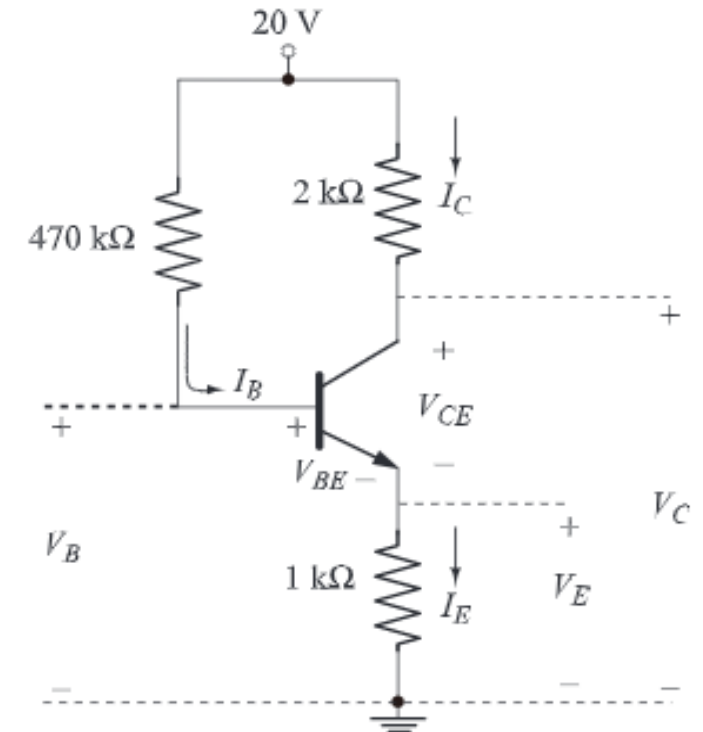
$V_{CC} = 20V$, $R_B = 470k\Omega$, $R_C = 2k\Omega$, $C_1 = C_2 = 10\mu F$
 $R_E = 1k\Omega$, $C_E = 47\mu F$

a. Base current and collector current

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

$$I_B = \frac{20 - 0.7}{470k + (1 + 60)1k} = 36.34\mu A$$

$$I_C = \beta * I_B = 60 * 36.34\mu = 2.18mA$$



DC Equivalent Circuit Diagram

Emitter Stabilized Bias Configuration

Given Data:

$$V_{CC} = 20V, R_B = 470k\Omega, R_C = 2k\Omega, C_1 = C_2 = 10\mu F, R_E = 1k\Omega, C_E = 47\mu F$$

b. Collector-emitter voltage

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

$$V_{CE} = 20 - 2.18m(2k + 1k) = 13.46V$$

c. Collector, emitter and base voltages to ground

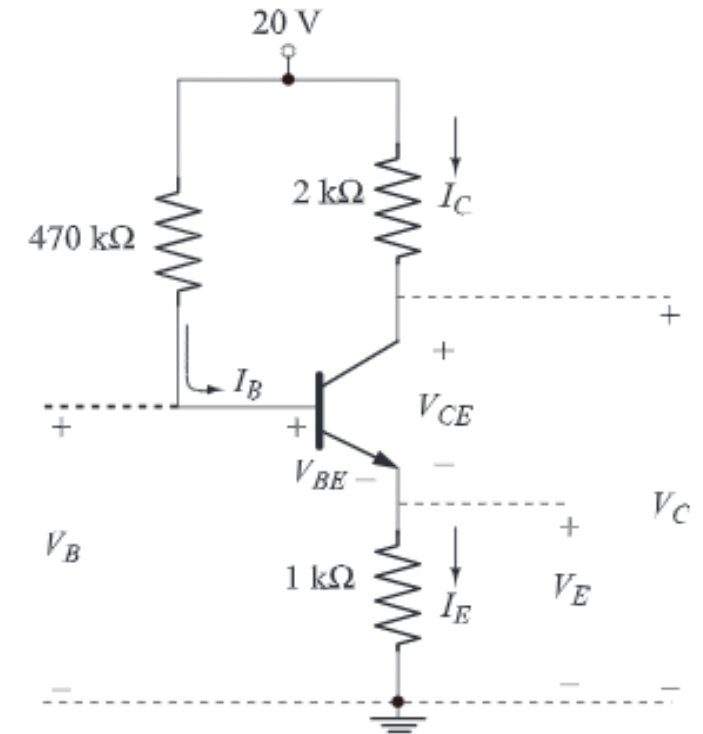
$$V_C = V_{CC} - I_C R_C = 20 - (2.18m * 2k) = 15.64V$$

$$V_E = V_C - V_{CE} = 15.64 - 13.46 = 2.18V$$

$$V_B = V_{BE} + V_E = 0.7 + 2.18 = 2.88V$$

d. Base-collector voltage

$$V_{BC} = V_B - V_C = 2.88 - 15.64 = -12.76V$$



DC Equivalent Circuit Diagram

Emitter Stabilized Bias Configuration

2. For the emitter bias circuit shown using silicon transistor $V_{BE} = 0.7\text{ V}$ and $\beta = 100$. Find;

- Quiescent values of base current, collector current and collector to emitter voltage.**
- Voltage at collector, base and emitter with respect to ground.**

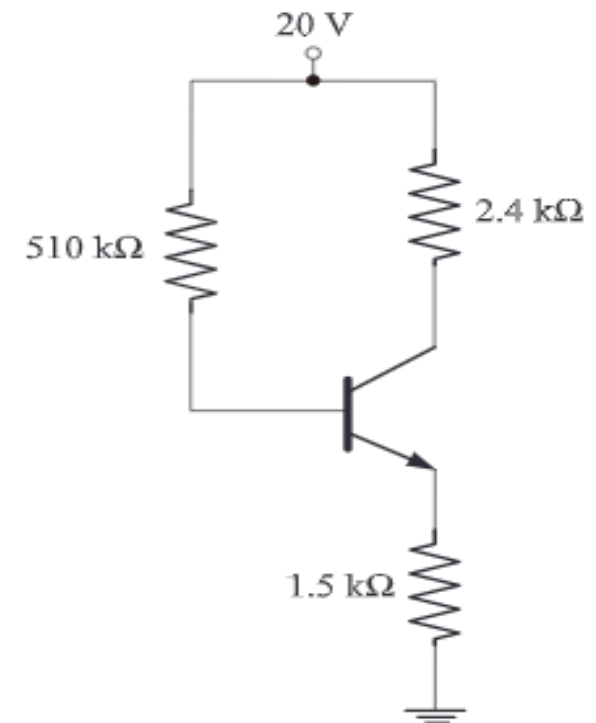
Given Data:

$$V_{CC} = 20\text{V}$$

$$R_B = 510\text{k}\Omega$$

$$R_C = 2.4\text{k}\Omega$$

$$R_E = 1.5\text{k}\Omega$$



Circuit Diagram

Emitter Stabilized Bias Configuration

Given Data:

$$V_{CC} = 20V, R_B = 510k\Omega, R_C = 2.4k\Omega, R_E = 1.5k\Omega$$

a. Base current, collector current and V_{CE} .

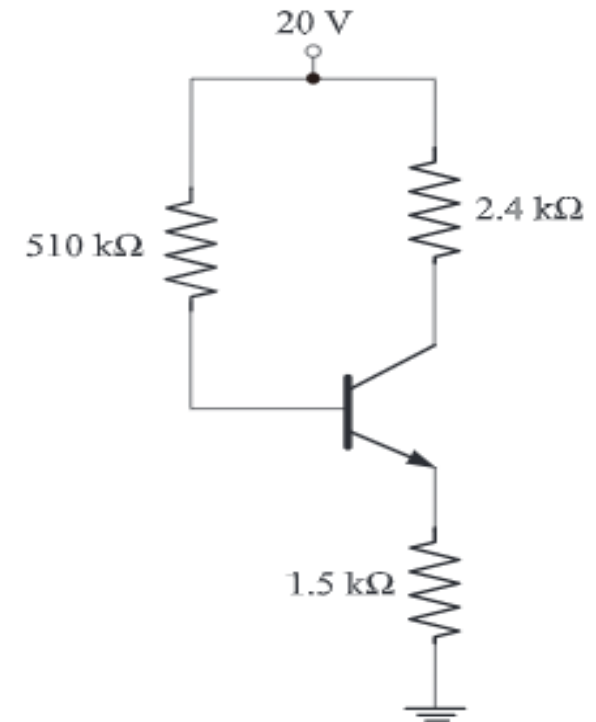
$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (1 + \beta)R_E}$$

$$I_B = \frac{20 - 0.7}{510k + (1 + 100)1.5k} = 29.18\mu A$$

$$I_C = \beta * I_B = 100 * 29.18\mu = 2.92mA$$

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

$$V_{CE} = 20 - 2.92m(2.4k + 1.5k) = 8.61V$$



Circuit Diagram

Emitter Stabilized Bias Configuration

Given Data:

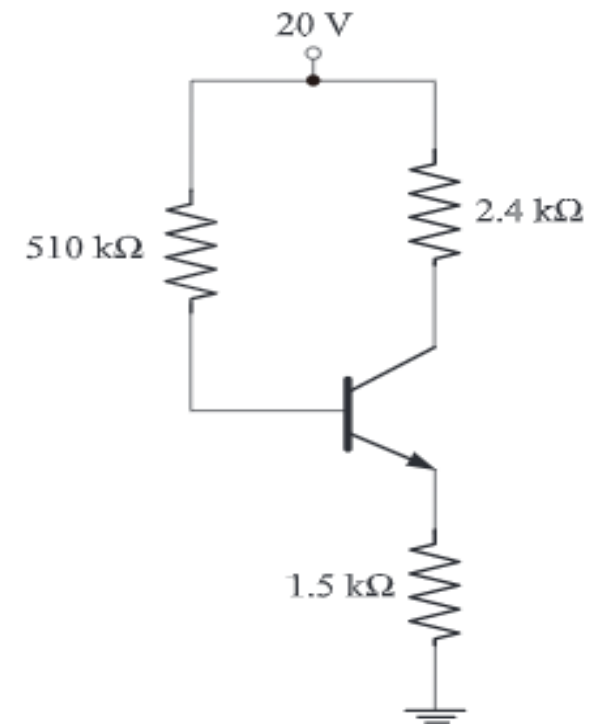
$$V_{CC} = 20V, R_B = 510k\Omega, R_C = 2.4k\Omega, R_E = 1.5k\Omega$$

b. Collector, emitter and base voltages to ground

$$V_C = V_{CC} - I_C R_C = 20 - (2.92m * 2.4k) = 13V$$

$$V_E = V_C - V_{CE} = 13 - 8.61 = 4.39V$$

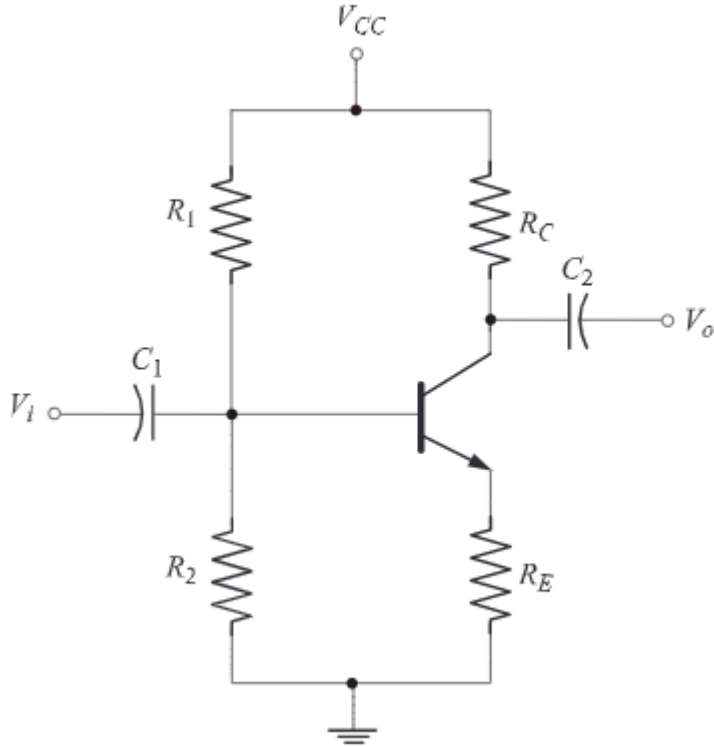
$$V_B = V_{BE} + V_E = 0.7 + 4.39 = 5.09V$$



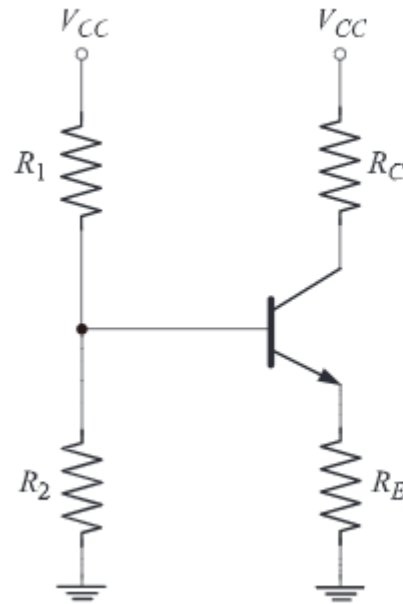
Circuit Diagram

Voltage Divider Bias Configuration

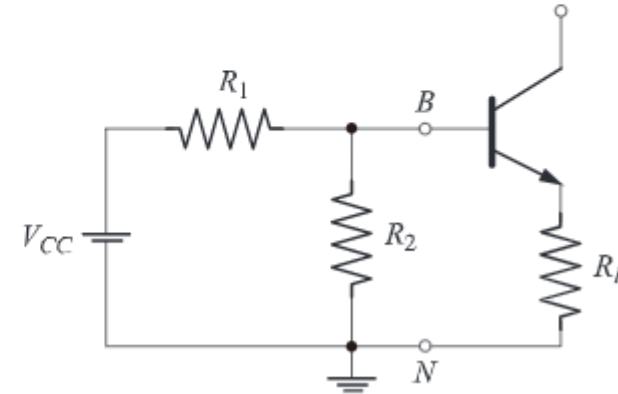
For the dc analysis we can replace capacitor with an **open circuit** (since capacitor blocks dc) because the reactance of capacitor is infinity



Circuit Diagram



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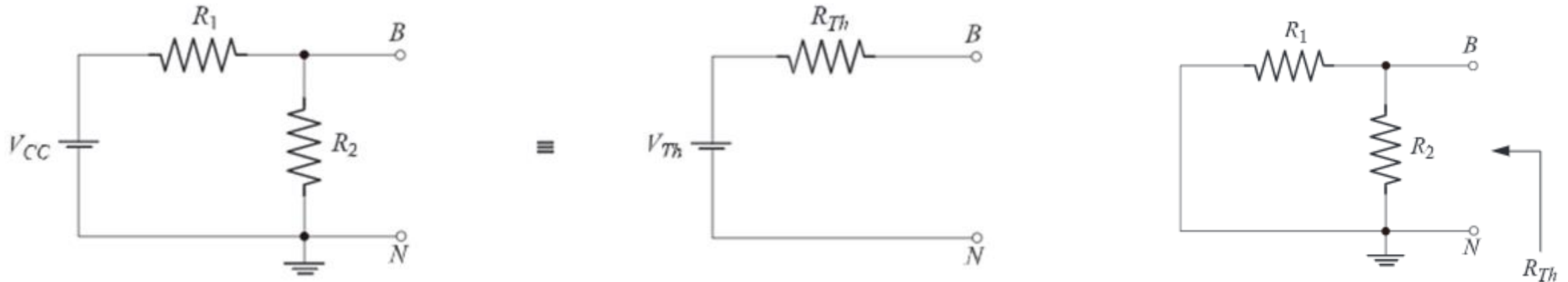


Base circuit

The two methods of Analysis:

1. **Exact Analysis Method**
2. **Approximate Analysis Method**

Voltage Divider Bias Configuration: Exact Analysis



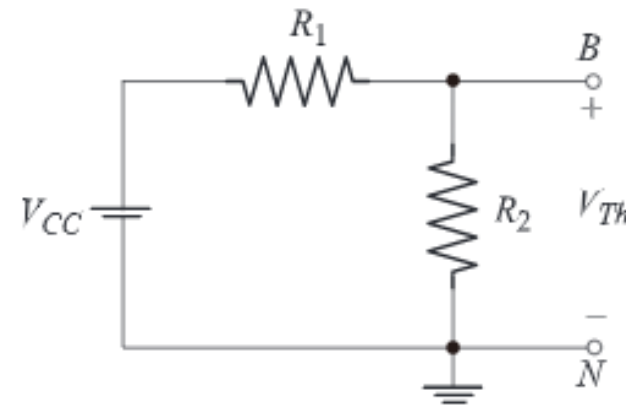
Thevenin Equivalent Circuit

Determination of R_{Th}

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

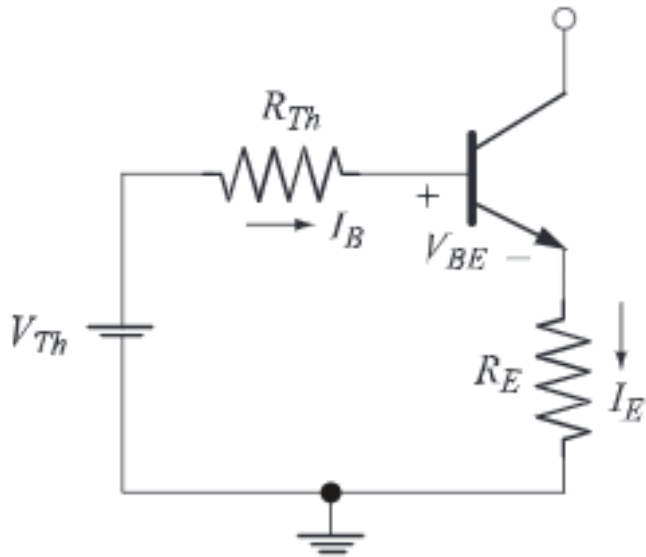
$$R_{Th} = \frac{R_1 R_2}{R_1 + R_2}$$

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



Determination of V_{Th}

Voltage Divider Bias Configuration: Exact Analysis



Base Circuit with Thevenin Equivalent

Apply KVL to the base circuit we get;

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

$$V_{Th} = I_B R_{Th} + V_{BE} + I_E R_E$$

$$I_E = I_C + I_B$$

$$I_C = \beta I_B$$

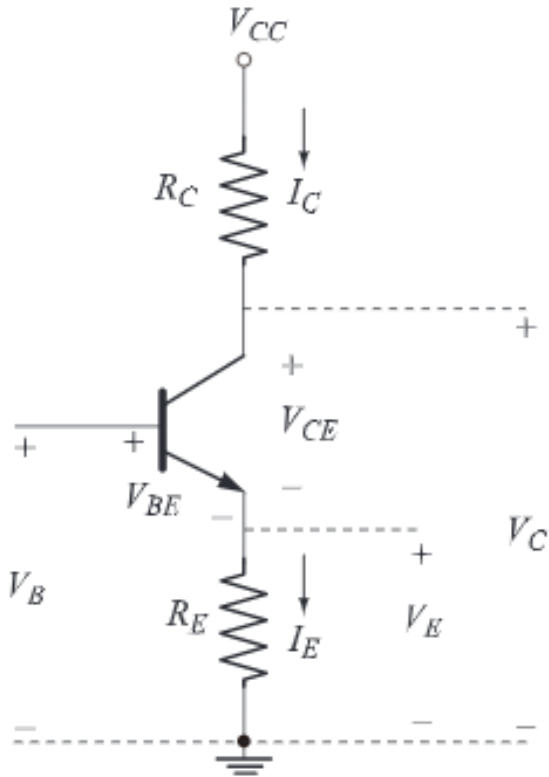
$$I_E = \beta I_B + I_B = (1 + \beta) I_B$$

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

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

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

Voltage Divider Bias Configuration: Exact Analysis



Collector Circuit

Apply KVL to the base circuit we get;

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

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

$$I_E = I_C$$

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

Voltage across emitter:

$$V_E = I_E R_E$$

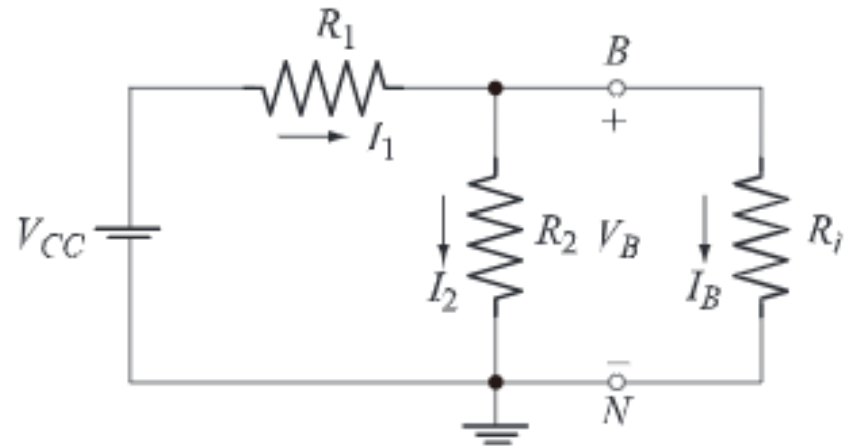
Collector to ground Voltage:

$$V_C = V_{CE} + I_E R_E = V_{CE} + V_E$$

Base to ground Voltage:

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

Voltage Divider Bias Configuration: Approximate Analysis



Input Circuit

Apply KCL to the base circuit we get;

$$I_1 = I_2 + I_B$$

$$R_i = (1 + \beta) R_E \approx \beta R_E, \quad \beta \gg 1$$

$$I_B = \frac{V_B}{R_i} \quad \text{and} \quad I_2 = \frac{V_B}{R_2}$$

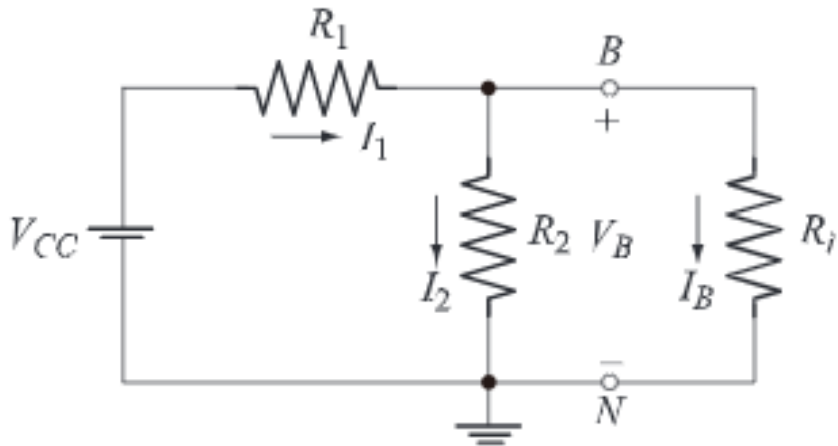
$$\text{If } R_i = (1 + \beta) R_E \gg 10 R_2,$$

$$\text{Then } I_B \ll 0.1 * I_2$$

We neglect I_B , then

$$I_1 \approx I_2$$

Voltage Divider Bias Configuration: Approximate Analysis



Input Circuit

Apply KVL to the circuit we get;

$$V_{CC} = I_1 R_1 + I_2 R_2$$

$$V_{CC} = I_2 (R_1 + R_2)$$

$$I_2 = \frac{V_{CC}}{R_1 + R_2}$$

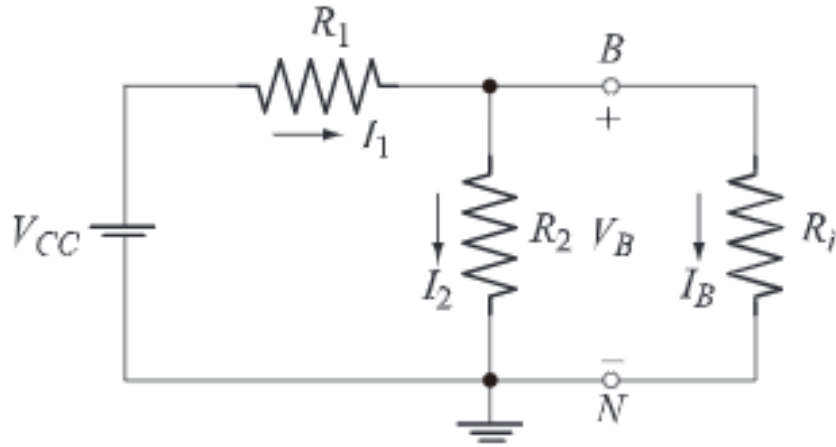
$$V_B = I_2 * R_2$$

$$V_B = \frac{V_{CC} R_2}{R_1 + R_2}$$

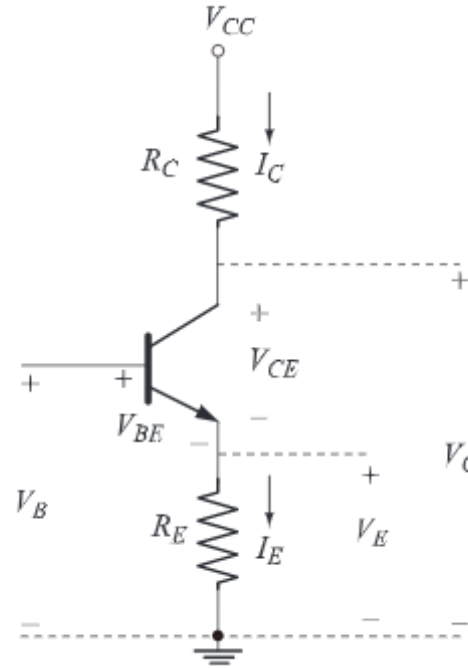
$$V_B = V_{BE} + V_E$$

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

Voltage Divider Bias Configuration: Approximate Analysis



Input Circuit



Collector Circuit

Apply KCL to the circuit we get;

$$I_E = \frac{V_E}{R_E} \text{ and } I_C \approx I_E$$

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

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

Voltage Divider Bias Configuration: Numericals

- Find the quiescent base current, collector current and V_{CE} for the circuit shown using silicon transistor with $V_{BE} = 0.7V$ and $\beta = 80$.
- Determine the values of collector, emitter and base voltages with respect to ground.
- Repeat (a) for $\beta = 150$.
- Draw the dc load line and locate the Q-points corresponding to two ' β ' values.

Given:

$$V_{CC} = 16V,$$

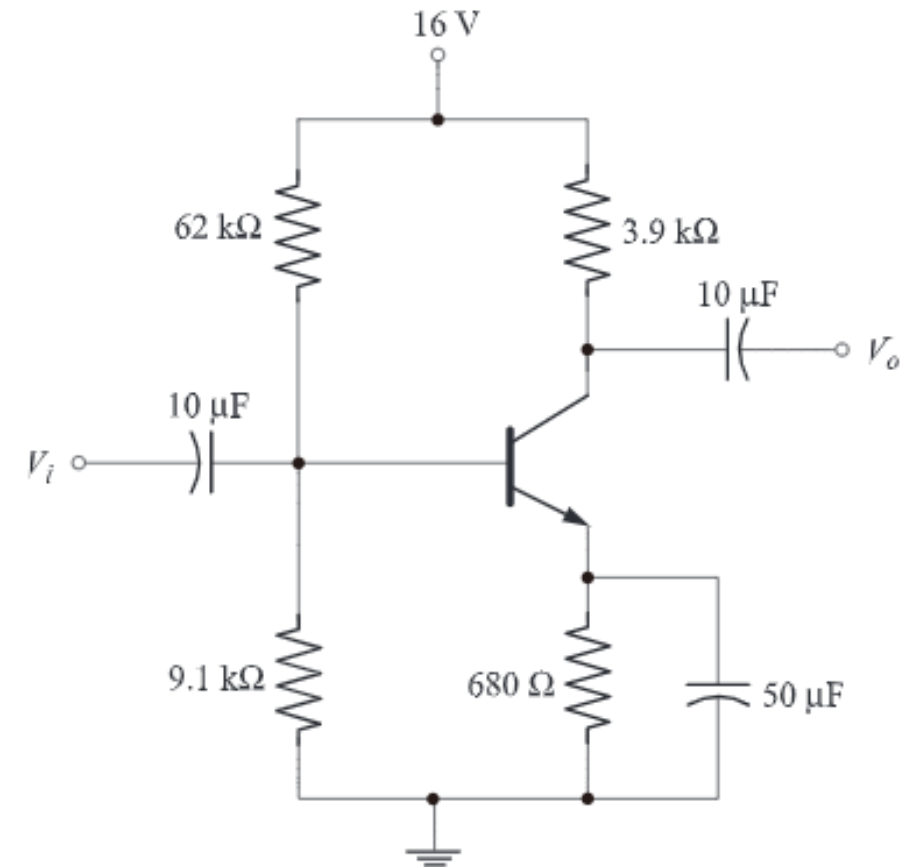
$$R_1 = 62k\Omega,$$

$$R_2 = 9.1k\Omega,$$

$$R_C = 3.9k\Omega,$$

$$R_E = 680\Omega,$$

$$C_1 = C_2 = 10\mu F, C_E = 50\mu F$$



Voltage Divider Bias Configuration: Numericals

- a. Find the quiescent base current, collector current and V_{CE} for the circuit shown using silicon transistor with $V_{BE} = 0.7V$ and $\beta = 80$.

Given:

$V_{CC} = 16V$, $R_1 = 62k\Omega$, $R_2 = 9.1k\Omega$, $R_C = 3.9k\Omega$,
 $R_E = 680\Omega$, $C_1 = C_2 = 10\mu F$, $C_E = 50\mu F$

$$R_{Th} = \frac{R_1 R_2}{R_1 + R_2}$$

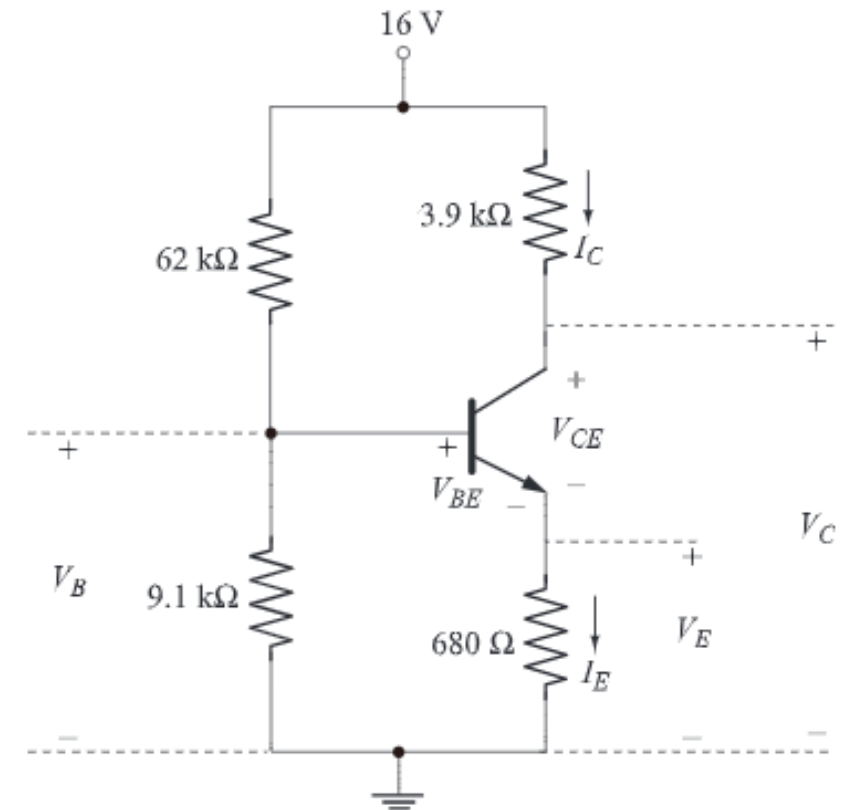
$$R_{Th} = \frac{62k * 9.1k}{62k + 9.1k}$$

$$R_{Th} = 7.94k\Omega$$

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

$$V_{Th} = \frac{16 * 9.1k}{62k + 9.1k}$$

$$V_{Th} = 2.05V$$



Voltage Divider Bias Configuration: Numericals

Given:

$V_{CC} = 16V$, $R_1 = 62k\Omega$, $R_2 = 9.1k\Omega$, $R_C = 3.9k\Omega$,
 $R_E = 680\Omega$, $C_1 = C_2 = 10\mu F$, $C_E = 50\mu F$

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

$$I_B = \frac{2.05 - 0.7}{7.94k + (1 + 80)680}$$

$$I_B = 21.42\mu A$$

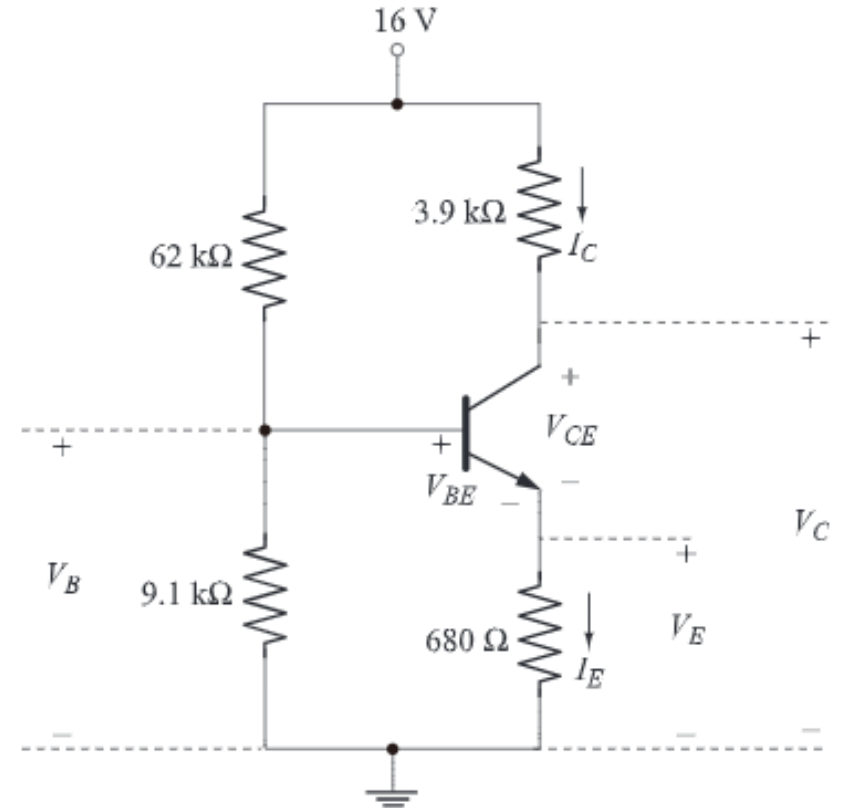
$$I_C = \beta I_B$$

$$I_C = 80 * 21.42 \mu = 1.71 \text{ mA}$$

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

$$V_{CE} = 16 - 1.71m(3.9k + 680)$$

$$V_{CE} = 8.17V$$



Voltage Divider Bias Configuration: Numericals

Given:

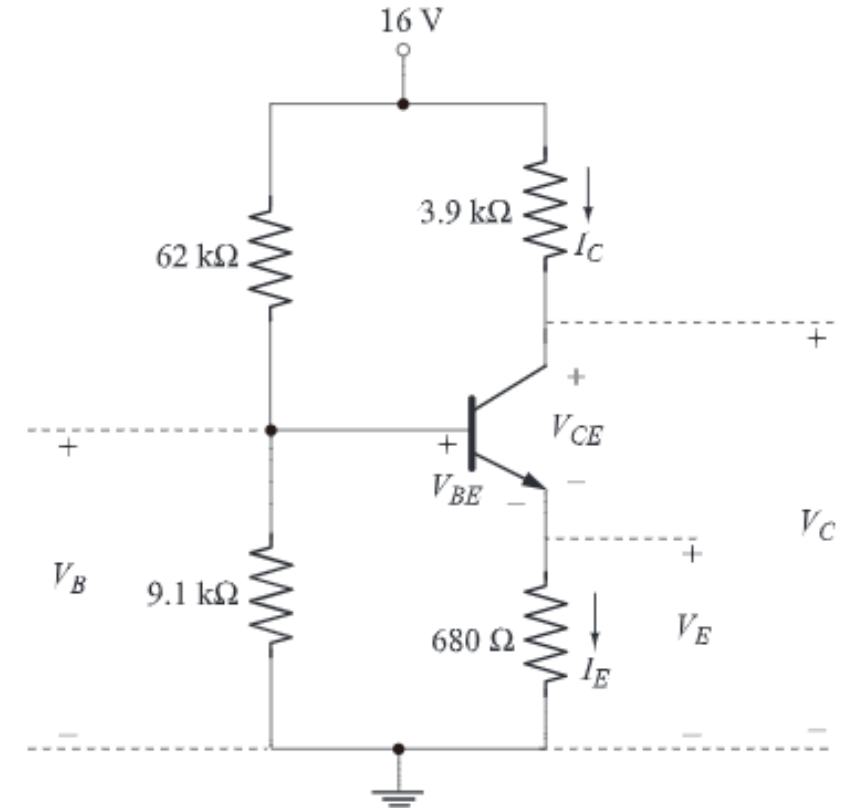
$V_{CC} = 16V$, $R_1 = 62k\Omega$, $R_2 = 9.1k\Omega$, $R_C = 3.9k\Omega$,
 $R_E = 680\Omega$, $C_1 = C_2 = 10\mu F$, $C_E = 50\mu F$

b. collector, emitter and base voltages with respect to ground.

$$V_C = V_{CC} - I_C R_C = 16 - (1.71m * 3.9k) = \mathbf{9.33 V}$$

$$V_E = I_E R_E \approx I_C R_C = (1.71m * 3.9k) = \mathbf{1.16 V}$$

$$V_B = V_{BE} + V_E = 0.7 + 1.16 = \mathbf{1.86V}$$



Voltage Divider Bias Configuration: Numericals

Given:

$V_{CC} = 16V$, $R_1 = 62k\Omega$, $R_2 = 9.1k\Omega$, $R_C = 3.9k\Omega$,
 $R_E = 680\Omega$, $C_1 = C_2 = 10\mu F$, $C_E = 50\mu F$

c. For $\beta = 150$

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

$$I_B = \frac{2.05 - 0.7}{7.94k + (1 + 150)680}$$

$$I_B = 12.2\mu A$$

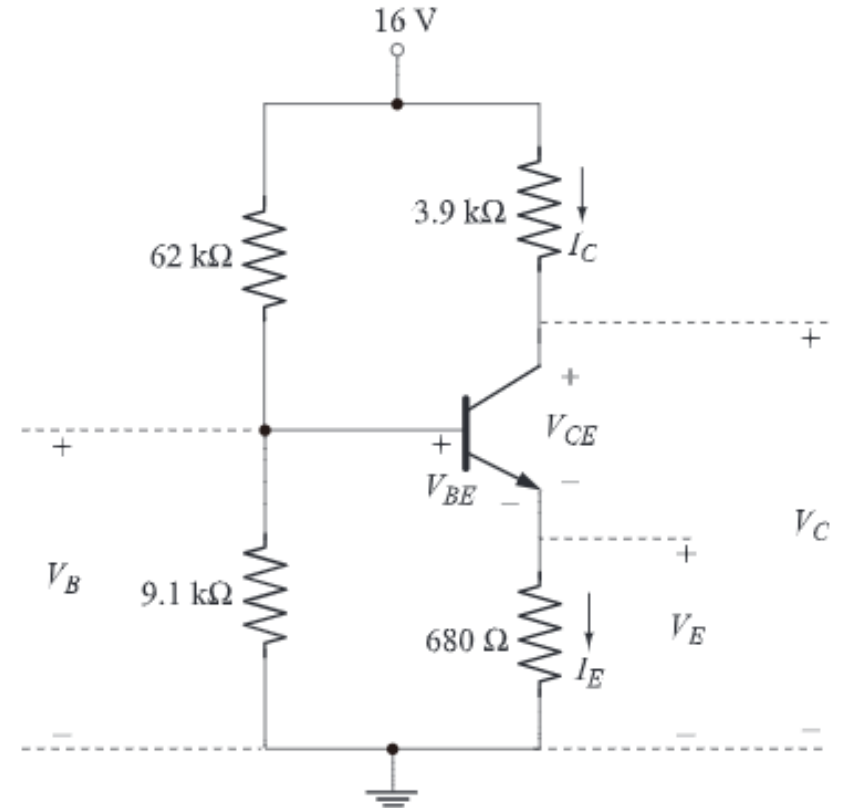
$$I_C = \beta I_B$$

$$I_C = 150 * 12.2 \mu = 1.83 \text{ mA}$$

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

$$V_{CE} = 16 - 1.83m(3.9k + 680)$$

$$V_{CE} = 7.62V$$

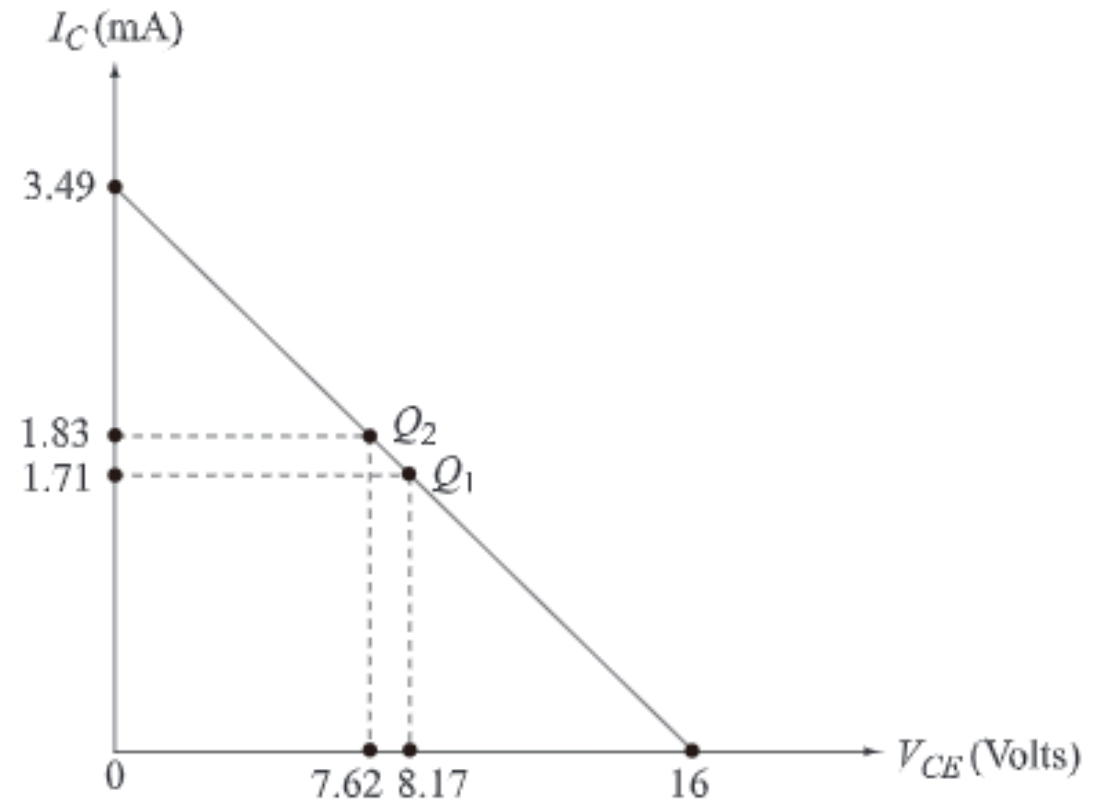


Voltage Divider Bias Configuration: Numericals

d. DC load line curve

$$I_{C(sat)} = \frac{V_{CC}}{R_C + R_E} = \frac{16}{3.9k + 680} = 3.49mA$$

β	I_{BQ}	I_{CQ}	V_{CEQ}
80	21.42 μA	1.71 mA	8.17 V
150	12.2 μA	1.83 mA	7.62 V



Voltage Divider Bias Configuration: Numericals

For the voltage divider bias configuration shown below,
Find

- I_C and V_{CE} using exact analysis
- I_C and V_{CE} using approximate analysis
- $I_{C(sat)}$
- Compare the results obtained in (a) and (b) and comment

Assume silicon transistor with $\beta = 150$.

Given:

$$V_{CC} = 20V,$$

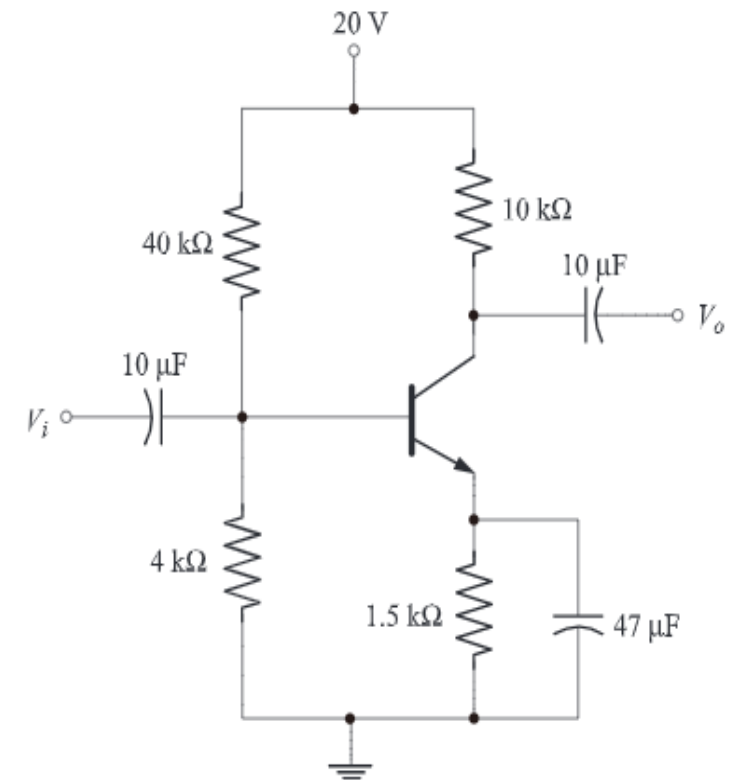
$$R_1 = 40k\Omega,$$

$$R_2 = 4k\Omega,$$

$$R_C = 10k\Omega,$$

$$R_E = 1.5k\Omega,$$

$$C_1 = C_2 = 10\mu F, C_E = 47\mu F$$



Voltage Divider Bias Configuration: Numericals

a. I_C and V_{CE} using exact analysis

Given:

$V_{CC} = 20V$, $R_1 = 40k\Omega$, $R_2 = 4k\Omega$, $R_C = 10k\Omega$,
 $R_E = 1.5k\Omega$, $C_1 = C_2 = 10\mu F$, $C_E = 47\mu F$, $V_{BE} = 0.7V$

$$R_{Th} = \frac{R_1 R_2}{R_1 + R_2}$$

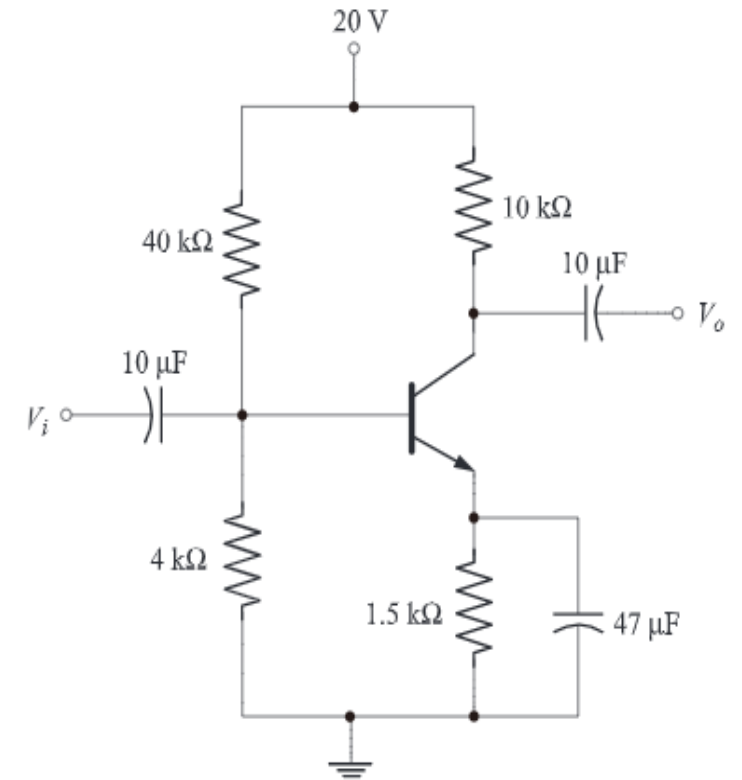
$$R_{Th} = \frac{40k * 4k}{40k + 4k}$$

$$R_{Th} = 3.63k\Omega$$

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

$$V_{Th} = \frac{20 * 4k}{40k + 4k}$$

$$V_{Th} = 1.82V$$



Voltage Divider Bias Configuration: Numericals

Given:

$V_{CC} = 20V$, $R_1 = 40k\Omega$, $R_2 = 4k\Omega$, $R_C = 10k\Omega$,
 $R_E = 1.5k\Omega$, $C_1 = C_2 = 10\mu F$, $C_E = 47\mu F$, $V_{BE} = 0.7V$

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

$$I_B = \frac{1.82 - 0.7}{3.63k + (1 + 150)1.5k}$$

$$I_B = 4.86\mu A$$

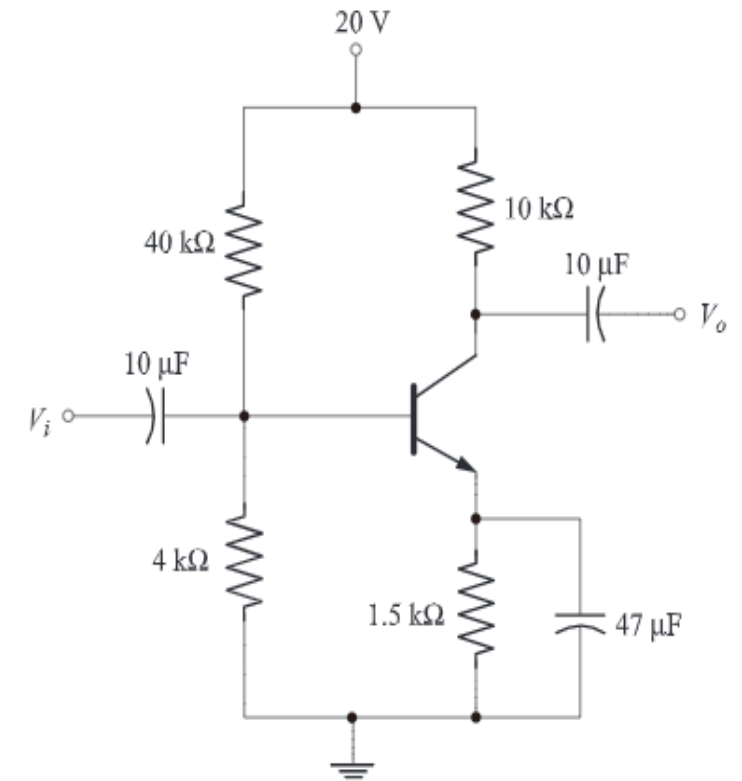
$$I_C = \beta I_B$$

$$I_C = 150 * 4.86 \mu = 0.729 \text{ mA}$$

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

$$V_{CE} = 20 - 0.729m(10k + 1.5k)$$

$$V_{CE} = 11.62V$$



Voltage Divider Bias Configuration: Numericals

b. I_C and V_{CE} using approximate analysis

Given:

$V_{CC} = 20V$, $R_1 = 40k\Omega$, $R_2 = 4k\Omega$, $R_C = 10k\Omega$,
 $R_E = 1.5k\Omega$, $C_1 = C_2 = 10\mu F$, $C_E = 47\mu F$, $V_{BE} = 0.7V$

$$\beta R_E = 150 * 1.5k = 225k\Omega$$

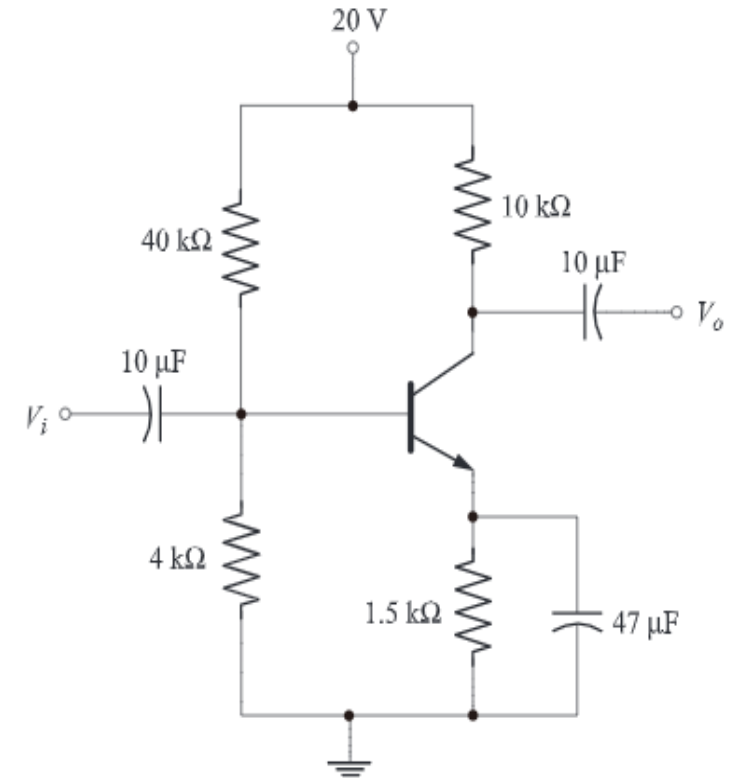
$$10R_2 = 10 * 4k = 40k\Omega$$

Note that $\beta R_E > 10R_2$,
hence we can use
approximate analysis.

$$V_B = \frac{V_{CC}R_2}{R_1 + R_2} = 1.82 V \quad (\text{Same as } V_{Th})$$

$$V_E = V_B - V_{BE} = 1.82 - 0.7 = 1.12 V$$

$$I_E = \frac{V_E}{R_E} = \frac{1.12}{1.5k} = 0.746 mA$$



Voltage Divider Bias Configuration: Numericals

Given:

$V_{CC} = 20V$, $R_1 = 40k\Omega$, $R_2 = 4k\Omega$, $R_C = 10k\Omega$,
 $R_E = 1.5k\Omega$, $C_1 = C_2 = 10\mu F$, $C_E = 47\mu F$, $V_{BE} = 0.7V$

$$I_C \approx I_E$$

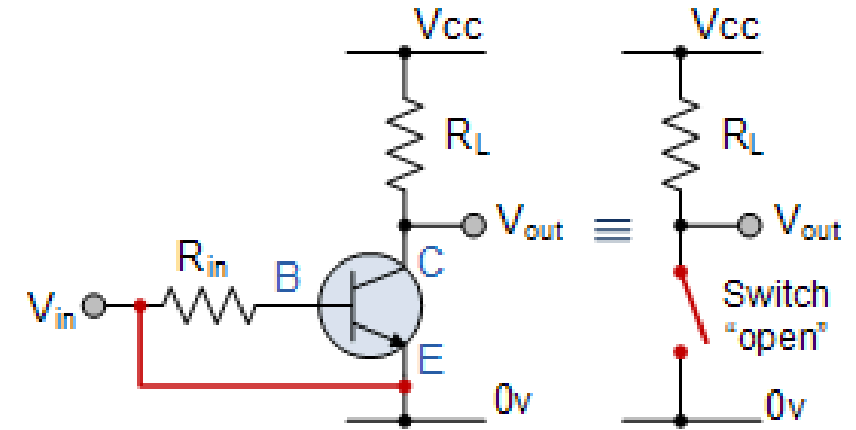
$$V_{CE} = V_{CC} - I_C (R_C + R_E) = 20 - 0.746m (10k + 1.5k) = \mathbf{11.42V}$$

$$I_{C(sat)} = \frac{V_{CC}}{R_C + R_E} = \frac{20}{10k + 1.5k} = \mathbf{1.74mA}$$

<i>Parameter</i>	<i>Exact analysis</i>	<i>Approximate analysis</i>
I_C	0.729 mA	0.746 mA
V_{CE}	11.62 V	11.42 V

Transistor Switching Networks

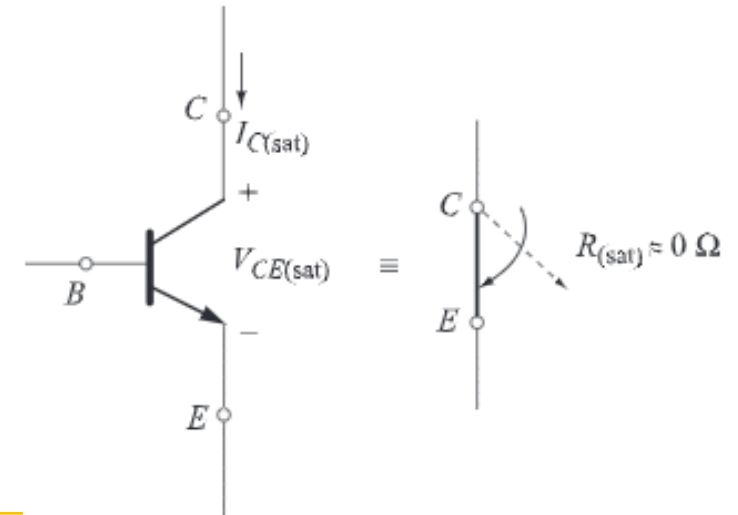
- To operate as switch, the transistor should operate in **Cut-off region and Saturation region**.
- In cut-off region **reverse current flows** and is **very small** hence neglected.
- No current flows through transistor in Cut-off region. The transistor acts as **open switch**.



Operating Regions	Emitter-Base Junction	Collector-Base Junction	Function
Cut-off region	Reverse Biased	Reverse Biased	OFF Switch
Saturation region	Forward Biased	Forward Biased	ON Switch

Transistor Switching Networks

- In saturation region the **collector current is very large** and controlled by external resistance in collector circuit.
- **V_{CE} is zero** in the saturation region. The transistor acts as **closed switch**.



Operating Regions	Emitter-Base Junction	Collector-Base Junction	Function
Cut-off region	Reverse Biased	Reverse Biased	OFF Switch
Saturation region	Forward Biased	Forward Biased	ON Switch

Transistor Switching Characteristics

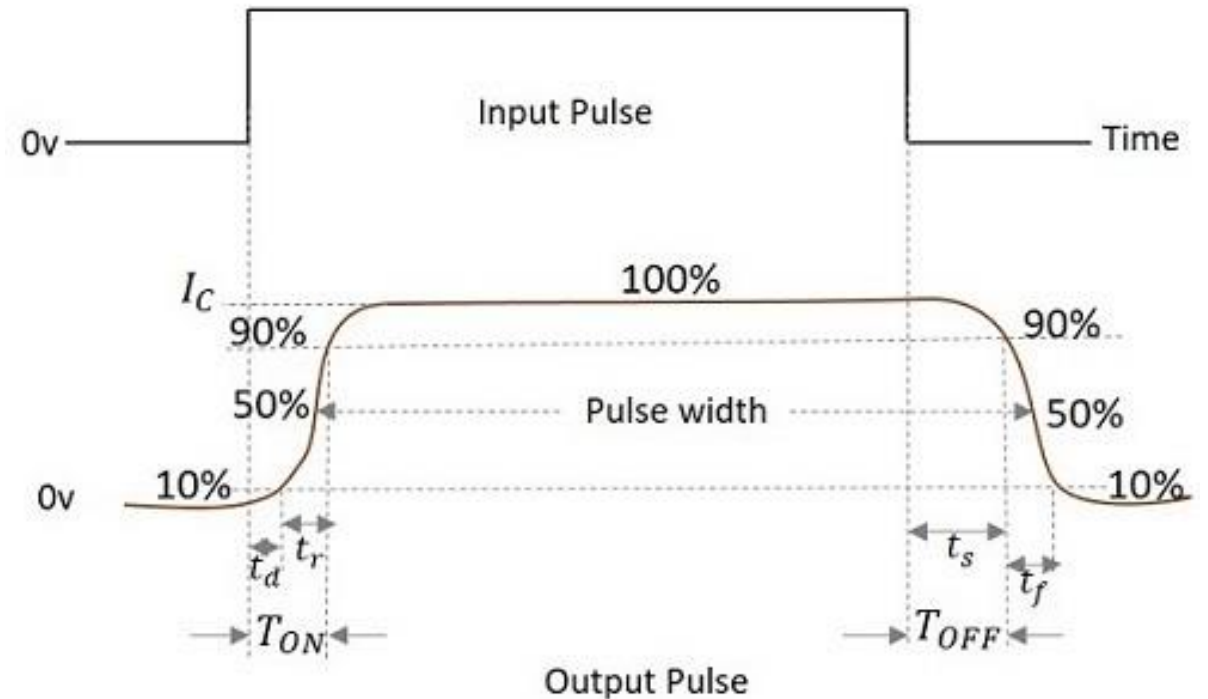
The time between the application of input pulse and commencement of collector current flow is termed as **delay time (T_d)**.

The time required for collector to reach 90% of its maximum value from 10% level is called **rise time (T_r)**.

$$T_{ON} = T_d + T_r$$

$$T_{OFF} = T_s + T_f$$

The time required for collector to reduce from 90% level to 10% level is called **fall time (T_f)**.



Stability Factors

Effects of Temperature on Transistor parameters:

1. Variation of leakage current, I_{CO} with temperature (**Doubles for 10°C rise in temperature**).
2. Variation of current gain, β with temperature (**Increases with rise in temperature**)
3. Variation of V_{BE} with temperature (**Decreases by 2.5mV for every degree Celsius rise in temperature**).

$$I_C = \beta * I_B$$

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

Stability factors:

$$S(I_{CO}) = \frac{\partial I_C}{\partial I_{CO}} = \frac{\Delta I_C}{\Delta I_{CO}}, \beta \text{ and } V_{BE} \text{ are constant}$$

$$S(V_{BE}) = \frac{\partial I_C}{\partial V_{BE}} = \frac{\Delta I_C}{\Delta V_{BE}}, \beta \text{ and } I_{CO} \text{ are constant}$$

$$S(\beta) = \frac{\partial I_C}{\partial \beta} = \frac{\Delta I_C}{\Delta \beta}, V_{BE} \text{ and } I_{CO} \text{ are constant}$$

Stability Factors

General Expression for $S(I_{CO})$:

$$I_C = I_{CEO} + \beta * I_B$$

$$I_C = (1 + \beta)I_{CO} + \beta * I_B$$

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

$$1 = (1 + \beta) \frac{\partial I_{CO}}{\partial I_C} + \beta \frac{\partial I_B}{\partial I_C}$$

$$(1 + \beta) \frac{\partial I_{CO}}{\partial I_C} = 1 - \beta \frac{\partial I_B}{\partial I_C}$$

$$S(I_{CO}) = \frac{\partial I_C}{\partial I_{CO}} = \frac{(1 + \beta)}{1 - \beta \frac{\partial I_B}{\partial I_C}}$$

$$1 - \beta \frac{\partial I_B}{\partial I_C} \gg 1 + \beta$$
$$\frac{\partial I_B}{\partial I_C} \ll -1 \Rightarrow \left| \frac{\partial I_B}{\partial I_C} \right| \gg 1$$

Stability Factors: Fixed Bias Configuration

Stability factor: $S(I_{CO})$:

$$S(I_{CO}) = \frac{\partial I_C}{\partial I_{CO}} = \frac{(1 + \beta)}{1 - \beta \frac{\partial I_B}{\partial I_C}}$$

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

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

$$I_B \approx \frac{V_{CC}}{R_B}$$

$$\frac{\partial I_B}{\partial I_C} = 0$$

$$S(I_{CO}) = (1 + \beta)$$

Stability factor: $S(V_{BE})$:

$$S(V_{BE}) = \frac{\partial I_C}{\partial V_{BE}} = \frac{\Delta I_C}{\Delta V_{BE}}, \beta \text{ and } I_{CO} \text{ are constant}$$

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

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

$$V_{BE} = V_{CC} - (I_C/\beta) R_B$$

Differentiating w.r.t. V_{BE} , keeping β constant

$$1 = 0 - \frac{R_B}{\beta} \frac{\partial I_C}{\partial V_{BE}}$$

$$S(V_{BE}) = \left(-\frac{\beta}{R_B} \right)$$

Stability Factors: Fixed Bias Configuration

Stability factor: $S(\beta)$:

$$S(\beta) = \frac{\partial I_C}{\partial \beta} = \frac{\Delta I_C}{\Delta \beta}, \text{ } V_{BE} \text{ and } I_{CO} \text{ are constant}$$

$$I_C = \frac{\beta}{R_B} [V_{CC} - V_{BE}]$$

Let $I_C = I_{C1}$, $\beta = \beta_1$, at Temperature T_1

$I_C = I_{C2}$, $\beta = \beta_2$, at Temperature T_2

$$I_{C1} = \frac{\beta_1}{R_B} [V_{CC} - V_{BE}]$$

$$I_{C2} = \frac{\beta_2}{R_B} [V_{CC} - V_{BE}]$$

$$\frac{I_{C2}}{I_{C1}} - 1 = \frac{\beta_2}{\beta_1} - 1$$

$$\frac{I_{C2} - I_{C1}}{I_{C1}} = \frac{\beta_2 - \beta_1}{\beta_1}$$

$$\frac{\Delta I_C}{I_{C1}} = \frac{\Delta \beta}{\beta_1}$$

$$S(\beta) = \frac{\Delta I_C}{\Delta \beta} = \frac{I_{C1}}{\beta_1}$$

Stability Factors: Emitter Stabilized Bias Configuration

Stability factor: $S(I_{CO})$:

$$S(I_{CO}) = \frac{\partial I_C}{\partial I_{CO}} = \frac{(1 + \beta)}{1 - \beta \frac{\partial I_B}{\partial I_C}}$$
$$S(I_{CO}) \approx 1 + \frac{R_B}{R_E}$$

Stability factor: $S(V_{BE})$:

$$S(V_{BE}) = \frac{\partial I_C}{\partial V_{BE}} = \frac{\Delta I_C}{\Delta V_{BE}}, \beta \text{ and } I_{CO} \text{ are constant}$$

$$S(V_{BE}) = \frac{\partial I_C}{\partial V_{BE}} = \frac{-\beta}{R_B + (1 + \beta)R_E}$$

Stability factor: $S(\beta)$:

$$S(\beta) = \frac{\partial I_C}{\partial \beta} = \frac{\Delta I_C}{\Delta \beta}, V_{BE} \text{ and } I_{CO} \text{ are constant}$$

$$S(\beta) = \frac{\Delta I_C}{\Delta \beta} = \frac{I_{C1} \left(1 + \frac{R_B}{R_E} \right)}{\beta_1 \left(1 + \beta_2 + \frac{R_B}{R_E} \right)}$$

Stability Factors: Voltage Divider Bias Configuration

Stability factor: $S(I_{CO})$:

$$S(I_{CO}) = \frac{\partial I_C}{\partial I_{CO}} = \frac{(1 + \beta)}{1 - \beta \frac{\partial I_B}{\partial I_C}}$$

$$S(I_{CO}) = (\beta + 1) \frac{\left[1 + \frac{R_{Th}}{R_E}\right]}{(\beta + 1) + \frac{R_{Th}}{R_E}}$$

Stability factor: $S(V_{BE})$:

$$S(V_{BE}) = \frac{\partial I_C}{\partial V_{BE}} = \frac{\Delta I_C}{\Delta V_{BE}}, \beta \text{ and } I_{CO} \text{ are constant}$$

$$S(V_{BE}) = \frac{\partial I_C}{\partial V_{BE}} = \frac{-\beta}{R_{Th} + (\beta + 1)R_E}$$

Stability factor: $S(\beta)$:

$$S(\beta) = \frac{\partial I_C}{\partial \beta} = \frac{\Delta I_C}{\Delta \beta}, V_{BE} \text{ and } I_{CO} \text{ are constant}$$

$$S(\beta) = \frac{I_{C1} \left[1 + \frac{R_{Th}}{R_E}\right]}{\beta_1 \left[1 + \beta_2 + \frac{R_{Th}}{R_E}\right]}$$

Stability Factors: Voltage Divider Bias Configuration

For the voltage divider bias circuit, find I_C , V_B , V_E , R_1 and $S(I_{CO})$.

$R_2 = 5.6k\Omega$, $R_C = 4.7k\Omega$, $R_E = 1.2k\Omega$, $V_{CC} = 18V$, $V_C = 12V$, $V_{BE} = 0.7V$ and $\beta = 100$

a. Collector current, I_C

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

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

$$I_C = \frac{18 - 12}{4.7k} = 1.276mA$$

b. Base Voltage, V_B

$$V_B = V_{BE} + I_E R_E = V_{BE} + (I_C + I_B) R_E = V_{BE} + (I_C + I_C/\beta) R_E$$

$$V_B = 0.7 + \left(1.267m + \frac{1.267m}{100}\right) 1.2k = 2.246V$$

Stability Factors: Voltage Divider Bias Configuration

For the voltage divider bias circuit, find I_C , V_B , V_E , R_1 and $S(I_{CO})$.

$R_2 = 5.6k\Omega$, $R_C = 4.7k\Omega$, $R_E = 1.2k\Omega$, $V_{CC} = 18V$, $V_C = 12V$, $V_{BE} = 0.7V$ and $\beta = 100$

c. V_E

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

$$V_E = 2.246 - 0.7 = 1.546V$$

d. R_1

$$V_B = \frac{V_{CC} R_2}{R_1 + R_2}$$

$$R_1 = \frac{V_{CC} R_2}{V_B} - R_2$$

$$R_1 = \frac{18 * 5.6k}{2.246} - 5.6k = 39.28k\Omega$$

e. $S(I_{CO})$

$$R_B = R_1 \parallel R_2 = 39.28k \parallel 5.6k = 4.9k\Omega$$

$$S(ICO) = \frac{(1 + \beta)}{1 + \frac{\beta R_E}{R_B + R_E}}$$

$$S(ICO) = \frac{(1 + 100)}{1 + \frac{100 * 1.2k}{1.2k + 4.9k}} = 4.885$$

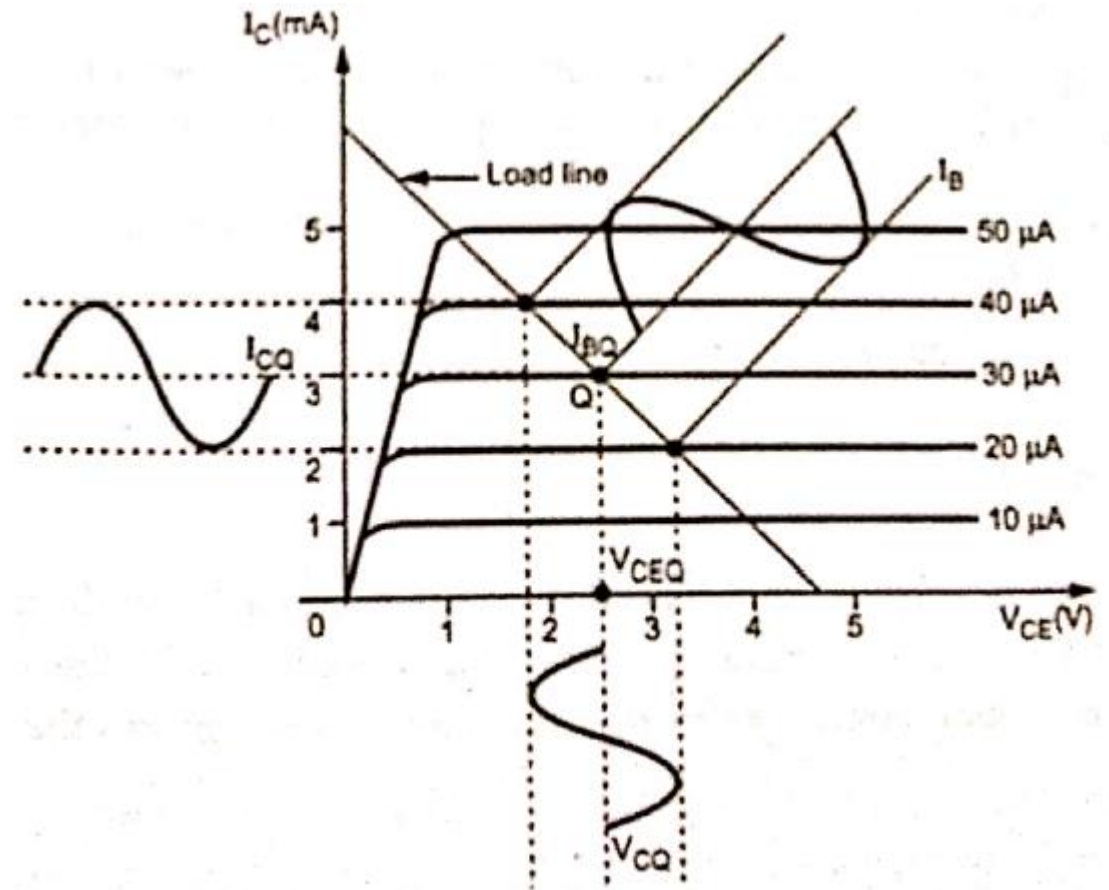
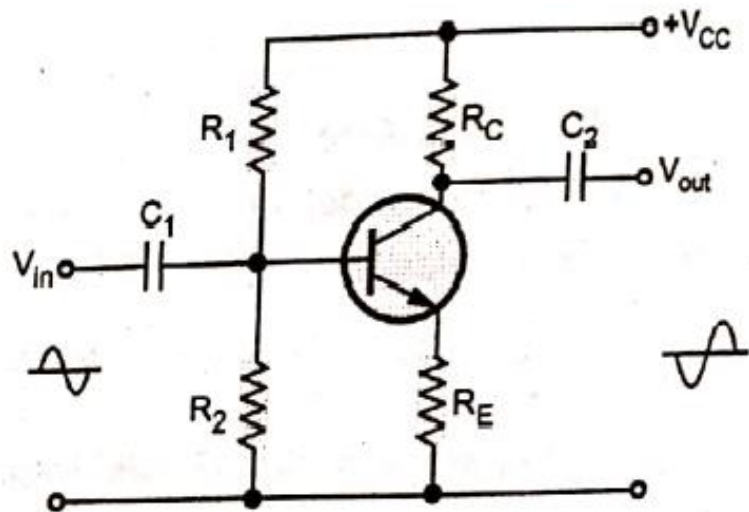
Transistor at Low Frequencies

Transistor at low frequencies: BJT transistor modeling, CE fixed bias configuration, voltage divider bias, emitter follower, CB configuration, collector feedback configuration, analysis using h – parameter model, relation between h – parameters model of CE, CC and CB modes, Millers theorem and its dual.

Basic Concepts

In the absence of input signal only dc voltages are present in the circuit. **This is called zero signal condition.**

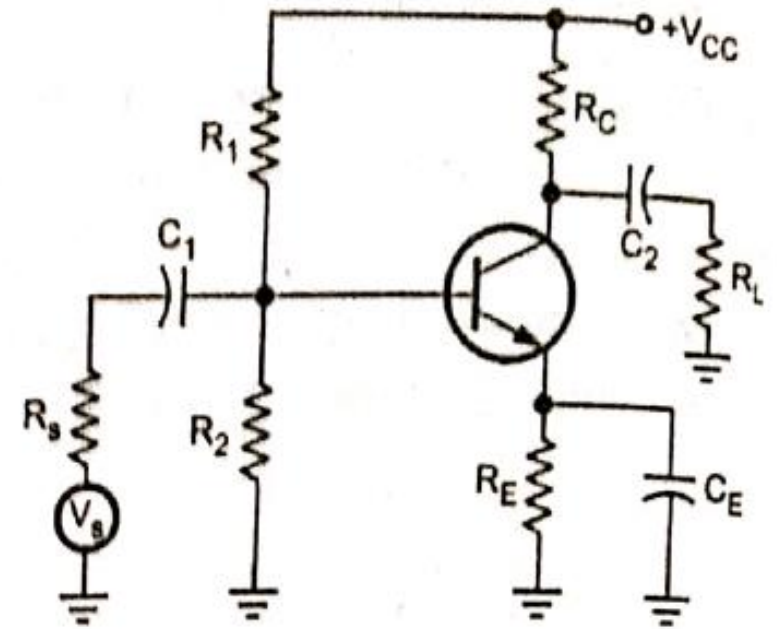
With small input signals, the transistor can be replaced by **a small linear model** called **small signal equivalent circuit.**



Basic Amplifiers

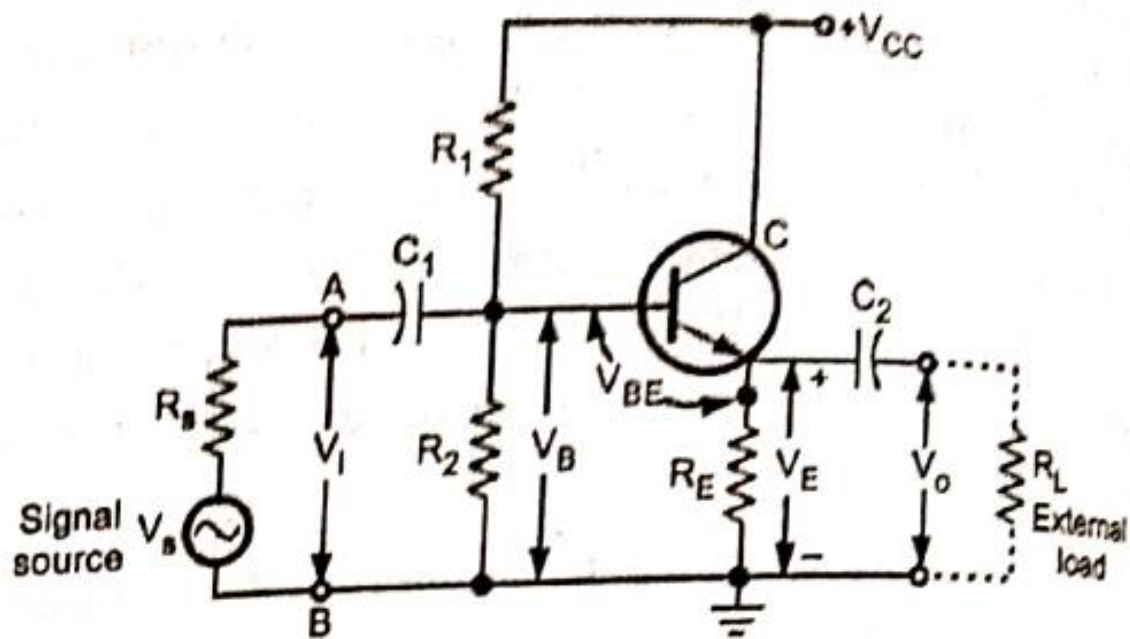
Common Emitter Amplifier

1. Biasing Circuit: R_1 , R_2 and R_E
2. Input Capacitor C_1
3. Emitter bypass capacitor C_E
4. Output Coupling Capacitor C_2

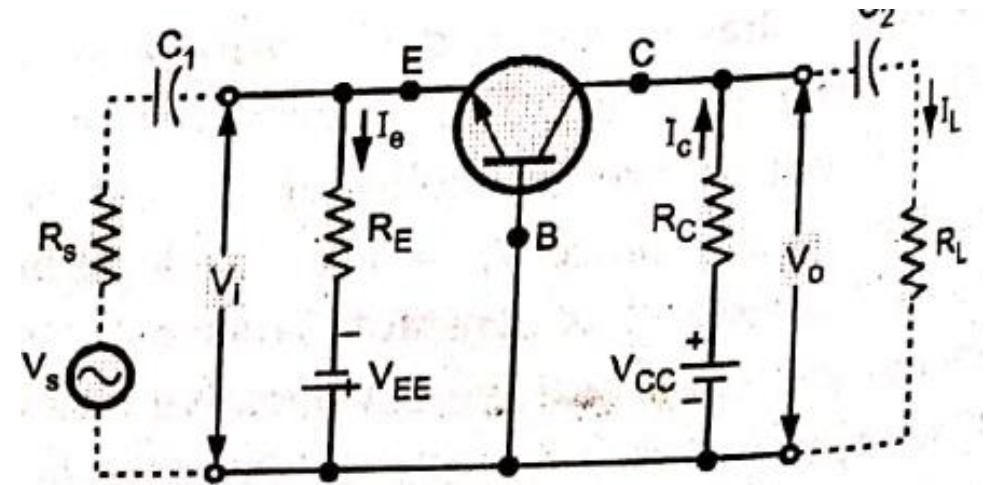


Basic Amplifiers

Common Collector Amplifier



Common Base Amplifier



Hybrid Equivalent Model of Transistor

To develop hybrid equivalent circuit we consider;

I_I and V_O as independent variables.

I_O and V_I as dependant variables.

$$V_I = f(I_I, V_O)$$

$$I_O = f(I_I, V_O)$$

$$V_I = h_{11} * I_I + h_{12} * V_O$$

$$I_O = h_{21} * I_I + h_{22} * V_O$$



Hybrid Equivalent Model of Transistor

$$V_I = h_{11} * I_I + h_{12} * V_O$$

$$I_O = h_{21} * I_I + h_{22} * V_O$$

h_{11} = Input impedance with output short circuited, unit is ohm.

$$h_{11} = \frac{V_I}{I_I} \text{ at } V_O = 0$$

h_{21} = short circuit forward transfer current ratio, no unit.

$$h_{21} = \frac{I_O}{I_I} \text{ at } V_O = 0$$



Hybrid Equivalent Model of Transistor

$$V_i = h_i * I_i + h_r * V_o \text{ ---- (1)}$$

$$I_o = h_f * I_i + h_o * V_o \text{ ----- (2)}$$

From equation (1);

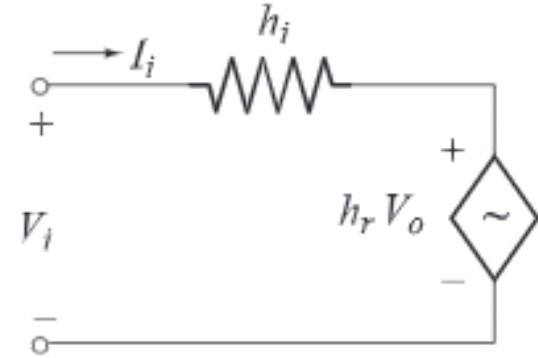
$h_i * I_i$ = Voltage drop across the impedance h_i

$h_r * V_o$ = Controlled voltage source

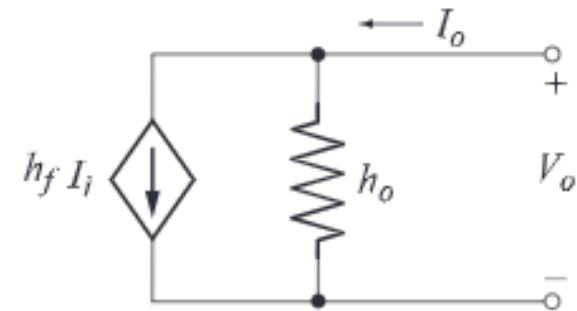
From equation (2);

$h_f * I_i$ = Controlled current source

$h_o * V_o$ = Current through admittance h_o



Circuit model of $V_i = h_i I_i + h_r V_o$



Circuit model of $I_o = h_f I_i + h_o V_o$

Hybrid Equivalent Model of Transistor

$$V_I = h_{11} * I_I + h_{12} * V_O$$

$$I_O = h_{21} * I_I + h_{22} * V_O$$

h_{12} = open circuit reverse transfer voltage ratio, no unit.

$$h_{12} = \frac{V_I}{V_O} \text{ at } I_I = 0$$

h_{22} = open circuit output admittance, unit is per ohms.

$$h_{22} = \frac{I_O}{V_O} \text{ at } I_I = 0$$

$$V_i = h_i * I_i + h_r * V_o \text{ ----- (1)}$$

$$I_o = h_f * I_i + h_o * V_o \text{ ----- (2)}$$



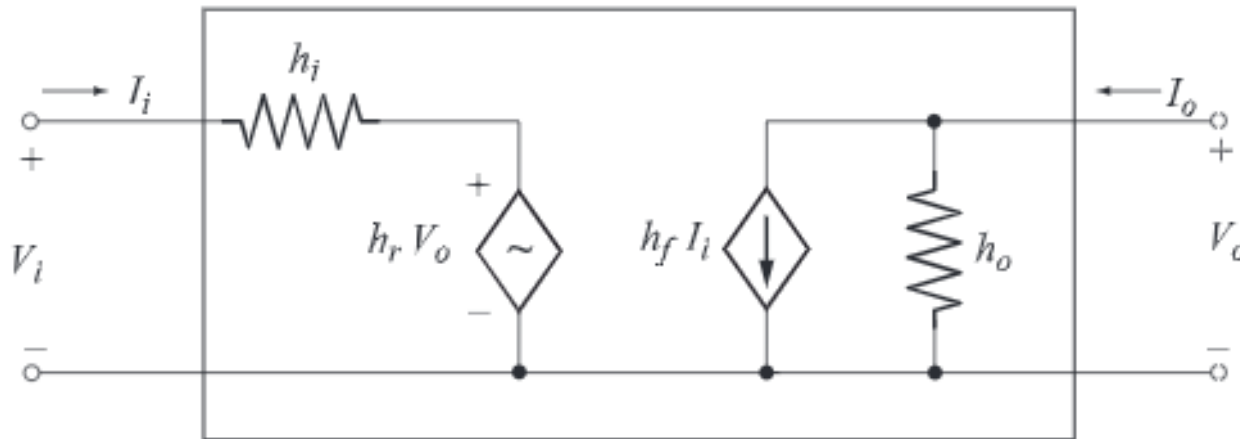
Hybrid Equivalent Model of Transistor

$$V_i = h_i * I_i + h_r * V_o \text{ ----- (1)}$$

$$I_o = h_f * I_i + h_o * V_o \text{ ----- (2)}$$

Hybrid Parameters	Configuration		
	CE	CB	CC
h_i	h_{ie}	h_{ib}	h_{ic}
h_f	h_{fe}	h_{fb}	h_{fc}
h_r	h_{re}	h_{rb}	h_{rc}
h_o	h_{oe}	h_{ob}	h_{oc}

Hybrid parameters nomenclature



Hybrid equivalent circuit of Transistor

Hybrid Model of Common Base Configuration

Basic equations:

$$V_i = h_i * I_i + h_r * V_o \text{ ----- (1)}$$

$$I_o = h_f * I_i + h_o * V_o \text{ ----- (2)}$$

$$V_i = V_{eb},$$

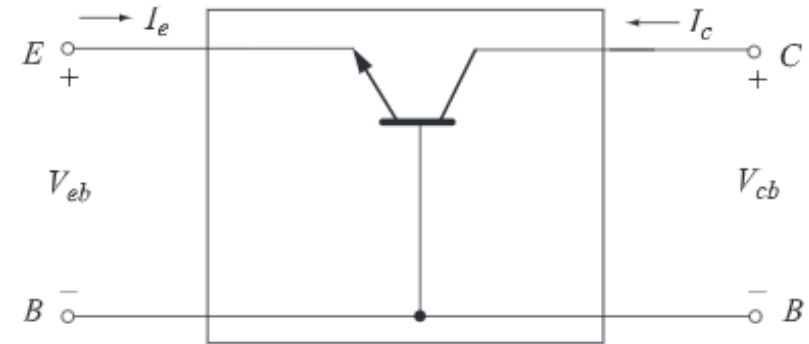
$$I_i = I_e,$$

$$V_o = V_{cb}$$

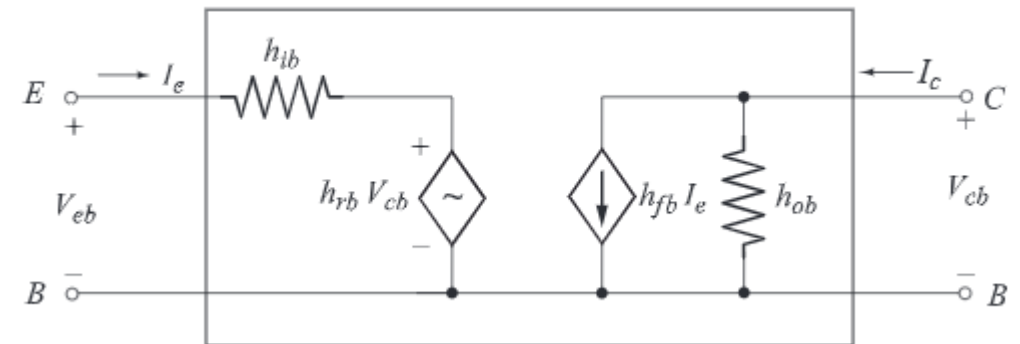
$$I_o = I_c$$

$$V_{eb} = h_{ib} * I_e + h_{rb} * V_{cb}$$

$$I_c = h_{fb} * I_e + h_{ob} * V_{cb}$$



Two port network of CB configuration



Hybrid equivalent circuit of CB configuration

Hybrid Model of Common Emitter Configuration

Basic equations:

$$V_i = h_i * I_i + h_r * V_o \text{ ----- (1)}$$

$$I_o = h_f * I_i + h_o * V_o \text{ ----- (2)}$$

$$V_i = V_{be}$$

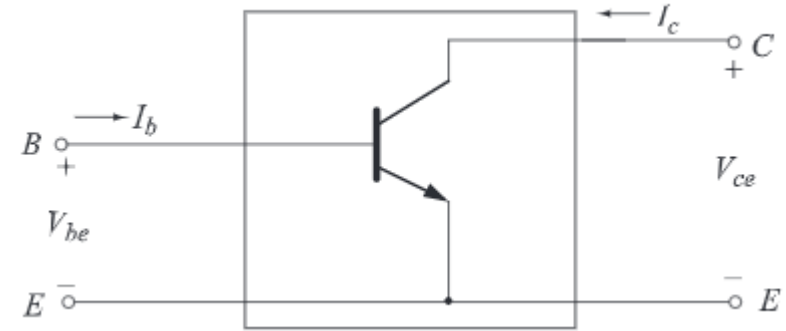
$$I_i = I_b$$

$$V_o = V_{ce}$$

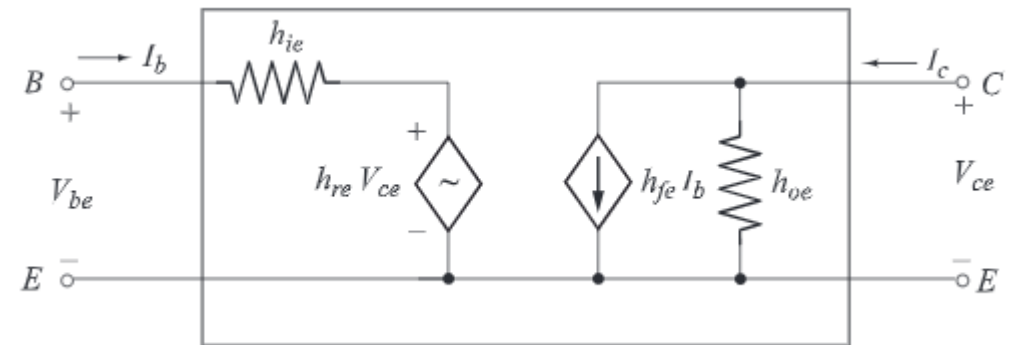
$$I_o = I_c$$

$$V_{be} = h_{ie} * I_b + h_{re} * V_{ce}$$

$$I_c = h_{fe} * I_b + h_{oe} * V_{ce}$$



Two port network of CE configuration



Hybrid equivalent circuit of CE configuration

Hybrid Model of Common Collector Configuration

Basic equations:

$$V_i = h_i * I_i + h_r * V_o \text{ ----- (1)}$$

$$I_o = h_f * I_i + h_o * V_o \text{ ----- (2)}$$

$$V_i = V_{bc},$$

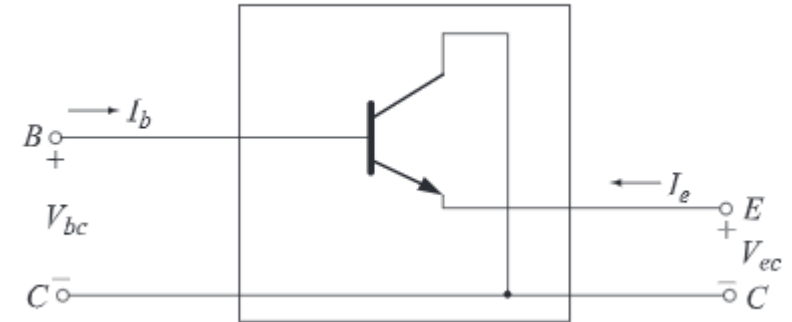
$$I_i = I_b,$$

$$V_o = V_{ec}$$

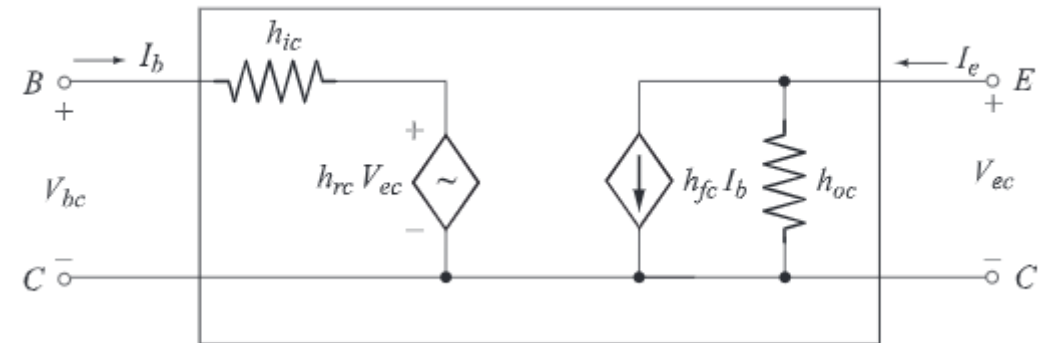
$$I_o = I_e$$

$$V_{bc} = h_{ic} * I_b + h_{rc} * V_{ec}$$

$$I_e = h_{fc} * I_b + h_{oc} * V_{ec}$$



Two port network of CC configuration



Hybrid equivalent circuit of CC configuration

Relationship between h-parameters

The h-parameters for the transistor are $h_{ie} = 1.1 \text{ k}\Omega$, $h_{fe} = 99$, $h_{re} = 2.5 \cdot 10^{-4}$ and $h_{oe} = 25 \text{ }\mu\text{A/V}$. Find the h-parameters for common base and common collector configuration.

For Common base configuration:

$$h_{ib} = \frac{h_{ie}}{1 + h_{fe}}$$

$$h_{ib} = \frac{1.1 \text{ k}}{1 + 99} = 11$$

$$h_{rb} = \frac{h_{ie}h_{oe}}{1 + h_{fe}} - h_{re}$$

$$h_{rb} = \frac{1.1 \text{ k} * 25 \mu}{1 + 99} - 2.5 * 10^{-4} = 2.5 * 10^{-5}$$

For Common base configuration:

$$h_{fb} = \frac{-h_{fe}}{1 + h_{fe}}$$

$$h_{fb} = \frac{-99}{1 + 99} = -0.99$$

$$h_{ob} = \frac{h_{oe}}{1 + h_{fe}}$$

$$h_{rb} = \frac{25 \mu}{1 + 99} = 0.25 * 10^{-6}$$

Relationship between h-parameters

The h-parameters for the transistor are $h_{ie} = 1.1 \text{ k}\Omega$, $h_{fe} = 99$, $h_{re} = 2.5 \times 10^{-4}$ and $h_{oe} = 25 \text{ }\mu\text{A/V}$. Find the h-parameters for common base and common collector configuration.

For Common collector configuration:

$$h_{ic} = h_{ie} = 1.1 \text{ k}\Omega$$

$$h_{rc} = 1 - h_{re} = 1 - 2.5 \times 10^{-4} = 1$$

$$h_{fc} = -(1 + h_{fe}) = -(1 + 99) = -100$$

$$h_{oc} = h_{oe} = 25 \text{ }\mu\text{A/V}$$

Analysis of Common Emitter Configuration

Derive the expressions for A_v , A_i , R_i and R_o for common emitter configuration using h-parameter model.

1. Current Gain

$$A_i = \frac{I_L}{I_b} = -\frac{I_c}{I_b}$$

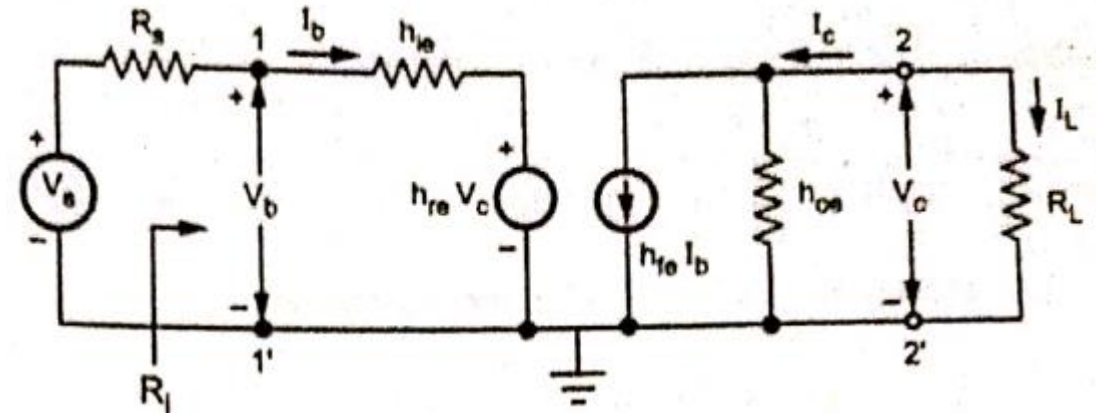
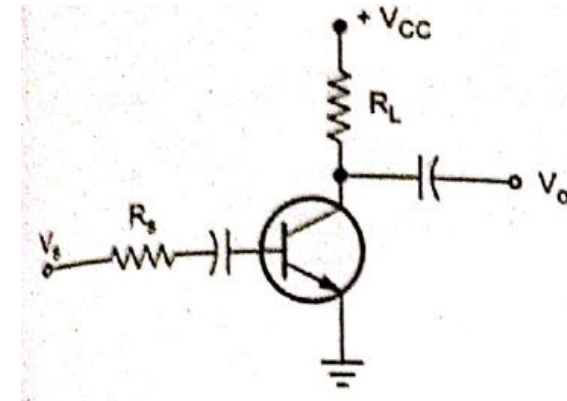
$$I_C = h_{fe} * I_b + h_{oe} * V_C$$

$$V_C = -I_C * R_L$$

$$I_C = h_{fe} * I_b + h_{oe} * (-I_C * R_L)$$

$$I_C + h_{oe} * I_C * R_L = h_{fe} * I_b$$

$$I_C (1 + h_{oe} * R_L) = h_{fe} * I_b$$



Analysis of Common Emitter Configuration

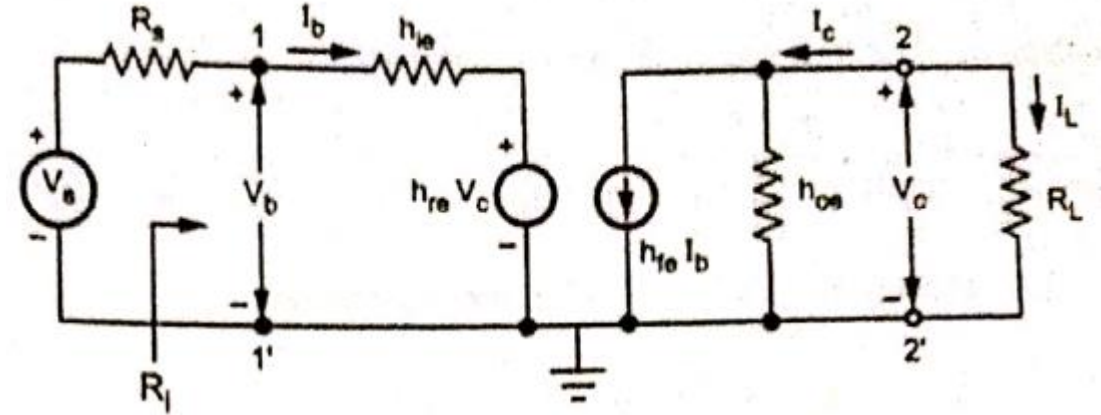
1. Current Gain

$$A_i = \frac{I_L}{I_b} = -\frac{I_c}{I_b}$$

$$I_C (1 + h_{oe} * R_L) = h_{fe} * I_b$$

$$\frac{I_c}{I_b} = \frac{h_{fe}}{1 + h_{oe} * R_L}$$

$$A_i = \frac{I_L}{I_b} = -\frac{I_c}{I_b} = \frac{-h_{fe}}{1 + h_{oe} * R_L}$$



Analysis of Common Emitter Configuration

2. Input resistance

$$R_i = \frac{V_b}{I_b}$$

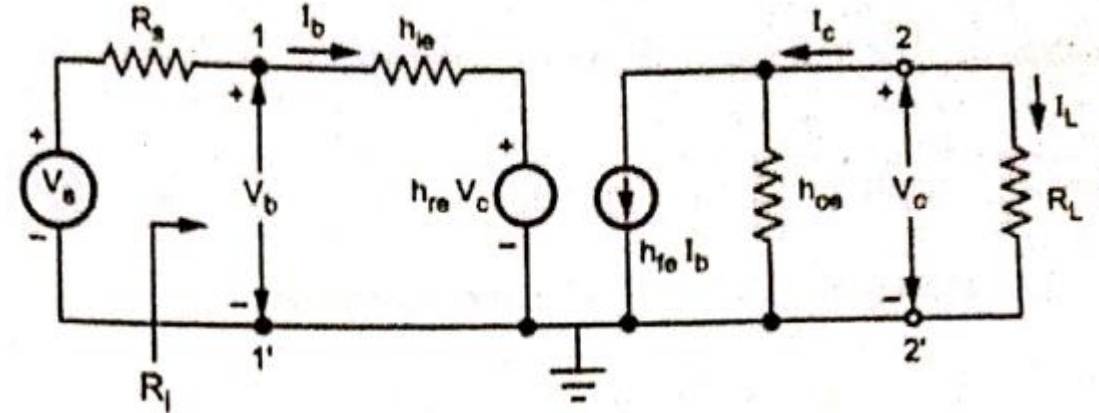
$$V_b = h_{ie} * I_b + h_{re} * V_c$$

$$V_c = -I_C * R_L = I_b * A_i * R_L$$

$$V_b = h_{ie} * I_b + h_{re} * A_i * I_b * R_L$$

$$R_i = \frac{h_{ie} * I_b + h_{re} * A_i * I_b * R_L}{I_b} = h_{ie} + h_{re} * A_i * R_L$$

$$R_i = h_{ie} - h_{re} * \frac{h_{fe}}{1 + h_{oe} * R_L} * R_L$$



Analysis of Common Emitter Configuration

3. Voltage Gain

$$A_V = \frac{V_c}{V_b}$$

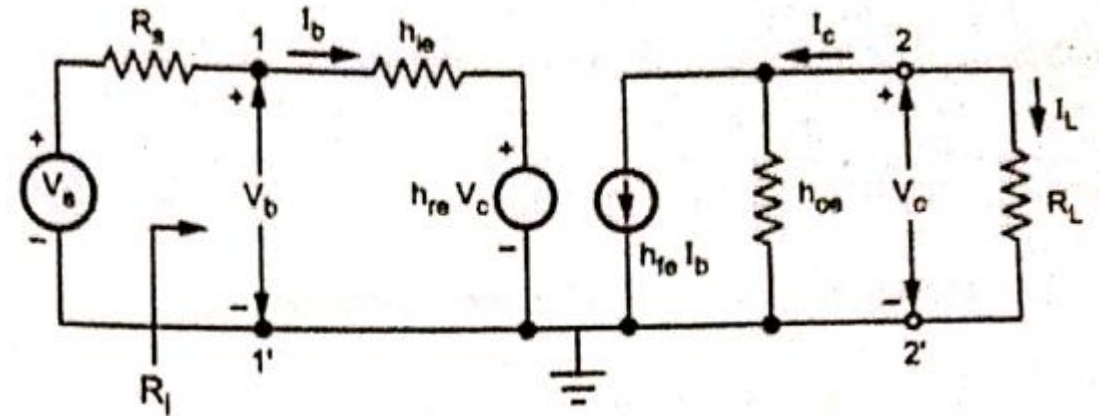
$$A_V = \frac{A_i I_b R_L}{V_b} = \frac{A_i R_L}{R_i}$$

4. Output Admittance

$$Y_O = \frac{I_c}{V_c} \text{ at } V_S = 0$$

$$I_C = h_{fe} * I_b + h_{oe} * V_C$$

$$Y_O = \frac{I_c}{V_c} = h_{fe} * I_b / V_C + h_{oe}$$



Analysis of Common Emitter Configuration

4. Output Admittance

$$Y_O = \frac{I_c}{V_c} \text{ at } V_S = 0$$

$$I_C = h_{fe} * I_b + h_{oe} * V_C$$

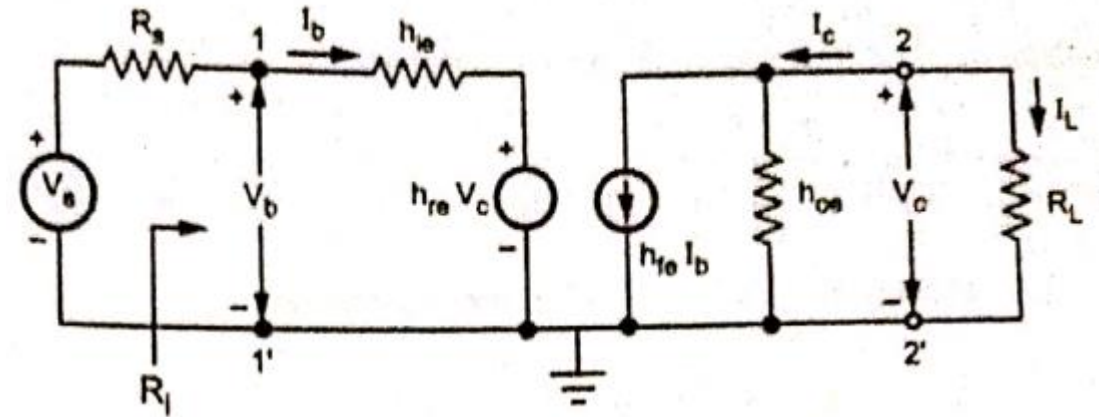
$$Y_O = \frac{I_c}{V_c} = h_{fe} * I_b / V_c + h_{oe}$$

$$R_S I_b + h_{ie} * I_b + h_{re} * V_c = 0$$

$$(R_S + h_{ie}) I_b = - h_{re} * V_c$$

$$I_b / V_c = - h_{re} / (R_S + h_{ie})$$

$$Y_O = h_{oe} - \frac{h_{fe} h_{re}}{R_S + h_{ie}}$$



$$R_O = \frac{1}{Y_O}$$

Analysis of Common Collector Configuration

Derive the expressions for A_V , A_I , R_I and R_O for common collector configuration using h-parameter model.

1. Current Gain

$$A_i = \frac{I_L}{I_b} = -\frac{I_e}{I_b}$$

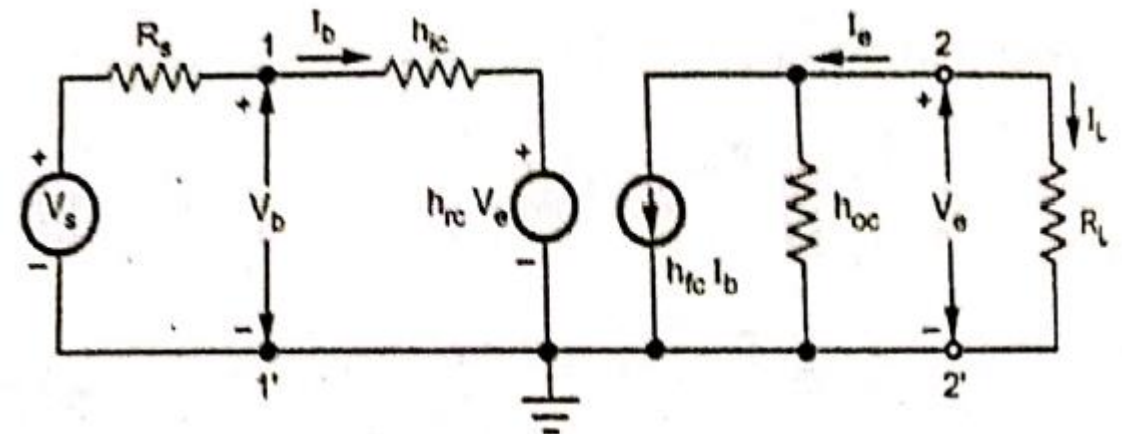
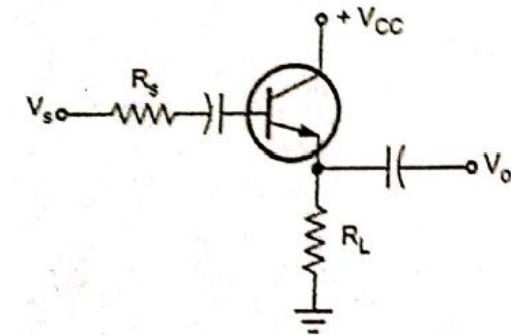
$$I_e = h_{fc} * I_b + h_{oc} * V_e$$

$$V_e = -I_e * R_L$$

$$I_e = h_{fc} * I_b + h_{oc} * (-I_e * R_L)$$

$$I_e + h_{oc} * I_e * R_L = h_{fc} * I_b$$

$$I_e (1 + h_{oc} * R_L) = h_{fc} * I_b$$



Analysis of Common Collector Configuration

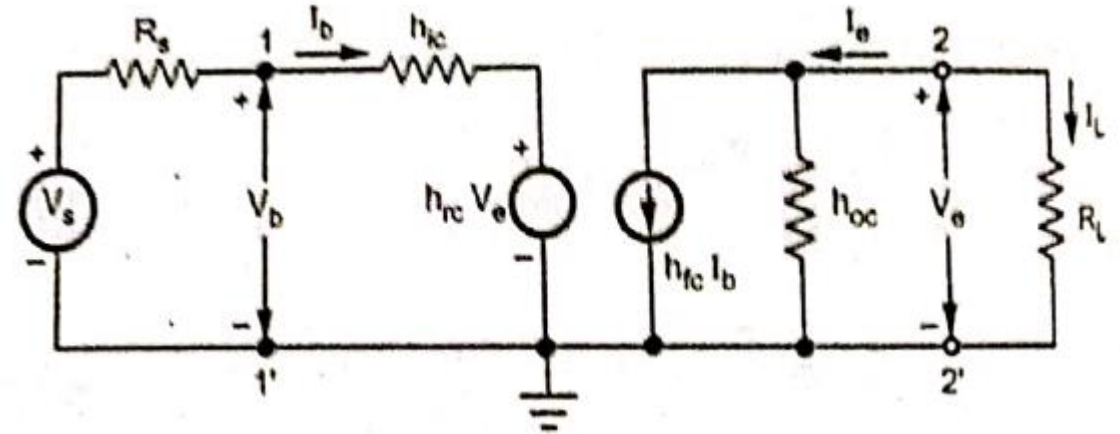
1. Current Gain

$$A_i = \frac{I_L}{I_b} = -\frac{I_e}{I_b}$$

$$I_e (1 + h_{oc} * R_L) = h_{fc} * I_b$$

$$\frac{I_e}{I_b} = \frac{h_{fc}}{1 + h_{oc} * R_L}$$

$$A_i = \frac{I_L}{I_b} = -\frac{I_e}{I_b} = \frac{-h_{fc}}{1 + h_{oc} * R_L}$$



Analysis of Common Collector Configuration

2. Input resistance

$$R_i = \frac{V_b}{I_b}$$

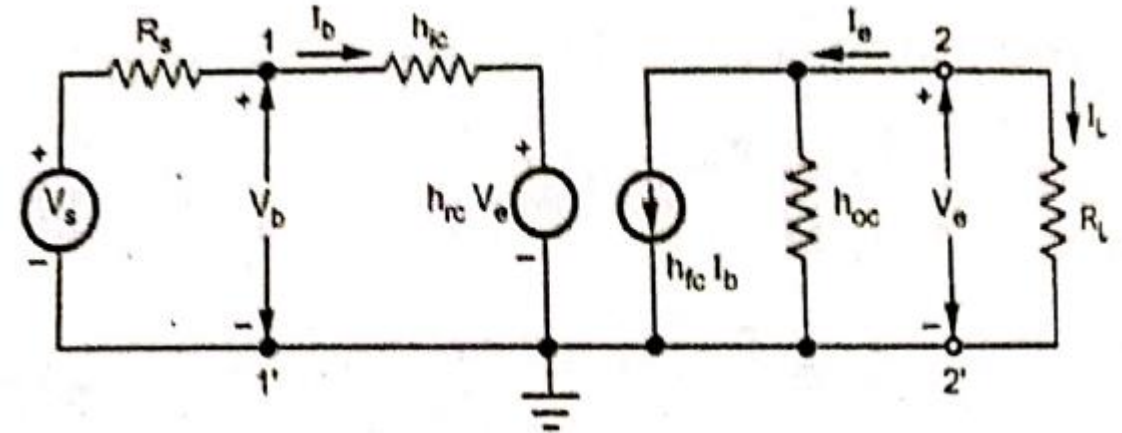
$$V_b = h_{ic} * I_b + h_{rc} * V_e$$

$$V_e = -I_e * R_L = I_b * A_i * R_L$$

$$V_b = h_{ic} * I_b + h_{rc} * A_i * I_b * R_L$$

$$R_i = \frac{h_{ic} * I_b + h_{rc} * A_i * I_b * R_L}{I_b} = h_{ic} + h_{rc} * A_i * R_L$$

$$R_i = h_{ic} - h_{rc} * \frac{h_{fc}}{1 + h_{oc} * R_L} * R_L$$



Analysis of Common Collector Configuration

3. Voltage Gain

$$A_V = \frac{V_e}{V_b}$$

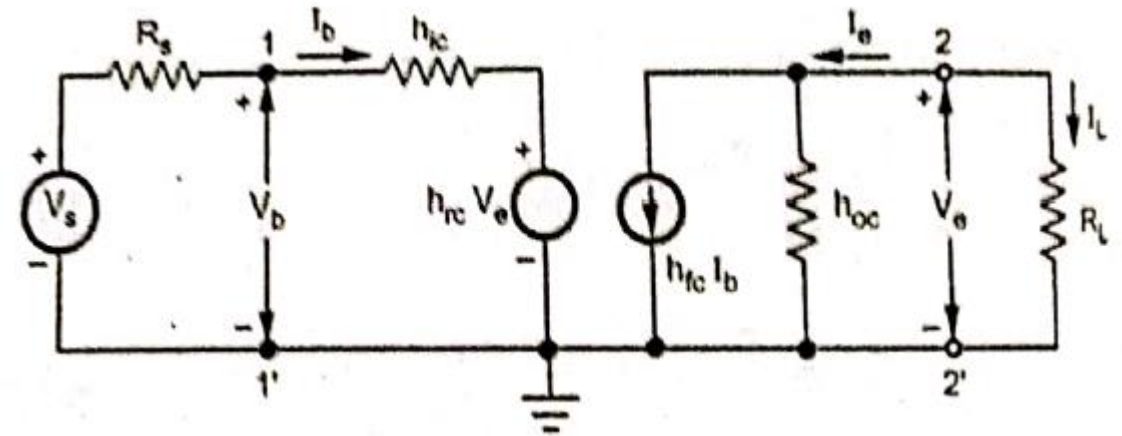
$$A_V = \frac{A_i I_b R_L}{V_b} = \frac{A_i R_L}{R_i}$$

4. Output Admittance

$$Y_O = \frac{I_e}{V_e} \text{ at } V_S = 0$$

$$I_e = h_{fc} * I_b + h_{oc} * V_e$$

$$Y_O = \frac{I_e}{V_e} = \frac{h_{fc} I_b}{V_e} + h_{oc}$$



Analysis of Common Collector Configuration

4. Output Admittance

$$Y_O = \frac{I_e}{V_e} \text{ at } V_S = 0$$

$$I_e = h_{fc} * I_b + h_{oc} * V_e$$

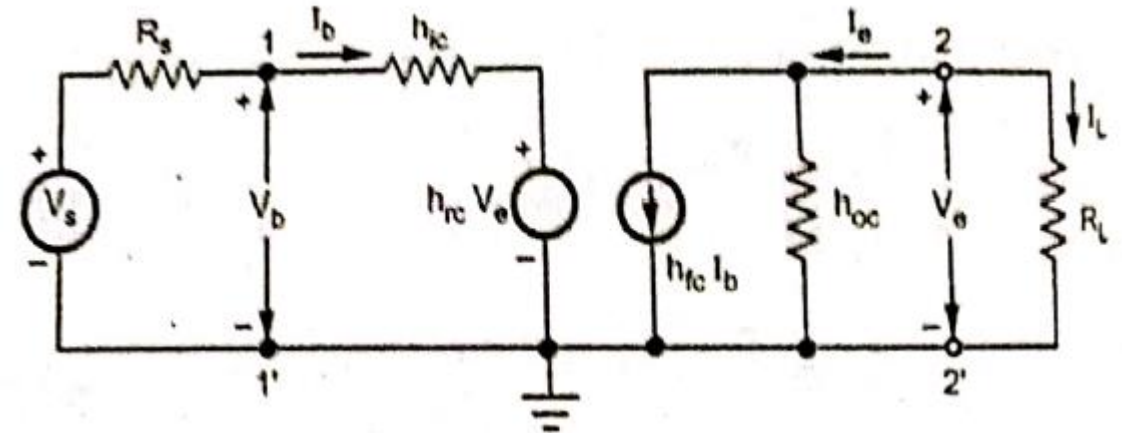
$$Y_O = \frac{I_e}{V_e} = \frac{h_{fc} I_b}{V_e} + h_{oc}$$

$$R_S I_b + h_{ic} * I_b + h_{rc} * V_e = 0$$

$$(R_S + h_{ic}) I_b = - h_{rc} * V_e$$

$$I_b / V_e = - h_{rc} / (R_S + h_{ic})$$

$$Y_O = h_{oc} - \frac{h_{fc} h_{rc}}{R_S + h_{ic}}$$



$$R_O = \frac{1}{Y_O}$$

Analysis of Common Base Configuration

Derive the expressions for A_v , A_i , R_i and R_o for common Base configuration using h-parameter model.

1. Current Gain

$$A_i = \frac{I_L}{I_e} = -\frac{I_c}{I_e}$$

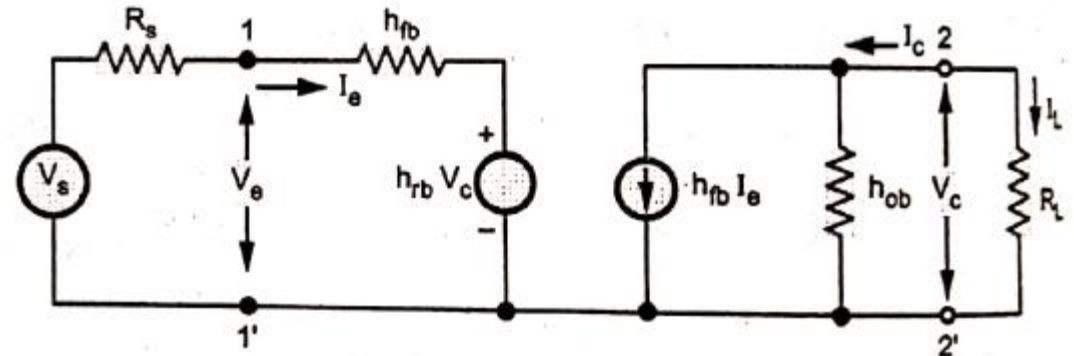
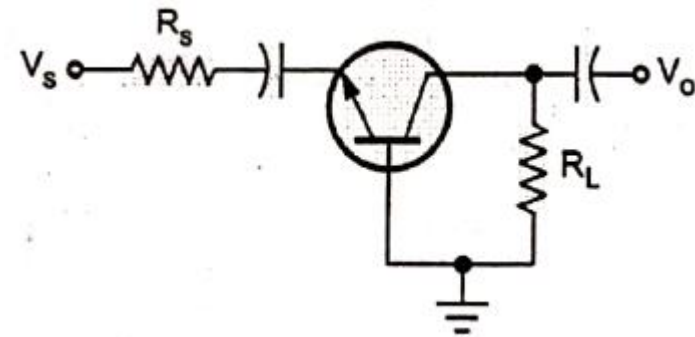
$$I_c = h_{fb} * I_e + h_{ob} * V_c$$

$$V_c = -I_c * R_L$$

$$I_c = h_{fb} * I_e + h_{ob} * (-I_c * R_L)$$

$$I_c + h_{ob} * I_c * R_L = h_{fb} * I_e$$

$$I_c (1 + h_{ob} * R_L) = h_{fb} * I_e$$



Analysis of Common Base Configuration

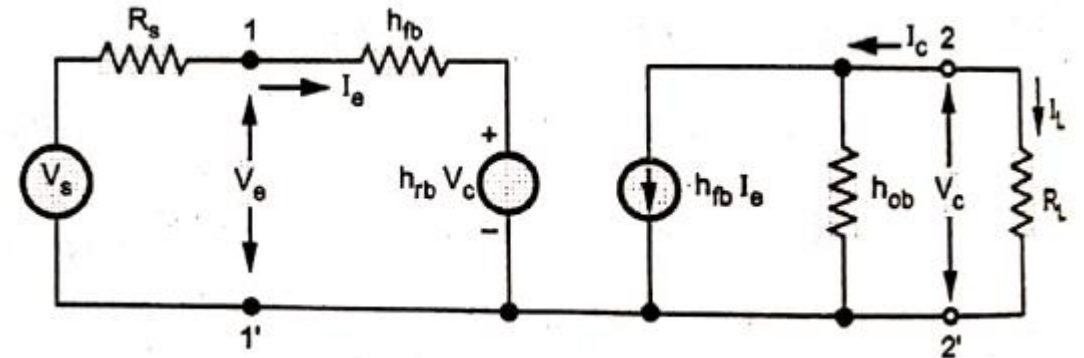
1. Current Gain

$$A_i = \frac{I_L}{I_e} = -\frac{I_c}{I_e}$$

$$I_c (1 + h_{ob} * R_L) = h_{fb} * I_e$$

$$\frac{I_c}{I_e} = \frac{h_{fb}}{1 + h_{ob} * R_L}$$

$$A_i = \frac{I_L}{I_e} = -\frac{I_c}{I_e} = \frac{-h_{fb}}{1 + h_{ob} * R_L}$$



Analysis of Common Base Configuration

2. Input resistance

$$R_i = \frac{V_e}{I_e}$$

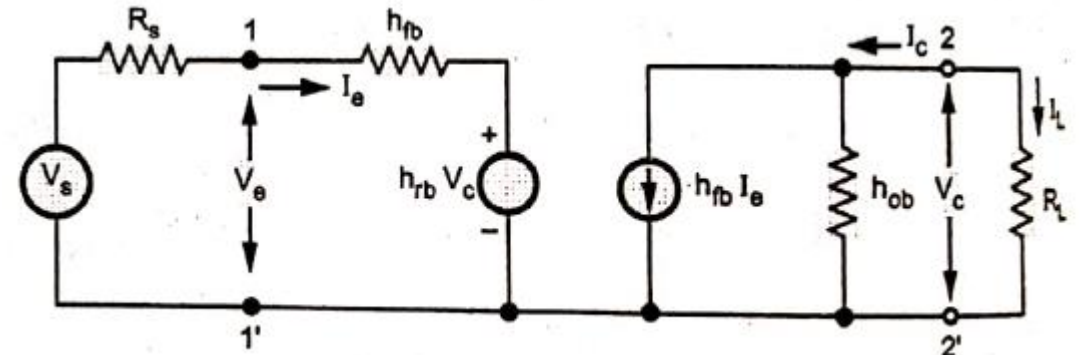
$$V_e = h_{ib} * I_e + h_{rb} * V_c$$

$$V_c = -I_c * R_L = I_e * A_i * R_L$$

$$V_e = h_{ib} * I_e + h_{rb} * A_i * I_e * R_L$$

$$R_i = \frac{h_{ib} * I_e + h_{rb} A_i I_e R_L}{I_e} = h_{ib} + h_{rb} A_i R_L$$

$$R_i = h_{ib} - h_{rb} * \frac{h_{fb}}{1 + h_{ob} * R_L} * R_L$$



Analysis of Common Base Configuration

3. Voltage Gain

$$A_V = \frac{V_c}{V_e}$$

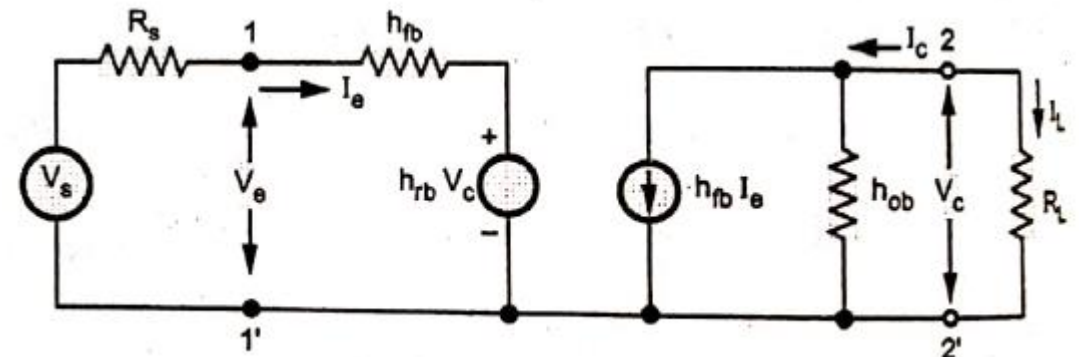
$$A_V = \frac{A_i I_e R_L}{V_e} = \frac{A_i R_L}{R_i}$$

4. Output Admittance

$$Y_O = \frac{I_c}{V_c} \text{ at } V_S = 0$$

$$I_c = h_{fb} * I_e + h_{ob} * V_c$$

$$Y_O = \frac{I_c}{V_c} = \frac{h_{fb} I_e}{V_c} + h_{ob}$$



Analysis of Common Collector Configuration

4. Output Admittance

$$Y_O = \frac{I_c}{V_c} \text{ at } V_S = 0$$

$$\mathbf{I}_c = \mathbf{h}_{fb} * \mathbf{I}_e + \mathbf{h}_{ob} * \mathbf{V}_c$$

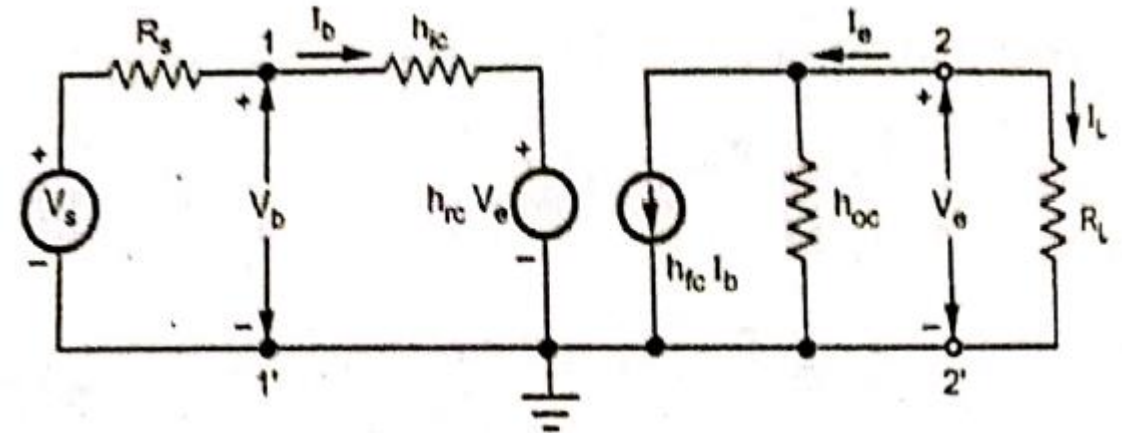
$$Y_O = \frac{I_c}{V_c} = \frac{h_{fb}I_e}{V_c} + h_{ob}$$

$$\mathbf{R}_S \mathbf{I}_e + \mathbf{h}_{ib} * \mathbf{I}_e + \mathbf{h}_{rb} * \mathbf{V}_c = 0$$

$$(\mathbf{R}_S + \mathbf{h}_{ib})\mathbf{I}_e = -\mathbf{h}_{rb} * \mathbf{V}_c$$

$$\mathbf{I_e / V_c = - h_{rb} / (R_S + h_{ib})}$$

$$Y_O = h_{ob} - \frac{h_{fb}h_{rb}}{R_S + h_{ib}}$$



$$R_o = \frac{1}{Y_o}$$

Solved Examples

1. For the transistor connected in CE configuration, determine A_v , A_i , R_i & R_o using complete hybrid equivalent model.

$R_L = R_S = 1k\Omega$, $h_{ie} = 1k\Omega$, $h_{re} = 2 \times 10^{-4}$, $h_{fe} = 100$, $h_{oe} = 20 \mu A/V$.

1. Current Gain

$$A_i = \frac{-h_{fe}}{1 + h_{oe} * R_L}$$

$$A_i = \frac{-100}{1 + 20 * 10^{-6} * 1k} = -98$$

2. Input resistance

$$R_i = h_{ie} + h_{re} * A_i * R_L$$

$$R_i = 1k + 2 \times 10^{-4} * -98 * 1k = 980.4 \Omega$$

3. Voltage Gain

$$A_v = \frac{A_i R_L}{R_i}$$

$$A_v = \frac{-98 * 1k}{980.4} = -99.9$$

Solved Examples

1. For the transistor connected in CE configuration, determine A_v , A_i , R_i & R_o using complete hybrid equivalent model.

$R_L = R_S = 1k\Omega$, $h_{ie} = 1k\Omega$, $h_{re} = 2 \times 10^{-4}$, $h_{fe} = 100$, $h_{oe} = 20 \mu A/V$.

4. Output resistance

$$Y_o = h_{oe} - \frac{h_{fe}h_{re}}{R_S + h_{ie}}$$

$$Y_o = 20\mu - \frac{100 * 2 * 10^{-4}}{1k + 1k} = 1.9 * 10^{-5}$$

$$R_o = \frac{1}{Y_o}$$

$$R_o = \frac{1}{1.9 * 10^{-5}} = 52.64 k\Omega$$

Solved Examples

1. A voltage source of negligible internal resistance drives a common collector transistor amplifier. The load resistance is $2.5\text{k}\Omega$. Determine A_v , A_i , R_i & R_o using complete hybrid equivalent model. $h_{ic} = 1\text{k}\Omega$, $h_{rc} = 1$, $h_{fc} = -50$, $h_{oc} = 25\text{ }\mu\text{A/V}$.

1. Current Gain

$$A_i = \frac{-h_{fc}}{1 + h_{oc} * R_L}$$

$$A_i = \frac{-(-50)}{1 + 25 * 10^{-6} * 2.5\text{k}} = 47$$

2. Input resistance

$$R_i = h_{ic} + h_{rc} * A_i * R_L$$

$$R_i = 1\text{k} + 1 * 47 * 2.5\text{k} = 118.5\text{k}\Omega$$

3. Voltage Gain

$$A_v = \frac{A_i R_L}{R_i}$$

$$A_v = \frac{47 * 2.5\text{k}}{118.5\text{k}} = 0.99156$$

Solved Examples

2. A voltage source of negligible internal resistance drives a common collector transistor amplifier. The load resistance is $2.5\text{k}\Omega$. Determine A_v , A_I , R_I & R_O using complete hybrid equivalent model. $h_{ic} = 1\text{k}\Omega$, $h_{rc} = 1$, $h_{fc} = -50$, $h_{oc} = 25 \mu\text{A/V}$.

4. Output resistance

$$Y_O = h_{oc} - \frac{h_{fc}h_{rc}}{R_S + h_{ie}}$$

$$Y_O = 25\mu - \frac{-50 * 1}{1k} = 0.050025$$

$$R_O = \frac{1}{Y_O}$$

$$R_O = \frac{1}{0.050025} = 19.99\Omega$$

Solved Examples

3. Consider a single stage CE amplifier with $R_L = 1.2 \text{ k}\Omega$ and $R_S = 1 \text{ k}\Omega$. Calculate A_i , R_i , A_v , A_{vs} , A_{is} and R_o if, $h_{ie} = 1.1 \text{ k}\Omega$, $h_{re} = 2.5 \times 10^{-4}$, $h_{fe} = 50$, $h_{oe} = 25 \text{ }\mu\text{A/V}$.

1. Current Gain

$$A_i = \frac{-h_{fe}}{1 + h_{oe} * R_L}$$

$$A_i = \frac{-50}{1 + 25 * 10^{-6} * 1.2k} = -48.54$$

2. Input resistance

$$R_i = h_{ie} + h_{re} * A_i * R_L$$

$$R_i = 1.1k + 2.5 * 10^{-4} * -48 * 54 * 1.2k = 1085.44 \text{ }\Omega$$

3. Voltage Gain

$$A_v = \frac{A_i R_L}{R_i}$$

$$A_v = \frac{-48.54 * 1.2k}{1085.44} = -53.663$$

$$A_{vs} = \frac{A_v R_i}{R_i + R_S}$$

$$A_{vs} = \frac{-53.663 * 1085.44}{1085.44 + 1000} = -27.93$$

Solved Examples

3. Consider a single stage CE amplifier with $R_L = 1.2 \text{ k}\Omega$ and $R_S = 1 \text{ k}\Omega$. Calculate A_i , R_i , A_v , A_{vs} , A_{is} and R_o if, $h_{ie} = 1.1 \text{ k}\Omega$, $h_{re} = 2.5 \times 10^{-4}$, $h_{fe} = 50$, $h_{oe} = 25 \mu\text{A/V}$.

$$A_{is} = \frac{A_i R_S}{R_i + R_S}$$

$$A_{is} = \frac{-48.54 * 1000}{1085.44 + 1000} = -23.28$$

Output resistance

$$Y_o = h_{oe} - \frac{h_{fe} h_{re}}{R_S + h_{ie}}$$

$$Y_o = 25\mu - \frac{50 * 2.5 * 10^{-4}}{1k + 1.2k} = 19 * 10^{-6}$$

$$R_o = \frac{1}{Y_o}$$

$$R_o = \frac{1}{19 * 10^{-6}} = 52.6 \text{ k}\Omega$$

Solved Examples

4. For the common base circuit shown, the transistor parameters are $h_{ib} = 22 \Omega$, $h_{rb} = 2.9 \times 10^{-4}$, $h_{fb} = -0.98$, $h_{oe} = 0.49 \mu\text{A/V}$. Calculate A_i , R_i , A_v , and R_o .

1. Current Gain

$$A_i = \frac{-h_{fb}}{1 + h_{ob} * R_L^1}$$

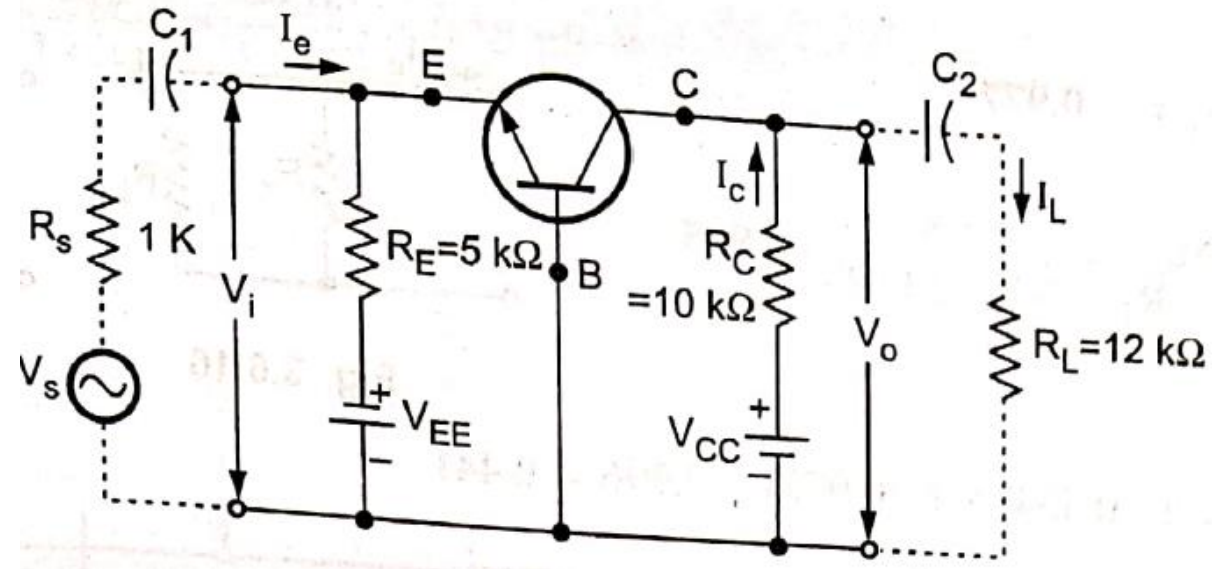
$$R_L^1 = R_C \parallel R_L = 10\text{k} \parallel 12\text{k} = 5.45\text{k}\Omega.$$

$$A_i = \frac{-(-0.98)}{1 + 0.49 * 10^{-6} * 5.45\text{k}} = 0.977$$

2. Input resistance

$$R_i = h_{ib} + h_{rb} * A_i * R_L^1$$

$$R_i = 22 + 2.9 \times 10^{-4} * 0.977 * 5.45\text{k} = 23.54 \Omega$$



$$R_i^1 = R_i \parallel R_s = 23.54 \parallel 5\text{k} = 23.43 \Omega.$$

Solved Examples

4. For the common base circuit shown, the transistor parameters are $h_{ib} = 22 \Omega$, $h_{rb} = 2.9 \times 10^{-4}$, $h_{fb} = -0.98$, $h_{oe} = 0.49 \mu\text{A/V}$. Calculate A_i , R_i , A_v , and R_o .

3. Voltage Gain

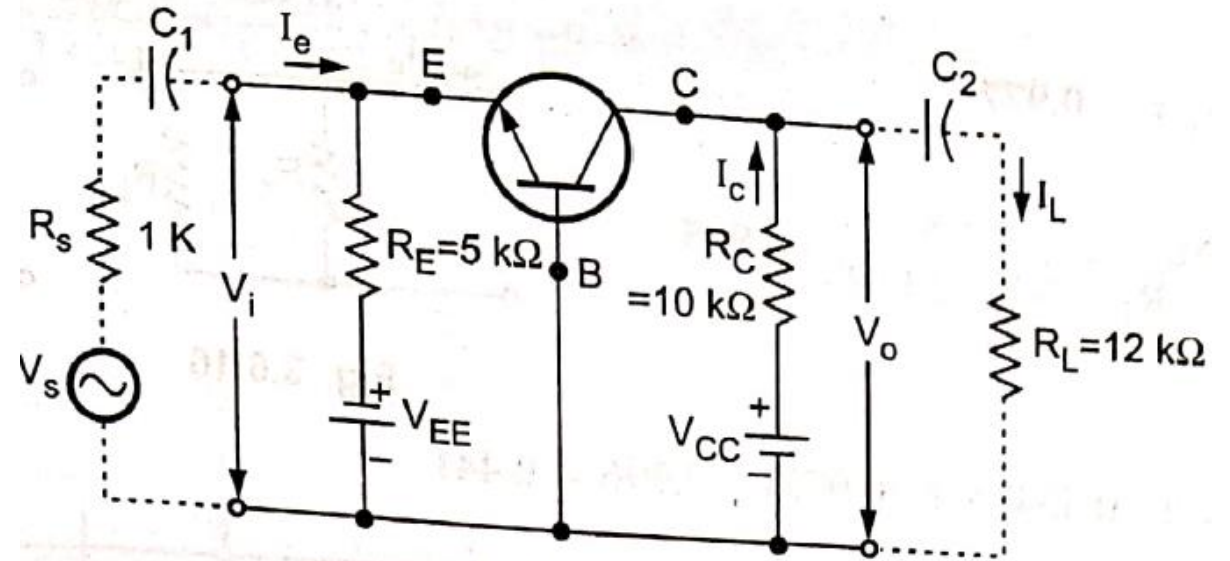
$$A_V = \frac{A_i R_L^1}{R_i}$$

$$A_V = \frac{0.977 * (5.45k)}{23.54} = 226$$

$$A_{VS} = \frac{V_O}{V_S} = \frac{V_O}{V_e} * \frac{V_e}{V_S}$$

$$\frac{V_O}{V_e} = A_V$$

$$\frac{V_e}{V_S} = \frac{R_i^1}{R_i^1 + R_S}$$



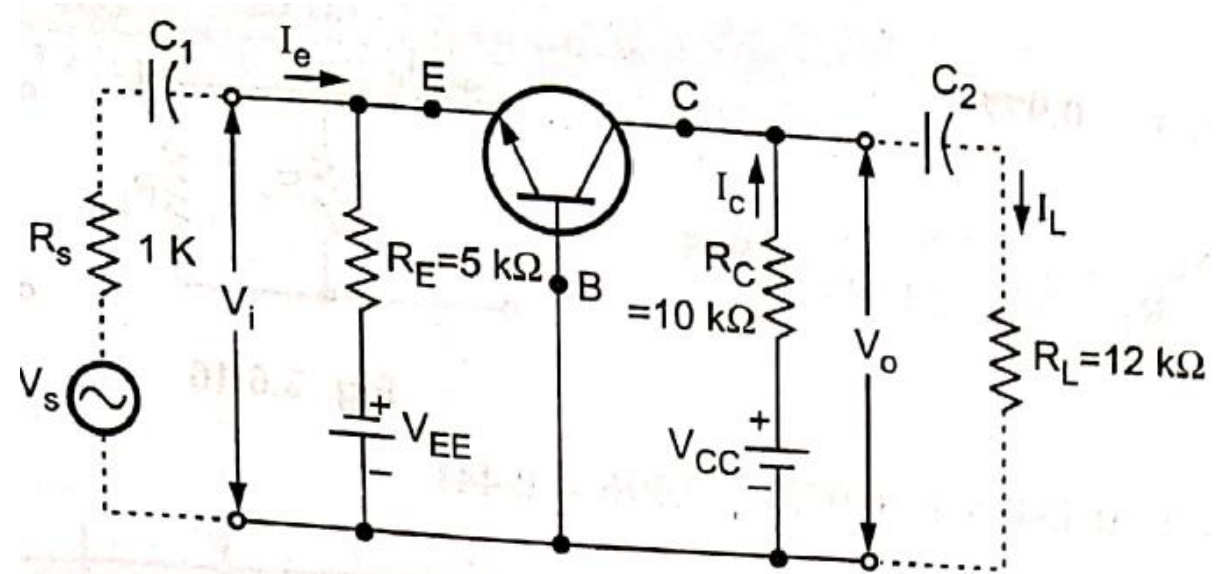
Solved Examples

4. For the common base circuit shown, the transistor parameters are $h_{ib} = 22 \Omega$, $h_{rb} = 2.9 \times 10^{-4}$, $h_{fb} = -0.98$, $h_{oe} = 0.49 \mu\text{A/V}$. Calculate A_i , R_i , A_v , and R_o .

3. Voltage Gain

$$A_{VS} = \frac{V_o}{V_s} = A_v * \frac{R_i}{R_i + R_s}$$

$$A_{VS} = \frac{V_o}{V_s} = 226 * \frac{23.43}{23.43 + 1k} = 5.174$$



Solved Examples

4. For the common base circuit shown, the transistor parameters are $h_{ib} = 22 \Omega$, $h_{rb} = 2.9 \times 10^{-4}$, $h_{fb} = -0.98$, $h_{oe} = 0.49 \mu\text{A/V}$. Calculate A_i , R_i , A_v , and R_o .

4. Overall Current Gain

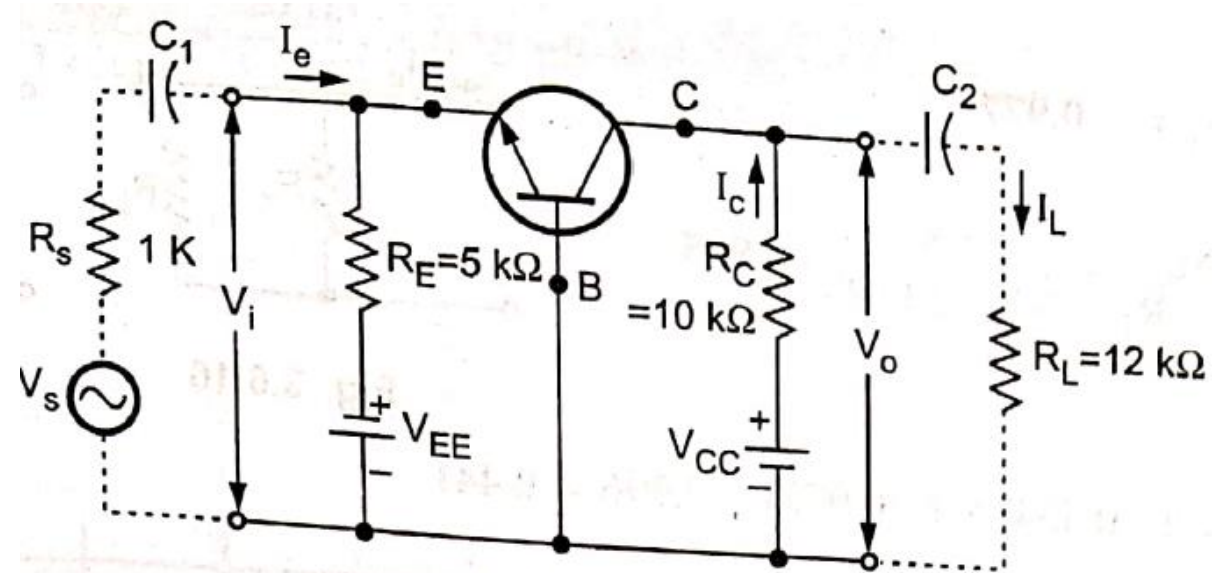
$$A_{iS} = \frac{I_L}{I_S} = \frac{I_L}{I_C} * \frac{I_C}{I_e} * \frac{I_e}{I_S}$$

$$\frac{I_L}{I_C} = -\frac{R_C}{R_C + R_L} = -\frac{10k}{10k + 12k} = -0.454$$

$$\frac{I_C}{I_e} = -A_i = -0.977$$

$$\frac{I_e}{I_S} = \frac{R_E}{R_E + R_i} = \frac{5k}{5k + 23.54} = 0.995$$

$$A_{iS} = (-0.454) * (-0.977) * (0.995) = 0.441$$



Solved Examples

4. For the common base circuit shown, the transistor parameters are $h_{ib} = 22 \Omega$, $h_{rb} = 2.9 \times 10^{-4}$, $h_{fb} = -0.98$, $h_{oe} = 0.49 \mu\text{A/V}$. Calculate A_i , R_i , A_v , and R_o .

Output resistance

$$Y_o = h_{ob} - \frac{h_{fb}h_{rb}}{R_S^1 + h_{ib}}$$

$$R_S^1 = R_S \parallel R_E = 1k \parallel 5k = 833.33$$

$$Y_o = 0.49\mu - \frac{-0.98 * 2.9 * 10^{-4}}{833.33 + 22} = 0.826\mu$$

$$R_o = \frac{1}{Y_o}$$

$$R_o = \frac{1}{0.826\mu} = 1.21 M\Omega$$

$$R_o^1 = R_o \parallel R_L^1 = 1.21 M \parallel 5.45k = 5.425k\Omega$$

THANK YOU