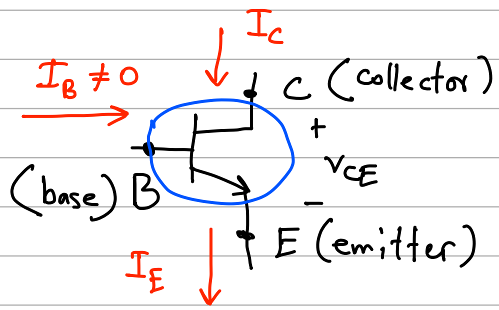
BJT (Bipolar Junction transistor):

BJT

npn | pnp

→ mainly will deal with npn.

BJT



$$\boxed{I_B + I_C = I_E}$$

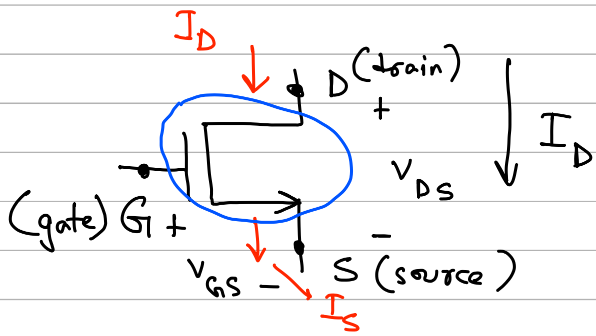
$$I_C \neq I_E$$

IV characteristics (I_C vs. V_{CE}):

→ I_B controls this graph

→ current controlled

MOSFET



$V_{GS} < V_T$: cutoff

$V_{GS} > V_T$: triode or saturation

↓ triode: $V_{DS} \leq V_{ov}$

↓ saturation: $V_{DS} > V_{ov}$

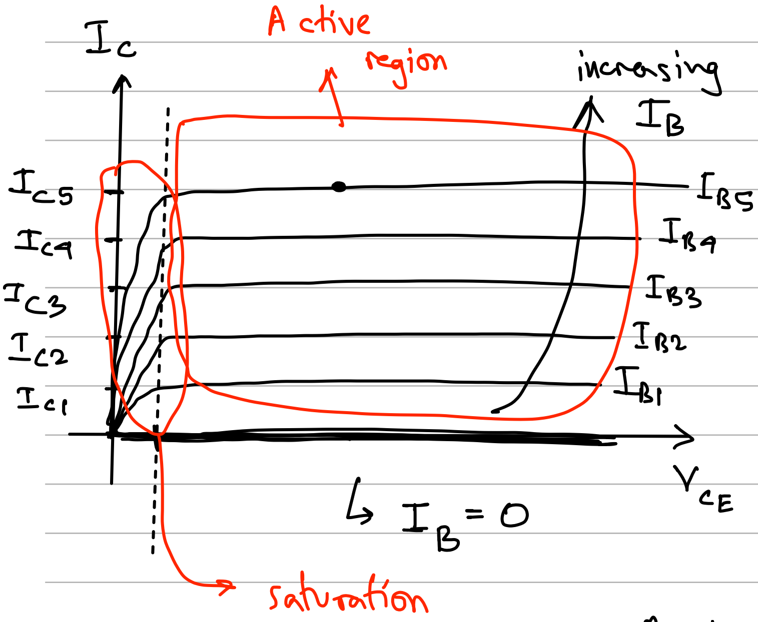
$$V_{ov} = V_{GS} - V_T$$

$$I_G = 0, \quad I_D = I_S$$

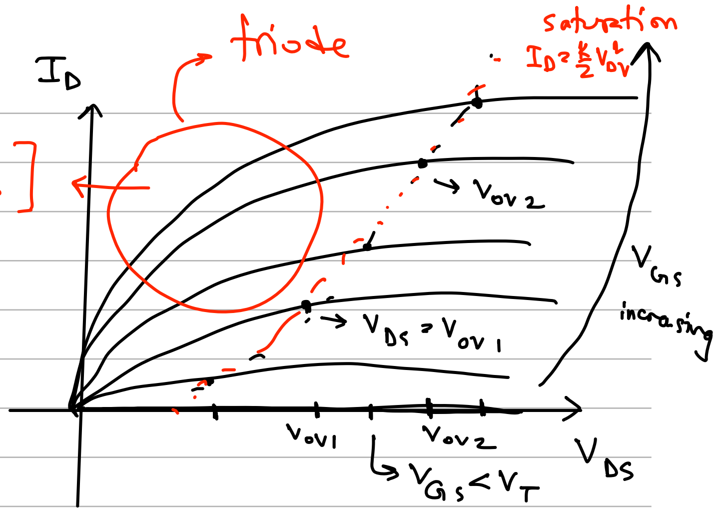
IV characteristics (I_D vs V_{DS}):

→ V_{GS} controls this graph

→ voltage controlled



$I_D = \frac{k}{2}\left[2V_{ov}V_{DS} - V_{DS}^2\right]$

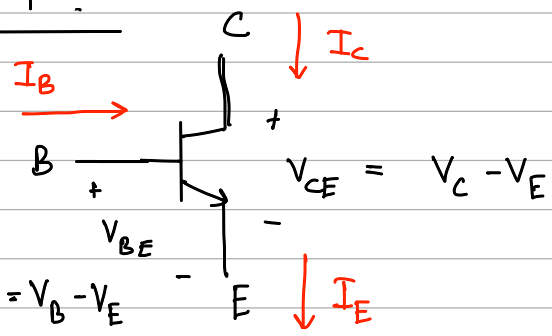


$V_{ov2} > V_{ov1}$

Analogue:

BJT	MOSFET
cutoff	cutoff
(much easier than MOSFET) saturation	triode
active	saturation

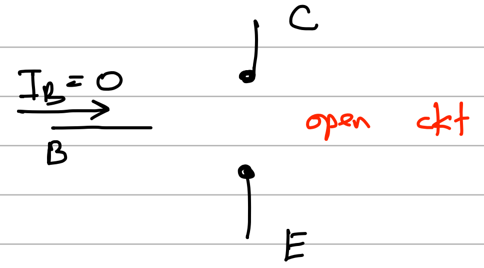
S- model of BJT:

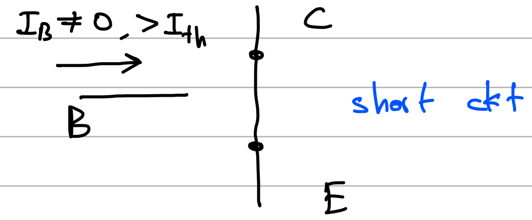


$\boxed{I_E = I_B + I_C}$

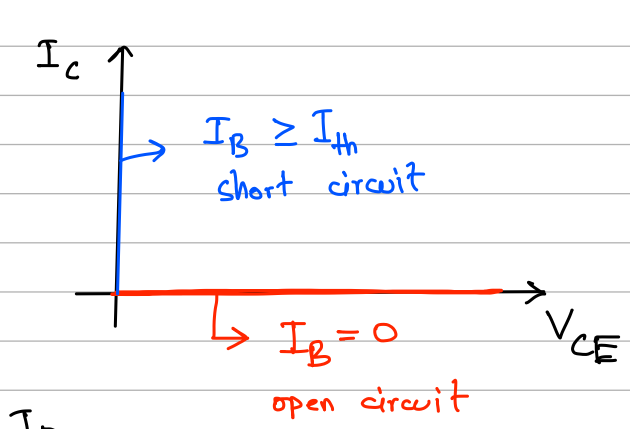
* Current controlled (I_B) switch.
* Interested in I_C, V_{CE}

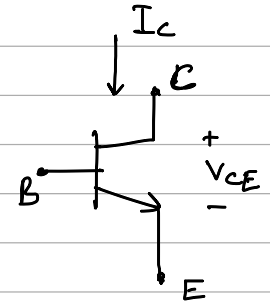
$I_B = 0$ | $I_B \geq I_{th}$

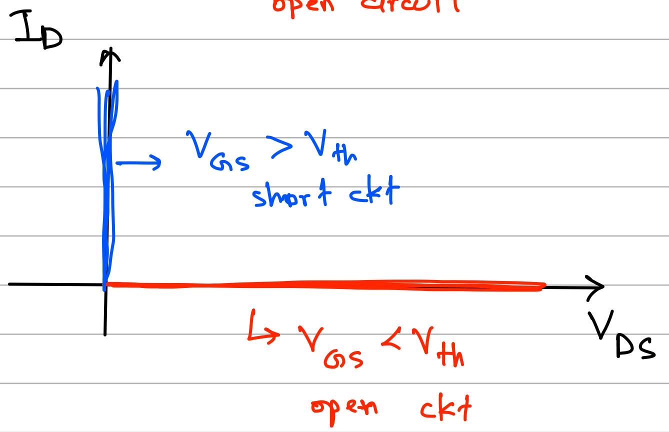


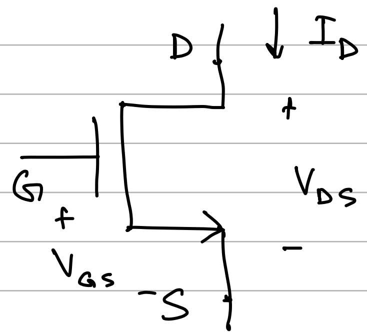


W OFF (logicstate 0) | W ON (logicstate 1)







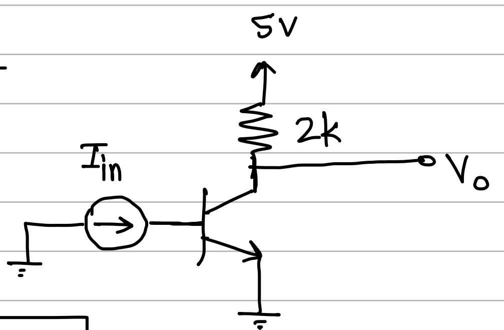


* What if $0 < I_B$ and $I_B < I_{th}$?

→ Invalid in S- model

→ $0 < I_B < I_{th}$: actually 'active mode' in BJT

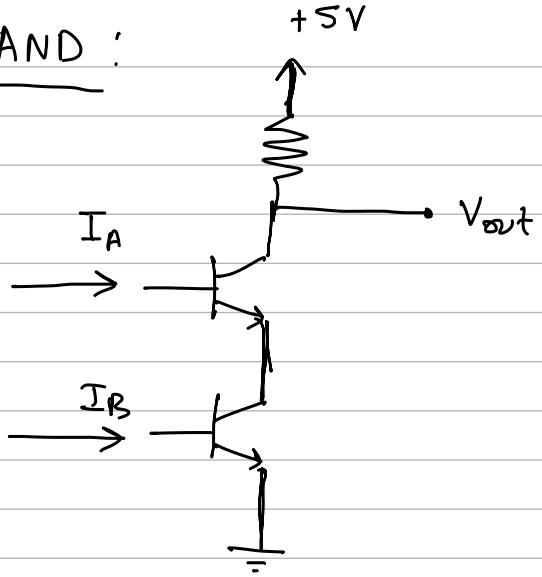
NOT inverter :



I_{in}	V_o
0 mA (0)	5V (1)
I_{th} (1)	0V (0)

$\boxed{\text{Output} = \overline{\text{Input}}}$

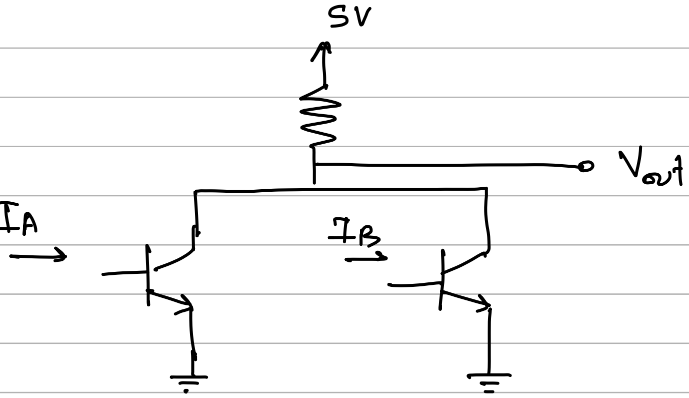
NAND :



out = $\overline{AB}$

I_A	I_B	V_{out}
0mA (0)	0mA (0)	5V (1)
0mA (0)	I_{th} (1)	5V (1)
I_{th} (1)	0mA (0)	5V (1)
I_{th} (1)	I_{th} (1)	0V (0)

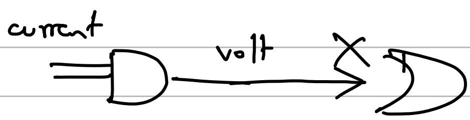
NOR :



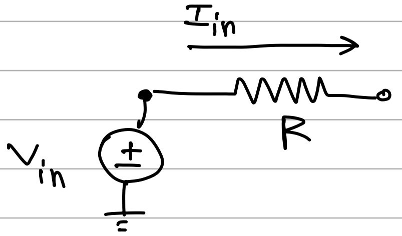
out = $\overline{A+B}$

Problem :

① Cascading issue [gate output voltage, but input current]



* Can be addressed by using voltage source to create base current.

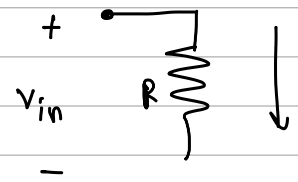


② Current source ?

③ current setting to zero is tough

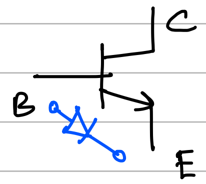
[for mosfet :
$V_{GS} < V_{th} \rightarrow$ logic 0
for BJT :
$I_B = 0 \rightarrow$ logic 0]

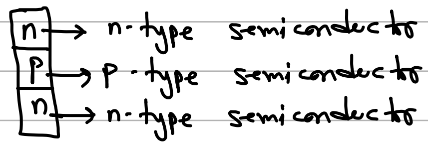
Voltage control :



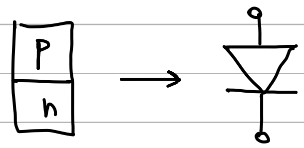
$i = \frac{V_{in}}{R} \Rightarrow V = Ri$

→ we use resistors to convert from voltage to current



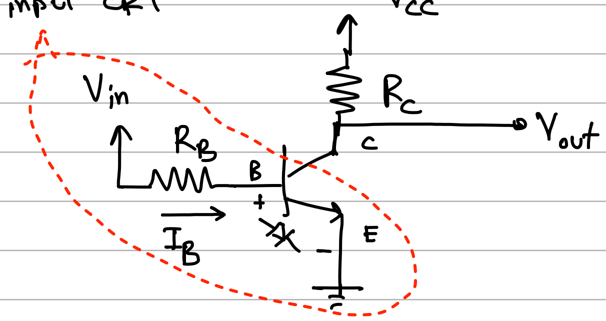


betn Base and Emitter :

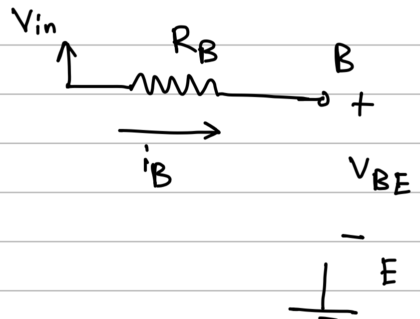


E.g : Inverter :

input ckt

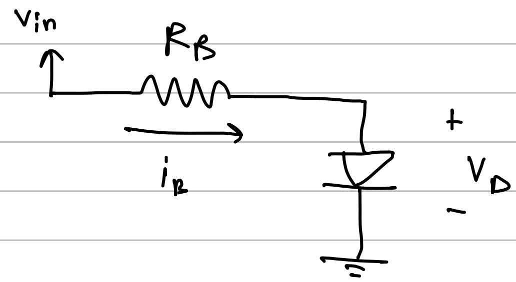


input (control) circuit :



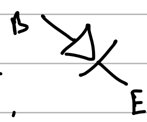
I_B	V_{in}	V_{out}
$I_B = 0mA (0)$	$V_{in} < 0.7V$	5V (1)
$I_B \geq I_{th} (1)$	$V_{in} > V_{th}$	0V (0)

⇓



$V_{in} < 0.7$:

→ BE is not forward biased

[ is 'OFF']

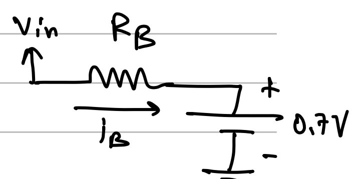
→ $I_B = 0$.

$V_{in} \geq 0.7$:

BE forward biased

$I_B > 0$.

when diode ON :



KVL :

$i_B R_B + 0.7 = V_{in} - 0$

or, $\boxed{i_B = \frac{V_{in} - 0.7}{R_B}}$

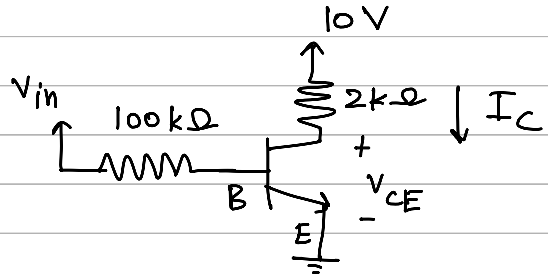
When $i_B = I_{th}$:

$$I_{th} = \frac{V_{th} - 0.7}{R_B} \Rightarrow V_{th} = (I_{th} R_B + 0.7)\ V$$

when, $I_B = I_{th}$, $V_{in} = V_{th}$.

$\therefore$ $V_{in} \geq V_{th}$, $I_B \geq I_{th}$.

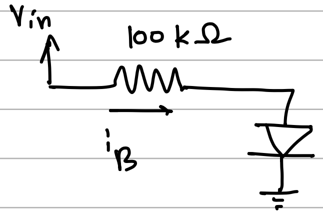
Eg :



$I_{th} = 0.2\ mA$

find threshold of v_{in} for which $I_B \geq I_{th}$.

input ckt:

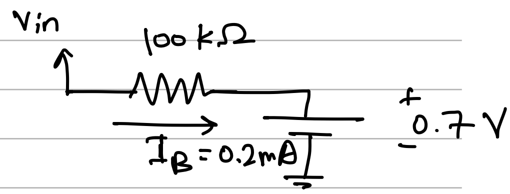


$i_B = \frac{v_{in} - V_D}{100k\Omega}$: when diode ON $\rightarrow$ $i_B = \frac{V_{in} - 0.7}{100\ k\Omega}$

$\therefore$ $v_{in} < 0.7V$: Diode OFF, BE junction reverse biased.

$\therefore$ $I_B = 0$ when $v_{in} < 0.7V$

$I_B = I_{th} = 0.2\ mA$:

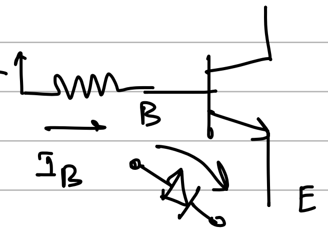


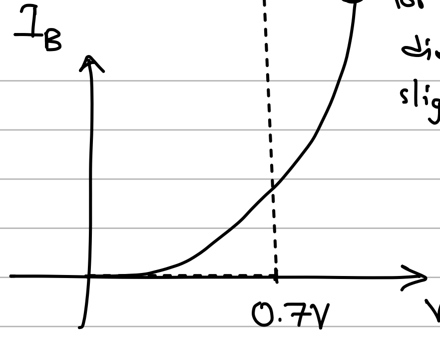
$0.2\ mA \times 100\ k\Omega = V_{in} - 0.8V$

$V_{th} \leftarrow V_{in} = 20 + 0.8 = 20.8\ V$

$V_{in} = 20.8V$, $I_B = 0.2\ mA \Rightarrow v_{in} \geq \underbrace{20.8V}_{V_{th}}$, $I_B \geq I_{th}$.

Slight correction:



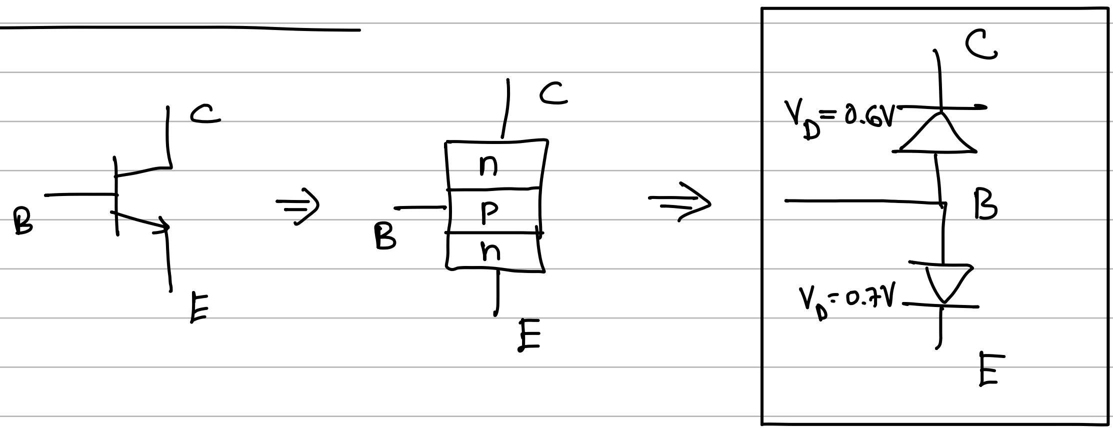


for very high diode current, slight gap from 0.7V

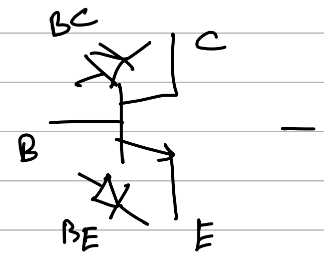
then for $I_B \geq I_{th}$:

→ very high current, so diode drop assumed slightly more than 0.7V. ⟹ 0.8V

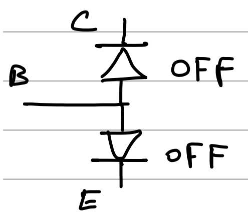
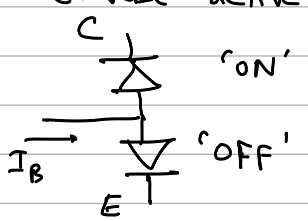
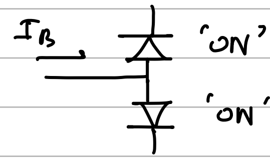
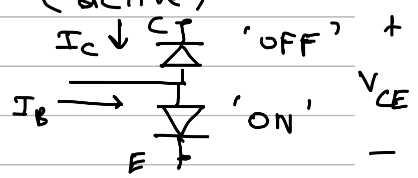
Physical structure:

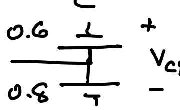


→ not actual BJT structure
→ only used for analysis simplification

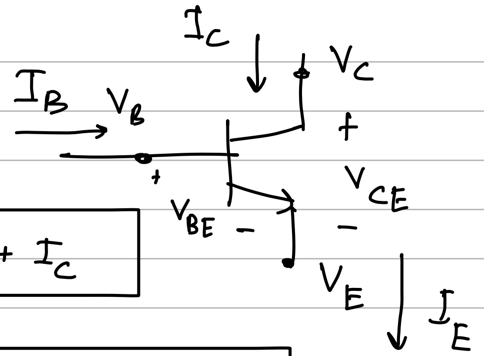


BE → ON, OFF } 4 combinations
BC → ON, OFF } 4 modes of operation

[cutoff]		[saturation]	
BE 'OFF', BC 'OFF'	BE 'OFF', BC 'ON') (reverse active)	BE 'ON', BC 'ON')	BE 'ON' BC 'OFF' (active)
			
→ $I_B = 0$. → $I_C = 0$	→ similar to 'active' → will not deal with this much	→ I_B ↑ → I_C ↑	→ I_B ↑ → I_C const, depends on I_B



$V_{CE} = 0.8 - 0.6 = 0.2V$



$$\boxed{I_E = I_B + I_C}$$

I_B input

I_C output

V_{CE} used in x-axis of I_C vs V_{CE} (output characteristic graph)

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

$$V_{BC} = V_B - V_C$$

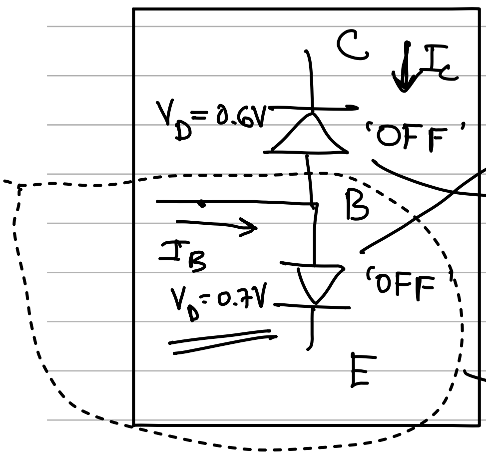
$$\boxed{V_{CE} = V_C - V_E}$$

$$V_{BC} = V_B - V_E + V_E - V_C$$

$$= (V_B - V_E) - (V_C - V_E)$$

$$\boxed{V_{BC} = V_{BE} - V_{CE}}$$

1 Cutoff :

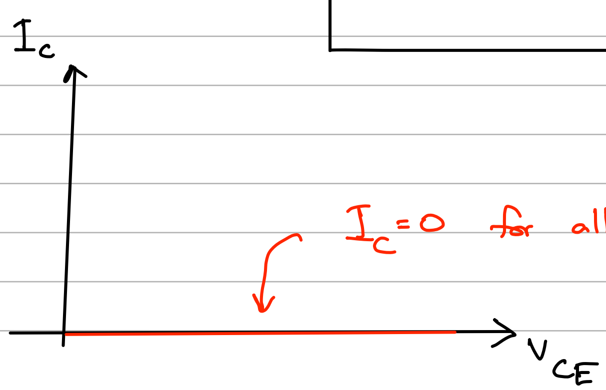


$V_{BE} < 0.7\,V$	→	BE diode 'OFF'
$V_{BC} < 0.6\,V$	→	BC diode 'OFF'

Consequence :

→ Input circuit current cannot be nonzero if BE OFF.

$$\boxed{\therefore\ I_B = 0,\quad I_C = 0,\quad I_E = 0}$$

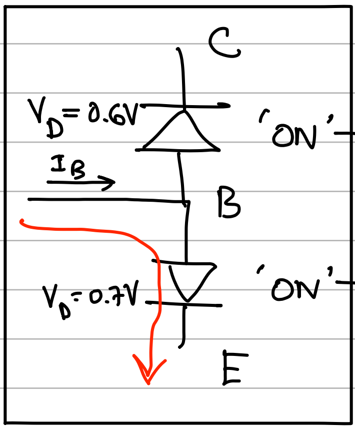


$I_C = 0$ for all V_{CE} in this mode

'open ckt'

② Saturation : BE and BC junction forward biased and

I_B very high, so consider $V_{BE} \approx 0.8V$

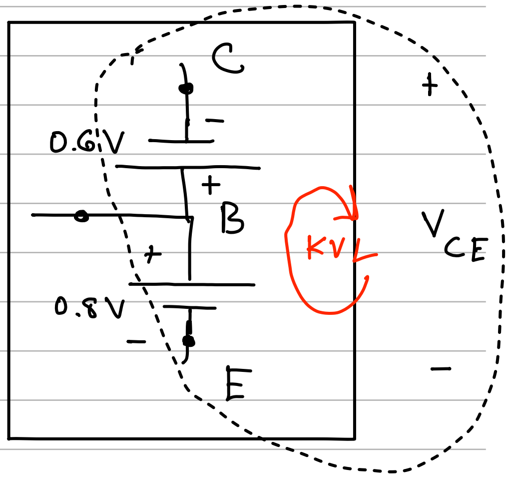


if :

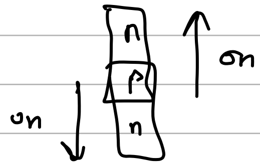
$V_{BC} \geq 0.6V$

$V_{BE} \geq 0.7V$

$\Rightarrow$



If in saturation, then :



→ $V_{CE} = 0.2V$

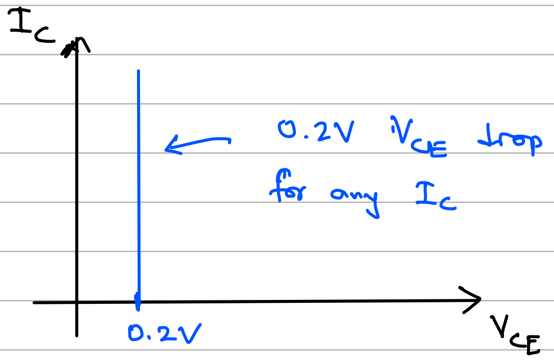
→ Both junction forward biased

$-V_{BE} + V_{BC} + V_{CE} = 0$

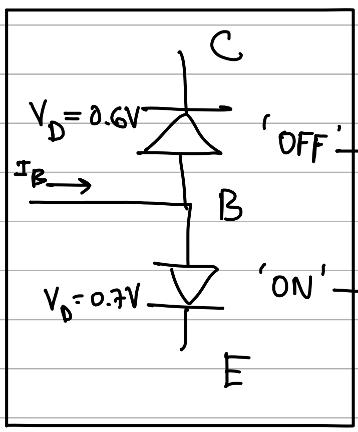
or, $V_{CE} = V_{BE} - V_{BC}$

$= 0.8 - 0.6$

$= 0.2V$



③ Active : I_C current saturates (and only depends on I_B).

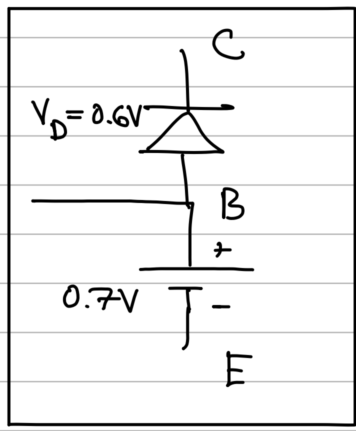


→ BC off, $V_{BC} < 0.6V$

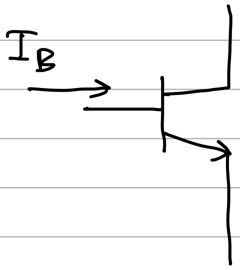
→ BE on, $V_{BE} > 0.7V$

→ $V_{CE} > 0.2V$

$\Rightarrow$



BC is not 'open ckt'-ed. In this config., huge I_c flows from C to B that depends only on I_B.



$\downarrow I_C = \beta I_B$ — ① where β = constant that is commonly called current gain

$$\boxed{\begin{aligned} \downarrow I_E &= I_B + I_C \quad \text{— ②} \\ &= I_B + \beta I_B \\ &= (\beta+1) I_B \end{aligned}}$$

$\beta = \dfrac{I_C}{I_B}$ common values 100, 150

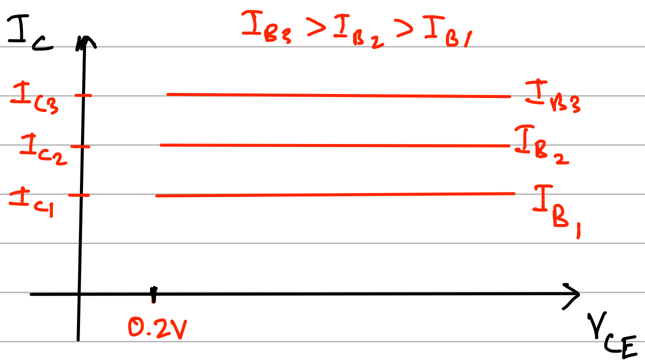
② $I_B = \frac{1}{\beta} I_C \Rightarrow I_E = \frac{1}{\beta} I_C + I_C = I_C\left(\frac{1}{\beta}+1\right) = I_C\left(\frac{\beta+1}{\beta}\right)$

$$\boxed{\therefore \; I_C = \left(\frac{\beta}{\beta+1}\right) I_E}$$

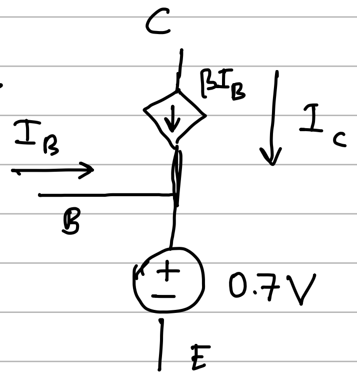
$I_C = \beta I_B$ → β: current gain [collector - base]

$\Rightarrow I_C = \alpha I_E$ → α: current gain [collector - emitter]

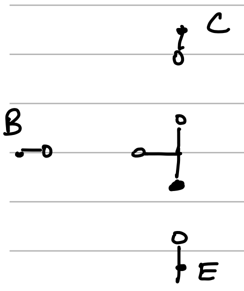
→ Behaves like a current source depending on input current I_B.



Active:

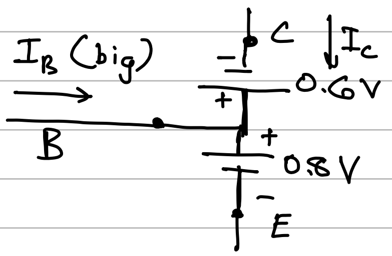


Cutoff:

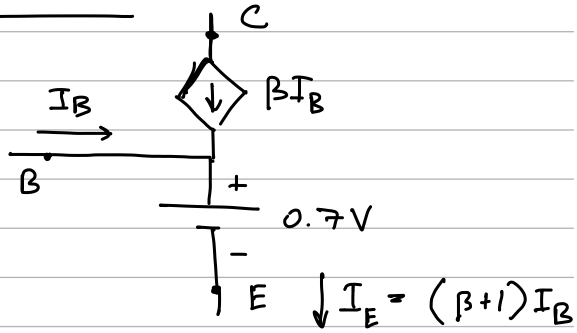


BJT OFF

Saturation:



Active:



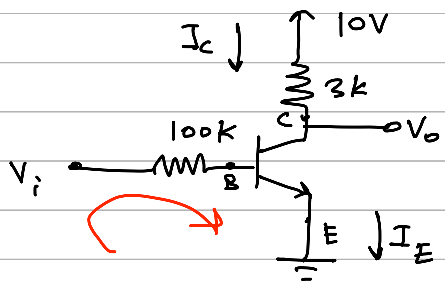
Method of Assumed State :

① Assume
- Active [$V_{BE} = 0.7V$, $I_C = \beta I_B$]
- Saturation [$V_{BE} = 0.8V$, $V_{BC} = 0.6V$, $V_{CE} = 0.2V$]
- Cutoff [$I_B = I_C = I_E = 0$]

② Solve [KCL, KVL, node]

③ Verify
- Active [$V_{CE} > 0.2V$]
- Saturation [$\frac{I_C}{I_B} < \beta$]
- Cutoff [$V_{BE} < 0.7V$, and $V_{BC} < 0.6V$]

Ex-1 :



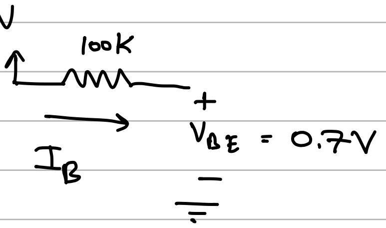
Find v_o for $v_i = 1V$

$\beta = 100$

Assume : Active — ① $V_{BE} = 0.7V$

② $I_C = \beta I_B$

Solve :



$\Rightarrow \quad I_B = \frac{1-0.7}{100k} = 0.003\ mA$

$V_o = V_C$ here.

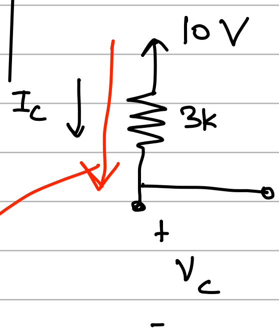
$I_C = \beta I_B$

$= 100 \times 0.003\ mA$

$= 0.3\ mA$

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

$= 0.303\ mA$



$V_o = 10 - I_c \times 3k$

$= 10 - .3 \times 3$

$= 10 - 0.9$

$= 9.1V$

KVL

$I_C \times 3k = 10 - V_C$

or, $V_C = 10 - I_C \times 3k$

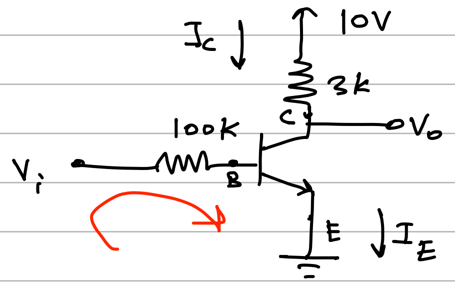
$V_C = 9.1V$, $V_E = 0$, $V_B = V_{BE} + V_E = 0.7V$

Verify :

$$V_{CE} = V_c - V_E = 9.1 - 0 = 9.1\,V > 0.2\,V.$$

$\therefore$ Correct assumption

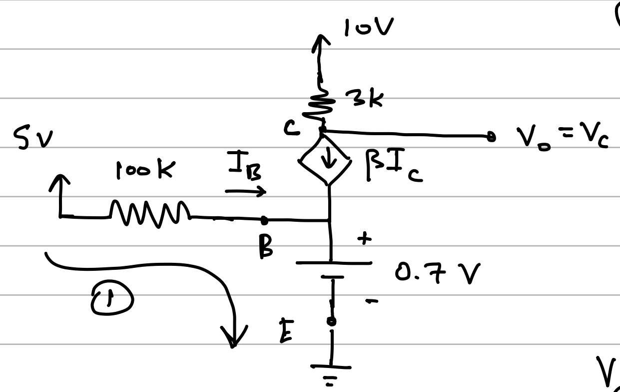
Ex-2 :



Find V_o for $v_i = 5V$

$\beta = 100$

Assume : Active



1 $\rightarrow$ $100 \times I_B + 0.7 = 5 - 0$

$$I_B = \frac{5 - 0.7}{100} = 0.043\ mA$$

$$I_c = \beta \times I_B = 100 \times 0.043$$
$$= 4.3\ mA$$

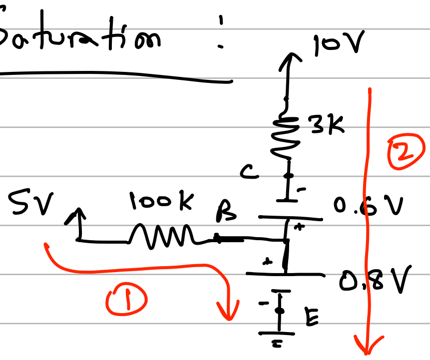
$$V_c = 10 - I_c \times 3k = -2.9V$$

$$V_E = 0V$$

$$V_{CE} = V_c - V_E = -2.9 < 0.2V$$

$\therefore$ Assumption wrong ! Not in active state

Saturation :



1 $\rightarrow$ $100\, I_B + 0.8 = 5 - 0$

$$I_B = \frac{5 - 0.8}{100} = 0.042\ mA$$

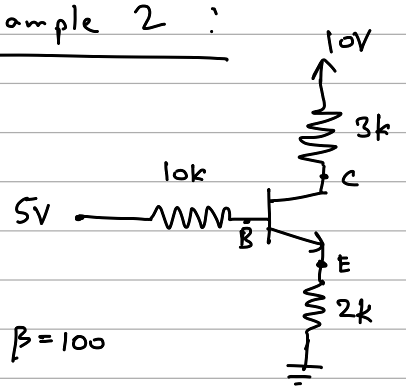
+0.2V

2 $\rightarrow$ $3 I_c - 0.6 + 0.8 = 10 - 0$

$$I_c = \frac{10 - 0.8 + 0.6}{3}$$

$$= \frac{9.8}{3} = 3.29\,mA$$

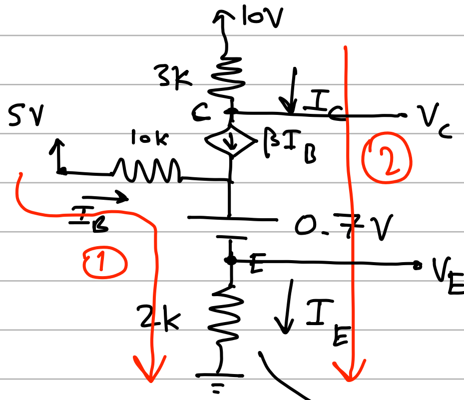
Example 2 :



$\beta = 100$

Find I_B, I_C, I_E, V_{CE}

① Assume : Active



$I_E = I_B + I_C = I_B + \beta I_B$

$I_E = (\beta+1) I_B$

$I_C = \beta I_B$

① → $10 I_B + 0.7 + 2 I_E = 5 - 0$

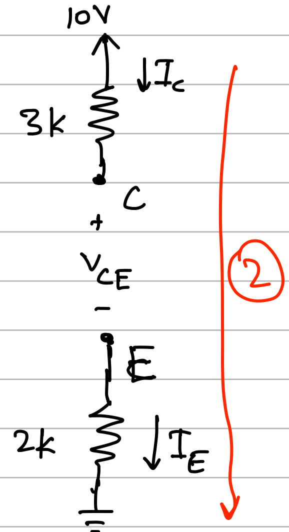
$\Rightarrow 10 I_B + 2 \times 100 I_B = 5 - 0.7$

$\Rightarrow I_B (210) = 4.3$

$I_B = 0.0205 \text{ mA}$

$V_C = 10 - 3 I_C$

$V_E = 2 I_E$



$3 I_C + V_{CE} + 2 I_E = 10 - 0$

$I_C = \beta I_B = 2.05 \text{ mA}$

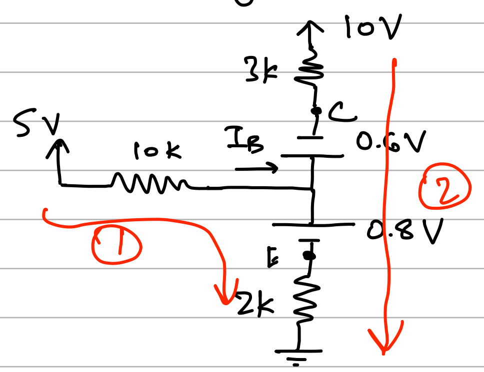
$V_{CE} = 10 - 6.15 - 4.141$

$= 10 - 10.3$

$\approx -0.3 < 0.2\text{V}$

$I_E = I_B + I_C = 2.0705 \text{ mA}$

Assumption wrong ! Assume saturation



① → $10 I_B + 0.8 + 2 I_E = 5 - 0$

but, $I_C \neq \beta I_B$, $I_E \neq (\beta+1) I_B$

[not in active]

In saturation, $\underset{\text{(approx.)}}{\underline{I_C \approx I_E}}$: ② → $3 I_C - 0.6 + 0.8 + 2 I_E = 10 - 0$ $(\approx I_C)$

$\Rightarrow 5 I_C = 10 - 0.2$

$I_C = 1.96 \text{ mA}$

① → $10 I_B = 5 - 0.8 - 2 \times 1.96 = 0.28 \Rightarrow I_B \approx 0.028 \text{ mA}$

Without approx. :

(1) → $10 I_B + 0 I_C + 2 I_E = 4.2$

(2) → $0 I_B + 3 I_C + 2 I_E = 9.8$

$-I_B + I_C + I_E = 0$

$I_E = I_B + I_C$

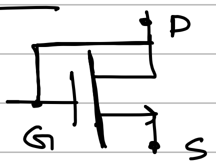
$\Rightarrow -I_B - I_C + I_E = 0$

3 eq^n's, 3 unknowns → solve

$I_B = 0.03$ mA , $I_C = 1.95$ mA , $I_E = 1.98$ mA

Mosfet :

(Neaman) - n-MOSFET ch3 → circuit solve using MAS



↳ we use $k = k_n' \frac{W}{L}$,

neaman uses $k = \frac{k_n'}{2} \frac{W}{L}$

Sedra Smith — n MOSFET ch 5

BJT :

(Neaman) - BJT ch 5 → circuit solve using MAS
(npn)

Sedra — BJT ch 6