ECE 65: Components & Circuits Lab

Lecture 10

Bipolar Junction Transistor (BJT)

Introduction

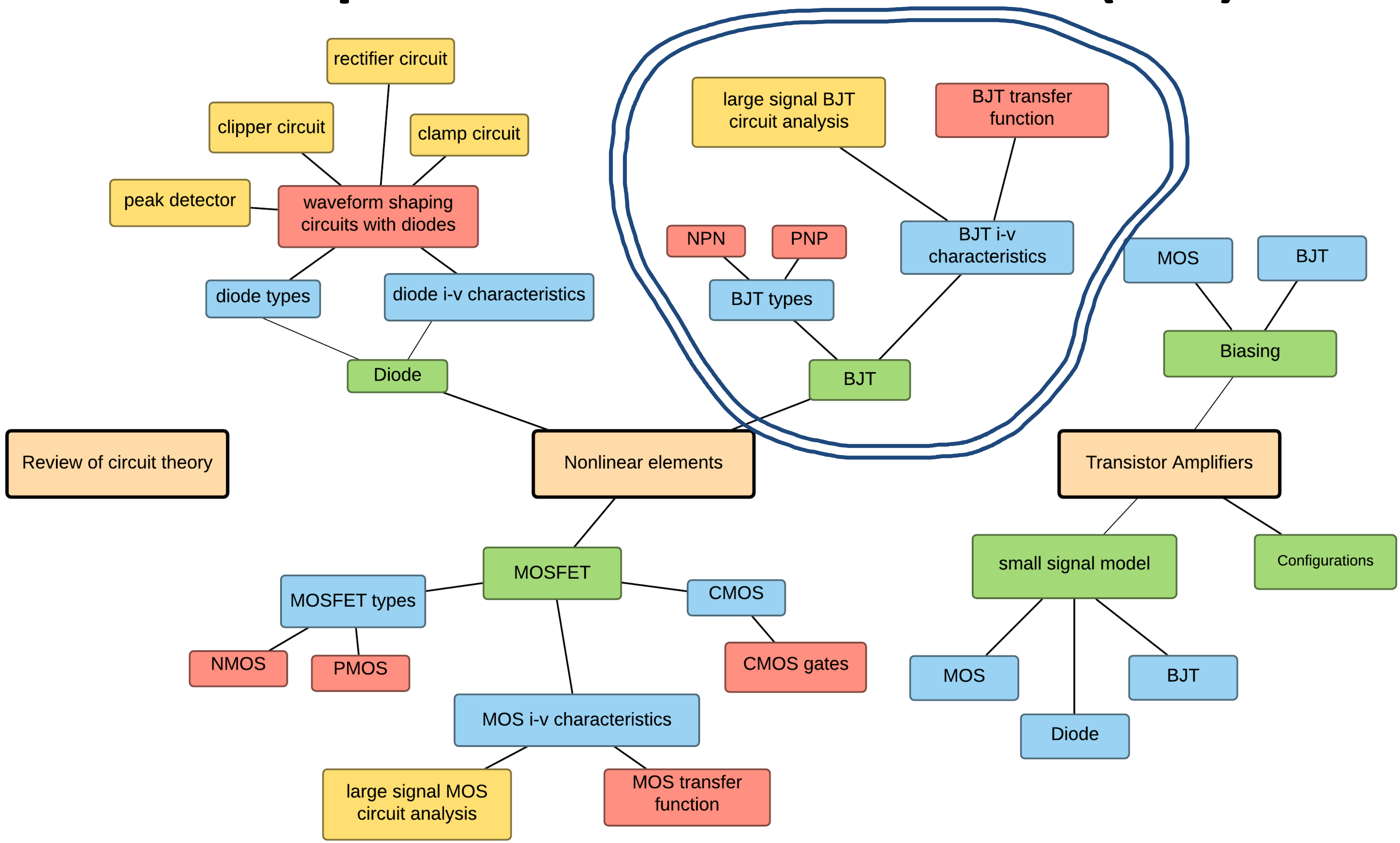
Reference notes: section 3.1

Sedra & Smith (7th Ed): sections 6.1,6.2

Saharnaz Baghdadchi

Course map

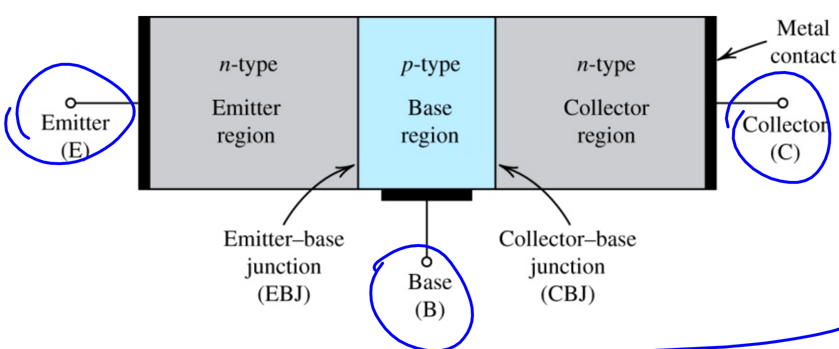
3. Bipolar Junction Transistor (BJT)



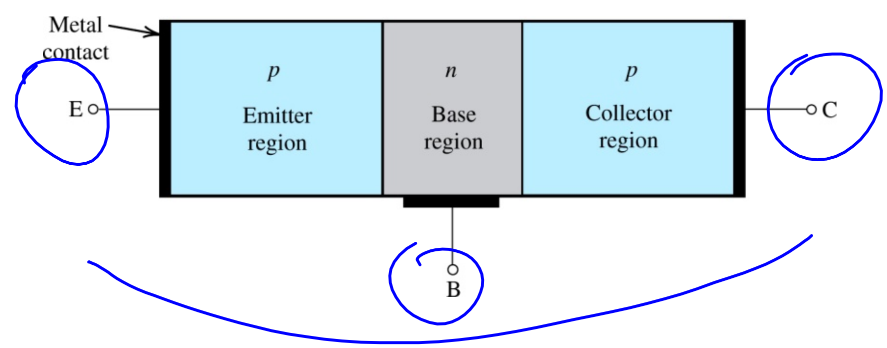
A BJT consists of three regions

Simplified physical structure

NPN transistor



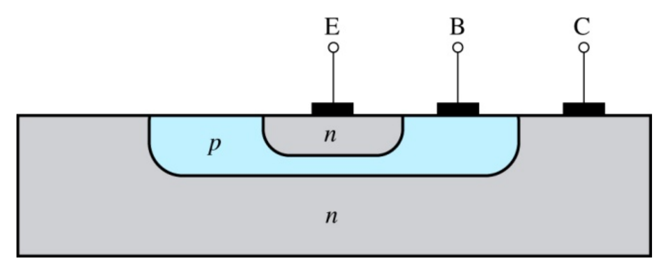
PNP transistor



Device construction is NOT symmetric

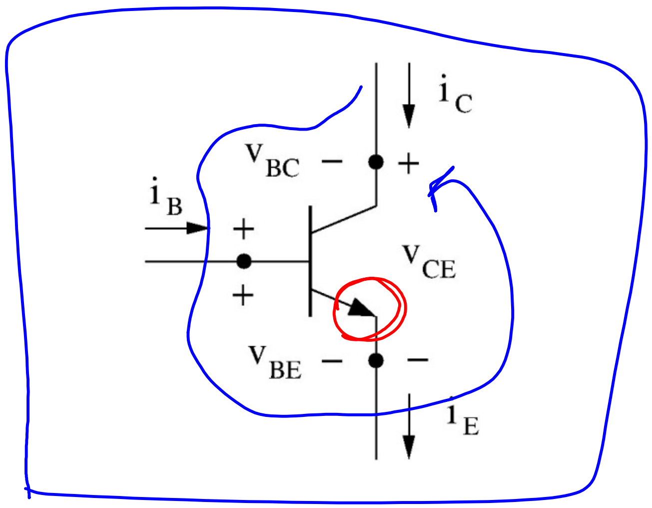
- “Thin” base region (between E & C)
- Heavily doped emitter
- Large area collector

An implementation on an IC (NPN)



NPN BJT iv parameters

NPN transistor



Circuit symbol and Convention for current directions

KCL: $i_E = i_C + i_B$

KVL: $v_{BC} = v_{BE} - v_{CE}$

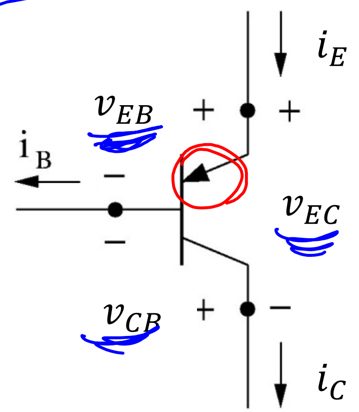
Note:

$$v_{CE} = v_C - v_E$$

BJT iv characteristics is the relationship among (i_B , i_C , v_{BE} , and v_{CE})

PNP BJT iv parameters

PNP transistor



Compared to a NPN:

1) **Current directions are reversed**
2) **Voltage subscripts switched**

KCL: $i_E = i_C + i_B$

KVL: $v_{CB} = v_{EB} - v_{EC}$

Note:

$$v_{EC} = v_E - v_C$$

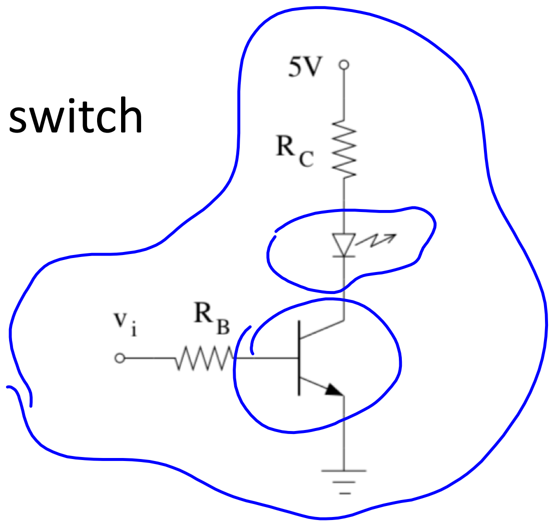
BJT modes of operation and applications

Cut-off

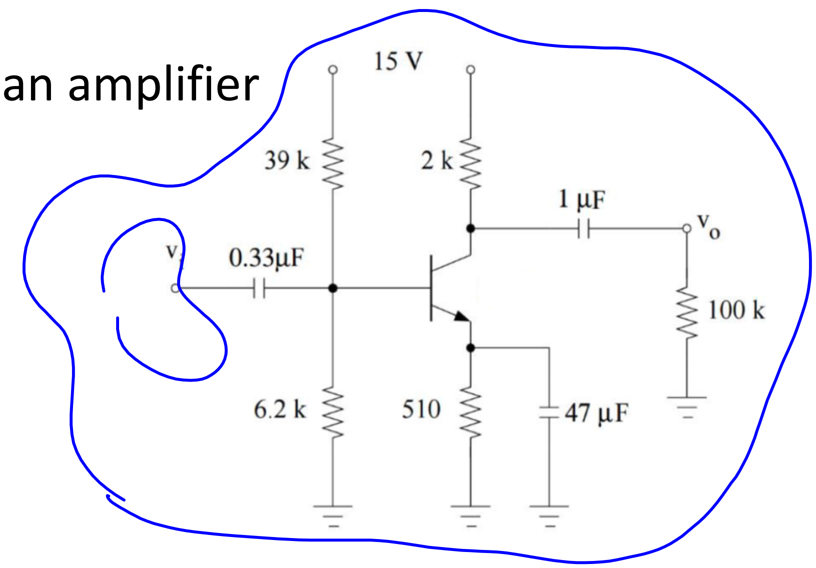
Saturation

Active

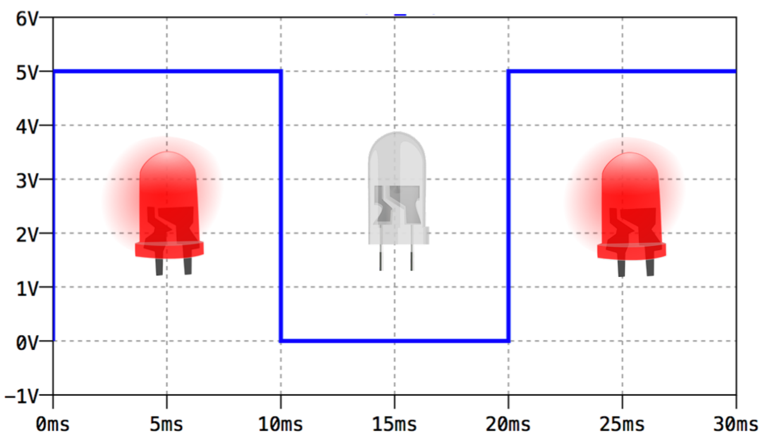
BJT as a switch

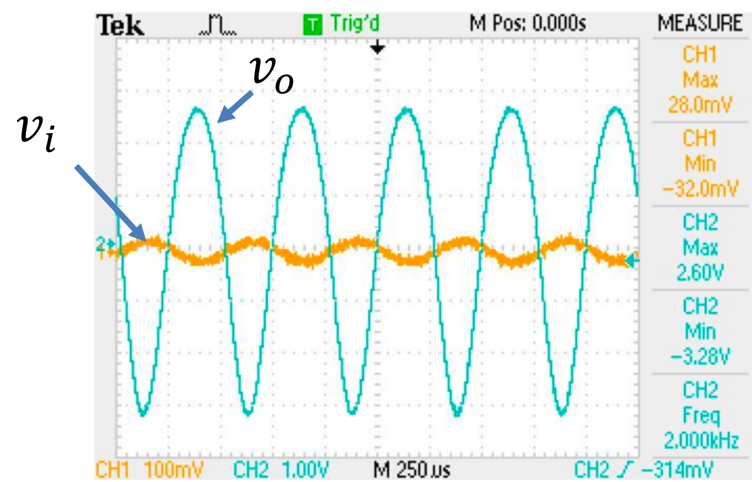


BJT as an amplifier



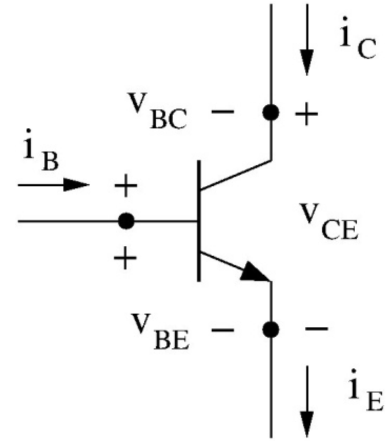
v_i





BJT operation in the cut-off mode

Operation of a BJT requires the presence of emitter-generated electrons near the BC junction (thus, the BE junction should be forward biased).



A BJT is called to be in “cut-off” if the BE junction is NOT forward biased.

In this case, $i_B = 0$ and $i_C = 0$ regardless of any voltage applied to the BC junction.

Cut-off mode:

$$\boldsymbol{i_B = 0}$$

$$\boldsymbol{i_C = 0}$$

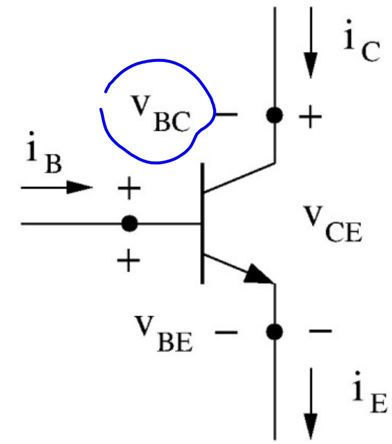
$$\boldsymbol{i_E = 0}$$

BJT operation in the active mode

BE junction is forward biased: $v_{BE} = V_{D0}$

BC junction is reverse biased: $v_{BC} \leq 0$

Since $v_{BC} = v_{BE} - v_{CE}$ → $\boxed{v_{CE} \geq V_{D0}}$



A BJT operates in active mode when $v_{CE} \geq V_{D0}$ and $v_{BE} = V_{D0}$

Active mode:

$i_B \geq 0$

$v_{BE} = V_{D0}$

$i_C = \beta i_B$

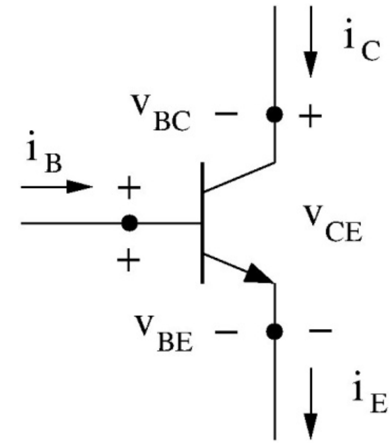
$v_{CE} \geq V_{D0}$

for PNP: $V_{EB} = V_{D0}$

for PNP $V_{EC} \geq V_{D0}$

BJT operation in the saturation mode

BE junction is forward biased: $v_{BE} = V_{D0}$



In **soft saturation**:

BC junction is forward biased and $0 < v_{BC} \leq 0.4\ V$ (for Si)

Since $v_{BC} = v_{BE} - v_{CE}$ → $0.3\ V \leq v_{CE} < 0.7\ V$

In **deep saturation**:

BC junction is forward biased and $v_{BC} > 0.4\ V$ (for Si)

Since $v_{BC} = v_{BE} - v_{CE}$ → $0.1V < v_{CE} < 0.3\ V$

We will use $v_{CE} \approx 0.2\ \text{V} = V_{sat}$ for Si

Deep saturation or saturation mode:

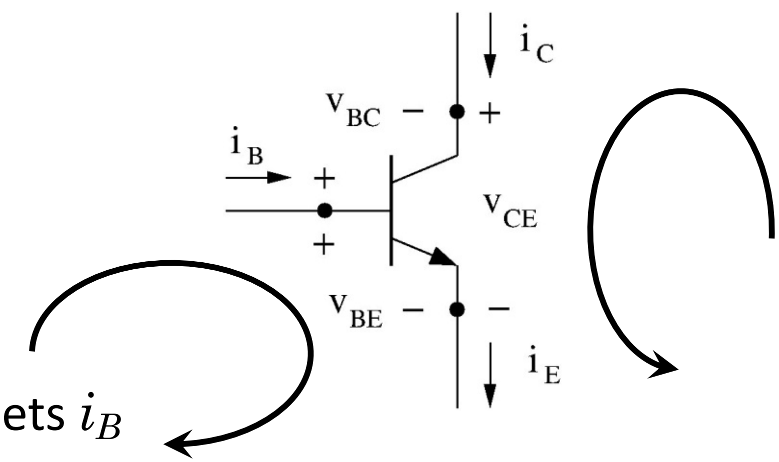
$$i_B \geq 0$$

$$v_{BE} = V_{D0}$$

$$\boxed{i_C < \beta i_B}$$

$$\boxed{v_{CE} = V_{sat}}$$

Transistor operates like a valve:

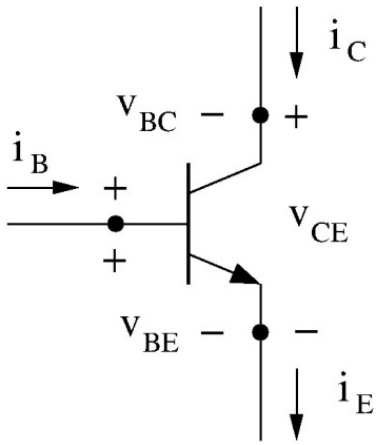


Controlled part:
i_C & v_{CE} are set by transistor state (& outside circuit)

Controller part:
Circuit connected to BE sets i_B

Cut-off $(i_B = 0)$:	**Valve Closed**	$i_C = 0$
Active $(i_B > 0)$:	**Valve partially open**	$i_C = \beta\, i_B$
Saturation $(i_B > 0)$:	**Valve open**	$i_C < \beta\, i_B$ i_C is limited by circuit connected to CE terminals, increasing i_B does not increase i_C

NPN BJT iv equations



"Linear" model*

Cut-off :
BE is reverse biased

$$i_B = 0, \quad i_C = 0$$
$$v_{BE} < V_{D0}$$

Active:
BE is forward biased
BC is reverse biased

$$v_{BE} = V_{D0}, \quad i_B \geq 0$$
$$i_C = \beta\, i_B, \quad v_{CE} \geq V_{D0}$$

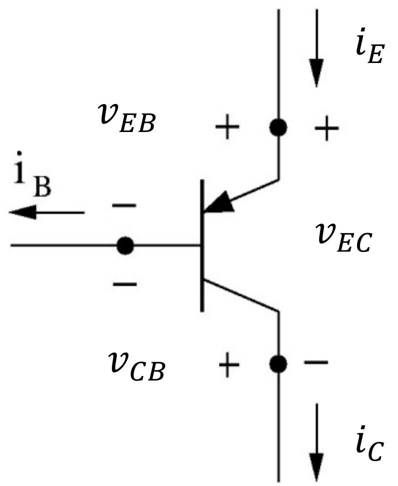
(Deep) Saturation:
BE is forward biased
BC is foward biased

$$v_{BE} = V_{D0}, \quad i_B \geq 0$$
$$v_{CE} = V_{sat}, \quad i_C < \beta\, i_B$$

$$\text{For Si,}\ V_{D0} = 0.7\ \text{V}, \quad V_{sat} = 0.2\ \text{V}$$

BJT Linear model is based on a diode "constant-voltage drop" model for the BE junction and ignores Early effect.

PNP BJT iv equations



"Linear" model

Cut-off :
EB is reverse biased

$$i_B = 0, \quad i_C = 0$$
$$v_{EB} < V_{D0}$$

Active:
EB is forward biased
CB is reverse biased

$$v_{EB} = V_{D0}, \quad i_B \geq 0$$
$$i_C = \beta\, i_B, \quad v_{EC} \geq V_{D0}$$

(Deep) Saturation:
EB is forward biased
CB is foward biased

$$v_{EB} = V_{D0}, \quad i_B \geq 0$$
$$v_{EC} = V_{sat}, \quad i_C < \beta\, i_B$$

$$\text{For Si,} \; V_{D0} = 0.7 \text{ V}, \; V_{sat} = 0.2 \text{ V}$$

BJT Linear model is based on a diode "constant-voltage drop" model for the BE junction and ignores Early effect.

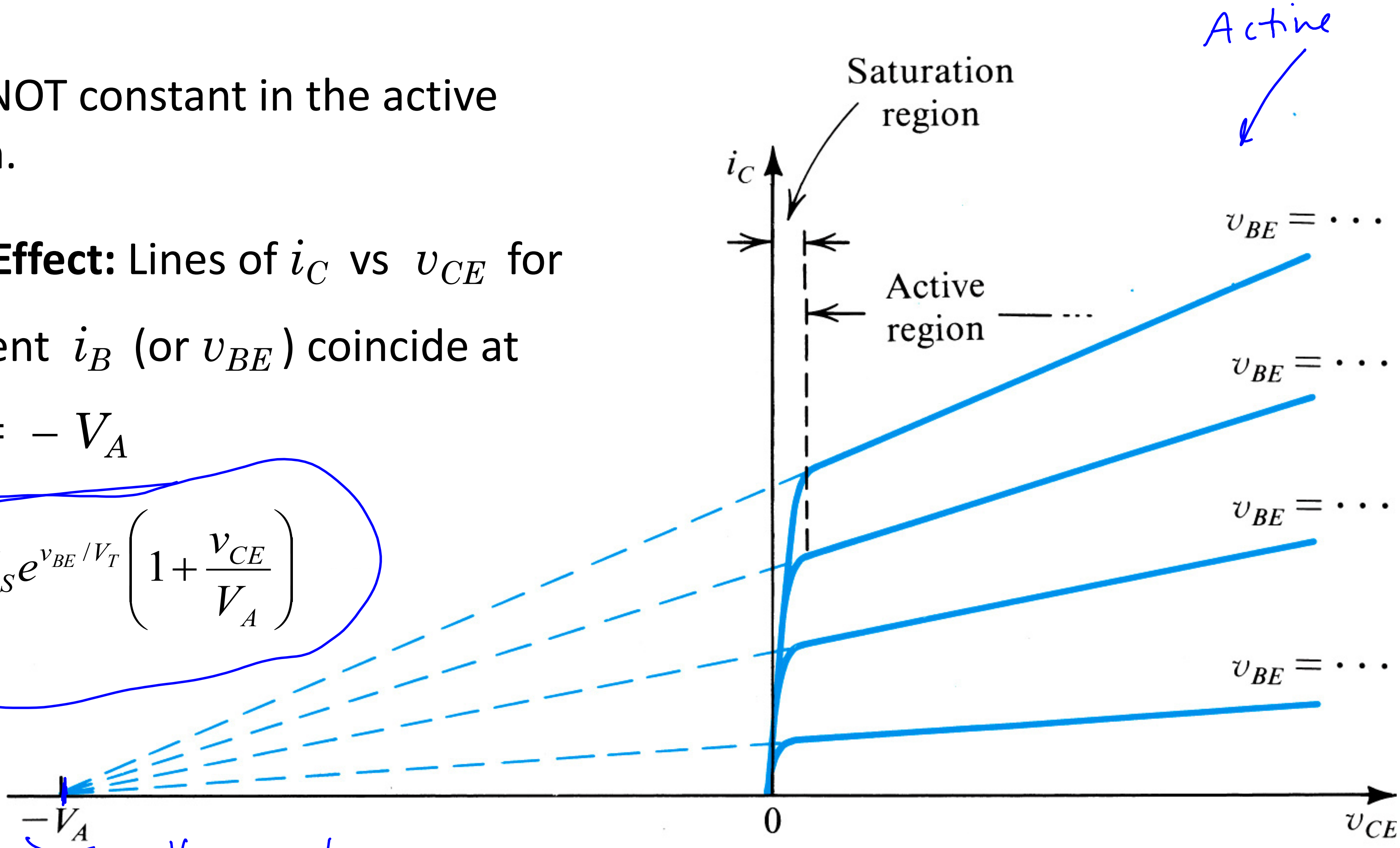
Early Effect modifies iv characteristics in the active mode

i_C is NOT constant in the active region.

Early Effect: Lines of i_C vs v_{CE} for different i_B (or v_{BE}) coincide at $v_{CE} = -V_A$

$$i_C = I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$$

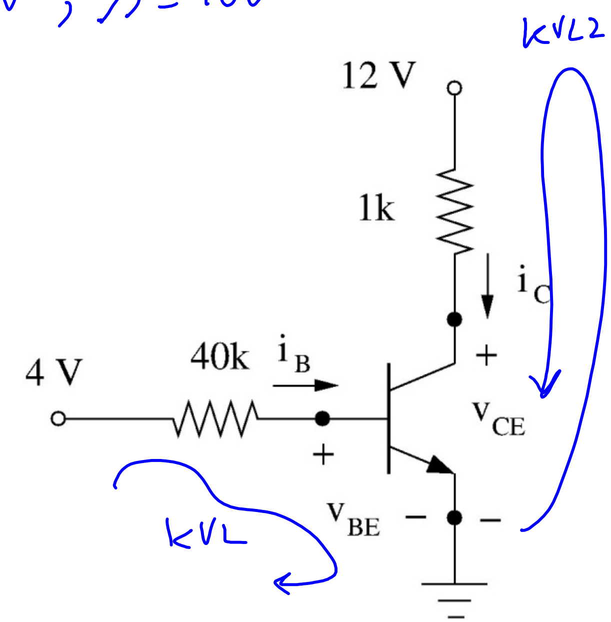
V_A : early



Solving BJT circuits

(State of BJT is unknown before solving the circuit)

$V_{D_0} = 0.7V$, $\beta = 100$



Assume BJT is in cut-off mode:

$i_B = 0$, $v_{BE} < V_{D_0}$

KVL: $4V = 40k \times i_B + V_{BE}$, $i_B = 0$, $V_{BE} = 4V > 0.7V$

Assumption was not correct. BJT is ON.

Assume BJT is in active mode.

$i_C = \beta i_B$, $\boxed{V_{CE} \geq V_{D_0}}$

$$i_B = \frac{4V - 0.7}{40k} = 82.5\,\mu A$$

$$i_C = 100 \times i_B = 8.25\,mA$$

KVL 2

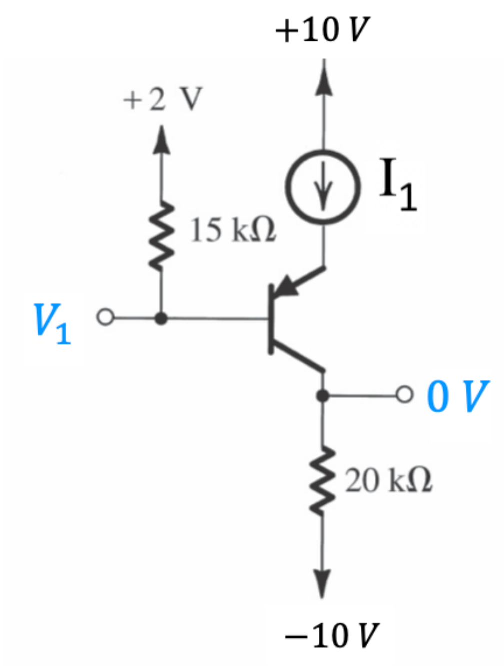
$12 = 1k \times i_C + V_{CE}$, $12 = 1k \times 8.25\,mA + V_{CE} \longrightarrow V_{CE} = 3.75\,V > V_{D_0}$

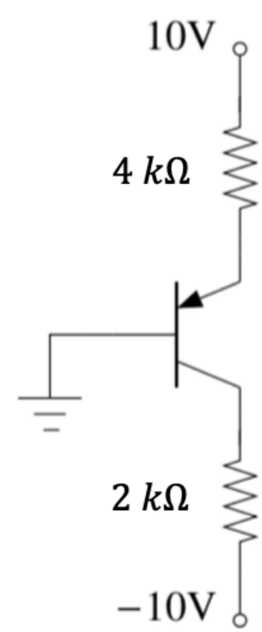
Assumption was correct and transistor operates in active mode

Note:

In the BJT and MOSFET circuits, to differentiate the applied node voltages from the measured node voltages:

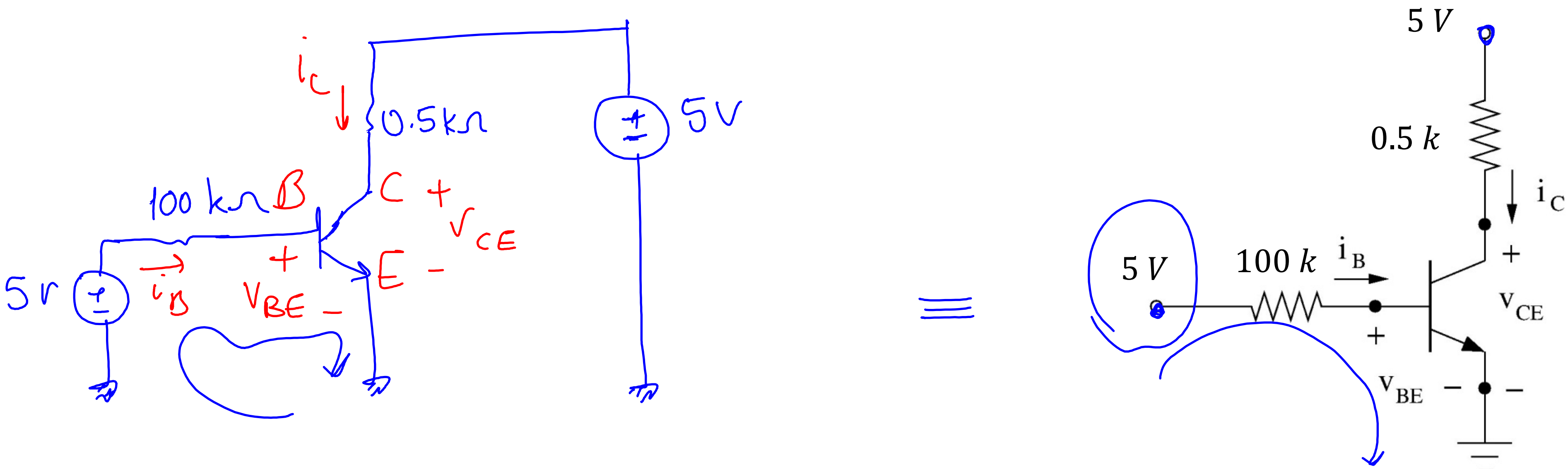
We will show the measured node voltages in **blue color** and the DC or AC voltage sources connected to different nodes in **black color**.

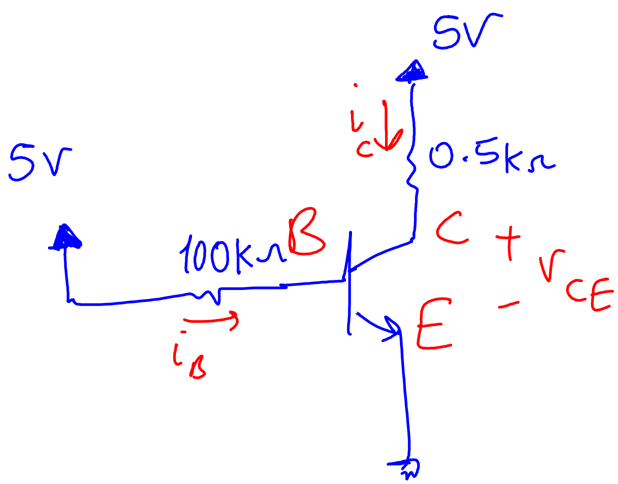




Lecture 10 reading quiz

Find the transistor parameters in this BJT circuit. ($\beta = 100$, $V_{D0} = 0.7V$).





Lecture 10 reading quiz

Find the transistor parameters in this BJT circuit. ($\beta = 100$, $V_{D0} = 0.7V$).

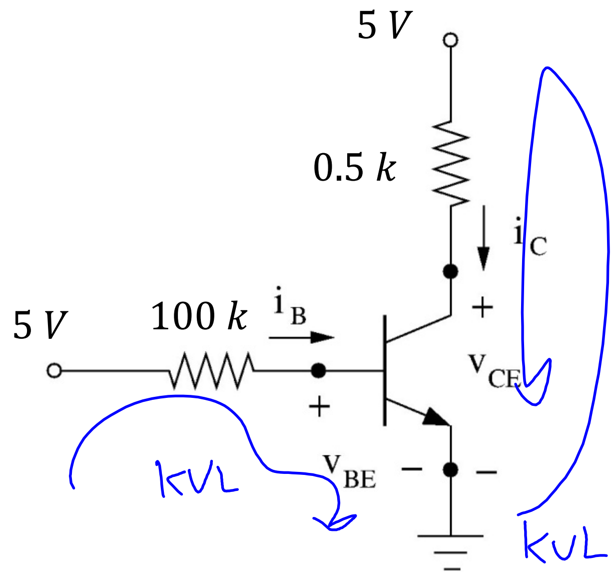
Assume BJT is in cut-off

$i_B = 0$, $v_{BE} < 0.7V$

$\boxed{\text{BE - KVL : } 5V = 100k\Omega \times i_B + v_{BE}}$

$5V = 0 + v_{BE} \longrightarrow v_{BE} = 5V > 0.7V$

$\Longrightarrow$ assumption was wrong.



Assuming BJT is in active mode: $i_C = \beta i_B$, $v_{CE} \geq V_{D0}$

CE KVL: $5 = 0.5k\Omega \times i_C + v_{CE}$, $i_C = \beta i_B$, $i_B = \dfrac{5V - 0.7V}{100k\Omega}$

$i_B = 43\mu A$

$v_{CE} = 2.85V > 0.7V$

Assumption was correct!

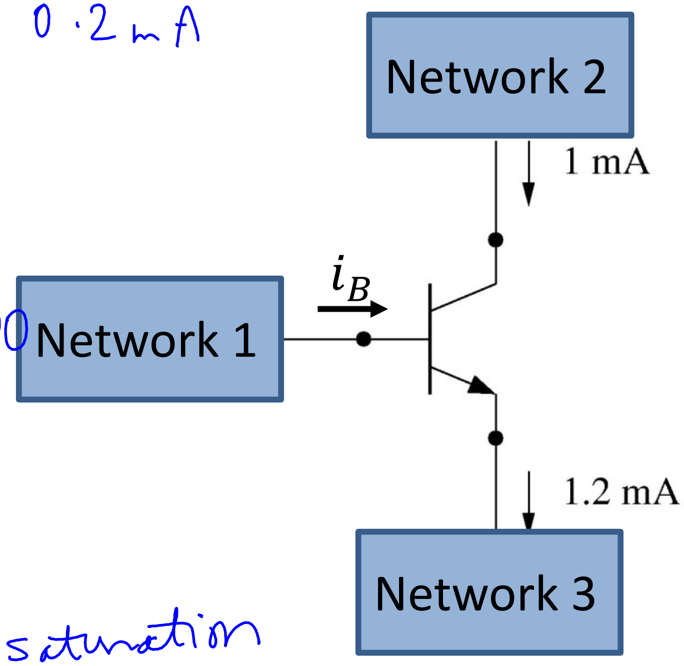
$\rightarrow i_C = 100 \times 43\mu A = 4.3mA$

Clicker question 1.

What is the region of the operation of this transistor? (Assume Si BJT with $\beta = 100$, $V_{sat} = 0.2\ V$)

Find i_B and v_{CE}.

$i_B = i_E - i_C = 1.2 - 1 = 0.2\,mA$



A. Saturation

B. Active

C. ~~Cut-Off~~

$\frac{i_C}{i_B} = \frac{1\,mA}{0.2\,mA} = 5 < 100$

$\Rightarrow i_C < \beta\, i_B$

$\Rightarrow$ BJT is in saturation

Cut-off :	Active:	Saturation:
$i_B = 0, \quad i_C = 0$	$v_{BE} = V_{D0}, \quad i_B \geq 0$	$v_{BE} = V_{D0}, \quad i_B \geq 0$
$v_{BE} < V_{D0}$	$i_C = \beta\, i_B, \quad v_{CE} \geq V_{D0}$	$v_{CE} = V_{sat}, \quad i_C < \beta\, i_B$

Clicker question 2.

What is the collector current in this BJT circuit. ($\beta = 100$, $V_{D0} = 0.7V$, $V_{sat} = 0.2\ V$).

$$i_B = \frac{5 - 0.7}{100\,k} = 43\,\mu A$$

$$\boxed{i_B = 43\,\mu A}$$

Assume active mode of operation:

$$i_C = \beta\, i_B = 4.3\,mA$$

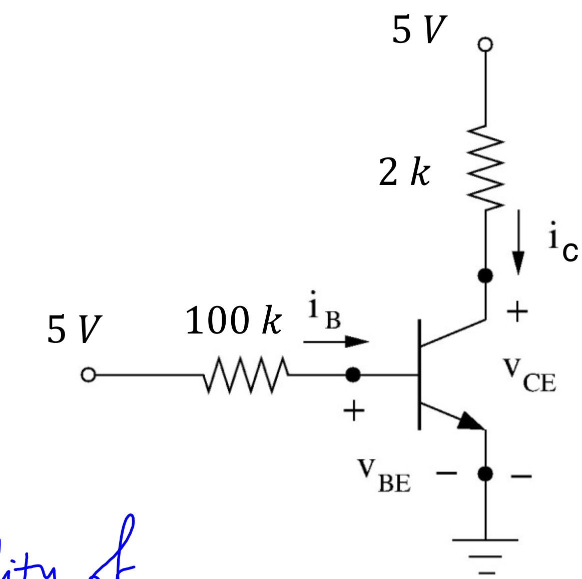
we need to check the validity of this assumption.

A. $i_C = 4.3\ mA$

B. $i_C = 2.4\ mA$

C. $i_C = 2\ mA$

D. $i_C = 2.15\ mA$



Cut-off :	**Active:**	**Saturation:**
$i_B = 0, \quad i_C = 0$	$v_{BE} = V_{D0}, \quad i_B \geq 0$	$v_{BE} = V_{D0}, \quad i_B \geq 0$
$v_{BE} < V_{D0}$	$i_C = \beta\, i_B, \quad v_{CE} \geq V_{D0}$	$v_{CE} = V_{sat}, \quad i_C < \beta\, i_B$

Clicker question 2.

What is the collector current in this BJT circuit. ($\beta = 100$, $V_{D0} = 0.7V$, $V_{sat} = 0.2\ V$).

$i_B = \frac{5 - 0.7}{100k} = 43\ \mu A$

$i_C = \beta i_B = 4.3\ mA$

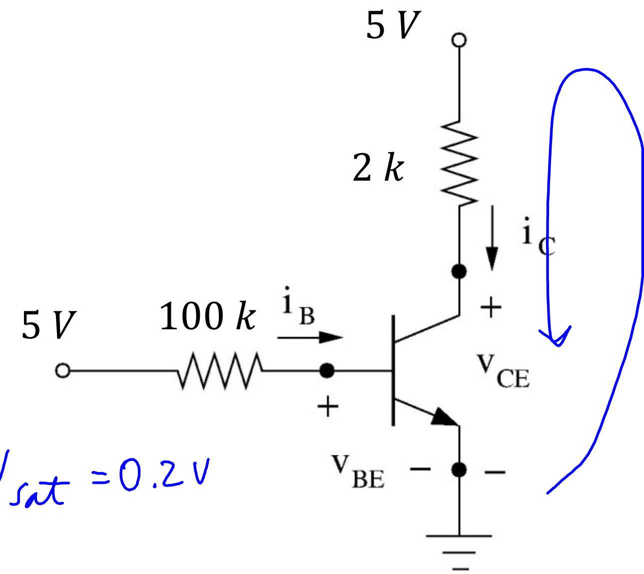
CE KVL : $5 = 2k \times i_C + V_{CE}$

$\rightarrow V_{CE} = -3.6 < 0.7V$

Assume sat. $\rightarrow V_{CE} = V_{sat} = 0.2V$

CE KVL: $5V = 2k \times i_C + 0.2$

$\rightarrow \boxed{i_C = 2.4mA}$ check $\rightarrow$ $i_C < \beta i_B$ $\quad 2.4mA < 100 \times 43\ \mu A$



A. $i_C = 4.3\ mA$

B. $i_C = 2.4\ mA$

C. $i_C = 2\ mA$

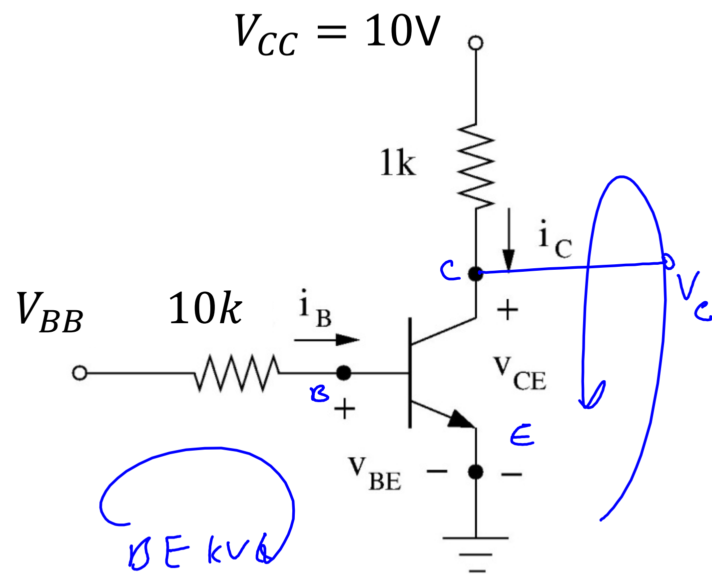
D. $i_C = 2.15\ mA$

Cut-off :	Active:	Saturation:
$i_B = 0, \quad i_C = 0$	$v_{BE} = V_{D0}, \quad i_B \geq 0$	$v_{BE} = V_{D0}, \quad i_B \geq 0$
$v_{BE} < V_{D0}$	$i_C = \beta i_B, \quad v_{CE} \geq V_{D0}$	$v_{CE} = V_{sat}, \quad i_C < \beta i_B$

Discussion question 1.

Find the value of voltage V_{BB} that results in the transistor operating in the active region with $V_C = 5V$.

(Assume Si transistor with $\beta = 100$ and $V_{sat} = 0.2\ V$).



$V_C = V_{CE}$

$V_{CE} = V_C - V_E = V_C - 0 = V_C$

CE KVL : $10 = 1k \times i_C + V_{CE} \longrightarrow i_C = 5\ mA$

$i_B = 50\ \mu A$

BE KVL : $V_{BB} = 10k \times i_B + \underbrace{V_{BE}}_{0.7\ V} \longrightarrow V_{BB} = 1.2\ V$