ELECTRONIC DEVICES

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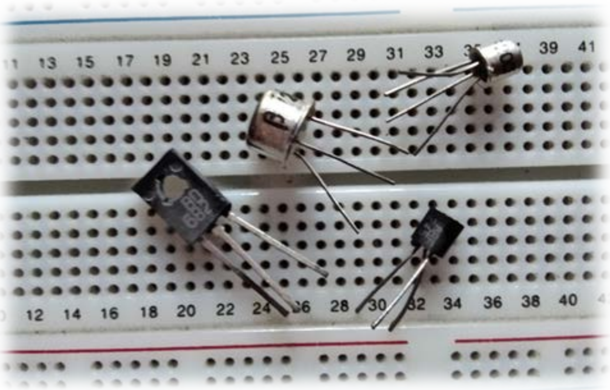
C12 – BJT operation



Contents

Previously on ED (C11):

Transistors

= active semiconductor devices, with three terminals

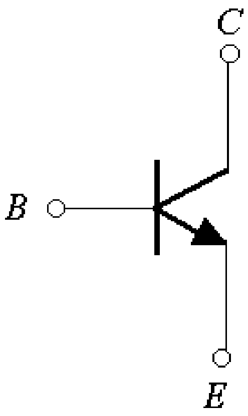
- used to amplify or switch signals
- essential components of electronic circuits
- discrete or integrated

Operating principle:

The voltage applied between two terminals (command) controls the current through the third terminal

Simplified structure of a BJT

npn



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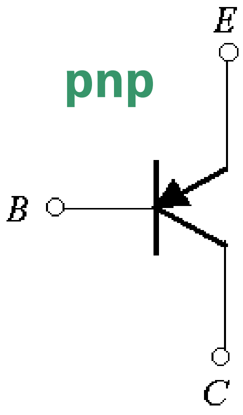
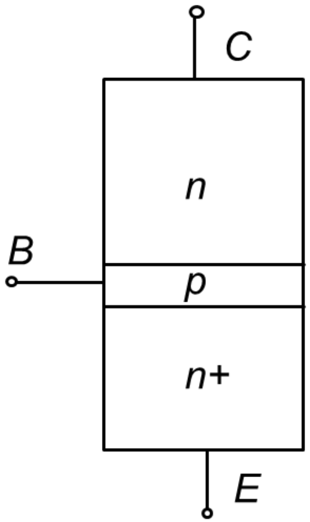
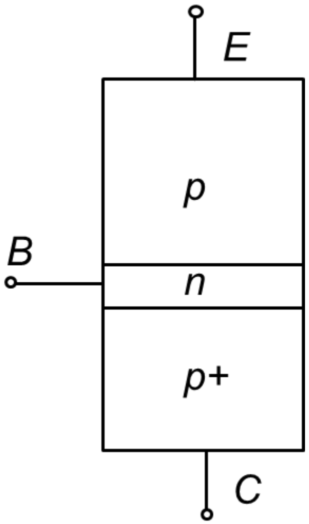
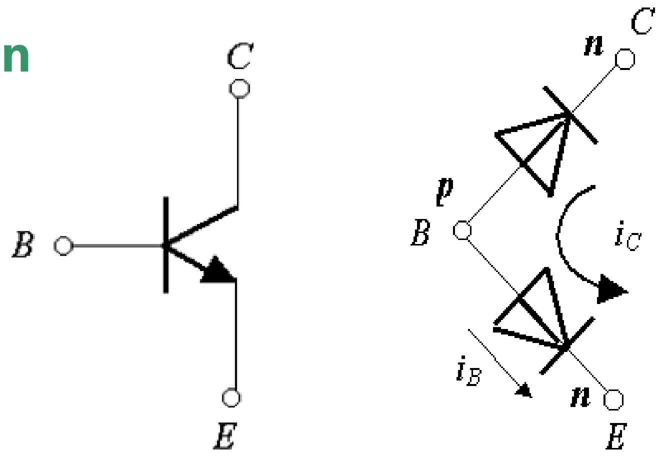


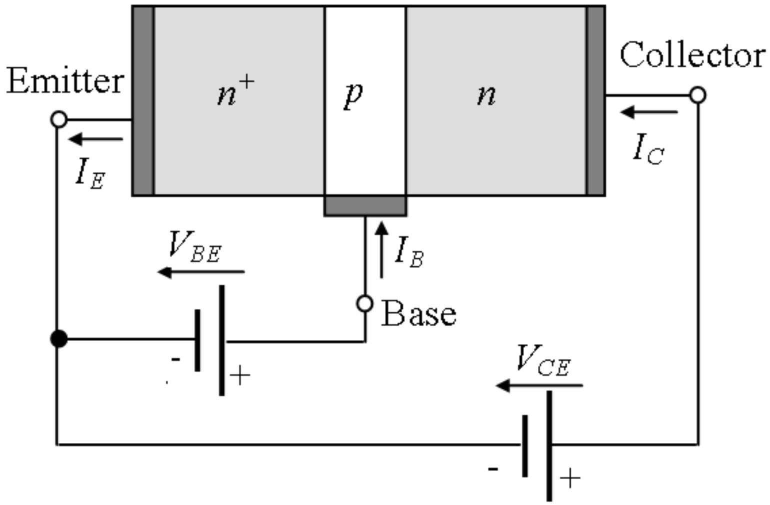




Simplified structure of a BJT

npn





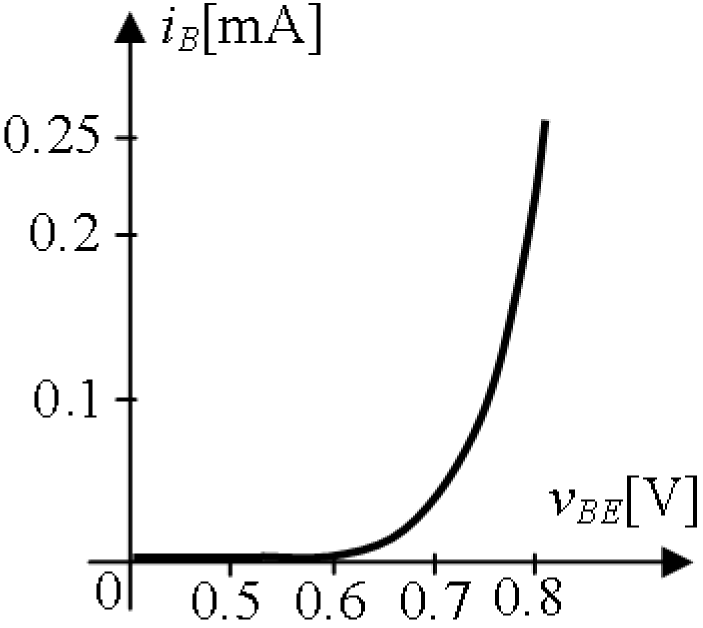
The transistor effect consists in a current flowing through a *reverse biased junction* (B-C) due to its interaction with a *forward biased junction* (B-E), placed in its very close vicinity.

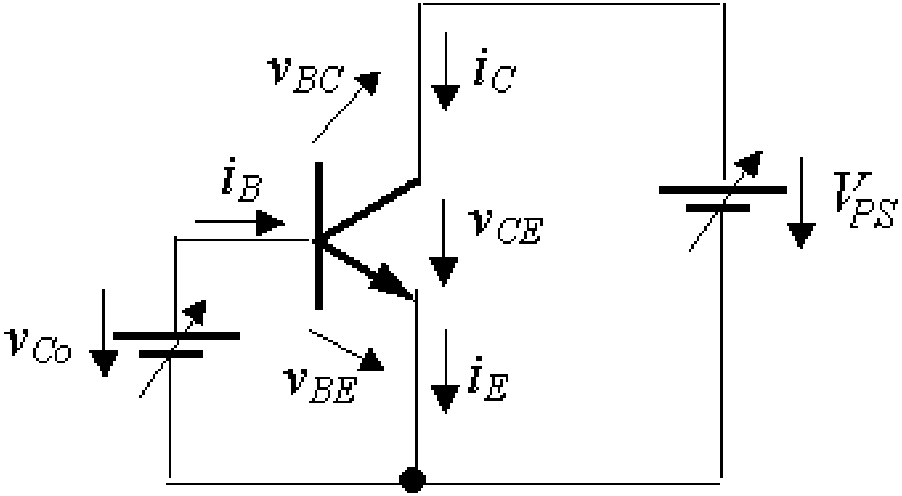
For the transistor effect

- base region - very thin; considerably thinner than the diffusion length of the minority carriers in the base region;
- emitter region - more doped than the base region
- emitter and collector regions - wider than the diffusion length of the minority carriers in these regions.

Input and transfer characteristics, npn BJT

- Input characteristic





$$i_B = \frac{I_S}{\beta} e^{\frac{v_{BE}}{V_T}}$$

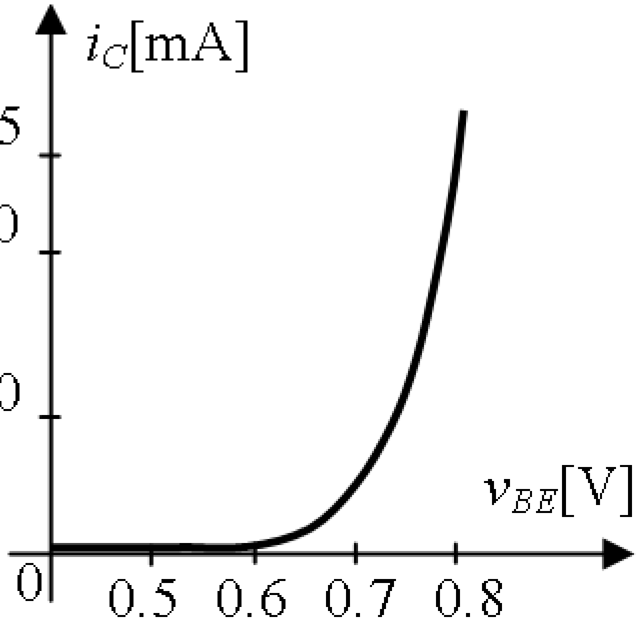
I_S - saturation current (~ nA - pA)

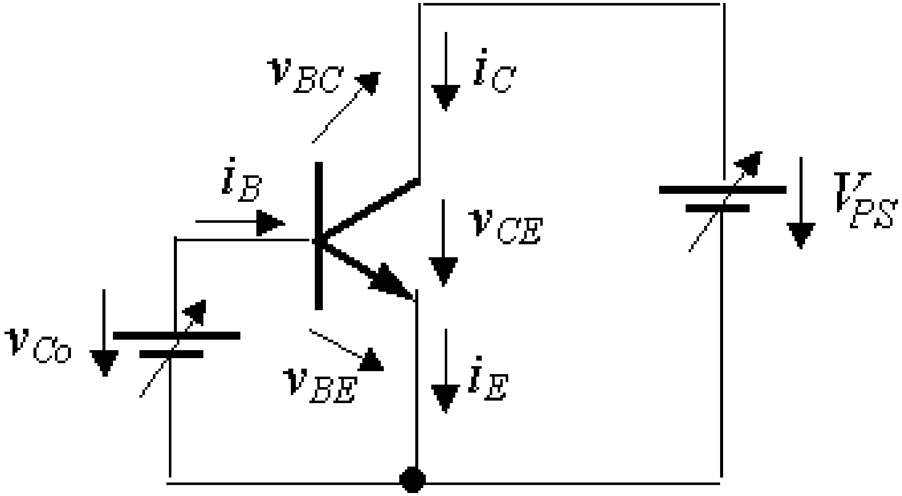
$V_T = \frac{KT}{q}$ thermal voltage $\boxed{V_T = 25\text{mV} \ @ \ 20^{\text{O}}\text{C}}$

β current gain (~ tens, hundreds, dimensionless)

Input and transfer characteristics, npn BJT

- Transfer characteristic





$$i_C = \beta i_B$$

$$i_C = I_S e^{\frac{v_{BE}}{V_T}}$$

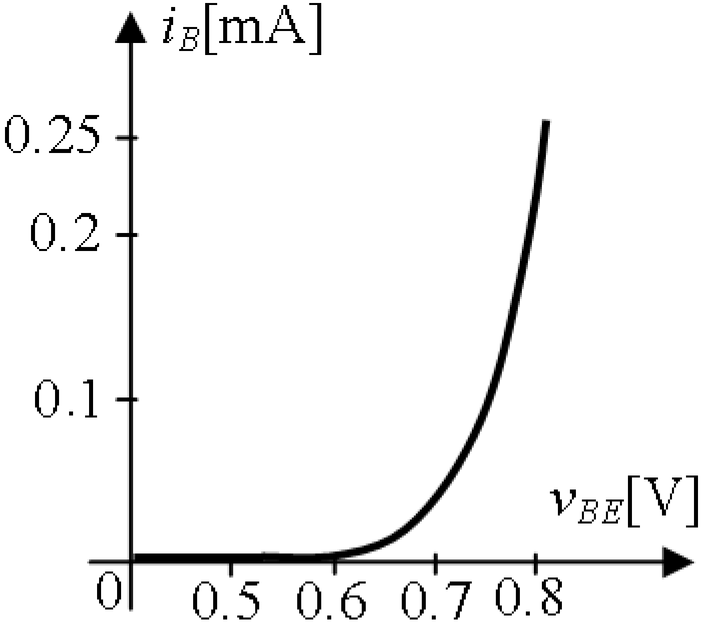
Input and transfer characteristics, npn BJT

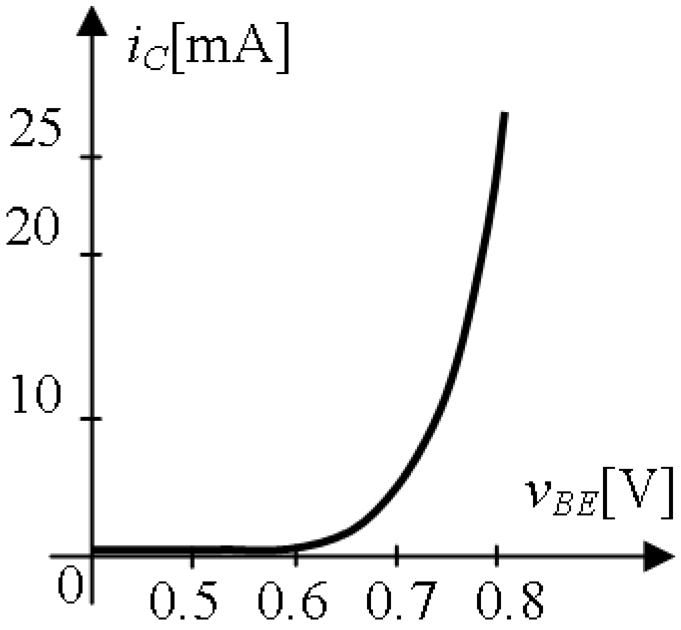
- Input and transfer characteristics

$$i_B = \frac{I_S}{\beta} e^{\frac{v_{BE}}{V_T}}$$

$$i_C = I_S e^{\frac{v_{BE}}{V_T}}$$

$$i_C = \beta i_B$$

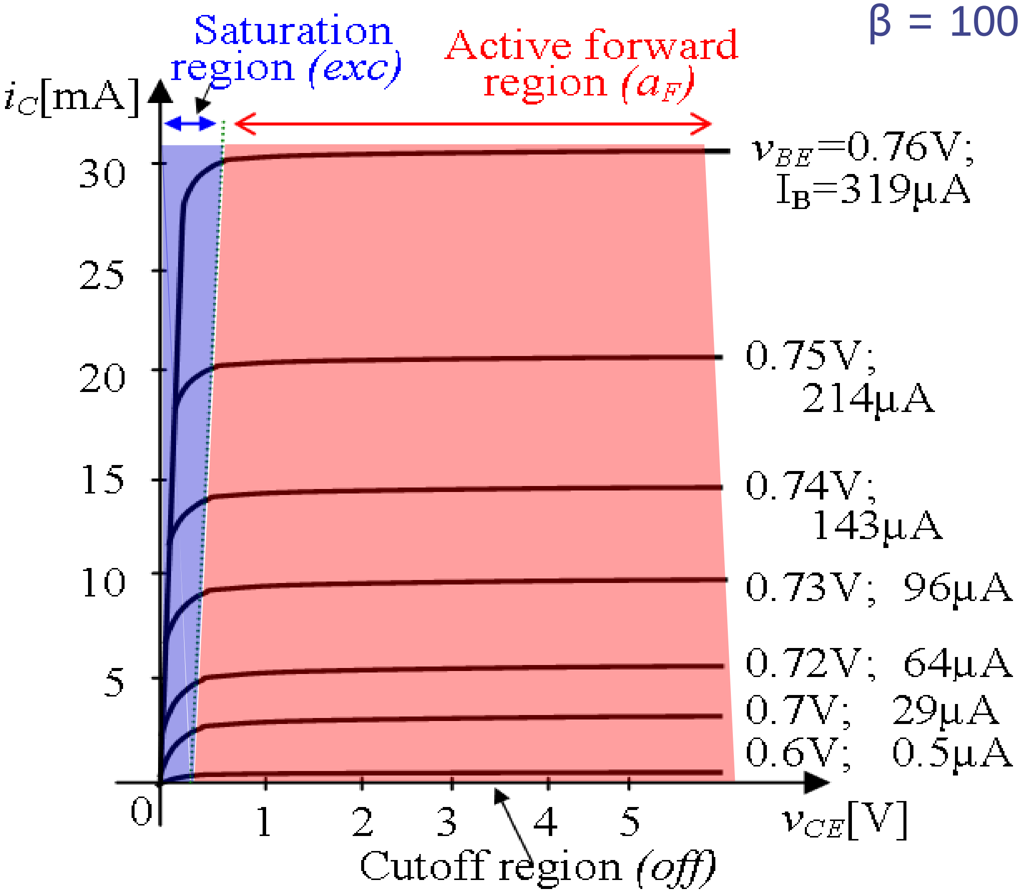


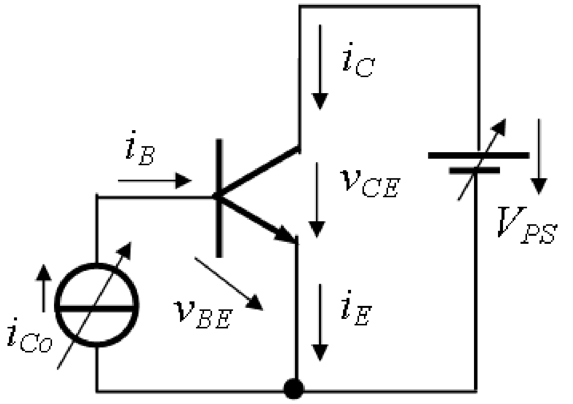


Output characteristics, npn BJT

- Family of output characteristics

$I_S = 2\cdot10^{-15}$ A
$\beta = 100$





Active region (a_F)

$i_C = \beta * i_B$ $$i_C = I_S e^{\frac{v_{BE}}{V_T}}$$

Saturation region (exc)

$i_C < \beta * i_B$
$V_{CEsat} \approx 0.2V$

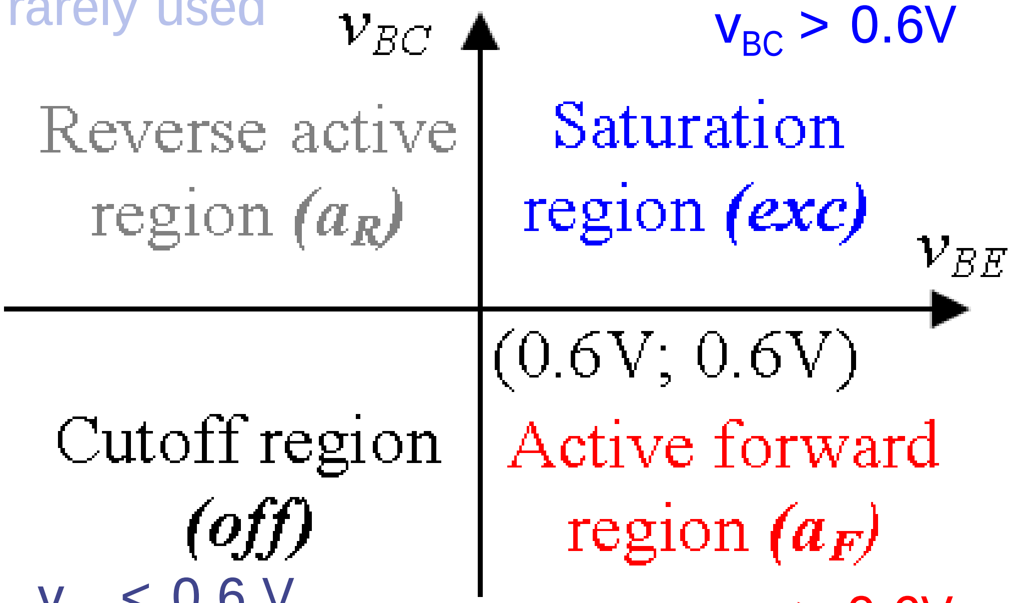
Cutoff region (off):

$i_C = i_B = 0$

Operating regions, npn BJT

rarely used

$v_{BE} > 0.6V$
$v_{BC} > 0.6V$



$v_{BE} < 0.6$ V
$v_{BC} < 0.6$ V

$v_{BE} > 0.6V$
$v_{BC} < 0.6V$

Note: the transistor shouldn't be biased very close to the origin of the axes or to one of the axis

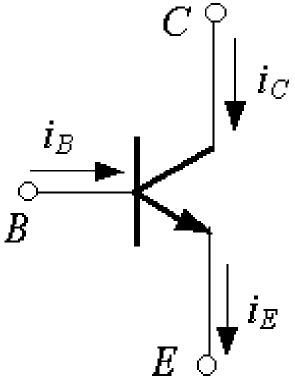
Modes of use
- switching mode: (off) / (exc)
- as an amplifier: (a_F), possibly (a_R)

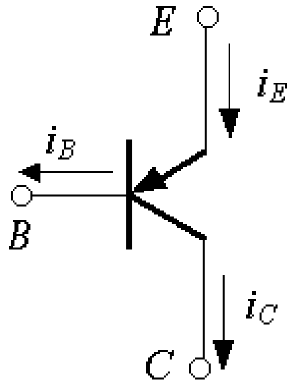
Currents. Limiting the command current.

- Currents

$i_E = i_C + i_B$

!Always valid, regardless of operating region!





In the active region (a_F):

$i_C = \beta i_B$

$$i_E = i_C + \frac{1}{\beta} i_C = i_C (1 + \frac{1}{\beta})$$

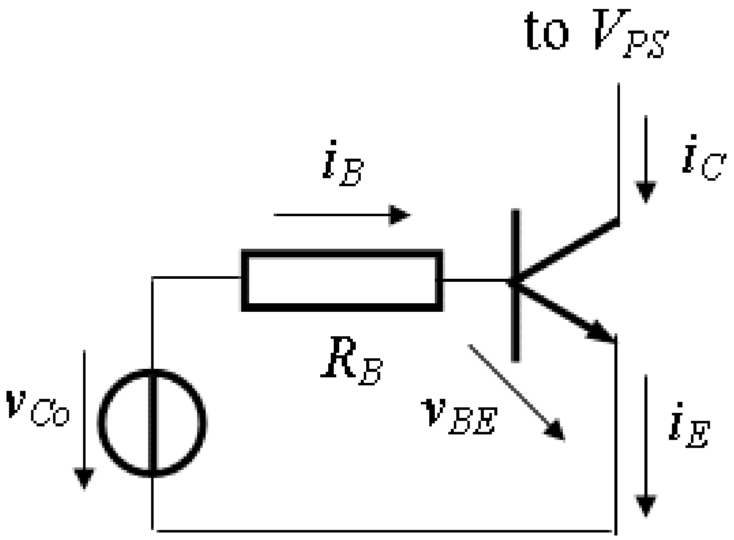
$i_E = (\beta+1)\ i_B \approx \beta i_B$ $\quad i_E \approx i_C$

In the saturation region (exc): $i_C < \beta i_B$

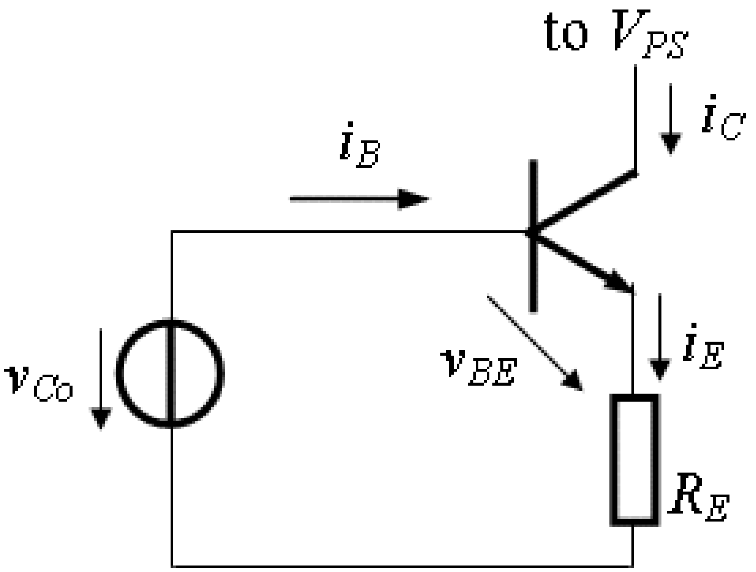
Currents. Limiting the command current.

➢ Limiting the command current

Command voltage is applied between B and E, so command current is I_B. Limit I_B by using a **series resistance** in B or E.



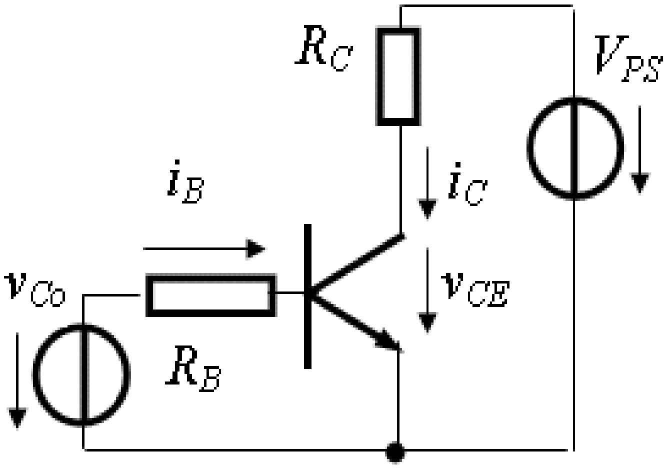
$$\boxed{i_B = \frac{v_{Co} - v_{BE}}{R_B}}$$

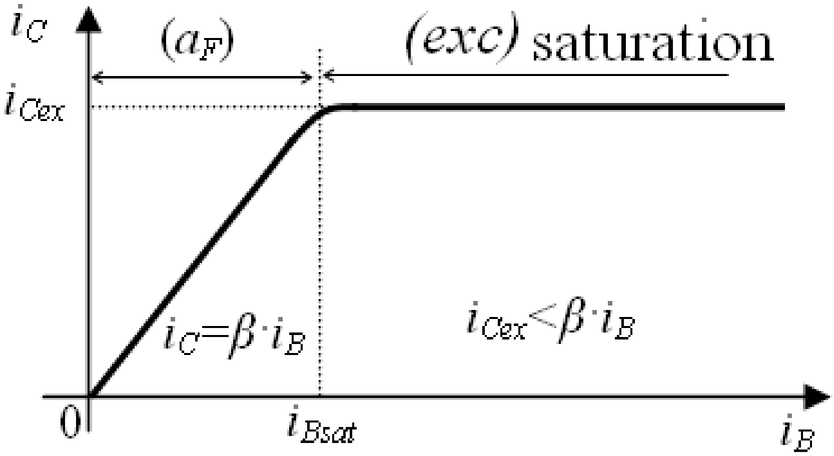


$$\boxed{i_E = \frac{v_{Co} - v_{BE}}{R_E}}$$

$$v_{BE} \approx 0.7\text{V}$$

BJT saturation





$$i_{Cex} = \frac{V_{PS} - v_{CEsat}}{R_C} \approx \frac{v_{PS}}{R_C}$$

Boundary
(a_F) - (exc)

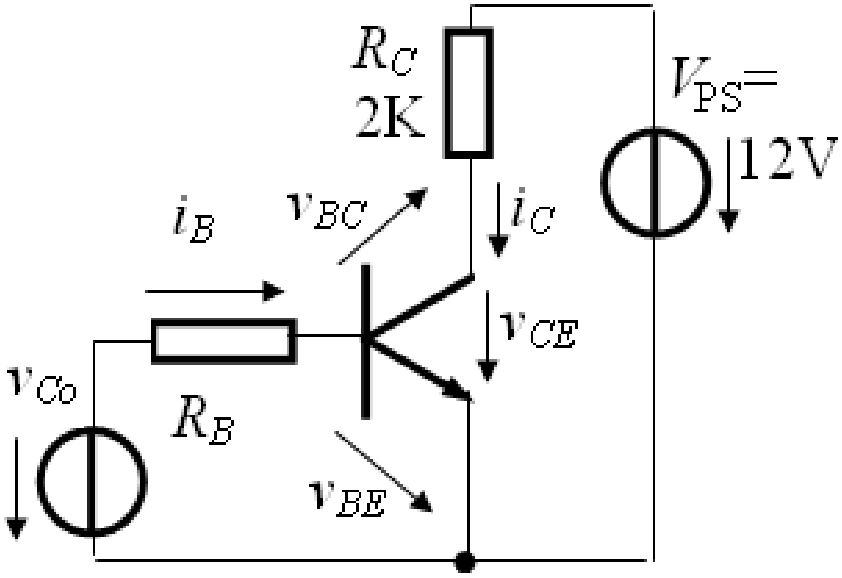
$$i_{Bsat} = \frac{i_{Cex}}{\beta}$$

- resistors and applied voltages are chosen based on the desired region (off, a_F or exc) of the BJT
- BJT can also be seen as a current-controlled current source ($i_C = \beta i_B$), when operating in the active region (a_F)

Quiescent point of the BJT

Quiescent point Q = a point on the output characteristic $i_C(v_{CE})$ of the BJT

- Q is defined by V_{CE} and I_C
- $Q(V_{CE}, I_C)$ is at the intersection between the load line and the output characteristic corresponding to v_{BE}

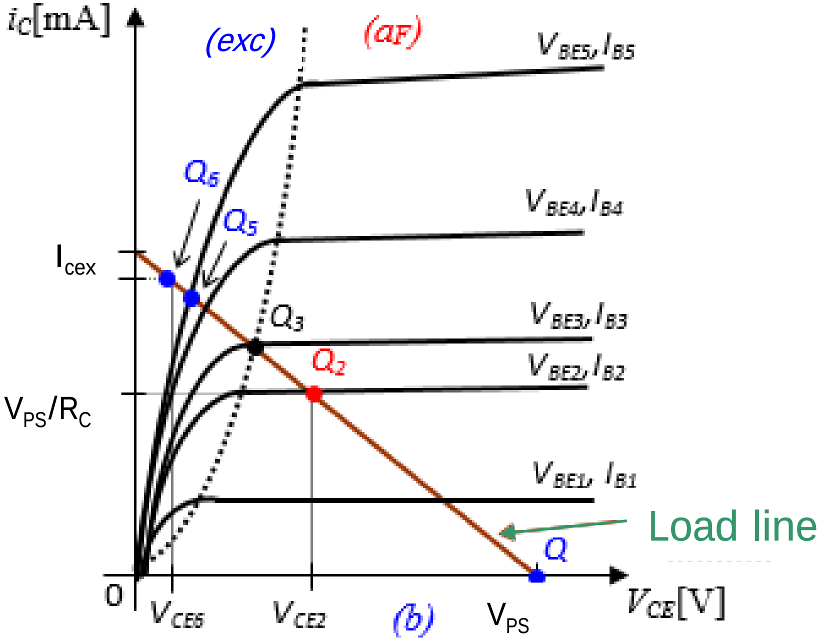


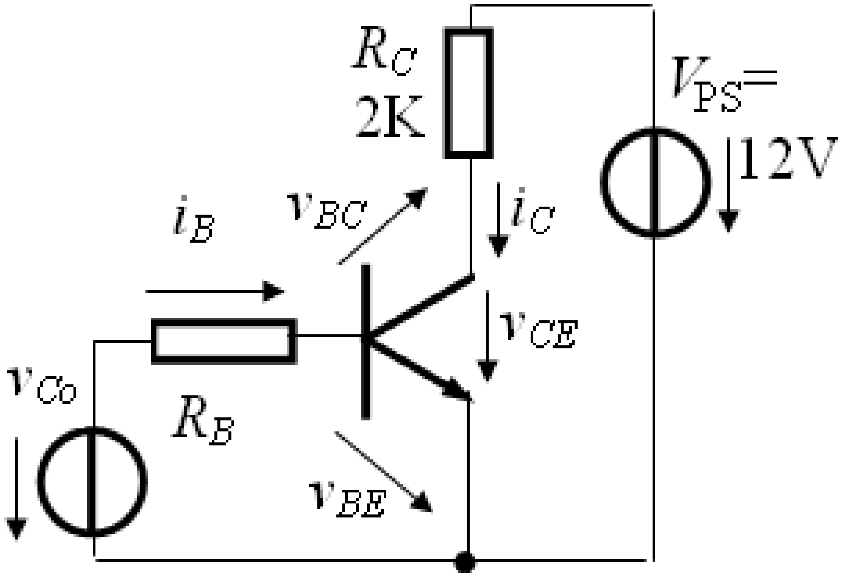
Load line:

$v_{CE} = V_{PS} - R_C\, i_C$

Quiescent point of the BJT

Quiescent point Q = a point on the output characteristic $i_C(v_{CE})$ of the BJT





$Q_2(V_{CE2}, I_{C2})$

$$i_B = \frac{v_{Co} - v_{BE}}{R_B}$$

$$i_C = \beta i_B$$

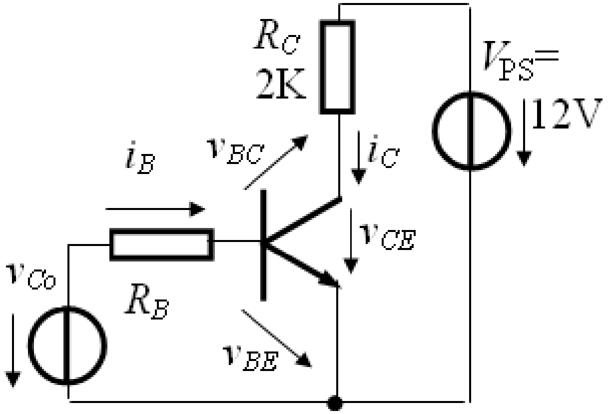
$$v_{CE} = V_{PS} - R_C \cdot i_C$$

Examples

➢ Example - 1

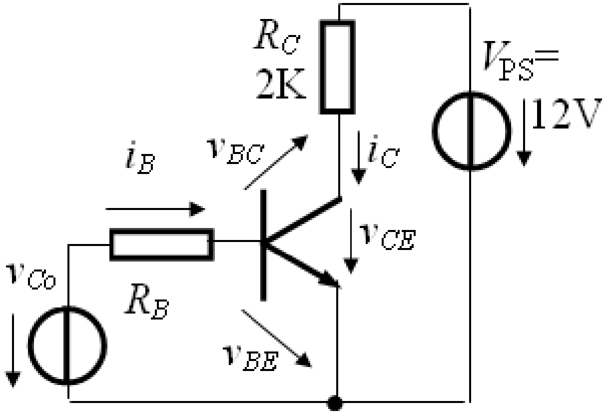
Find the operating region and compute Q(V_{CE}, I_C) for R_B = 50 kΩ and

i) v_{Co} = 0.4 V;
ii) v_{Co} = 1.7 V;
iii) v_{Co} = 5 V



Examples

Example - 1



Solution:

i) because v_{Co}= 0.4 V < $V_{Th,n}$ = 0.6 V   T - (off)

$$Q(V_{CE}, I_C) = Q(12\ V, 0\ mA)$$

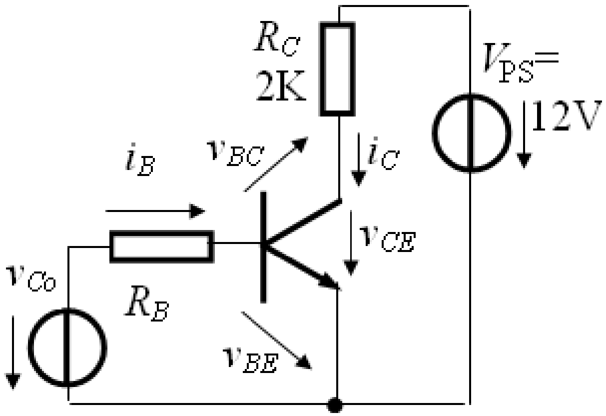
ii) $v_{Co} > V_{Th} \Rightarrow$ T is on, in (a_F) or in (exc).

- Assume v_{BE} = 0.7 V for conduction and $\beta = 100$
- Assume T in (a_F), so that $i_C = \beta * i_B$
- Compare i_B with i_{Cex}/β:

If $i_B > i_{Cex}/\beta$, the assumption was false, and T is in (exc)

If $i_B < i_{Cex}/\beta$, the assumption was true, and T is in (a_F)

➢ Example - 1



Solution:

$$i_{Cex} = \frac{V_{PS} - v_{CEsat}}{R_C} = \frac{12 - 0.2}{2} = 5.9\text{mA}$$

$$i_B = \frac{v_{Co} - v_{BE}}{R_B} = \frac{1.7 - 0.7}{50} = 0.02\,\text{mA}$$

$$\frac{i_{Cex}}{\beta} = \frac{5{,}9}{100} = 0.059mA$$

Because $i_B = 20\ \mu A < i_{Cex}/\beta = 59\ \mu A \Rightarrow$ T is in (a_F)

$$i_C = \beta i_B = 100 \cdot 0.02 = 2\text{mA}$$

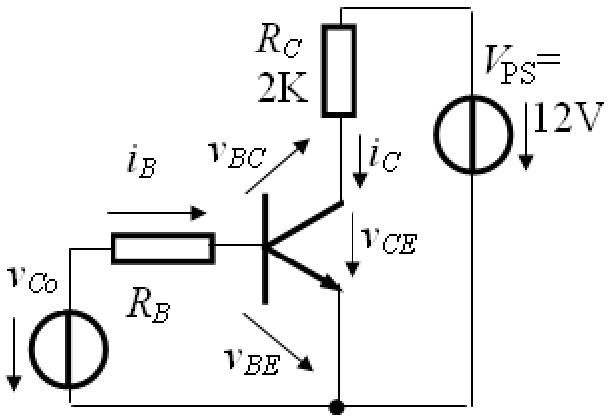
$$v_{CE} = V_{Al} - R_C i_C = 12 - 2 \cdot 2 = 8\text{V}$$

$$\boxed{Q(8\text{V}; 2\text{mA})}$$

$$v_{BC} = v_{BE} - v_{CE} = 0.7 - 8 = -7.3\text{V} < 0.6\text{V}$$

Examples

➢ Example - 1



Solution:

iii) $$i_B = \frac{v_{Co} - v_{BE}}{R_B} = \frac{5 - 0.7}{50} = 0.086\text{mA}$$

Because i_B = 86 µA > i_{Cex} /β = 59 µA ⇒ T is in (exc)

$v_{BEsat} \approx 0.8$V; $v_{BC} = v_{BEsat} - v_{CEsat} \approx 0.8\text{ V} - 0.2\text{ V} = 0.6\text{ V} = V_{Thn}$

Alternative method: assume T in (a_F) ⇒ $i_C = \beta * i_B = 8.6$ mA

$v_{CE} = V_{PS} - R_C \cdot i_C = 12 - 2 \cdot 8.6 = -5.2$V

But v_{CE} can only be positive, so the assumption is false ⇒ T is in (exc)

$$V_{CE} = v_{CEsat} = 0.2\text{V}$$
$$I_C = i_{Cex} = 5.9\text{mA}$$

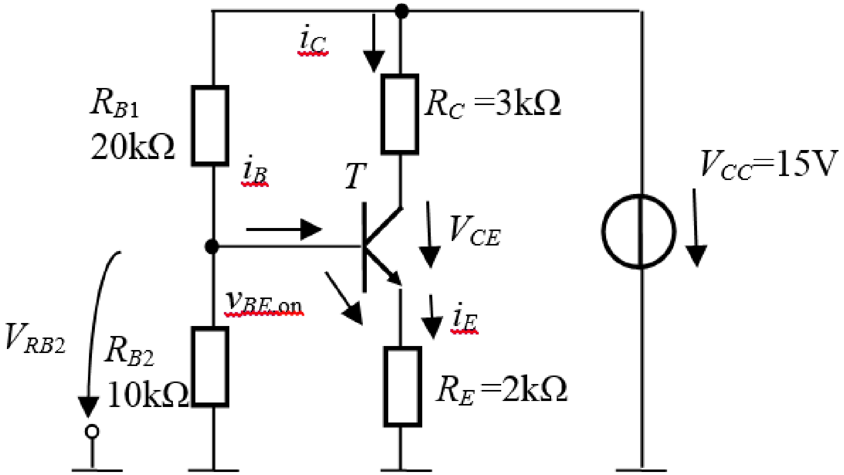
Q(0.2 V; 5.9 mA)

Examples

➢ Example - 2

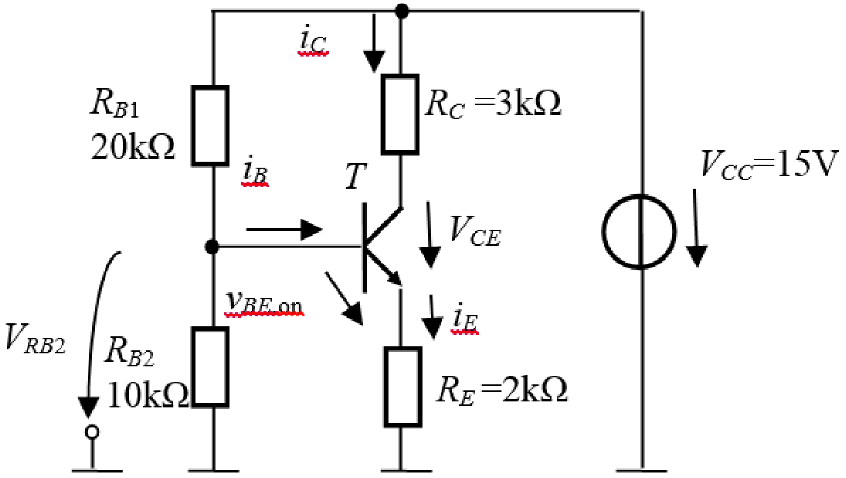
$\beta = 100, v_{BE,on} = 0.7\ V$

a) Find $Q(V_{CE}, I_C)$.
b) What is the operating region of T ?



Examples

➢ Example - 2



Solution:

a) Since $I_B << I_C$ and $I_E = I_c + I_B$:

$$I_C = I_E$$

V_{RB2} – obtained from the voltage divider between R_{B1} and R_{B2}, out of V_{CC}

$$V_{RB2} = \frac{R_{B2}}{R_{B1} + R_{B2}} \cdot V_{CC}$$

$$V_{RB2} = \frac{10k}{30k} \cdot 15V = 5V$$

$$-V_{RB2} + v_{BE,\,on} + V_{RE} = 0$$

$$V_{RE} = V_{RB2} - v_{BE,\,on}$$

$$V_{RE} = 5 - 0.7 = 4.3V$$

$$V_{RE} = I_E \cdot R_E$$

$$I_C = \frac{V_{RE}}{R_E}$$

$$I_C = \frac{4.3V}{2k\Omega} = 2.15mA$$

➢ Example - 2

Solution:

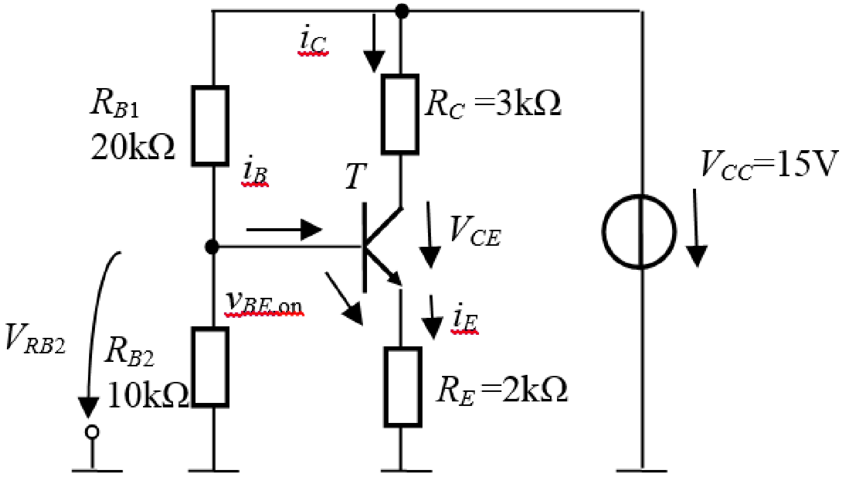
a)

$$-V_{CC} + I_C \cdot R_C + V_{CE} + I_C \cdot R_E = 0$$

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

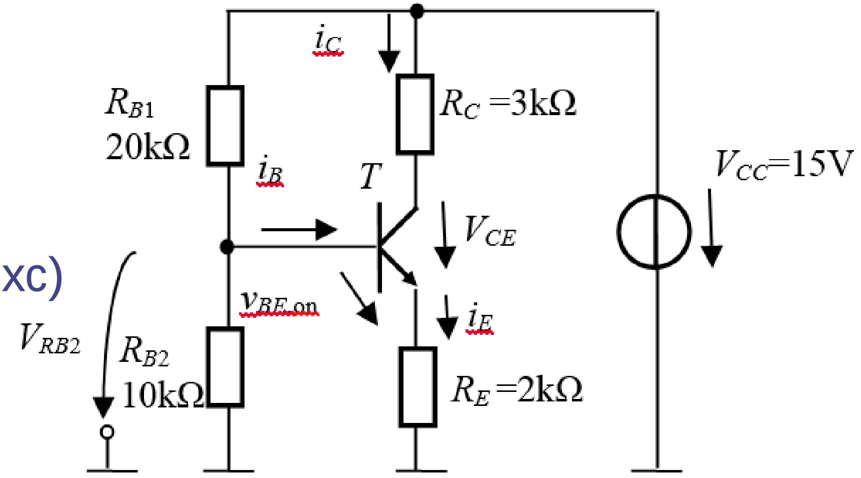
$$V_{CE} = 15 - 2.15 * 10^{-3} * 5 * 10^{3}$$

$$V_{CE} = 4.25V$$



Q(4.25 V; 2.15 mA)

➢ Example - 2



Solution:

b) $v_{Co} = V_{RB2} > v_{BE,on} \Rightarrow$ T is on, in (a_F) or in (exc)

Assume T in (a_F).

Compare i_C with i_{Cex} :

If $i_C > i_{Cex}$, the assumption was false, and T is in (exc)

If $i_C < i_{Cex}$, the assumption was true, and T is in (a_F)

$$I_{Cex} = \frac{V_{CC} - V_{CEsat}}{R_C + R_E}$$

$$\boxed{2.15 \text{ mA} < 2.96 \text{ mA}} \quad \Rightarrow \quad \text{T is in } (a_F)$$

$$I_{Cex} = \frac{15 - 0.2}{3k + 2k} = \frac{14.8}{5 \cdot 10^3} = 2.96mA$$

Summary

The BJT (almost) holds no secrets from us, after investigating:

- Simplified structure of a BJT
- Input and transfer characteristics, npn BJT
- Operating regions
- Currents. Limiting the command current.
- BJT saturation
- Quiescent point of the BJT
- Examples

Next week: MOSFET operation

To do: Homework 9