ELECTRONIC DEVICES

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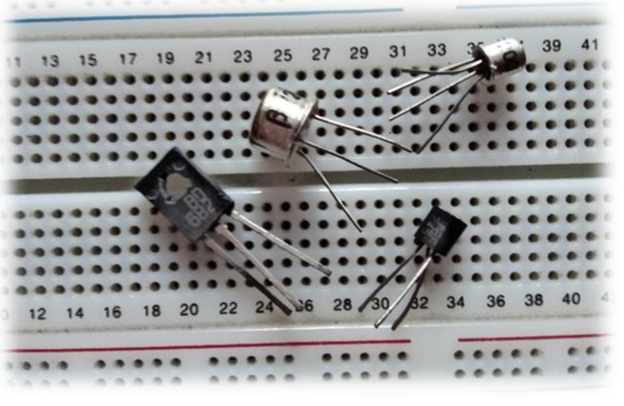
C12 – BJT operation



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- npn BJT characteristics
- Currents. Limiting the command current.
- BJT saturation
- Quiescent point of the BJT
- Operating regions
- Examples

Previously on ED (C11):

Transistors

= active semiconductor devices, with three terminals

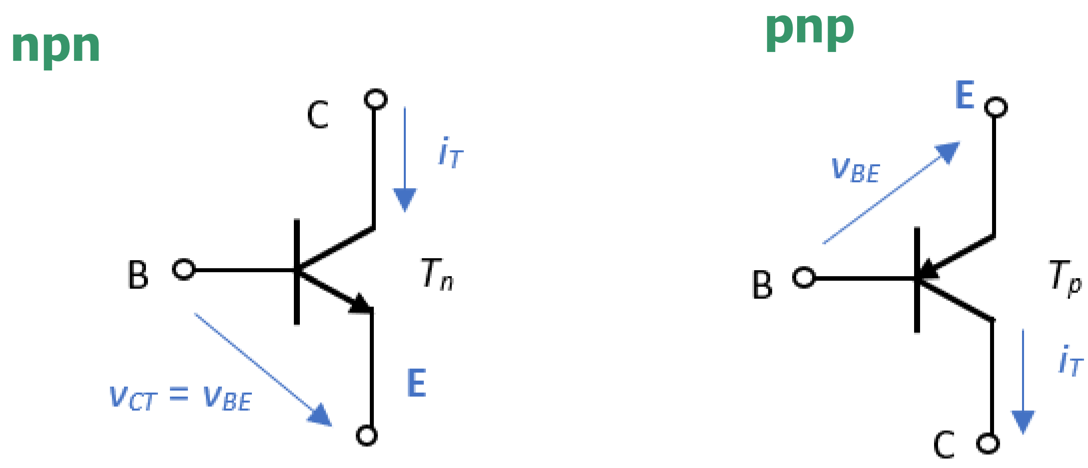
- used to amplify or switch signals
- essential components of electronic circuits
- discrete or integrated

Operating principle:

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

Simplified structure of a BJT

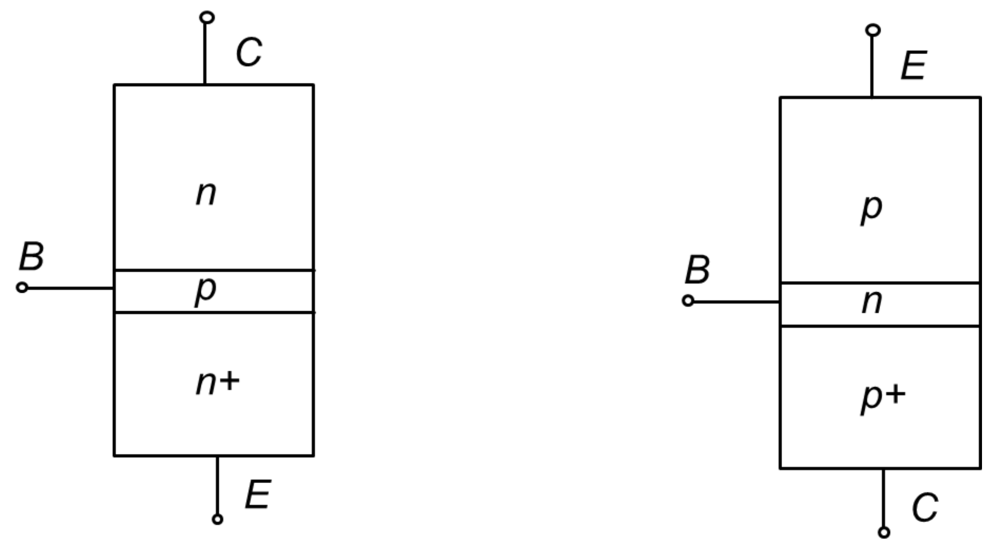
Circuit symbols



B – base, C – collector, E – emitter

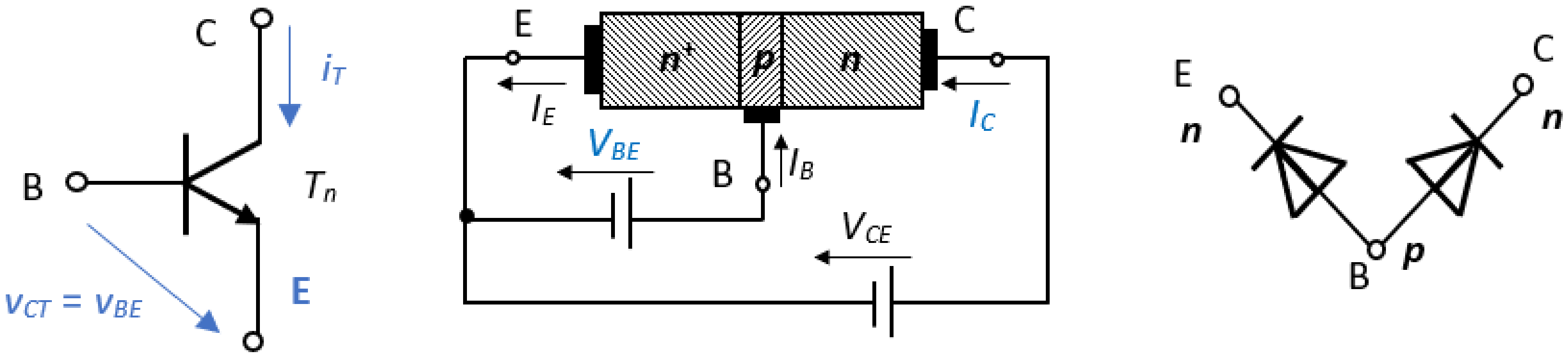
The arrow on the emitter terminal indicates the direction of the positive current.

Simplified physical structure



Simplified structure of a BJT

npn



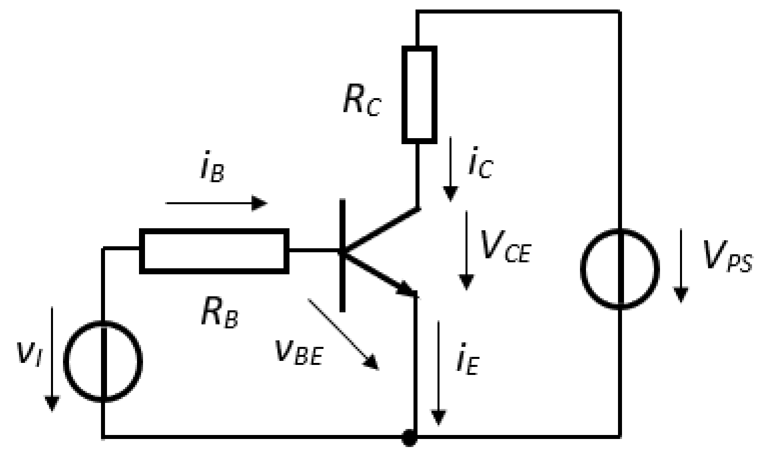
The transistor effect consists in a current flowing through a *reverse biased junction* (B-C) due to its interaction with a *forward biased junction* (B-E), placed in its very close vicinity.

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.

npn BJT characteristics

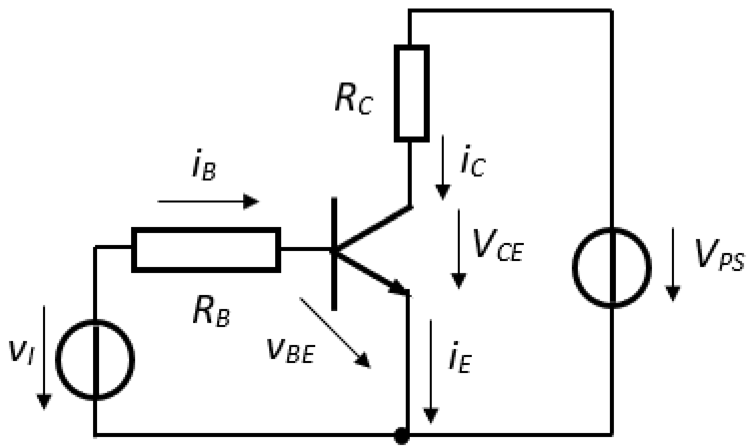
- input characteristic - $i_B (v_{BE})$
- transfer characteristic - $i_C (v_{BE})$

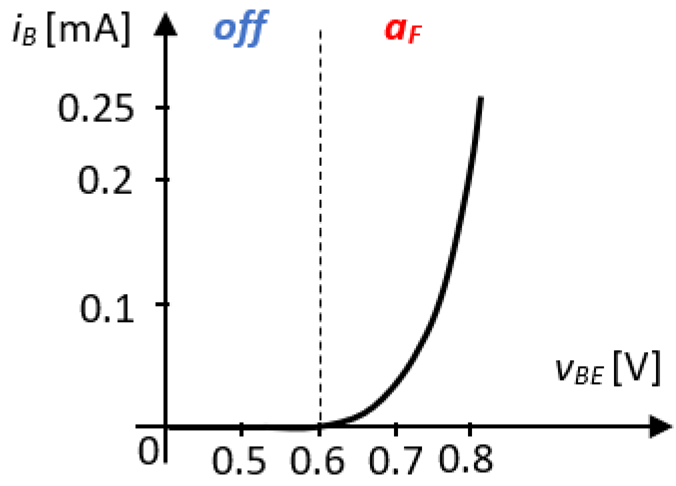


- family of output characteristics - $i_C (v_{CE})$, with v_{BE} and/or i_B as parameters

npn BJT characteristics

- Input characteristic





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

I_S - saturation current (~ nA - pA)

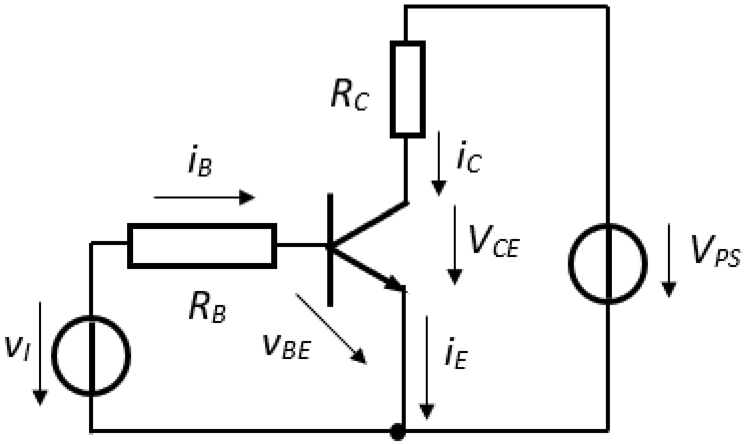
$V_T = \frac{KT}{q}$ thermal voltage $V_T = 25\text{mV} @ 20^{\text{O}}\text{C}$

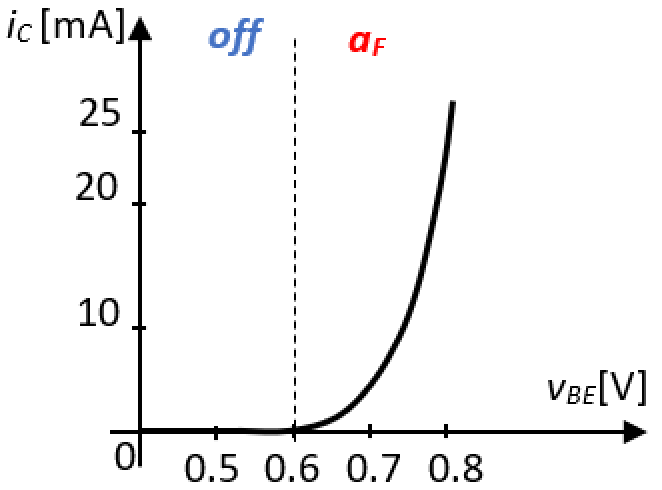
β current gain (~ tens, hundreds, dimensionless)

forward current gain factor (also denoted h_{FE} in dc or h_{fe} in ac)

npn BJT characteristics

- Transfer characteristic





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

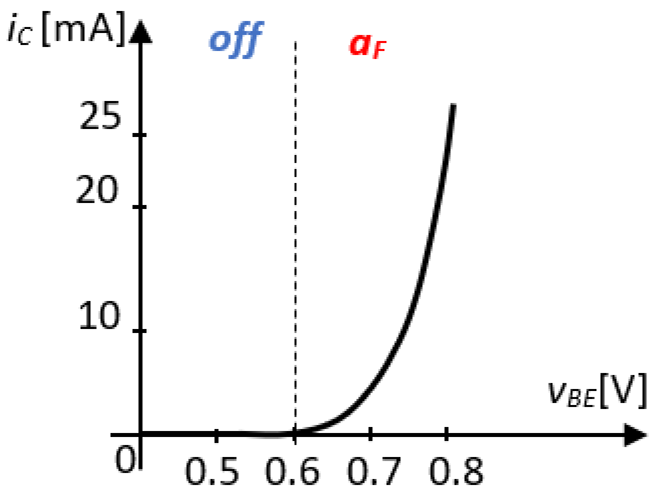
npn BJT characteristics

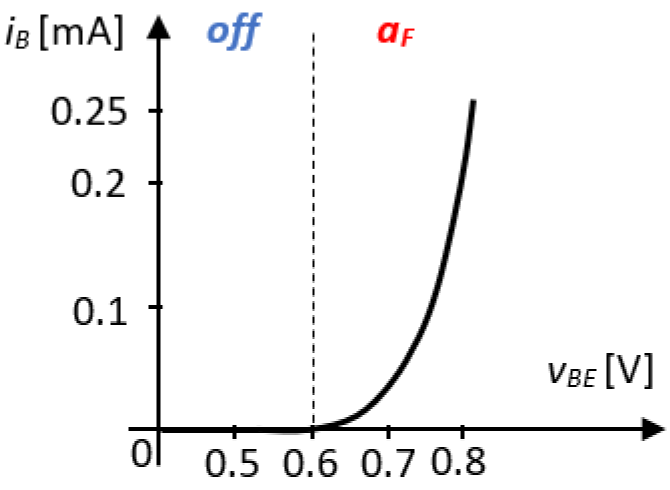
- Transfer and input characteristics

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

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

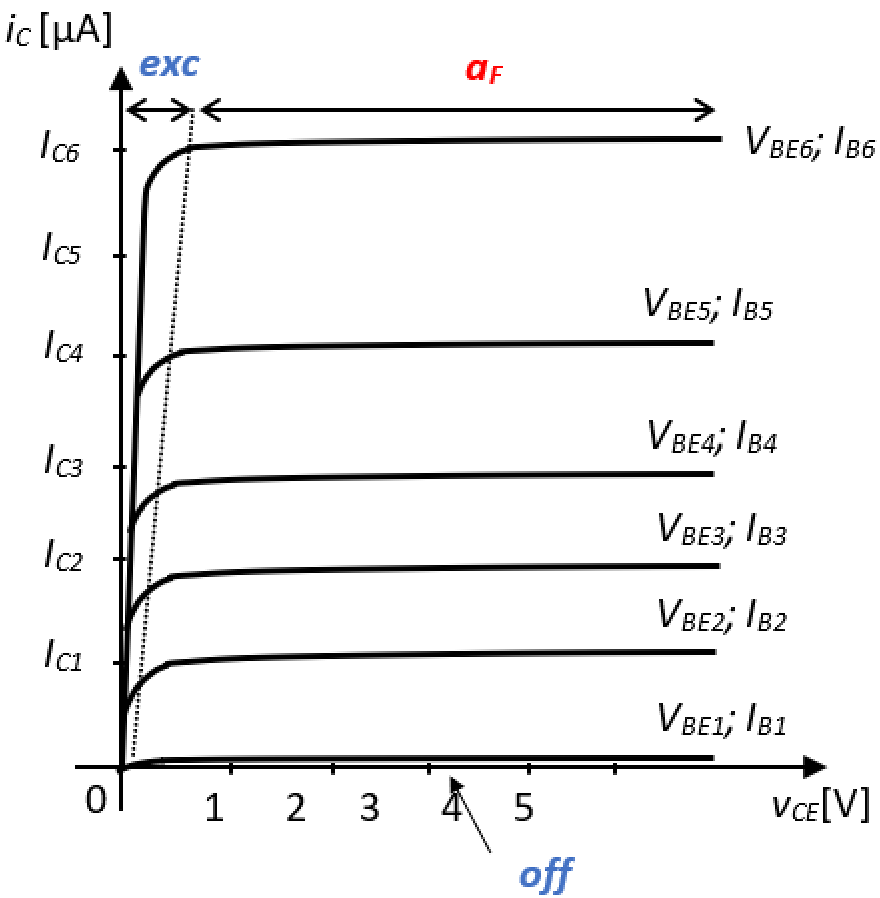
$$i_C = \beta i_B$$





npn BJT characteristics

- Family of output characteristics



Active forward (linear) region (a_F)

$i_C = \beta * i_B$

Extreme conduction (saturation) (exc)

$i_C = i_{Cex} < \beta * i_B$

$V_{CEsat} \approx 0.2$ V

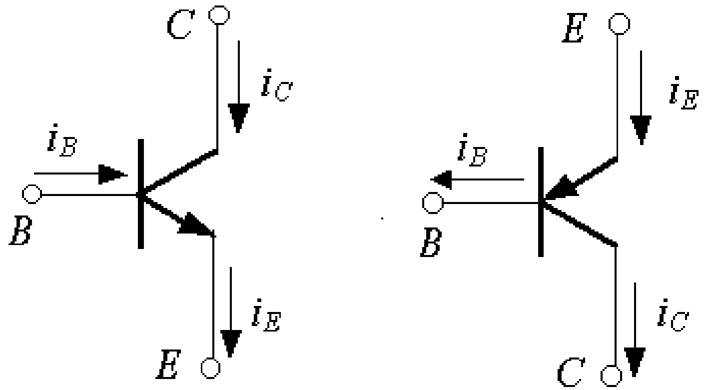
Cutoff region (off):

$i_C = i_B = i_E = 0$

Currents. Limiting the command current.

- Currents

$i_E = i_C + i_B$!Always valid, regardless of operating region!



In the active region (a_F):

$i_C = \beta i_B$

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

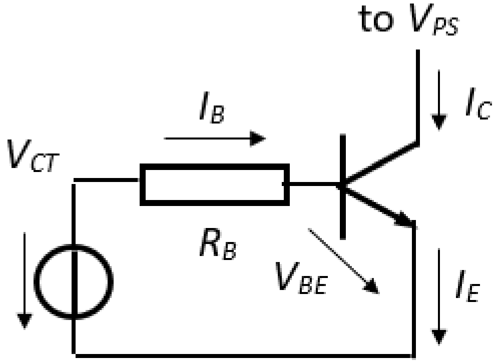
$i_E = (\beta+1)\, i_B \approx \beta i_B$ $i_E \approx i_C$

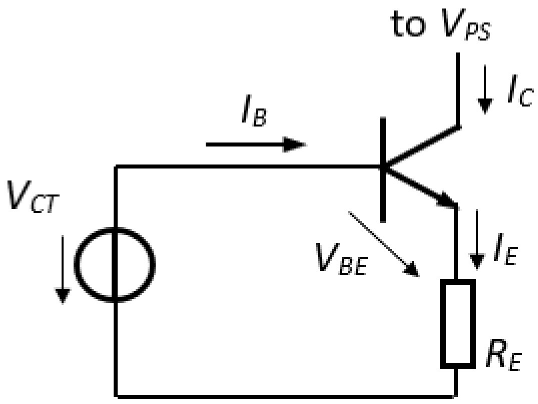
In the saturation region (exc): $i_C < \beta i_B$

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 resistor** in B or E.





$$V_{CT} - V_{BE} - I_B \cdot R_B = 0$$

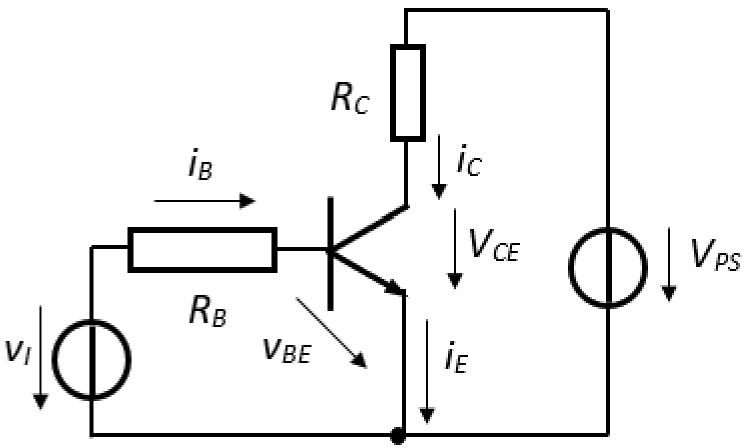
$$I_B = \frac{V_{CT} - V_{BE}}{R_B}$$

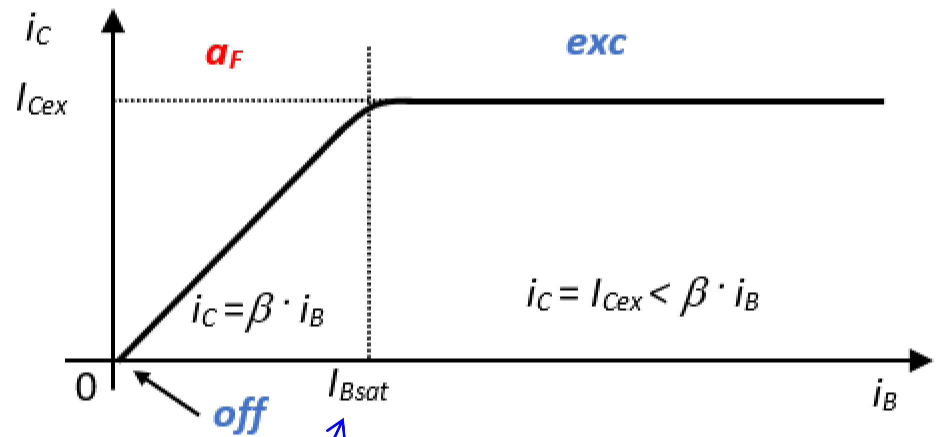
$$V_{CT} - I_E \cdot R_E - V_{BE} = 0$$

$$I_E = \frac{V_{CT} - V_{BE}}{R_E}$$

$V_{BE} \approx 0.6$ V

BJT saturation





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

$V_{CEsat} \approx 0.2$ V

Boundary (a_F) - (exc)

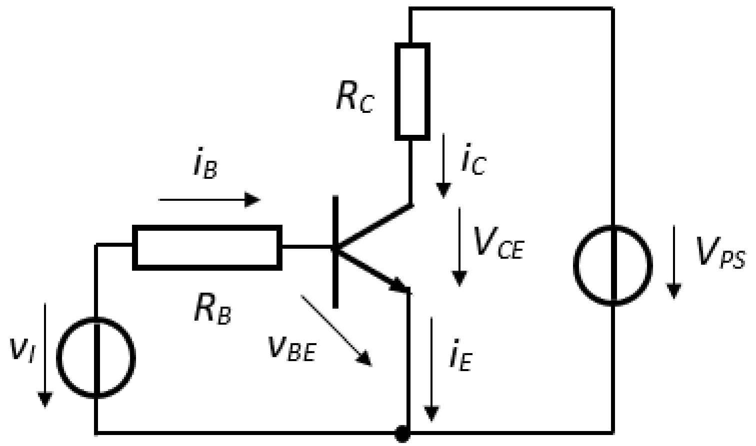
$$i_{Bsat} = \frac{i_{Cex}}{\beta}$$

- 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}

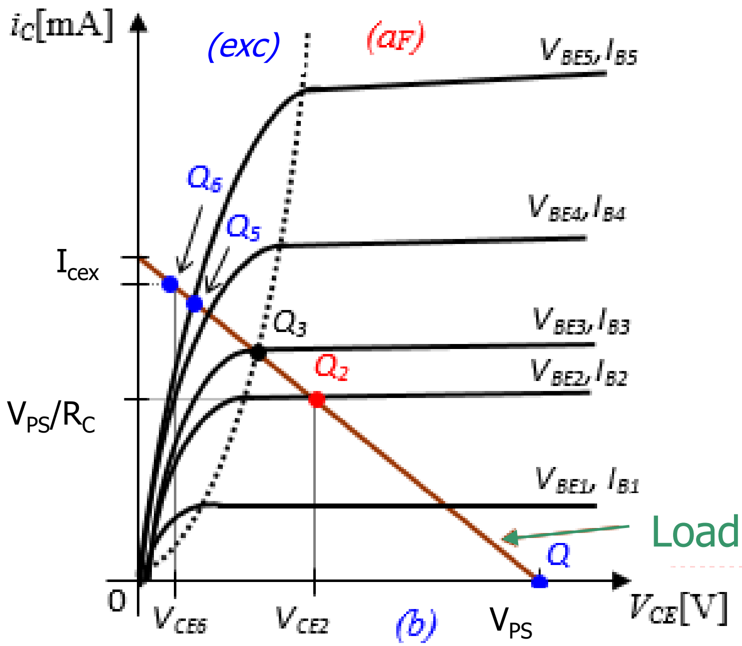


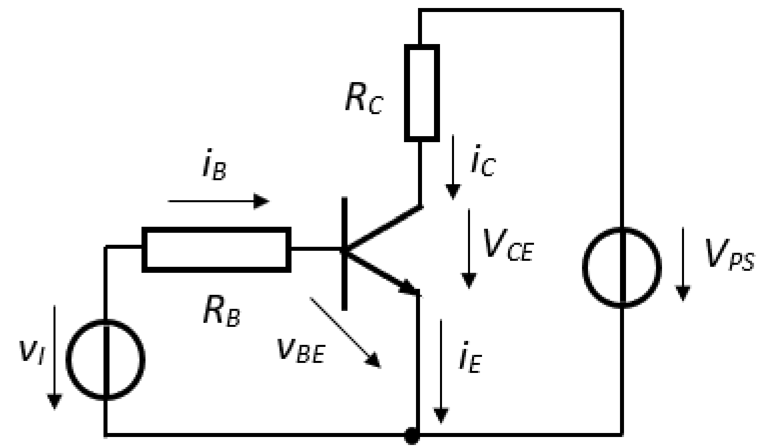
Load line:

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

Quiescent point of the BJT

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



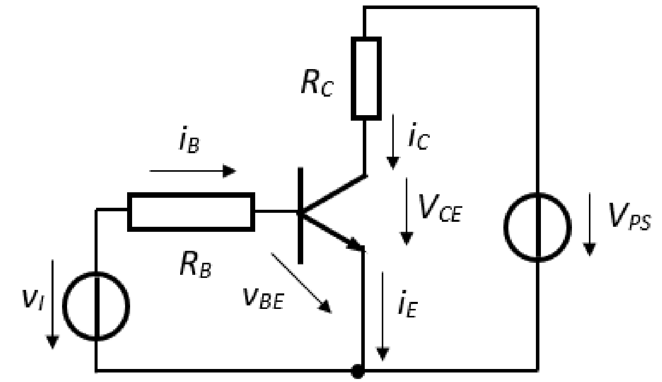


$Q_2(V_{CE2}, I_{C2})$

$$i_C = \beta i_B$$

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

Operating regions, npn BJT



- ***cutoff* (*off*),** BJT - open switch:

$$v_{BE} < V_{BE,on} \approx 0.6\ \text{V}$$
$$I_B = I_C = I_E = 0\ \text{mA}$$
$$V_{CE} = V_{PS}$$

- ***extreme conduction* or *saturation* (*exc*),** BJT - closed switch:

$$v_{BE} > V_{BEsat}$$

$$I_{Bsat} = \frac{I_{Cex}}{\beta};\ i_B > I_{Bsat}$$

$$I_C = I_{Cex} = \frac{V_{PS} - V_{CEsat}}{R}$$

$$v_{CE} = V_{CEsat} \approx 0.2\ \text{V}$$

- ***active forward* or *linear* (*a_F*)**, BJT - amplifier:

$$V_{BE,on} < v_{BE} < V_{BEsat}$$

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

$$i_C = \beta \cdot i_B$$

$$i_E = i_B + i_C = (\beta + 1) \cdot i_B$$

$$0\ \text{mA} < i_C < I_{Cex}$$

$$0.2\ \text{V} < V_{CE} < V_{PS}$$

➢ Example - 1

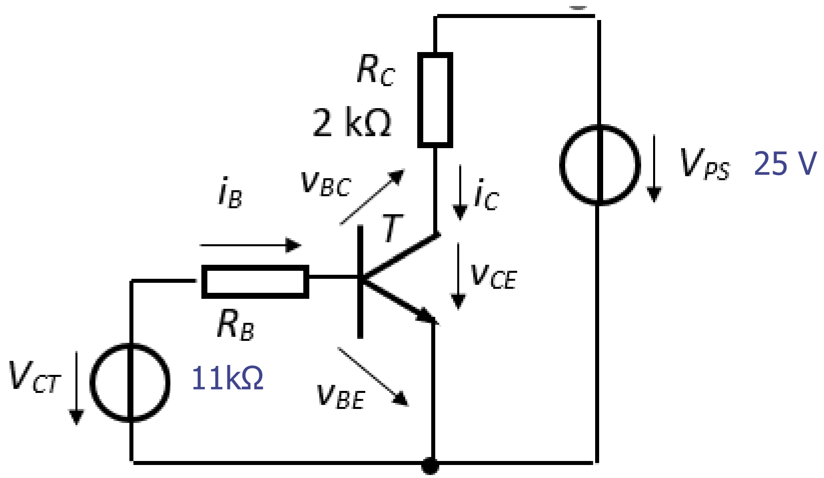
$\beta = 100, v_{BE,on} = 0.6$ V, $V_{CE,sat} = 0.2$ V

Find the operating region and compute $Q(V_{CE}, I_C)$ for:

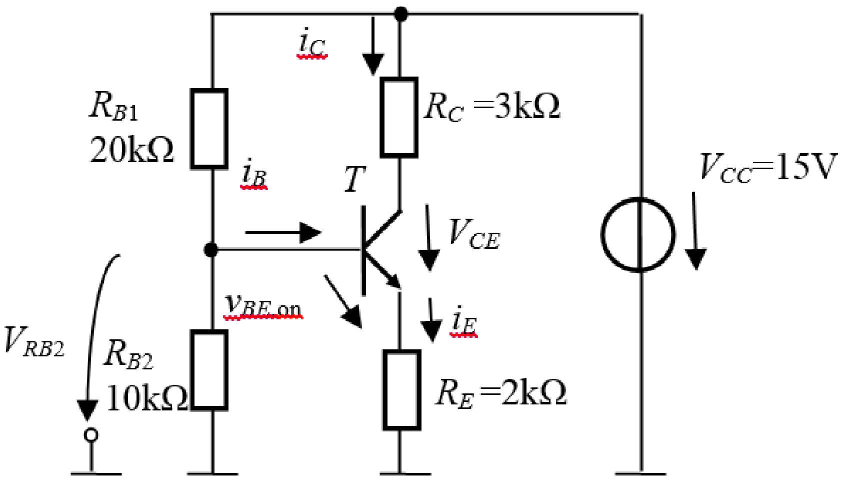
i) $V_{CT} = 0.4$ V;

ii) $V_{CT} = 1.7$ V;

iii) $V_{CT} = 5$ V



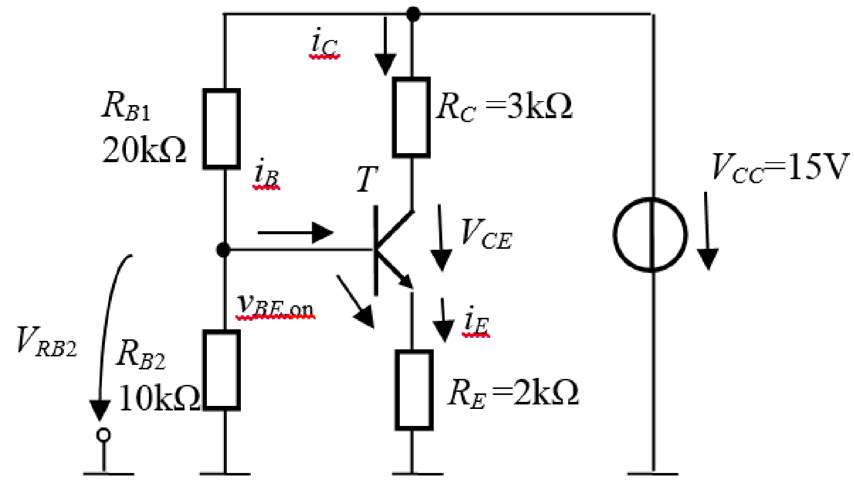
➢ Example - 2



$\beta = 100, v_{BE,on} = 0.7\ V, V_{CE,sat} = 0.2\ V$

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

➢ 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}

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

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

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

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

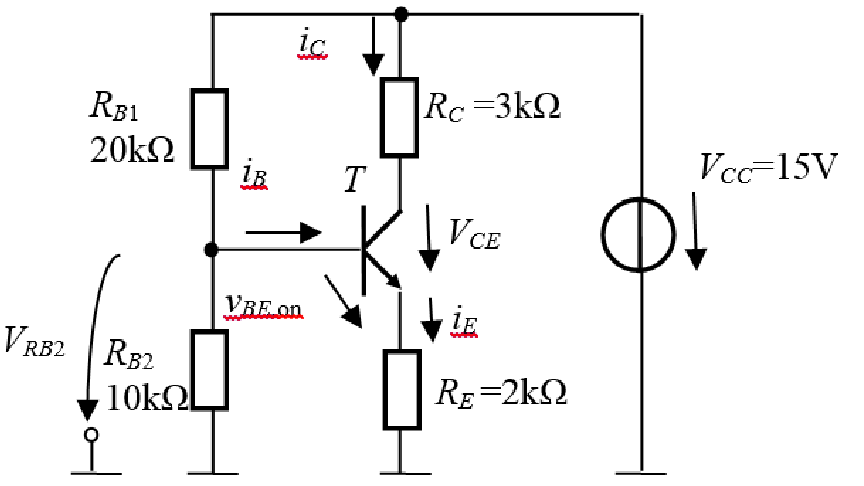
$$V_{RE} = 5 - 0.7 = 4.3V$$

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

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

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

➢ Example - 2



Solution:

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

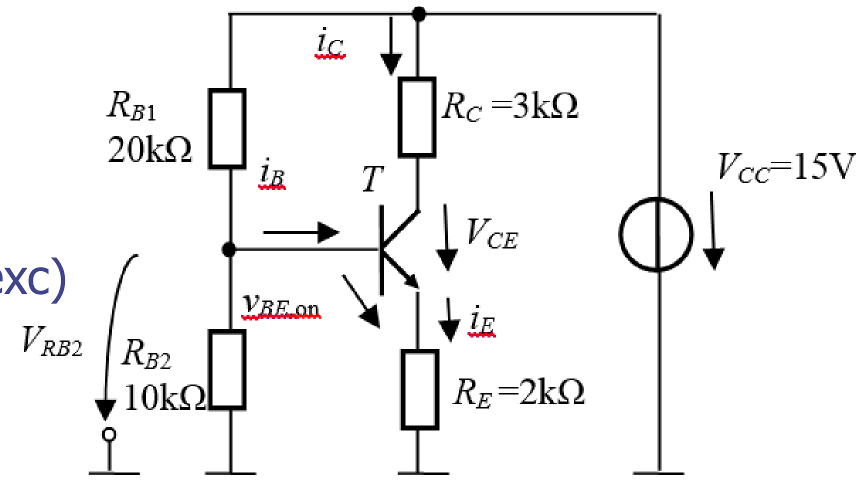
$$V_{CE} = V_{CC} - I_C \cdot (R_C + R_E)$$

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

$$V_{CE} = 4.25V$$

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)

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

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

2.15 mA < 2.96 mA $\Rightarrow$ T is in (a_F)

Summary

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

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

Next week: MOSFET operation