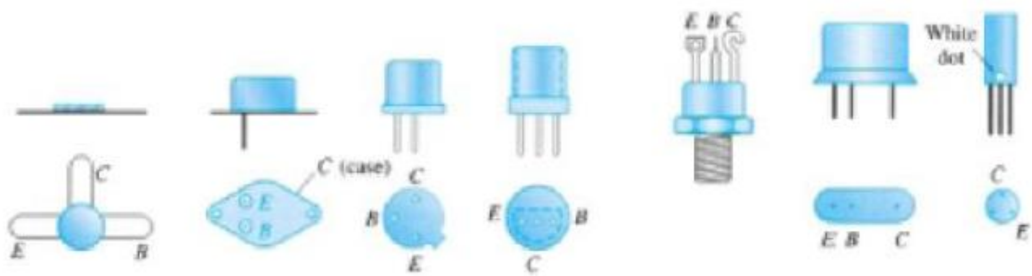
L9 - part 2
sec 1
27/7/2021



ENEE2360 Analog Electronics

T6:
Bipolar Junction Transistor

BJT

Instructor : Nasser Ismail

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The First Transistor

Co-inventors of the first transistor at Bell Laboratories: Dr. William Shockley (seated); Dr. John Bardeen (left); Dr. Walter H. Brattain. (Courtesy of AT&T Archives.)

Dr. Shockley Born: London, England, 1910
PhD Harvard, 1936

Dr. Bardeen Born: Madison, Wisconsin, 1908
PhD Princeton, 1936

Dr. Brattain Born: Amoy, China, 1902
PhD University of Minnesota, 1928

All shared the Nobel Prize in 1956 for this contribution.

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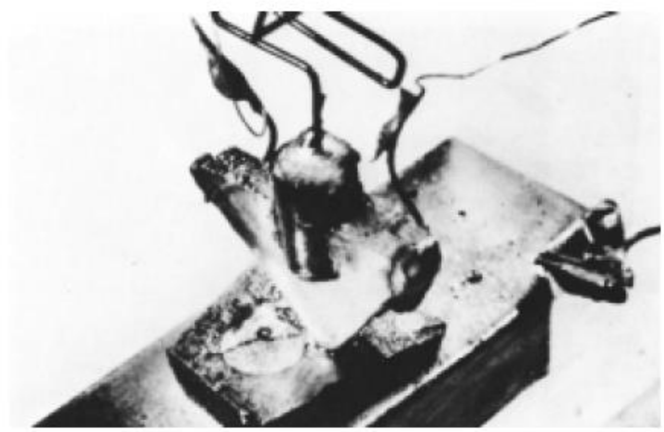


Figure 3.1 The first transistor. (Courtesy Bell Telephone Laboratories.)

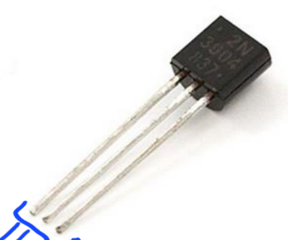
Bipolar Junction Transistor (BJT):

BJT:

1. It's a semiconductor device that can amplify electrical signals such as radio or television signals.

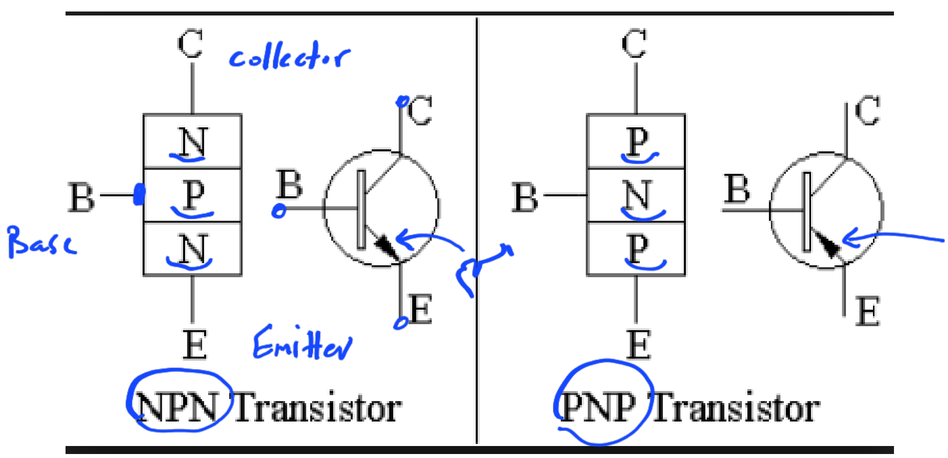
2. Its essential ingredient of every electronic circuits; from the simplest amplifier or oscillator to the most elaborate digital computer.

3. It's a three terminal device; Base, Emitter, and Collector.

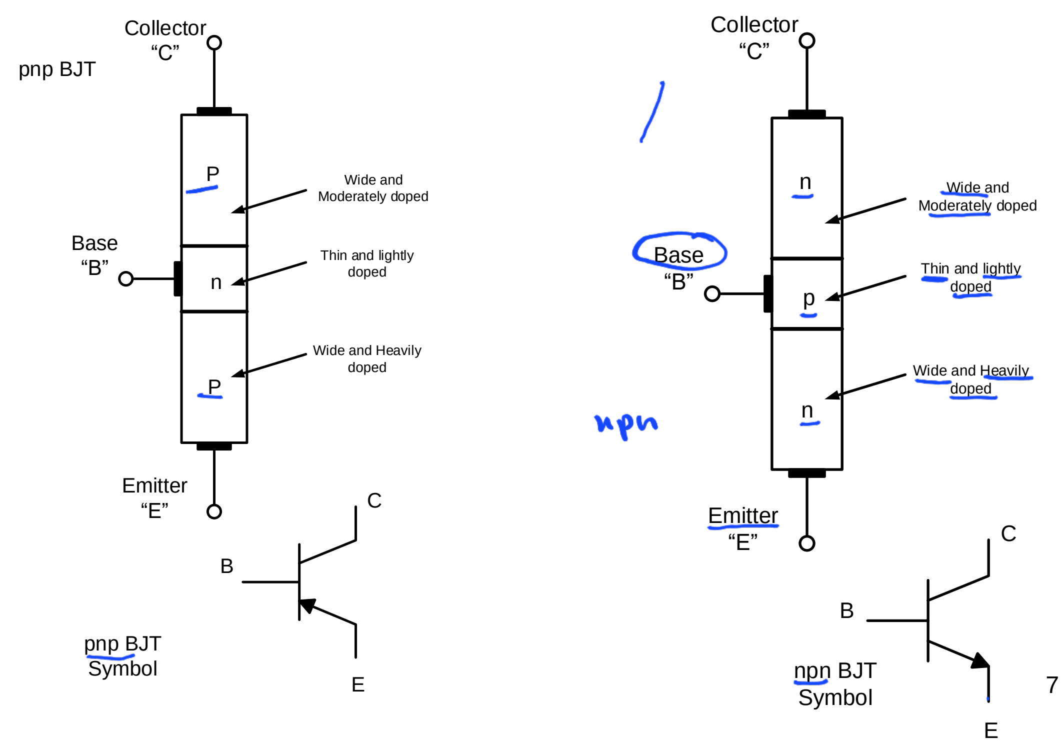


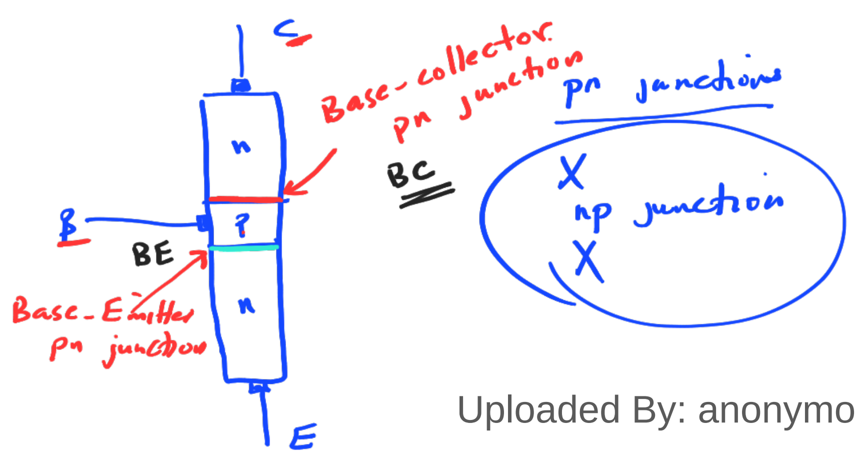
There are two type of BJT:

- **npn** type — الأكثر استخداما
- **pnp** type

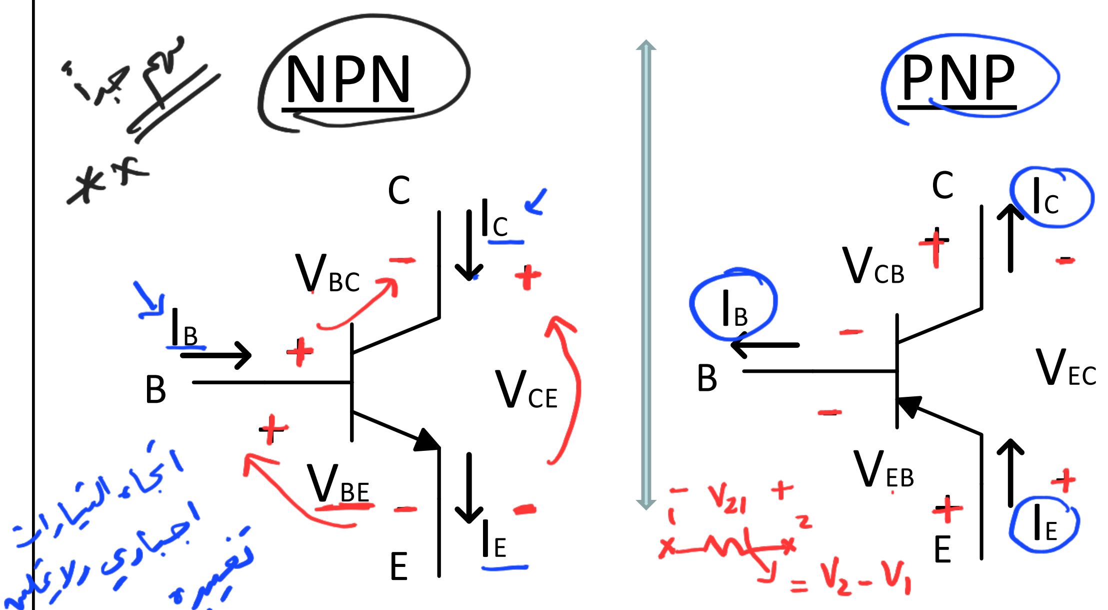


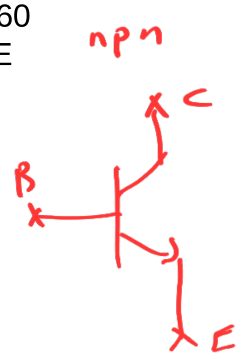
Construction and Symbol





Transistor structure:





pn junction → BE → ON / OFF
pn junction → BC → ON / OFF

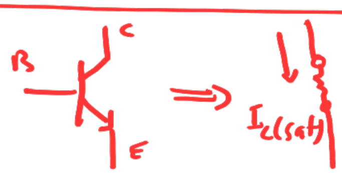
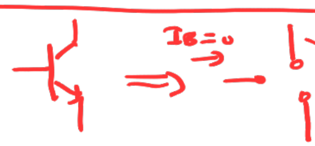
4 possible combinations ⇓ 4 possible modes of operation

Transistor biasing:

- ✓ In order to operate properly as an amplifier, it's necessary to correctly bias the two pn-junctions with external voltages.
- ✓ Depending upon external bias voltage polarities used; the transistor works in one of **four regions** (modes).
- ✓ For transistor to be used as an Active device **(Amplifier);** the emitter-base junction must be forward bias, while the collector-base junction must be reverse biased.

npn transistor modes of operation

	Junction/ Mode	BE	BC	Remarks
1)	**Saturation Mode**	Forward	Forward	Equivalent to short circuit Ic=Ic(sat) Vce=Vce(sat)=~ 0.2V
2)	**Active Mode (Linear Region)**	Forward	Reverse	Ic proportional to Ib Vce defined by circuit
3)	**Cut-off Mode**	Reverse	Reverse	Equivalent to open circuit Ic=Ib=0 Vce defind by circuit
X 4)	Inverse Mode	Reverse	Forward	Rarely used and will not be discussed in this course X

	BE	BC	Model or equivalent circuit
Saturation	ON	ON	 $V_{CE} = V_{CE(sat)} \approx 0.2\,V$ closed switch (digital electronics)
Cut-off	OFF	OFF	 $I_C = 0$, V_{CE} ?? , $I_E = 0$ open switch (Digital electronics)

	BE	BC
Linear (Active)	ON	OFF

$I_C \cong \beta I_B$

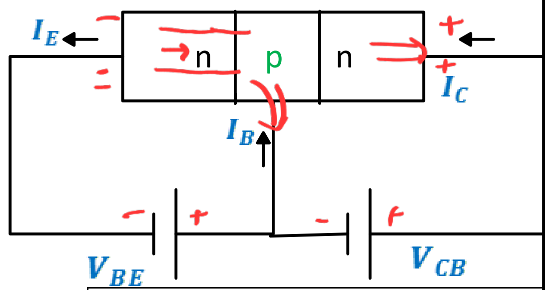
$I_C = \alpha I_E$

$I_E = I_B + I_C$

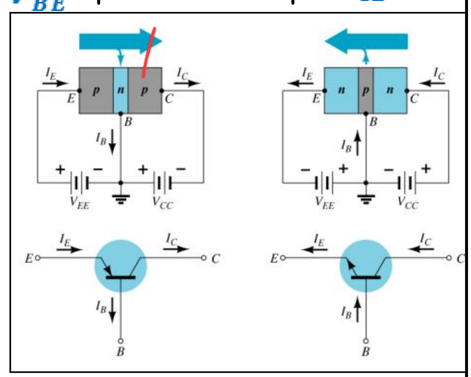
used in analog electronics "Amplifiers"

$V_{CE(sat)} < V_{CE} < V_{CE(max)}$

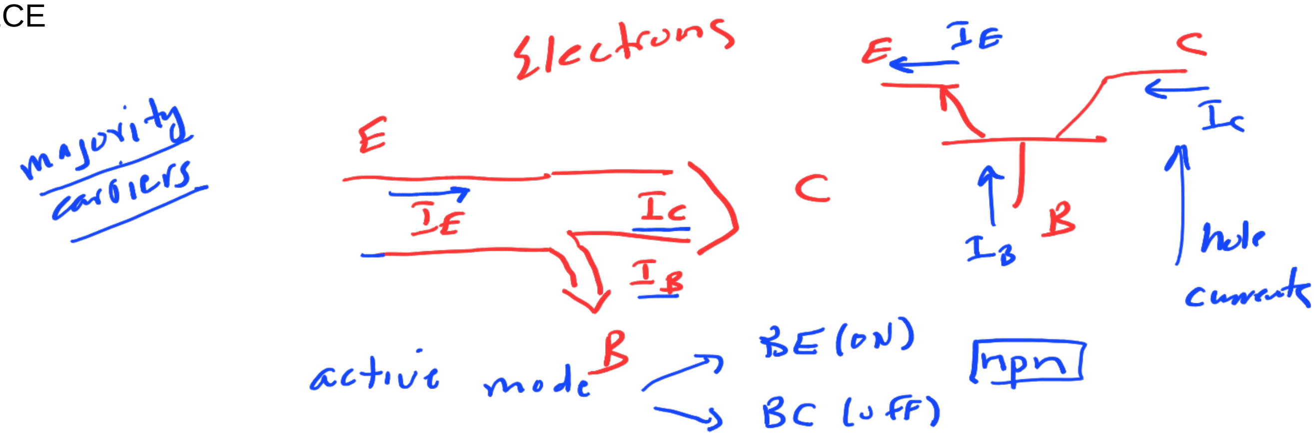
In active region



- ✓ The base region is thin and lightly doped
- ✓ The base-emitter junction is forward biased, thus the depletion region at this junction **is reduced**.
- ✓ The base-collector junction is reverse biased, thus the depletion region at this junction **is increased**.



- ✓ The forward biased BE-junction causes the electrons in the n-type emitter to flow toward the base; this constitutes the emitter current I_E.
- ✓ As these electrons flow through the P-type base; they tend to recombine with holes in p-type base.



- Since the base region is **lightly doped**; very few of the electrons injected into the base from the emitter recombine with holes to constitute base current I_B and the remaining large number of electrons cross the base and move through the collector region to the positive terminal of the external DC source; this constitute collector current I_C

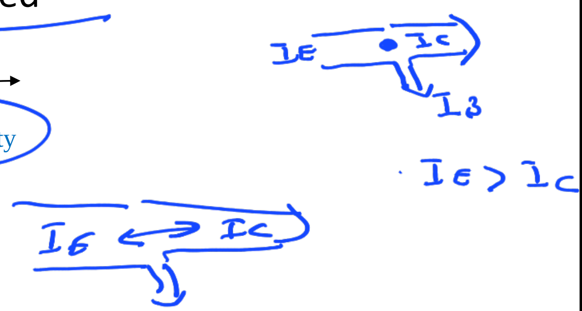
- There is another component for I_C due to the minority carrier; I_{CBO} which will be ignored

- $I_C = \alpha I_E + I_{CBO}$

Majority

Minority

$0.998 > \alpha > 0.9$



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$$I_C = \alpha I_E + I_{CBo}$$

$$I_E = I_C + I_B$$

$$I_C = \alpha(I_C + I_B) + I_{CBo}$$

❖ $I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBo}$

Let Beta, $\beta = \frac{\alpha}{1-\alpha}$

❖ $I_C = \beta I_B + (\beta + 1) I_{CBo}$

$$I_C = \beta I_B + I_{CEo}$$

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

If $\alpha = 0.99$ → $\beta = 99$

If $\alpha = 0.995$ → $\beta = 199$

In active region:

$$I_C = \alpha I_E + I_{CBo}$$

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

$$I_C = \beta I_B + I_{CEo}$$

$$I_E = I_C + I_B$$

Summary

Approximate relationships: will be used in this course

$$I_C \cong \alpha I_E \cong I_E$$

$$I_C \cong \beta I_B$$

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

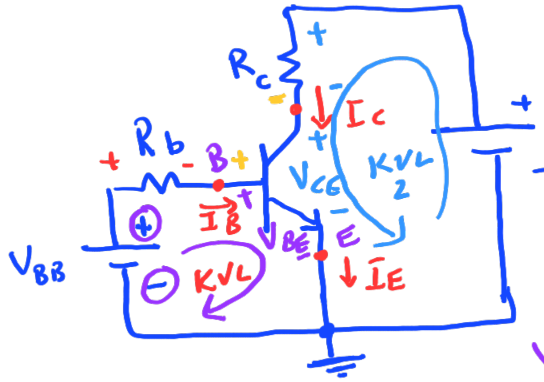
$$\beta = \frac{\alpha}{1 - \alpha}$$

- https://www.youtube.com/watch?v=7ukDKVHnac4

	BE	BC
Active	ON	OFF ← $V_{BC} < 0$
saturation	ON	ON

$V_{BE} > 0$

assume Active mode



KVL 2: $V_{CC} = I_C R_C + V_{CE}$

npn

KVL 1: $V_{BB} = I_B R_b + V_{BE}$

Basic BJT Amplifiers Circuits

BJT in Active Mode

$I_E = I_B + I_C$

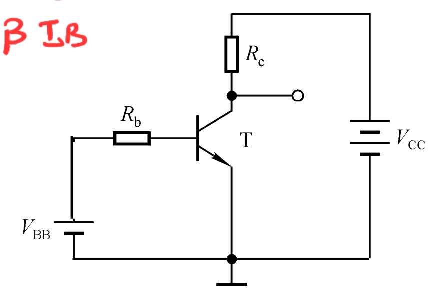
$$\alpha \approx \frac{I_C}{I_E}$$

$I_C = \alpha I_E$

$$\beta \approx \frac{I_C}{I_B}$$ ---common-emitter current gain

$I_C = \beta I_B$

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



BJT DC Analysis

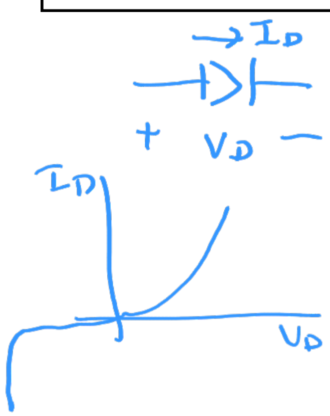
- Make sure the BJT current equations and region of operation match

  $V_{BE} > 0$,
  $V_{BC} < 0$, → $V_E < V_B < V_C$

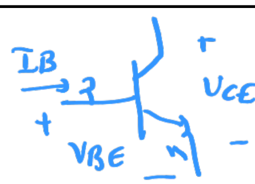
- Utilize the relationships (β and α) between collector, base, and emitter currents to solve for all currents

$$\begin{cases} I_E = I_C + I_B = (1+\beta) I_B \\ I_C = \beta I_B \\ I_C = \alpha I_E \end{cases}$$

** Active region



input characteristic



$I_B = f(V_{BE})$

$i_B(t) = I_{B0}\left(e^{\frac{V_{BE}}{\eta V_T}} - 1\right)$

$i_B(t) = I_{B0}\, e^{\frac{V_{BE}}{\eta V_T}}$

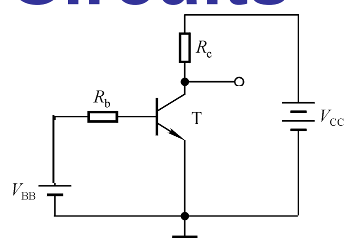
$i_C(t) = \beta i_B(t)$

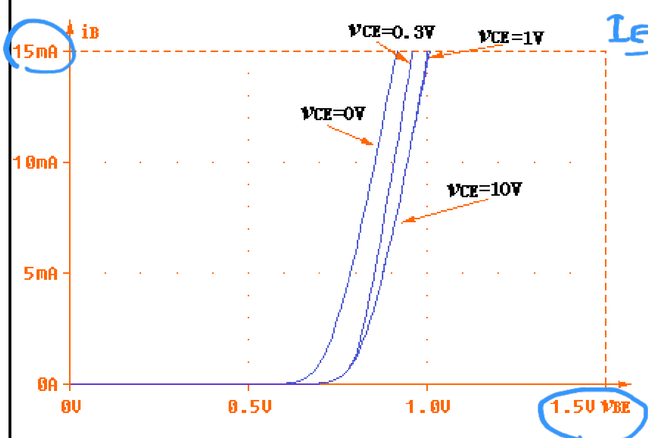
Basic BJT Amplifiers Circuits

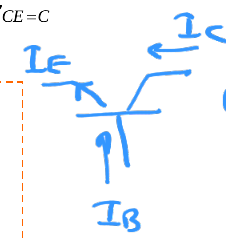
C-E Circuits I-V Characteristics

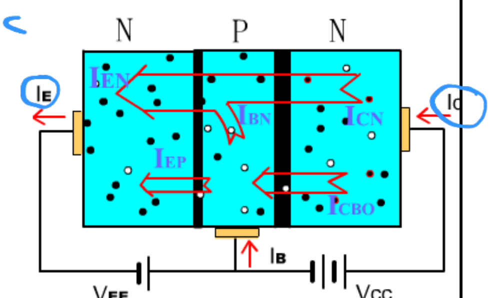
Base-emitter Characteristic(Input characteristic)

$$i_B = f(v_{BE})\,\Big|_{v_{CE}=C}$$









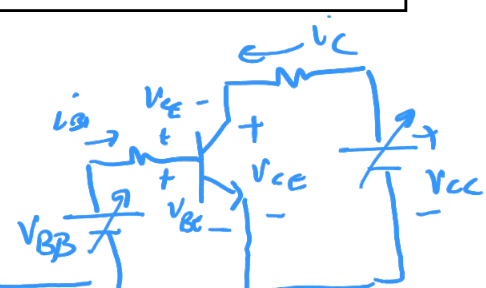
$$i_{B(t)} = I_{Bo}\left(e^{\frac{V_{BE}(t)}{\eta V_T}} - 1\right)$$

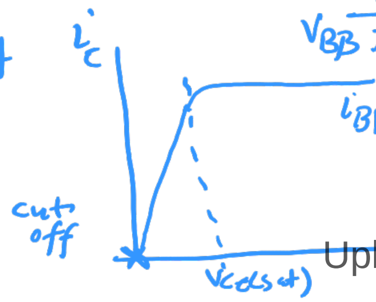
$$i_{C(t)} \cong I_S\left(e^{\frac{V_{BE}(t)}{\eta V_T}}\right)$$

$$i_{B(t)} \cong I_{Bo}\left(e^{\frac{V_{BE}(t)}{\eta V_T}}\right)$$

2) Output (collector) characteristic

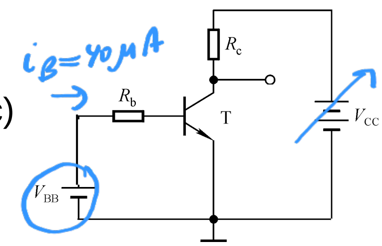
$$i_C = f(V_{CE})\Big|_{i_B = const}$$





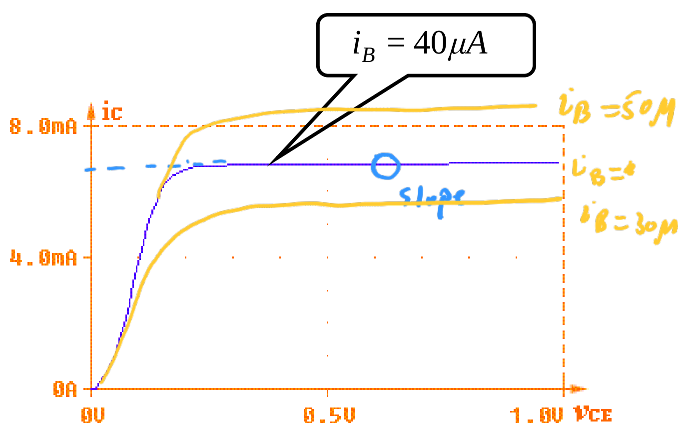
Basic BJT Amplifiers Circuits

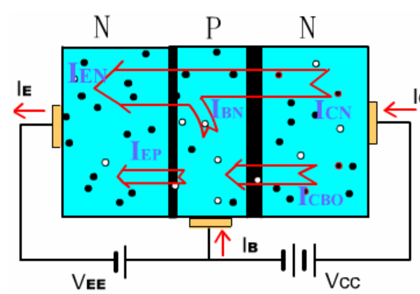
C-E Circuits I-V Characteristics



Collector characteristic (output characteristic)

$$i_C = f_{(V_{CE})}\Big|_{i_B=C}$$

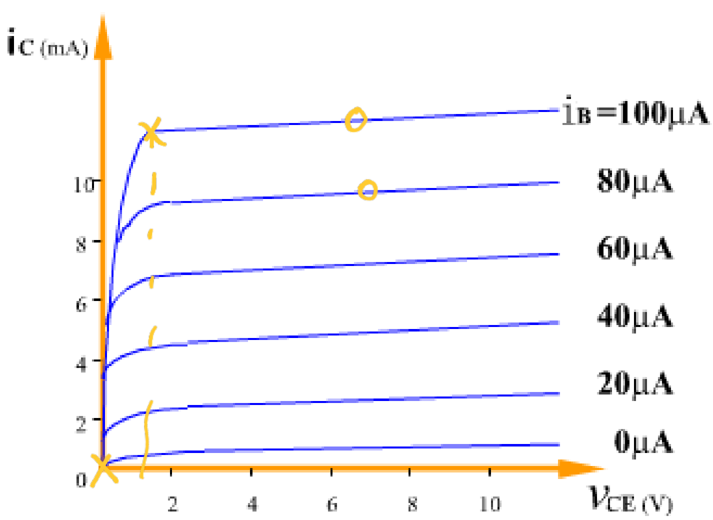




Basic BJT Amplifiers Circuits

C-E Circuits I-V Characteristics

Collector characteristic (output characteristic) $i_C = f_{(V_{CE})}\Big|_{i_B = C}$



In general

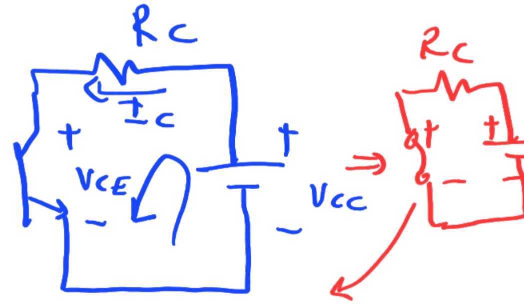
$V_{CC} - I_C R_C - V_{CE} = 0$

in saturation mode

$V_{CE} = V_{CE(sat)} \approx 0.2\,V$

$I_C = I_{C(sat)} = \frac{V_{CC} - 0.2}{R_C}$

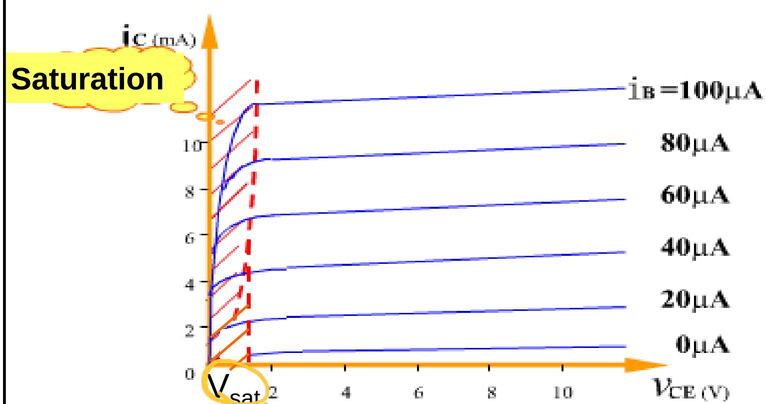
if $V_{CE(sat)}$ assumed $= 0 \Rightarrow$ $I_{C(sat)} = \frac{V_{CC}}{R_C}$

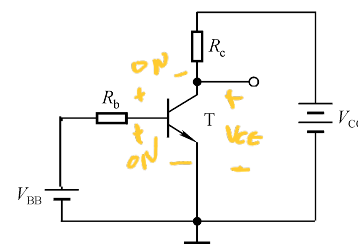


Basic BJT Amplifiers Circuits

C-E Circuits I-V Characteristics

Collector characteristic





$V_{CE(sat)} \approx 0.2\,V$

Saturation occurs when the supply voltage, V_{CC}, is across the total resistance of the collector circuit, R_C.

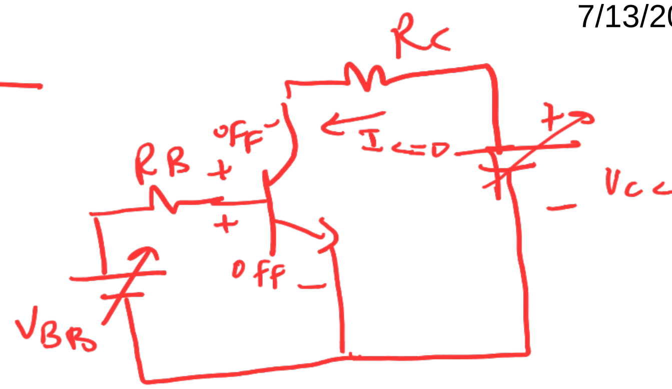
$I_{C(sat)} = V_{CC}/R_C$

Once the base current is high enough to produce saturation, further increases in base current have no effect on the collector current and the relationship $I_C = \beta I_B$ is no longer valid. When V_{CE} reaches its saturation value, $V_{CE(sat)}$, the base-collector junction becomes forward-biased.

in cut off mode

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

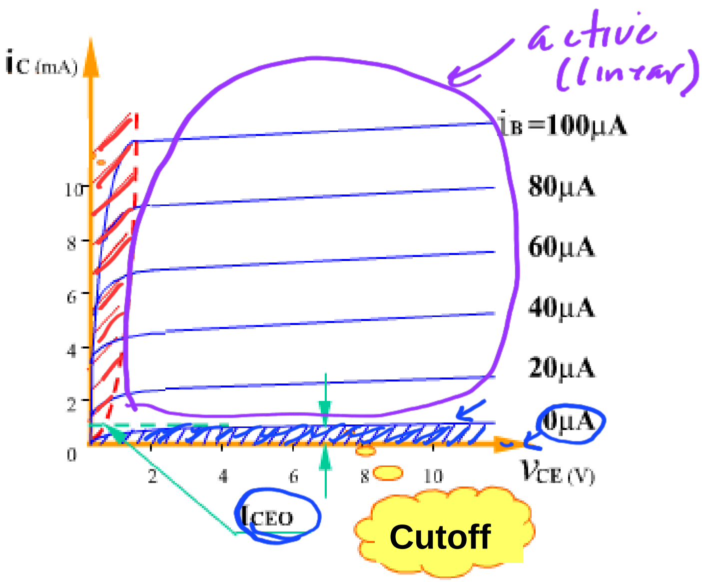
$\therefore V_{CE} = V_{CC} = V_{CE(cut\text{-}off)}$

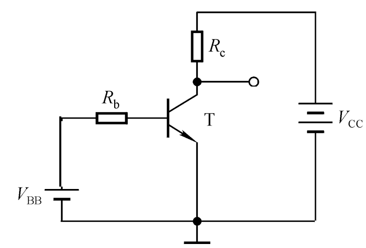


Basic BJT Amplifiers Circuits

C-E Circuits I-V Characteristics

Collector characteristic





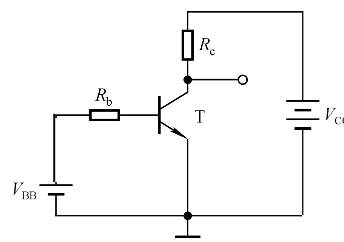
When $I_B = 0$, the transistor is in cutoff and there is essentially no collector current except for a very tiny amount of collector leakage current, I_{CEO}, which can usually be neglected. $I_C \approx 0$.

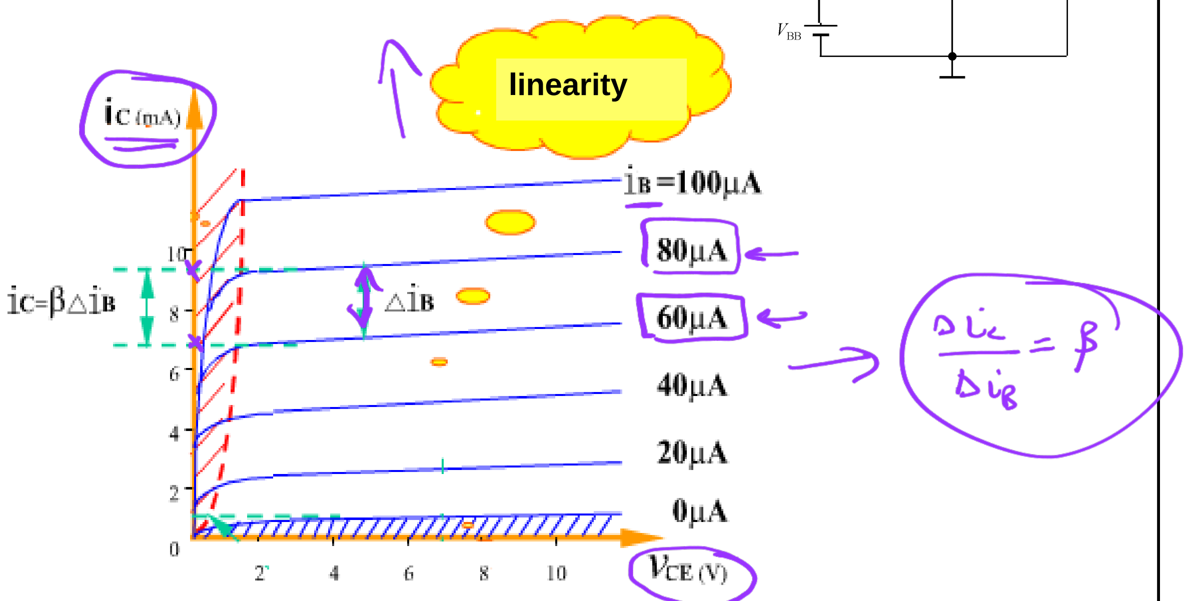
In cutoff both the base-emitter and the base-collector junctions are reverse-biased.

Basic BJT Amplifiers Circuits

C-E Circuits I-V Characteristics

Collector characteristic





* Summary

1. In the cutoff region :

$I_B = I_C = I_E = 0$

2. In the active region :

$I_C = \alpha I_E$

$I_C = \beta I_B$

$I_E = (\beta+1) I_B$

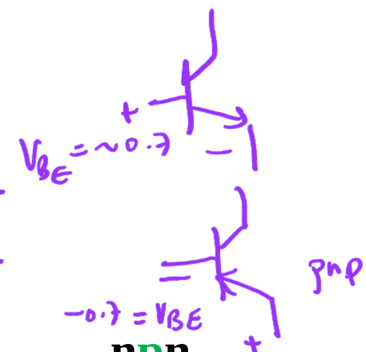
3. In the saturation region :

$V_{CE} = V_{CE,sat}$

$V_{BE} = 0.7\ v$, Si , npn

$V_{BE} = -0.7\ v$, Si , pnp

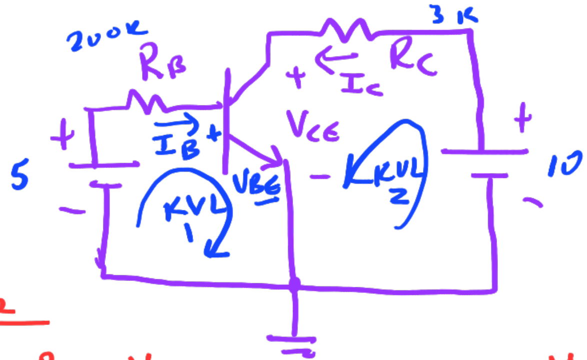
or $V_{EB} = 0.7$



$V_{CE} > V_{CE,sat} = 0.2\ v$, Si , npn

$V_{CE} < V_{CE,sat} = -0.2\ v$, Si , pnp

or $V_{EC(sat)} = 0.2$



KVL 1

$$5 - I_B \cdot 200k - V_{BE} = 0$$

$V_{BE} = 0.7 \leftarrow$ active

$$\therefore I_B = \frac{5 - 0.7}{200k} = 21.5\,\mu A$$

$$I_C = \beta I_B = 100 \times 21.5\,\mu A = 2.15\,mA$$

KVL 2

$$10 - I_C R_C - V_{CE} = 0$$

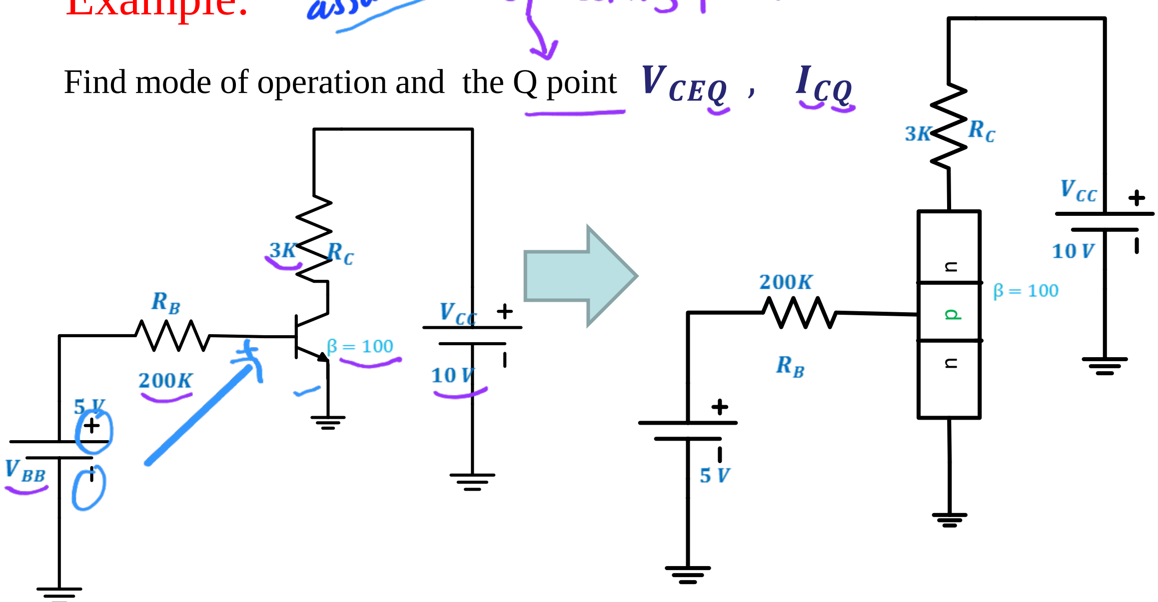
$V_{CE} = 10 - (2.15\,mA \times 3k) = 3.55\,V \rightarrow V_{CE(sat)}$?

BJT assumed in active mode

Example:

operating point

Find mode of operation and the Q point V_{CEQ} , I_{CQ}



Since the base emitter junction is forward bias; the transistor could be either in the active or the saturation region

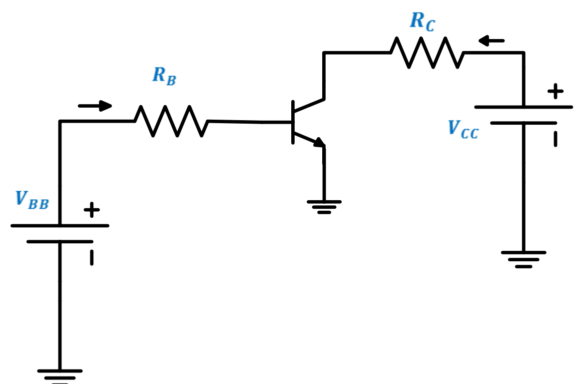
In General

1)In the active region:

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

$$I_C = \beta I_B$$

$$V_{CE} = V_{CC} - R_c I_c$$



As : R_B ↓ , I_B ↑ , I_C ↑ , V_{CE} ↓

2) In the saturation region:

$V_{CE} = V_{CE,sat} = 0.2\ v$, Si , npn

$$I_C = I_{C,sat} = \frac{V_{CC} - V_{CE,sat}}{R_C}$$

➢ Assume that the transistor in the active region:

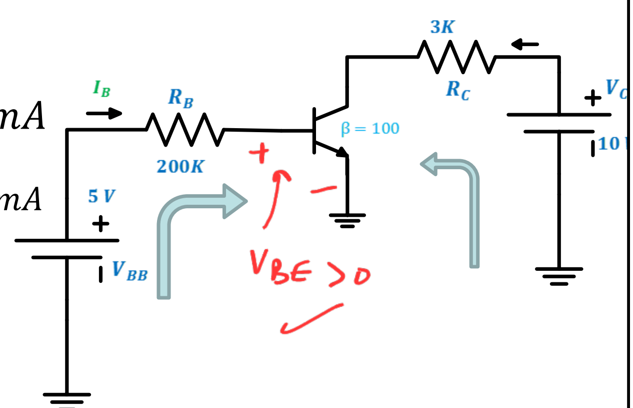
KVL: $5 = 200k\, I_B + V_{BE}$

$$I_B = \frac{5 - 0.7}{200k} = 0.0215\; mA$$

$$I_C = \beta\, I_B = 100 * 0.0215 = 2.15\; mA$$

KVL: $10 = R_C I_C + V_{CE}$

$$V_{CE} = 10 - R_c I_c$$



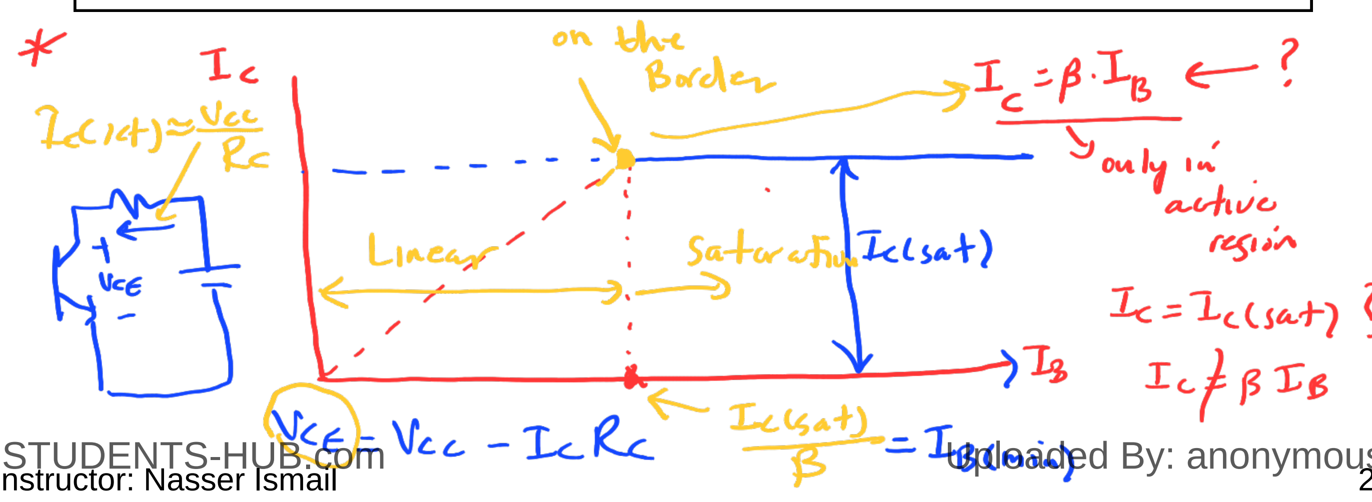
❖ $V_{CE} = 10 - 3k * 2.15mA = 3.55\; Volt$

Since

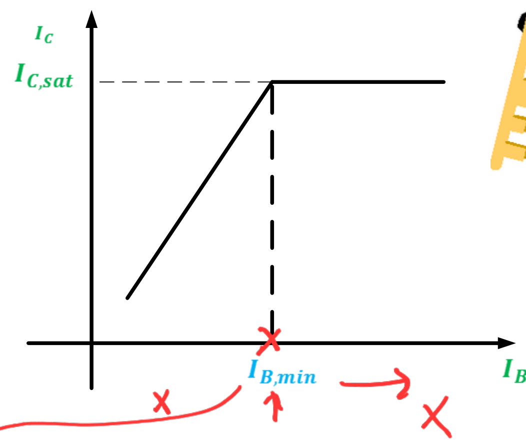
$V_{CE} > V_{CE,sat}$ >>> The transistor is in the active region

➢ $V_{CEQ} = 3.55\;\; Volt$

➢ $I_{CQ} = 2.15\; mA$



Let define: $I_B(min) = \frac{I_{C,sat}}{\beta}$



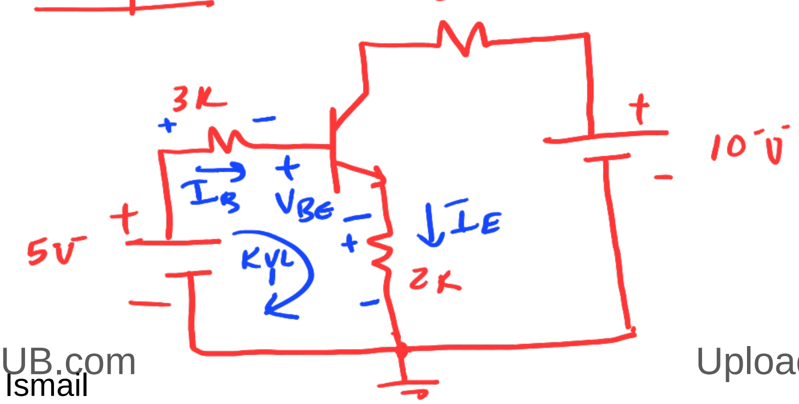
$$I_B(min) = \frac{I_{C,sat}}{\beta}$$

- If $I_B > I_B(min)$ the transistor is in the **Saturation** region.
- If $I_B < I_B(min)$ the transistor is in the **Active** region.

Example

$\beta = 100$

Find Mode of operation & I_C, V_{CE}?



$V_{BE} > 0 \longrightarrow$ BJT → active / → saturation

assume active mode

$5 = 3k(I_B) + V_{BE} + 2k(I_E)$ (? , 0.7 , ?)

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

$I_B = \frac{5-0.7}{3k + 2k(\beta+1)}$

$I_B = 10.7\,\mu A$

Determine Mode of Operation of BJT?

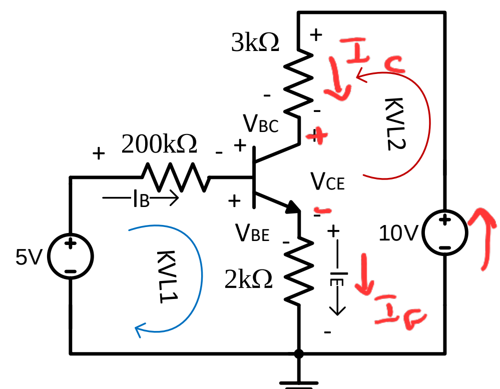
- Solution 1:
- 1) Since BE junction is forward biased ==> Q1 can be either in Active (Linear) or Saturation mode
- Assume it is in Active Mode

$$5 = 200\text{ k}\Omega \, . \, I_B + V_{BE} + 2\text{ k}\Omega . \, I_E$$

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

$$\text{Solve for } I_B = \frac{5 - V_{BE}}{200\text{ k}\Omega + (1+\beta).\,2\text{ k}\Omega}$$

$$I_B = \frac{5 - 0.7}{200\text{ k}\Omega + (1+100).\,2\text{ k}\Omega} = \frac{4.3\text{ V}}{402\text{ k}\Omega} = 10.7\ \mu\text{A}$$



$I_C = \beta I_B = 100 \times 10.7\mu = 1.07\,mA$

$I_E = (\beta+1) I_B = 101 \times 10.7\mu = 1$

KVL 2: $10 = I_C \cdot 3k + V_{CE} + I_E \cdot 2k$

$V_{CE} = 10 - 1.07mA \times 3k - 1.087mA \times 2k$ (1.07, 1.087)

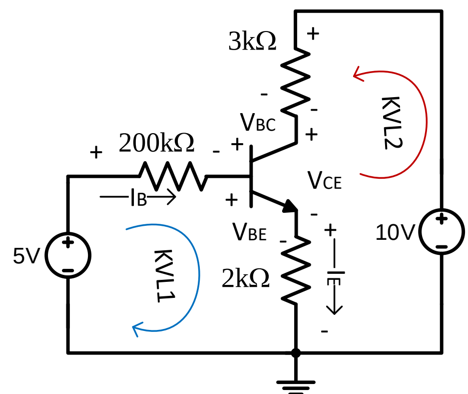
$\cong 4.63 > V_{CE(sat)}$

active: $V_{BE} > 0$, $V_{BC} < 0$

V_{BC} ? $V_{BC} = V_{BE} - V_{CE}$?

$$I_C = \beta I_B$$
$$= (100).(10.7\ \mu A)$$
$$= 1.07\ \ mA$$
$$I_E = (\beta + 1)I_B$$
$$= 1.0807\ mA$$

Now we find V_{CE} from output circuit



$$10 - I_C\ .3\ k\Omega - I_E\ .2\ k\Omega = V_{CE}$$
$$\Rightarrow V_{CE} = 4.63\ V > V_{CE(sat)}$$

$\therefore$ Q1 is in active mode and the assumption is true we can also verify that the BC junction is reverse biassed which is required so that the BJT operates in active mode

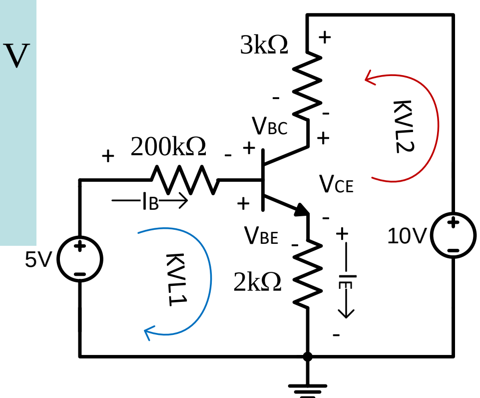
$$10 - I_C .3\,k\Omega - I_E .2\,k\Omega = V_{CE}$$

$$\Rightarrow V_{CE} = V_{CB} - V_{EB}$$

$$\Rightarrow V_{CB} = V_{CE} - V_{BE} = 4.63 - 0.7 = 3.93\,V$$

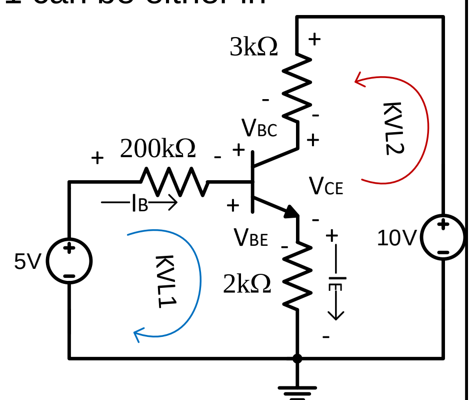
$$\therefore V_{BC} = -V_{CB} = -3.33\,V$$

BC junction is reverse biased



OR Second method: Assume Saturation

- 1) Since BE junction is forward biased ==> Q1 can be either in Active (Linear) or Saturation mode
- Assume it is in **saturation mode**:



$$10 - I_{C(sat)}.3k\Omega - I_{E(sat)}.2k\Omega = V_{CE(Sat)}$$

$$\text{assume} \quad I_{E(sat)} = I_{C(sat)}$$

$$\therefore I_{C(sat)} = \frac{10-0.2}{5k\Omega} = 1.96 \text{ mA}$$

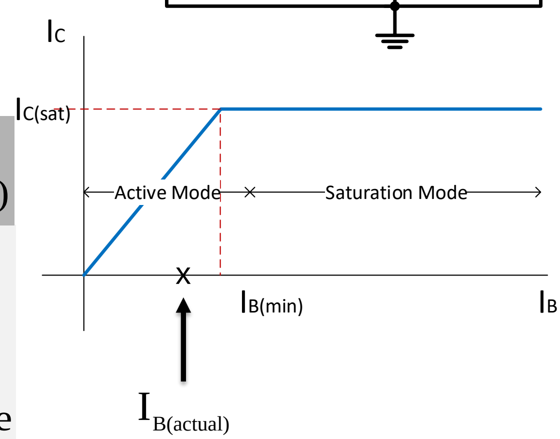
$$I_{B(min)} = \frac{I_{C(sat)}}{\beta} = 19.6 \ \mu A$$

Now we find the actual value of IB

$I_{B(actual)} = 10.7 \ \mu A$ (it was found previously)

since

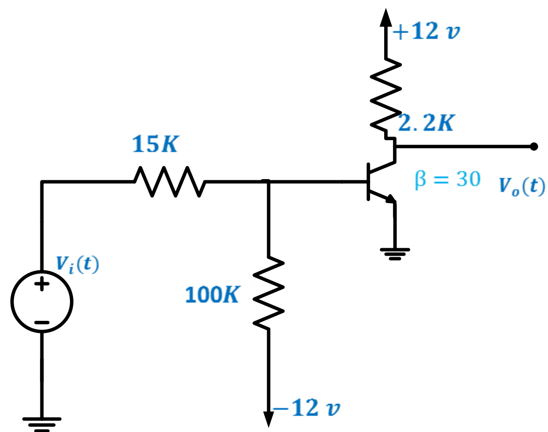
$I_{B(actual)} < I_{B(sat)} = I_{B(min)} \Rightarrow$ the assumption made earlier that BJT in saturation mode is wrong, and actually it is in active mode

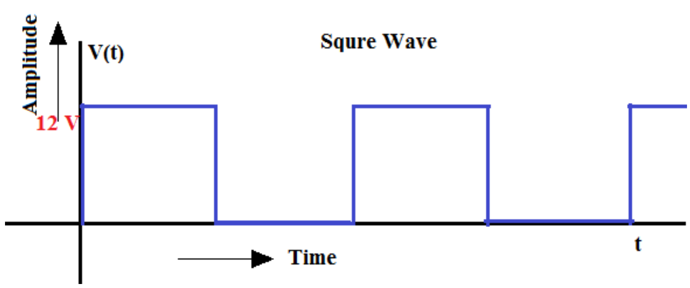


BJT as switch:

Example:

Find $V_o(t)$ for the input given below:

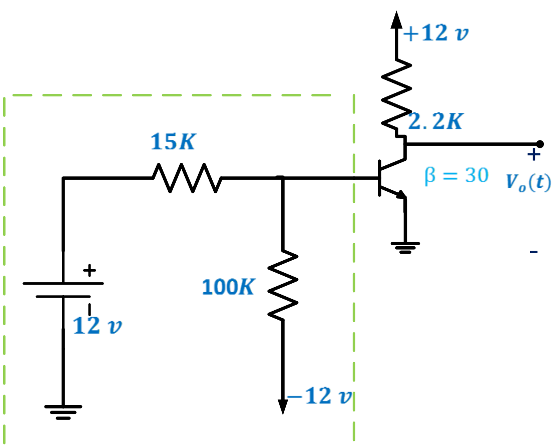


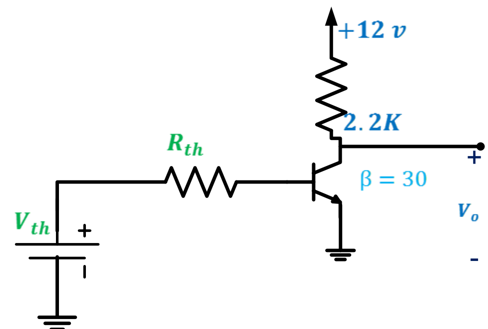


Solution:

❖Let $V_i(t) = +12\ volt$

Calculate V_{th}&R_{th}





$$R_{th} = 15k\ //\ 100k = \frac{100k*15k}{15k+100k} = 13k$$

$$V_{th} = 8.9\ volt$$

Proof!!

Since the base emitter junction is forward bias; the transistor could be either in the active or the saturation region

- Assume that the transistor in the saturation region

$$I_C = I_{C,sat} = \frac{V_{CC} - V_{CE,sat}}{R_C} = \frac{12 - 0.2}{2.2k} = 5.36\ mA$$

$$I_B(min) = \frac{I_{C,sat}}{\beta} = \frac{5.36mA}{30} = 0.18mA$$

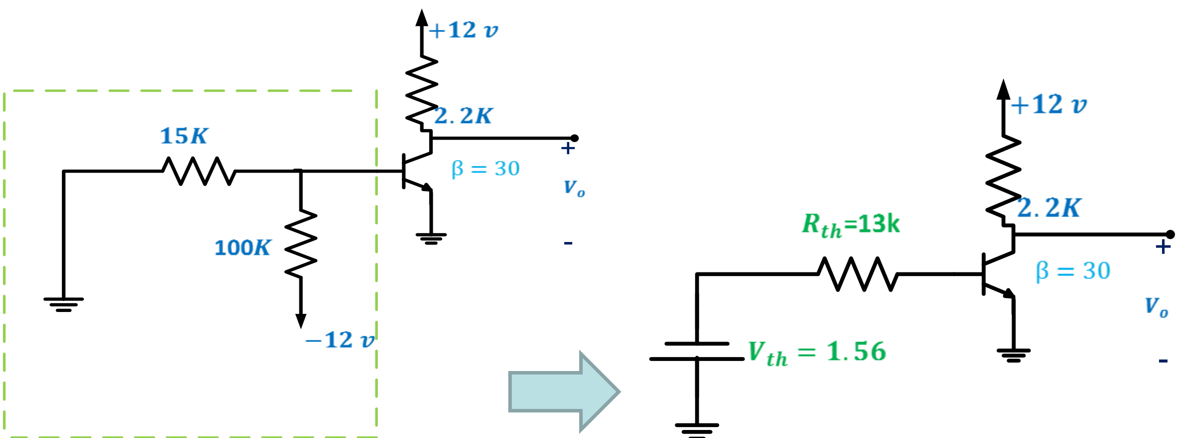
$$I_B = \frac{V_{th} - V_{BE}}{R_{TH}} = \frac{8.9 - 0.8}{13k} = 0.62\ mA$$

- Since $I_B > I_B(min)$ the transistor is in the saturation region.

✓ $V_o = V_{CE,sat} = 0.2\ \ volt$

✓ $I_C = 5.36\ mA$

❖Let $V_i(t) = \ 0\ volt$



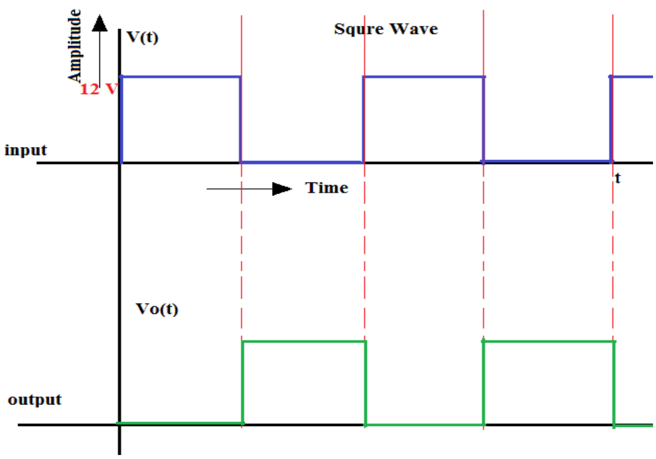
Since $V_{th} = -1.56\ volt$

Base emitter junction is revers biased the transistor in cutoff region

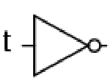
✓$V_o = V_{CE} = 12\ \ volt$

✓$I_C = 0\ mA$

The circuit acts as inverter or not gate



NOT gate truth table



Input	Output
0	1
1	0