4-3 The Transistor

A transistor is a three terminal device whose i-v characteristics can change as a result of an input. We consider only one type of transistor here - the BJT or bipolar junction transistor.

\[
\begin{align*}
\text{i}_e &= \text{i}_b + \text{i}_c \\
\text{The transistor operates in three modes:} \\
\text{active:} & \quad \text{i}_c = \beta \text{i}_b \quad \text{v}_{BE} = \text{V}_Y \\
\text{cutoff (OFF):} & \quad \text{i}_b = 0 \quad \text{i}_c = 0 \\
\text{saturation (ON):} & \quad \text{v}_{CE} = 0 \quad \text{v}_{BE} = \text{V}_Y
\end{align*}
\]

Typical circuit

What are the operating bounds? \( 0 \leq \text{i}_c \leq \text{i}_{sc} \)

\[\text{v}_{cc} > \text{v}_{ce} \geq 0\]

1. This means that the current \( \text{i}_{c} \) can never be larger than \( \text{i}_{sc} = \frac{\text{v}_{cc}}{\text{R}_e} \), i.e., the CE junction is a short.

2. This also means that \( \text{v}_{CE} \) can never be larger than the open circuit voltage \( \text{v}_{cc} \) when \( \text{i}_c = 0 \).
Let's assume that the transistor is in the active mode where \( V_{BE} = V_Y \) and \( i_c = \beta i_B \).

KVL around the input loop:

\[-V_s + i_B R_B + V_{BE} = 0\]

Solving for \( i_B \) gives

\[i_B = \frac{V_s - V_Y}{R_B}\]

At the output

\[i_c = \beta i_B = \beta \left( \frac{V_s - V_Y}{R_B} \right)\]

If \( V_s > V_Y \) the device is in the active mode.

If \( V_s < V_Y \) the device is cutoff since \( i_c \) cannot become negative.

If we stay in the active region we can apply KVL to the output loop

\[-V_{CE} - i_c R_c + V_{CC} = 0\]

Solving for \( V_{CE} \):

\[V_{CE} = V_{CC} - i_c R_c\]

As the result for the active region.

As long as \( i_c < \frac{V_{CC}}{R_c} \) \( V_{CE} \) will be \( > 0 \).

When \( i_c > \frac{V_{CC}}{R_c} \) the device is at its short circuit limit and the transistor is saturated.

![Diagram showing the active region with labels for cutoff, active, and saturation.](attachment:diagram.png)
Example 4-9

Given that $\beta = 100$ and $V_Y = 0.7$ volts find $i_c$ and $V_{CE}$ for $V_S = 2$ volts and $V_S = 6$ volts.

Assume transistor is active. Then KVL at input and $i_c = \beta i_B$ give

$$-V_S + i_B R_B + V_Y = 0$$

$$i_B = \frac{V_S - V_Y}{R_B}$$

$$i_c = \beta i_B = \beta \left( \frac{V_S - V_Y}{R_B} \right)$$

Substituting values gives $(V_S = 2V)$

$$i_c = 100 \left( \frac{2 - 0.7}{100 \times 10^3} \right) = 1.3 \text{ mA}$$

This is greater than zero but is it more than available short circuit current?

$$i_{sc} = \frac{V_{CC}}{R_c} = \frac{5}{1 \times 10^3} = 5 \text{ mA} \Rightarrow \text{transistor is active}$$

Since transistor is active do KVL at output loop

$$-V_{CE} - i_c R_c + V_{CC} = 0$$

$$V_{CE} = V_{CC} - i_c R_c = 5 - (1.3 \times 10^{-3})(1 \times 10^3) = 3.7 \text{ volts}.$$

For $V_S = 6$ volts.

$$i_c = 100 \left( \frac{6 - 0.7}{100 \times 10^3} \right) = 5.3 \text{ mA}$$

This is more than the available short circuit current and the transistor $i_c$ stops at its saturation limits of $i_c = 5 \text{ mA}$, $V_{CE} = 0 \text{ volts}$. 
Example 4-11

Given that $\beta = 100$ and $V_T = 0.7$ volts find $R_B$ such that

1. $V_{CE} = 5$ volts when $V_S = 0$ volts
2. $V_{CE} = 0$ volts when $V_S = 5$ volts.

For condition 1, the transistor must be cutoff. This occurs whenever $V_S < V_T$ or $V_S < 0.7$ volts. and is independent of $R_B$.

For condition 2, the transistor must be saturated.

At input: $-V_S + i_B R_B + V_{BE} = 0$

$$i_B = \frac{V_S - V_{BE}}{R_B} = \frac{5 - 0.7}{R_B} = \frac{4.3}{R_B}$$

At output: $i_C = \beta i_B = 100 \left( \frac{4.3}{R_B} \right)$

For saturation $i_C > i_{SC} = \frac{V_{CC}}{R_C} = \frac{5}{1 \times 10^3} = 5mA$

$$100 \left( \frac{4.3}{R_B} \right) > 5 \times 10^{-3}$$

Solving gives $R_B \leq \frac{100 \times (4.3)}{5 \times 10^{-3}} = 86k\Omega$