ECE 65: Components & Circuits Lab

Lecture 10

Bipolar Junction Transistor (BJT)

Introduction

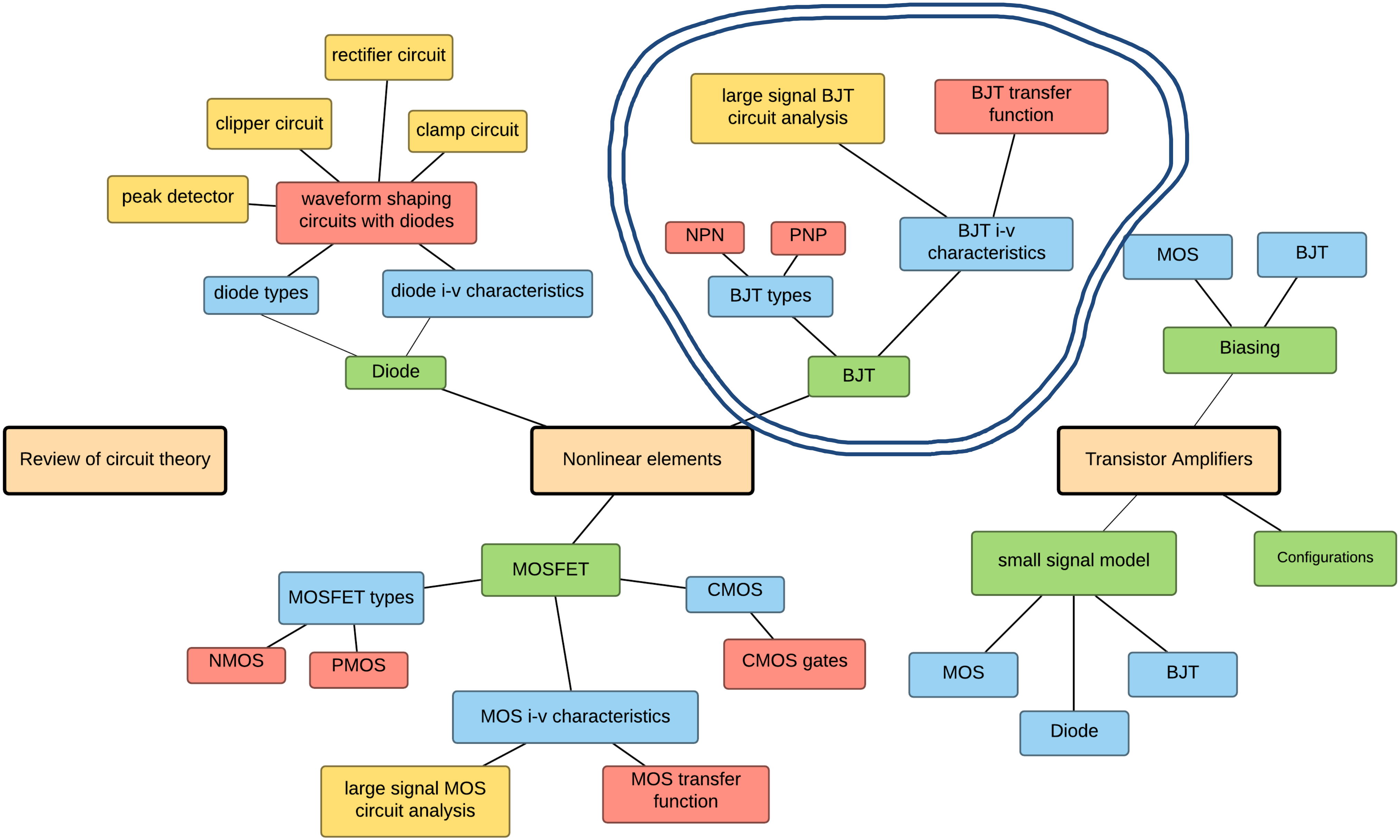
Reference notes: section 3.1

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

Saharnaz Baghdadchi

Course map

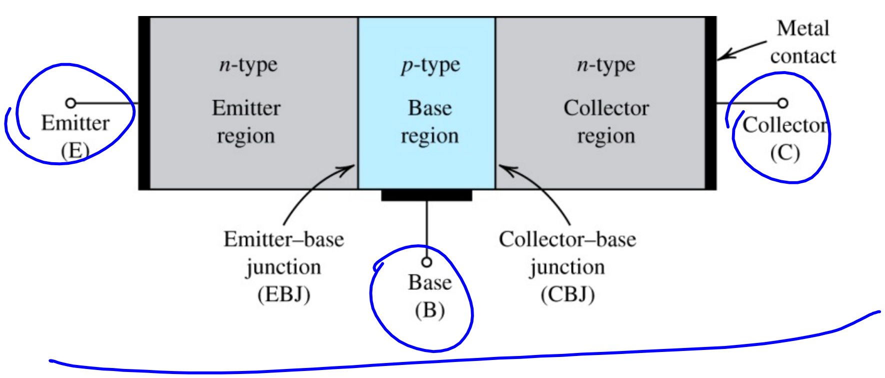
3. Bipolar Junction Transistor (BJT)



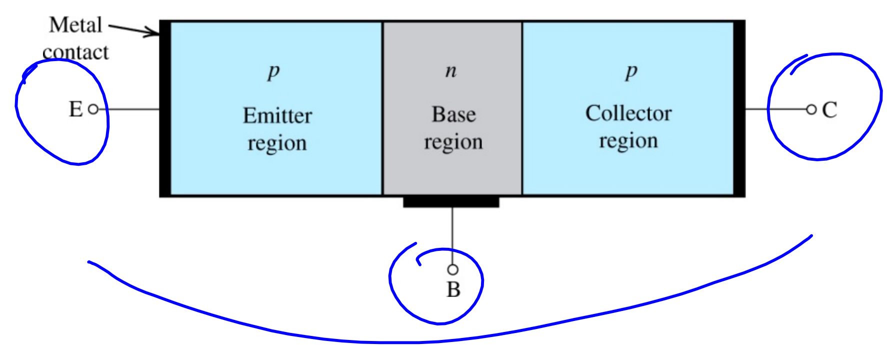
A BJT consists of three regions

Simplified physical structure

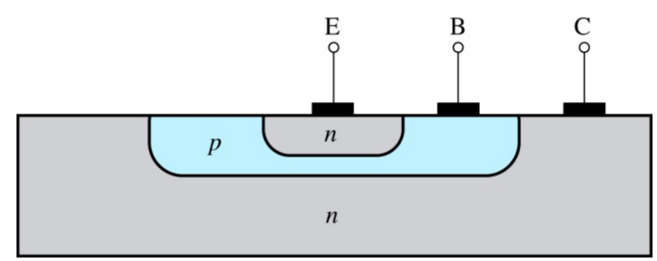
NPN transistor



PNP transistor



An implementation on an IC (NPN)

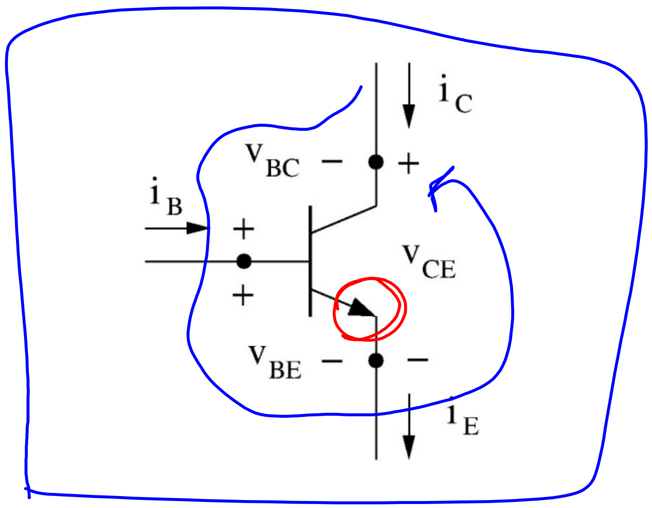


Device construction is NOT symmetric

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

NPN BJT iv parameters

NPN transistor



Circuit symbol and
Convention for current directions

KCL: $i_E = i_C + i_B$

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

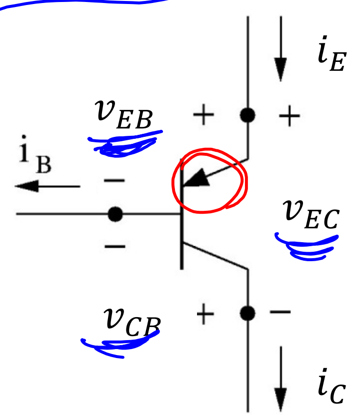
Note:

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

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:

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

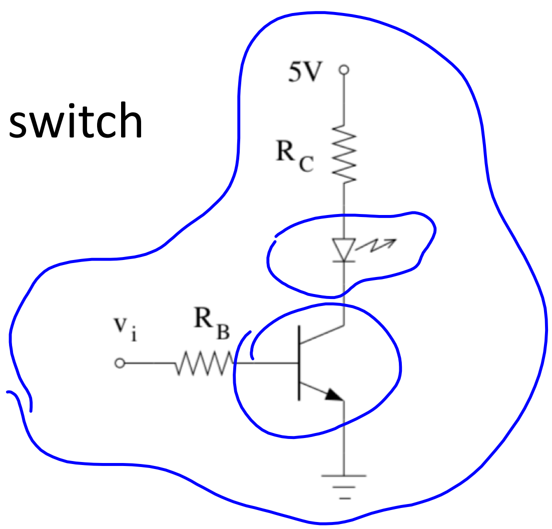
BJT modes of operation and applications

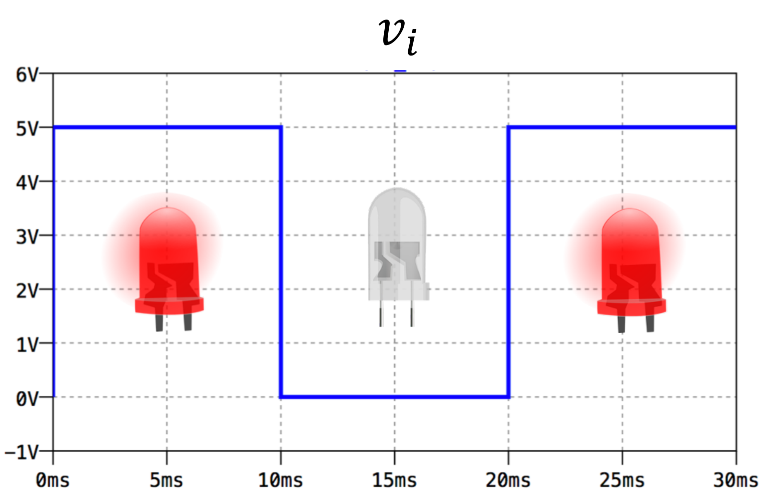
Cut-off

Saturation

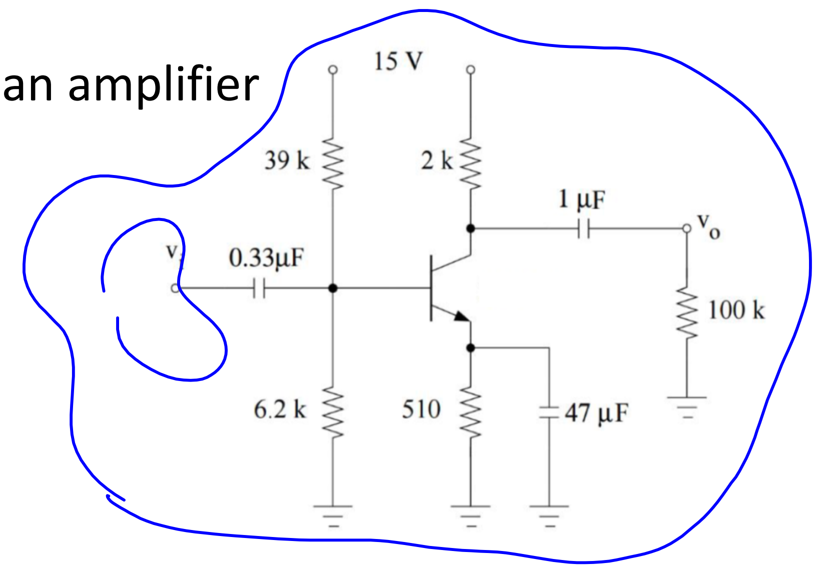
Active

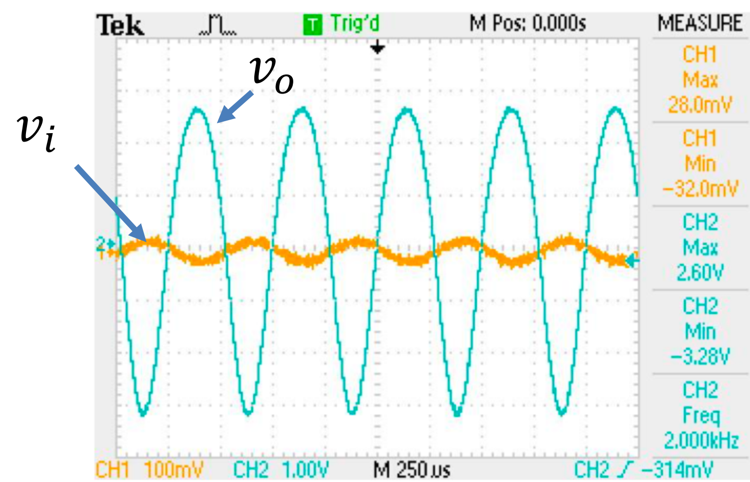
BJT as a switch





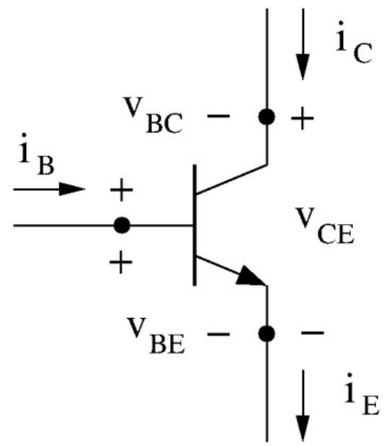
BJT as an amplifier





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:

$$\boldsymbol{i_B = 0}$$

$$\boldsymbol{i_C = 0}$$

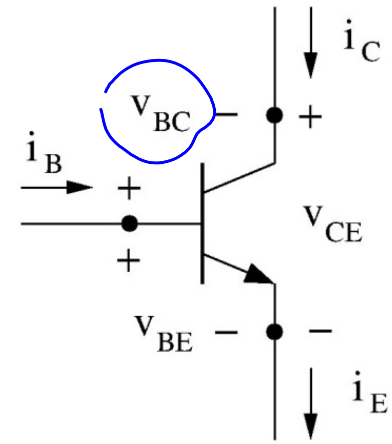
$$\boldsymbol{i_E = 0}$$

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



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

Active mode:

$i_B \geq 0$

$v_{BE} = V_{D0}$

$i_C = \beta i_B$

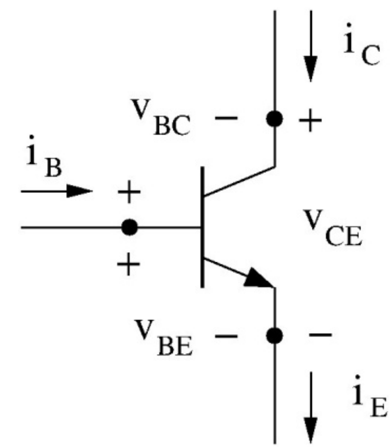
$v_{CE} \geq V_{D0}$

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 $v_{CE} \approx 0.2\ \mathrm{V} = V_{sat}$ for Si

Deep saturation or saturation mode:

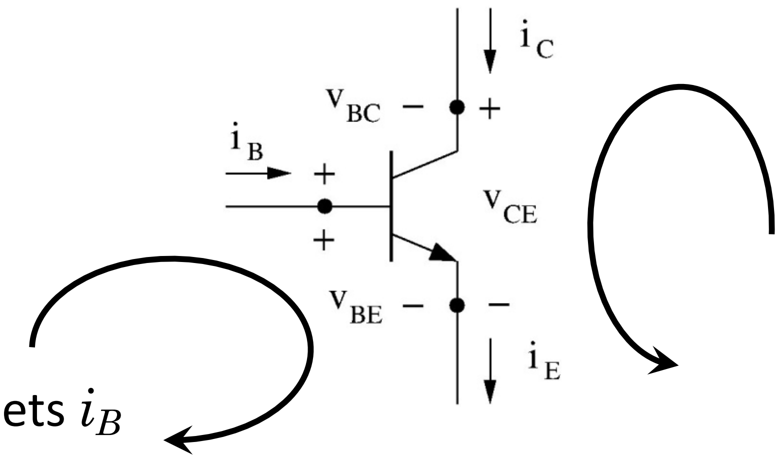
$$i_B \geq 0$$

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

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

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

Transistor operates like a valve:

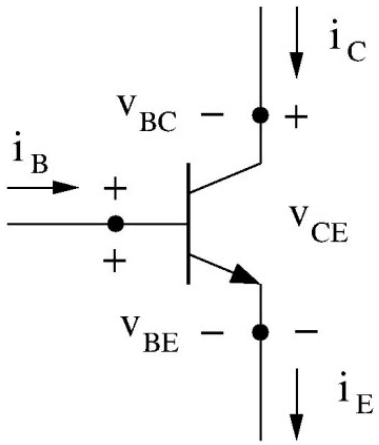


Controlled part:
i_C & v_{CE} are set by transistor state (& outside circuit)

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

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

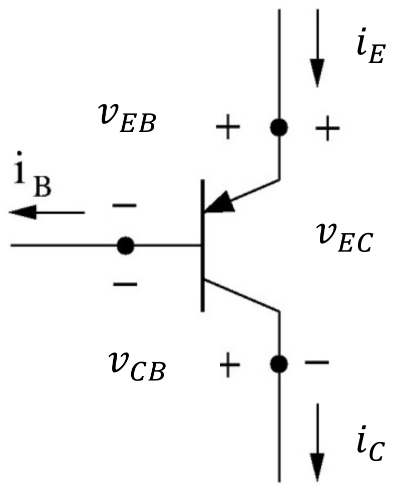
(Deep) Saturation:
BE is forward biased
BC is foward biased

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

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

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

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

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

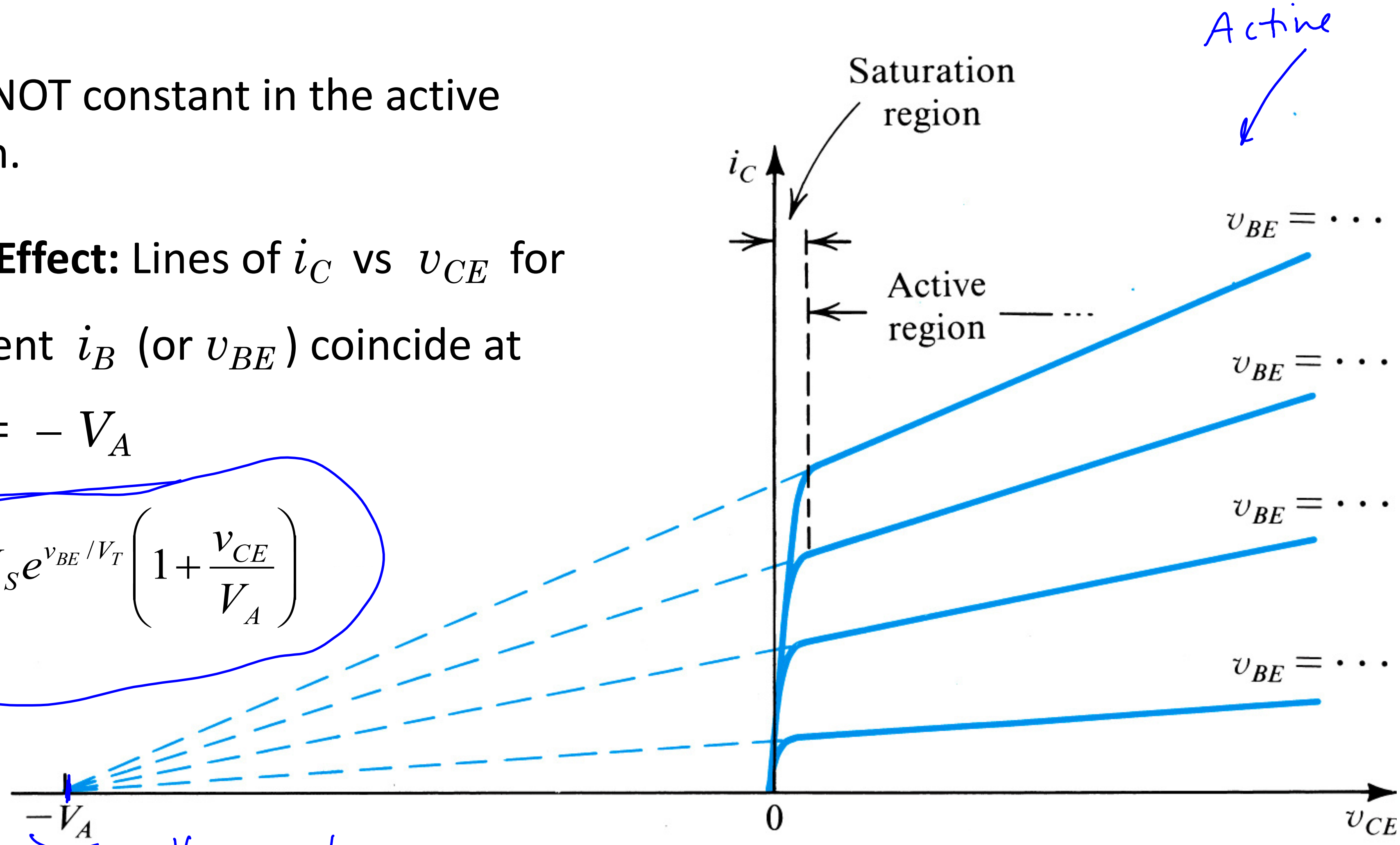
BJT Linear model is based on a diode "constant-voltage drop" model for the BE junction and ignores Early effect.

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 $v_{CE} = -V_A$

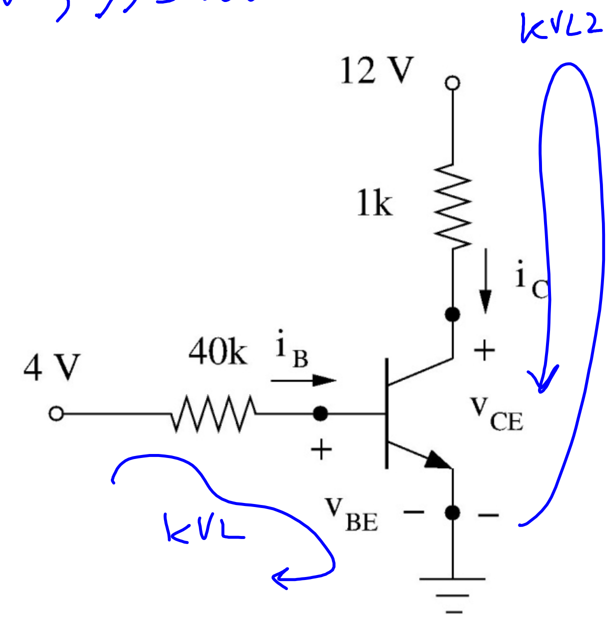
$$i_C = I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$$



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

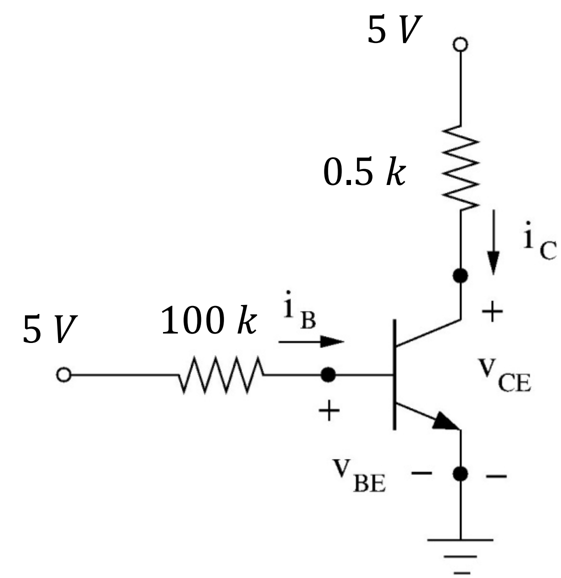
$12 = 1k \times i_C + V_{CE}$, $12 = 1k \times 8.25\,mA + V_{CE} \longrightarrow V_{CE} = 3.75\,V > V_{D_0}$

Assumption was correct and transistor operates in active mode

Lecture 10 reading quiz

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

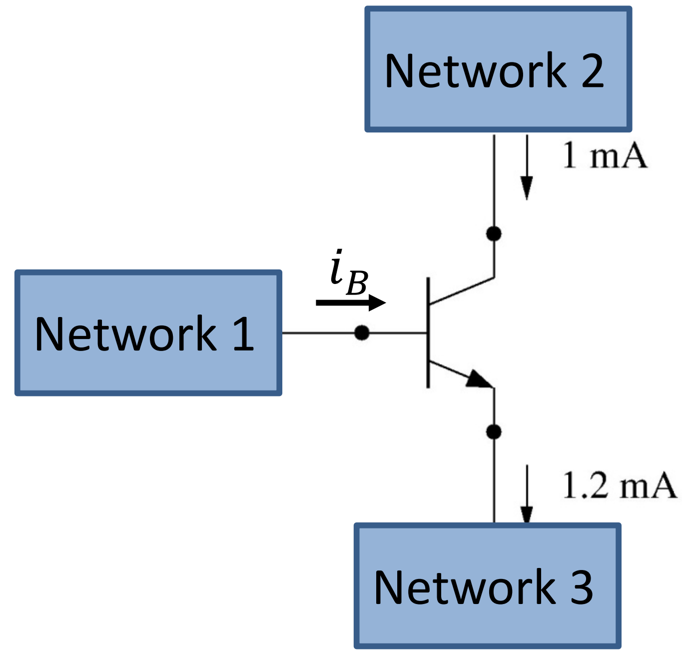
To differentiate between the measured node voltages and the DC or AC voltage sources connected to different nodes, in all of the future lecture notes (BJT and MOSFET transistors) the measured node voltages will be shown in blue color.



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}.



A. Saturation

B. Active

C. Cut-Off

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

Hints:

Clicker question 1.

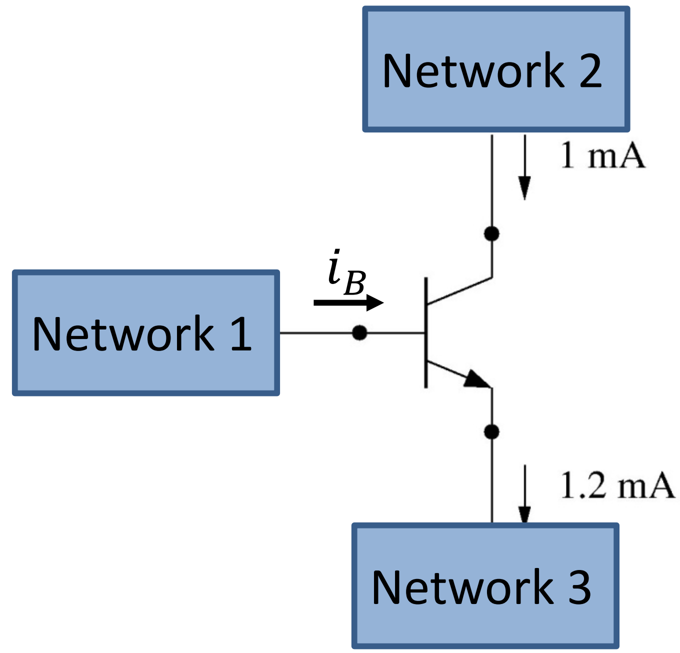
What is the region of the operation of this transistor? (Assume Si BJT with $\beta = 100$, $V_{sat} = 0.2\ V$)

Find i_B and v_{CE}.

I_E is always equal to I_C + I_B

What are the amplitudes of a BJT currents when the BJT is in the cut-off mode? Is this BJT in cut-off?

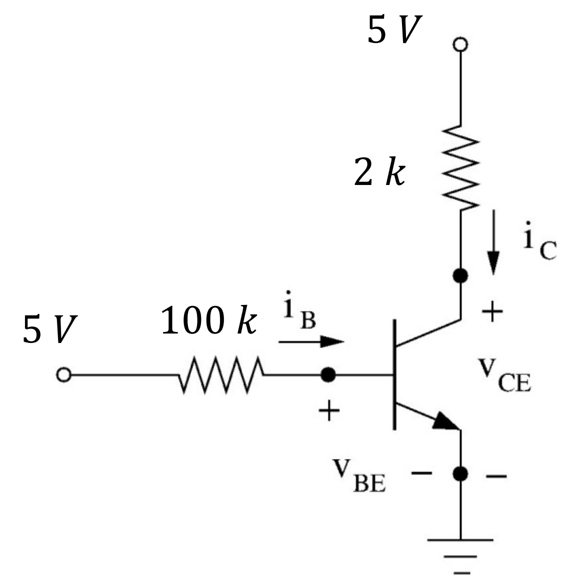
Using the relationship between I_B and I_C in different modes of operation of BJT, you can find the correct mode.



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. ($\beta = 100$, $V_{D0} = 0.7V$, $V_{sat} = 0.2\ V$).



A. $i_C = 4.3\ mA$

B. $i_C = 2.4\ mA$

C. $i_C = 2\ mA$

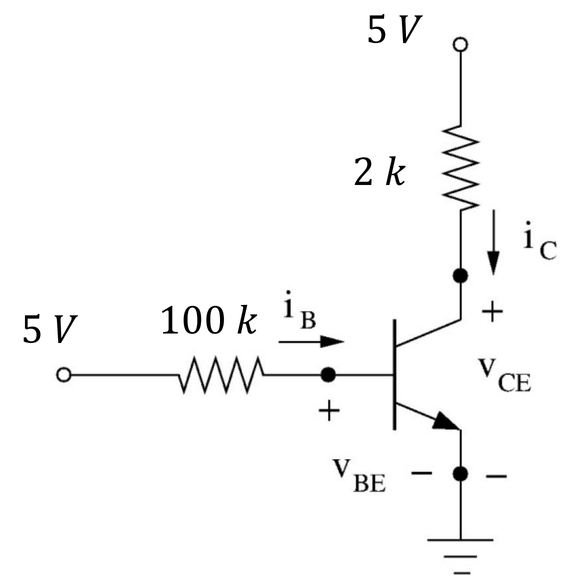
D. $i_C = 2.15\ mA$

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

Hints:

Clicker question 2.

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



- Write the BE KVL and test if the BJT is in cut-off.

- If the BJT is ON, you can either assume active mode of operation or saturation mode of operation.

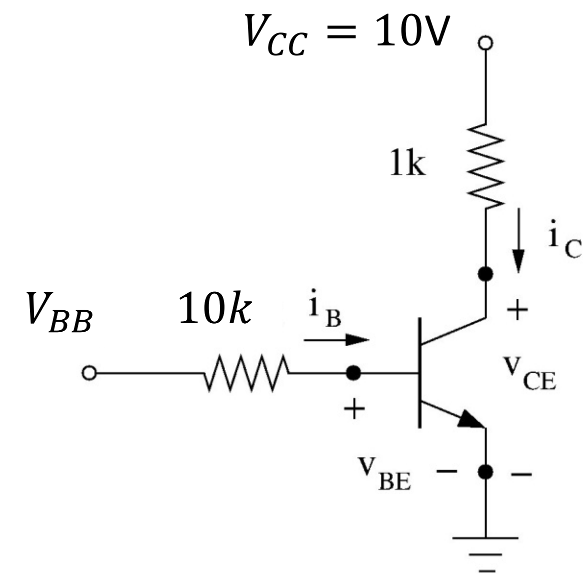
- If you assume active mode, you can use the relationship between I_C and I_B and the CE KVL to find V_{CE}, compare it with V_D0, and confirm or reject your assumption.

- If you assume saturation mode, you can use V_{CE} =V_{sat}, the CE KVL, and the KCL relating the BJT currents to find I_C. Compare I_C with I_B and confirm or reject your assumption.

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 $V_{sat} = 0.2\ V$).



Discussion question 2.

Design this BJT circuit to establish a collector current of 0.5 mA and a reverse-bias voltage on the collector-base junction of 2V. ($\beta = 100$, $V_{D0} = 0.7V,\ V_{sat} = 0.2\ V$).