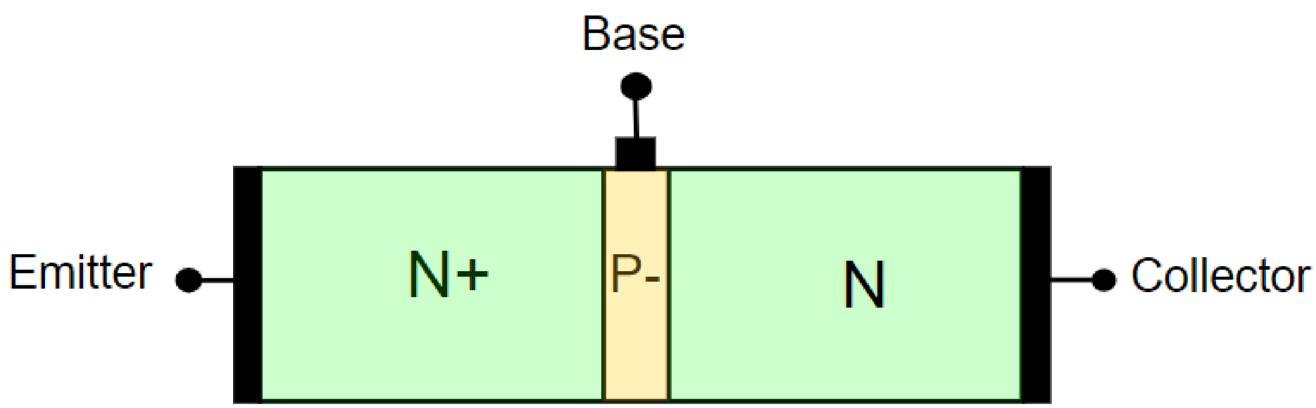
III: Bipolar Junction Transistors

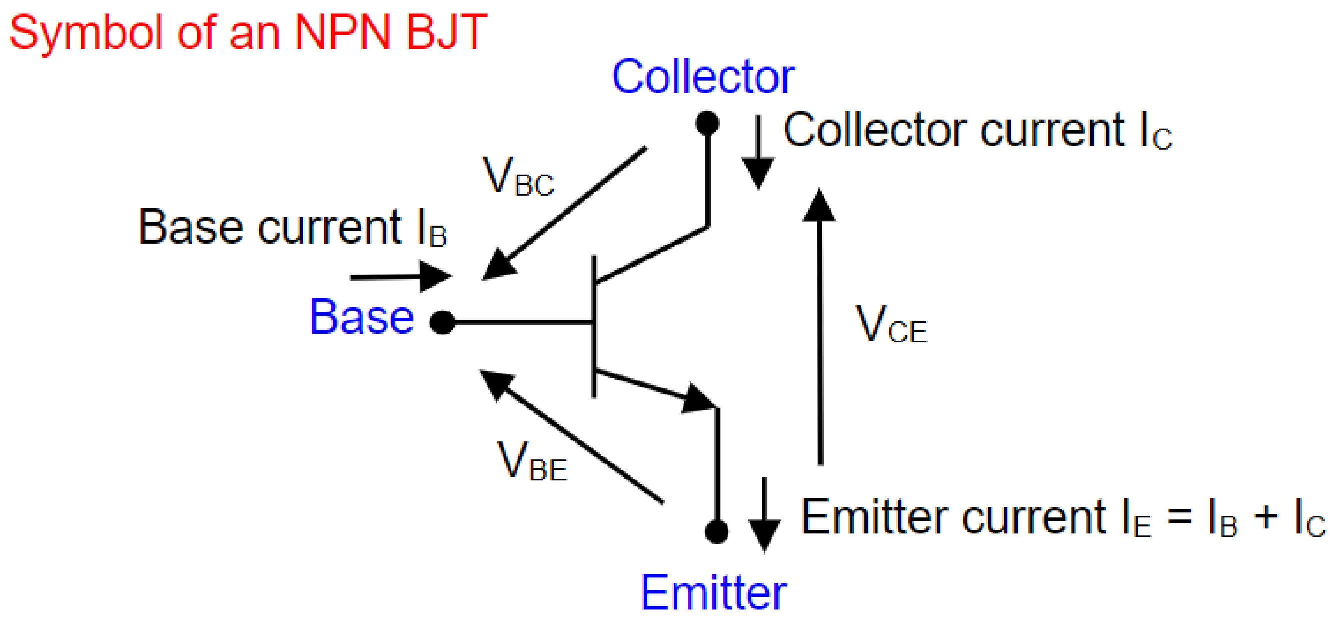
1: Basic operation

- An NPN BJT is a semiconductor device consisting a narrow P-type region which called the **base**, while the two N-type regions called the emitter and the collector.



- The N-type emitter is **heavily** doped (N+), where the P-type is lightly doped (P-). The N-type collector has a **moderate** doping.
- This is not a symmetrical structure.
- The transistor is an active device and it is mainly used as amplifier or electronic switch.
- We can also build the *PNP bipolar junction transistor*.

2: Symbol of NPN BJT

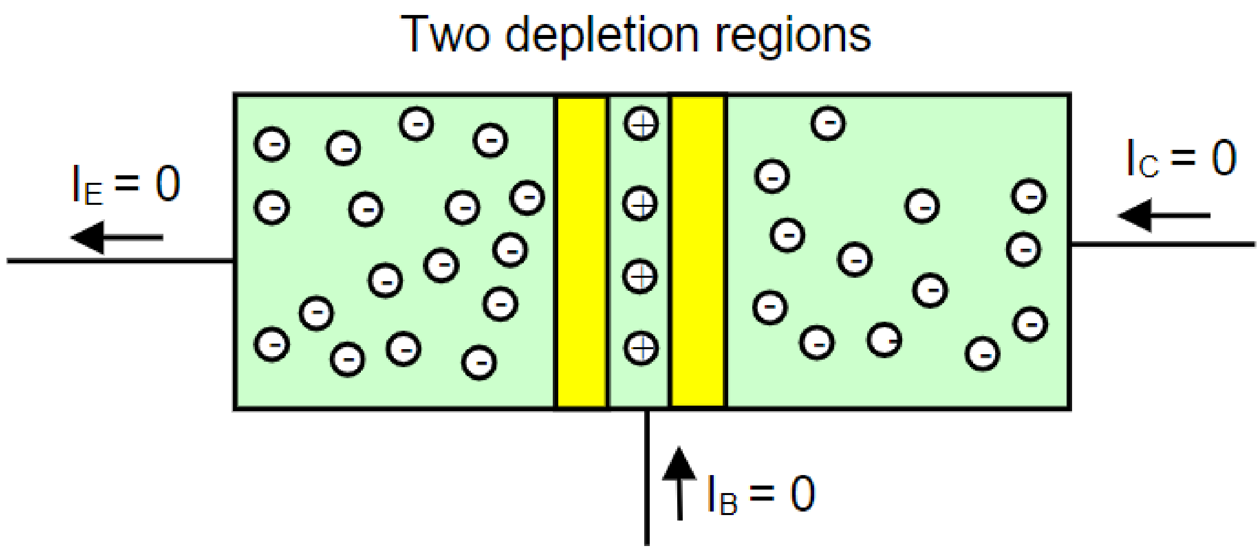


- In order to simplify the analysis, we assumed V_{CE} is greater or equal to zero as we always connects the collector to V_{CC} and connects the emitter to the ground.
- So the collector side have the high voltage and the emitter side have the low voltage side.
- As we always choose the as reference, V_{CE} can be written as $V_{CE} = V_{CB} + V_{BE} = V_{BE} - V_{BC}$

3: Four mode of operation

3.1: Cut-off mode, when both BE and BC diodes are off

- As the base-collector junction and base-emitter junction have same threshold voltage, so we mark it as $V_{BE,on}$.
- For a silicon BJT, we have $V_{BE.on}$~ 0.7 volts.



- As the existence of the two depletion region, carriers from both sides cannot enter the base,

$$I_B = 0, I_C = 0, I_E = 0$$

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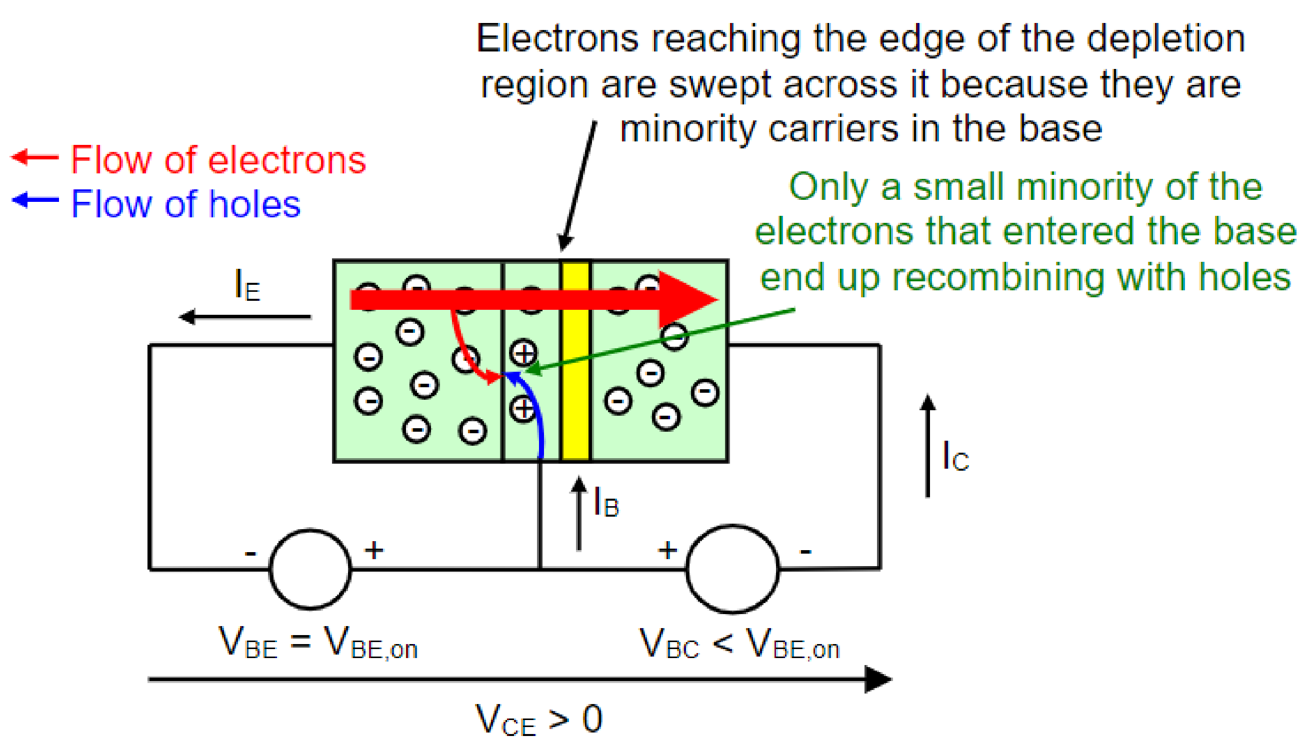
3.2: Forward-active mode, when the BE is on but BC is off

- The forward-active mode means $V_{BE} = V_{BE,on}$ and $V_{BC} < V_{BE,on}$.
- We can find that $V_{CE} > 0$ in this condition.



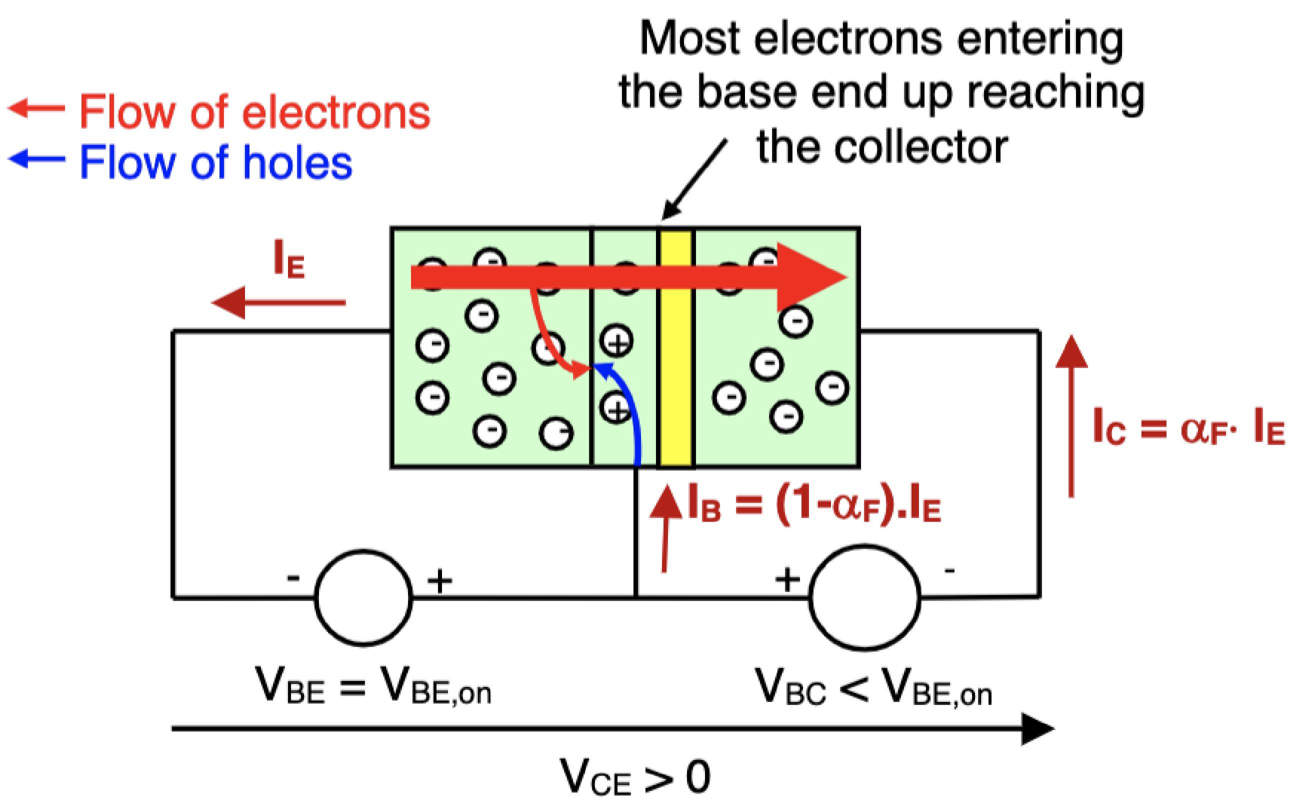
- As the electrons are minor carriers in base (lightly doped), only few electrons will combine with the holes in base.
- Most of the electrons from the emitters will across the base entering collector side.
- With the reverse-bias voltage, these electrons into the collector formed a collector current.
- Recalling the knowledge of the diode: **The depletion region cannot be crossed by majority carriers but the minority carriers.
- The plenty of electrons in BJT form the collector current.
- If we mark α_F as a constant parameter indicating the proportion of electrons coming form the emitters and reach the collector:

$$I_C = \alpha_F I_E$$
$$I_B = (1 - \alpha_F) I_E$$

- We typically have α 0.99.
- From the previous equations, we can find that:

$$I_C = \frac{\alpha_F}{1 - \alpha_F} I_B$$

- We notes $\beta_F = \frac{\alpha_F}{1-\alpha_F}$, which is called *forward current gain*.
- It shows the BJT can used as a linear current amplifier.

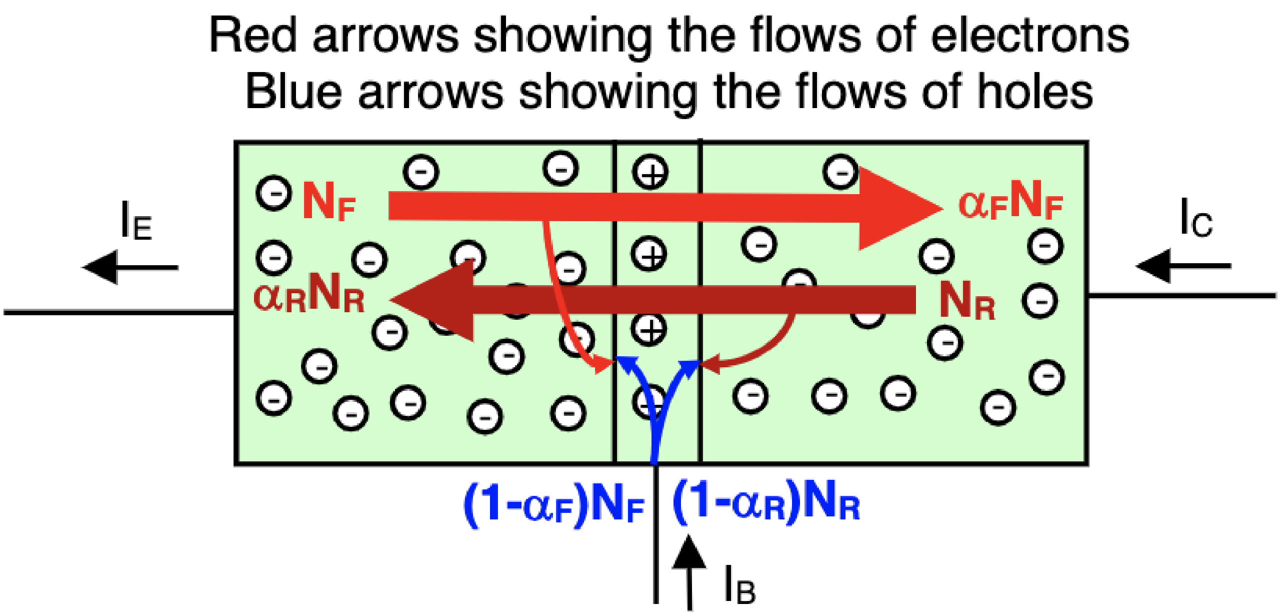


3.3: Reverse-active mode, when BE diode is off and BC is on

- If $V_{BE} < v_{BE,on}$ and $V_{BC} = V_{BE,on}$.
- If we take the emitter as a reference, since $V_{CE} = V_{BE} - V_{BC}$, we can get that $V_{CE} < 0$.
- $V_{CE} < 0$ is contradicted with the original assumption that $V_{CE} \geq 0$. So that BJT can never in this mode under this assumption.

3.4: Saturation mode, when both BE and BC diodes are on

- A BJT is said to be in saturation mode if $V_{BE} = V_{BE,on}$.
- $V_{BE} = V_{BE,on}$ and $V_{CE} = 0$.



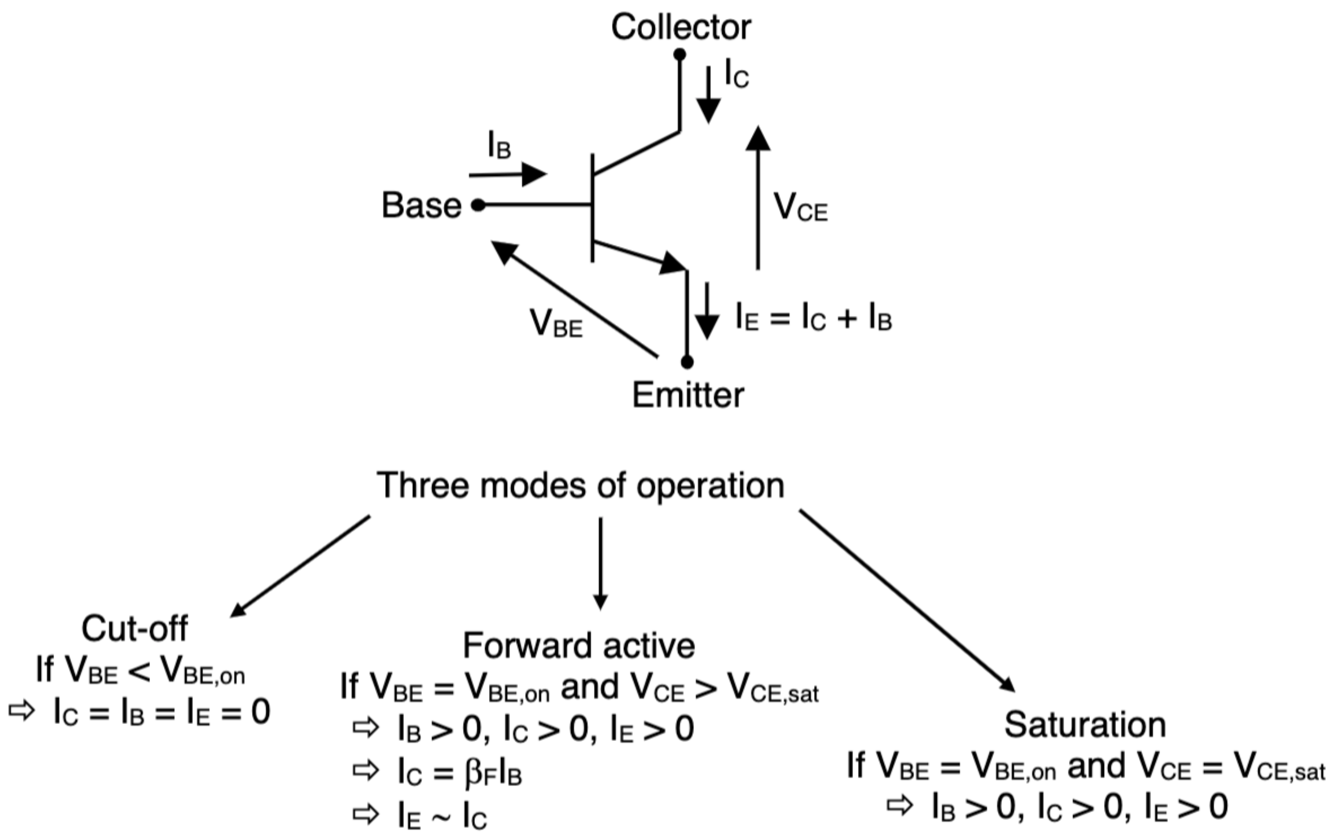
- There are two transistor effects to consider in this mode: a first one in forward direction and a second in the reverse mode.
- Note the forward effect is more powerful cause α_F 0.99 and α_R 0.5.
- Since the concentration of free electrons is higher in the emitter than in collector, it is much easier to diffuse in forward direction.

3.5: Summary

- Strictly speaking, the forward-active mode is defined as the mode for which the current in reverse direction are negligible compared to the forward current.
- In practice, V_{CE} is slightly greater than zero.
- So for the forward mode, the accurate statement should be "the BJT is forward active when $V_{BE} = V_{BE,on}$ and $V_{CE} > V_{CE,sat}$".
- Hereafter, we use $V_{CE,sat} = 0.2$ volts.

- For the saturated mode, the statement should be "the BJT is saturated when $V_{BE} = V_{BE,on}$ and $V_{CE} = V_{CE,sat}$".
- For simplicity sake, we take $V_{CE} = V_{CE,sat}$ in saturation mode instead of $V_{CE} < V_{CE,sat}$.

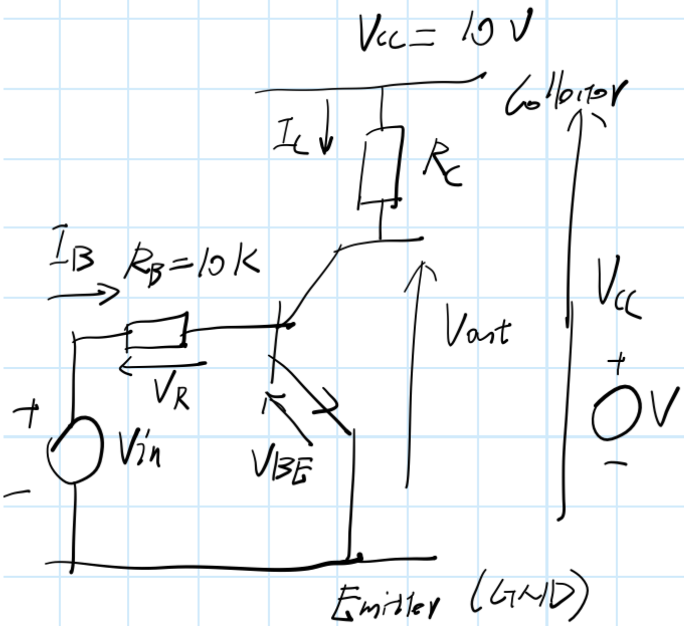
4: Summary about BJT



5: Application of BJT

5.1: Example_1

- According to the KVL and Ohm's Law, we can get the expression below:



$$V_{in} - V_{BE} - R_B I_B = 0$$

$$V_{CE} = V_{out}$$

$$V_{out} + R_C I_C - V_{CC} = 0$$

- If the BJT is in Cut-off mode:

① If it is Cut-off mode:

$$V_{BE} < V_{BE,on} \qquad I_B = I_C = I_E = 0$$

$$\Rightarrow V_{in} = V_{BE} \qquad V_{out} = V_{CC}$$

$$\therefore \boxed{V_{in} < V_{BE,on}, \quad V_{out} = V_{CC}}$$

- Forward-active mode:

② Forward - Active mode

$V_{BE} = V_{BE,on}$, $V_{CE} > V_{CE,sat}$

$I_C = \beta_F \cdot I_B$, $I_B > 0$ $I_E > 0$

$I_E = I_C + I_B$

$\Rightarrow V_{in} = V_{BE,on} + R_B I_B$

$\because I_B > 0$ $\therefore \frac{V_{in} - V_{BE,ON}}{R_B} > 0$

$\Rightarrow V_{in} > V_{BE,ON}$

$V_{CE} = V_{out} > V_{CE,sat}$

$\because V_{out} + R_C(\beta_F \cdot I_B) = V_{CC}$

$I_B > 0$

$\Rightarrow V_{out} < V_{CC}$

In summary,

$$\boxed{\begin{gathered} V_{CE,sat} < V_{out} < V_{CC} \\ V_{in} > V_{BE,ON} \end{gathered}}$$

$\because I_B = \frac{V_{in} - V_{BE,ON}}{R_B}$

$$\boxed{\begin{aligned} V_{out} &= V_{CC} - R_C \cdot \beta_F \cdot I_B \\ &= V_{CC} - R_C \cdot \beta_F \left(\frac{V_{in} - V_{BE,ON}}{R_B}\right) \\ &= \left(-\frac{R_C \beta_F}{R_B}\right) V_{in} + \left(\frac{R_C \beta_F}{R_B} V_{BE,ON} + V_{CC}\right) \end{aligned}}$$

which is Linear Relation between V_{in} and V_{out}

- Saturation mode:

③ Saturation Mode

$$V_{BE} = V_{BE,on} \qquad I_B > 0$$

$$I_E > 0$$

$$V_{CE} = V_{CE,sat} \qquad I_C > 0$$

$$\Rightarrow \boxed{V_{out} = V_{CE} = V_{CE,sat}}$$

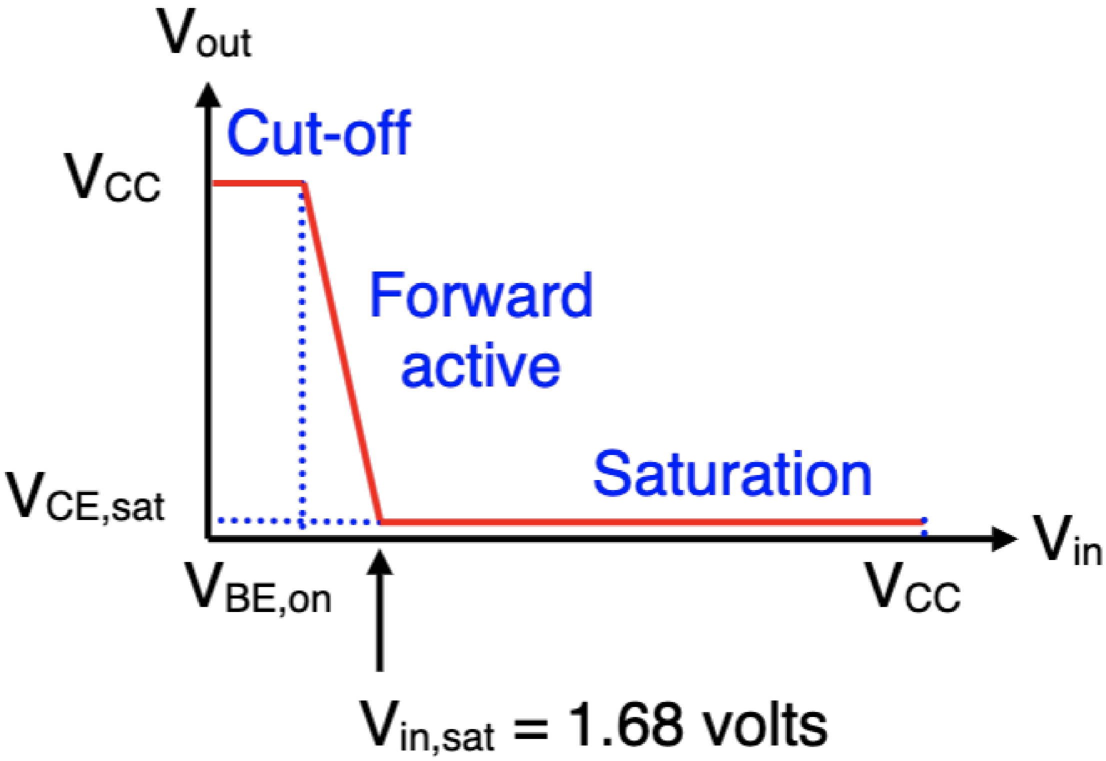
$$V_{BE} + R_B I_B = V_{in} \quad / \quad I_B > 0$$

$$\Rightarrow \quad V_{BE,on} < V_{in}$$

$$V_{out} + R_C I_C = V_{CC} \quad / \quad I_C > 0$$

$$\Rightarrow \quad V_{out} < V_{CC}$$

- Using the results above, we can get the curve below, which shows the function of V_{in} and V_{out}:



- This circuits can be used as an inverter (NOT gate) as it can invert the high volts to low and vice versa.
- The linear part of the graph can also be used as amplifier.
- As $V_{out} = V_{CC} = \beta_F \cdot \frac{R_C}{R_B} \cdot (V_{in} - V_{BE,on})$., we can defined the new input voltage as the increasing of the amount of ΔV_{in}: $V'_{in} = V_{in} + \Delta V_{in}$.
- The new output voltage V'_{out} due to V'_{in} is given by:

$$V'_{out} = V_{CC} - \beta_F \cdot \frac{R_c}{R_B} \cdot (V'_{in} - V_{BE,on}) - \beta_F \cdot \frac{R_C}{R_B} \cdot \Delta V_{in}$$

- So that we can find the increment:

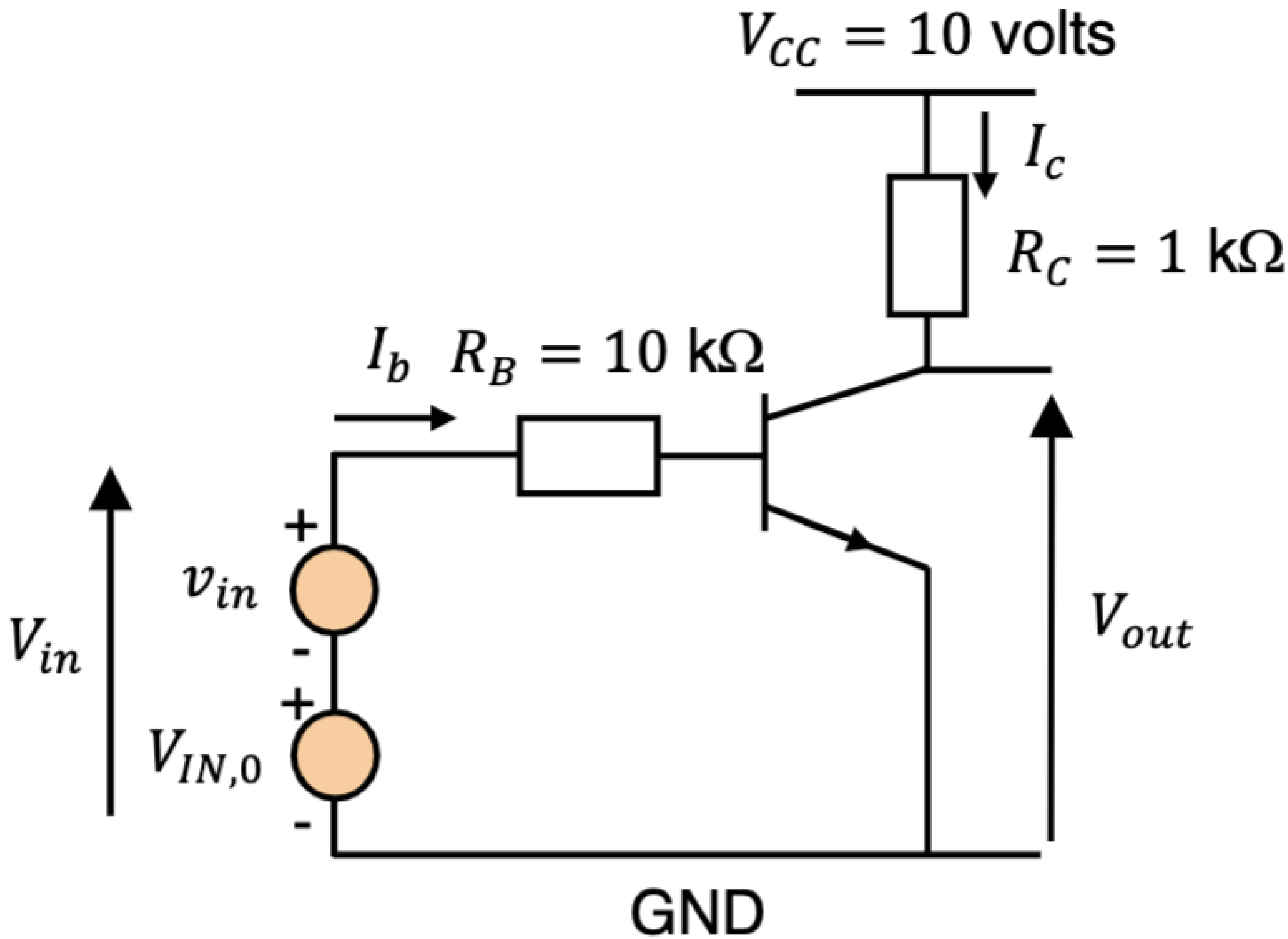
$$\Delta V_{out} = -\beta_F \cdot \frac{R_C}{R_B} \cdot \Delta V_{in}.$$

- This is the behaviour of a linear voltage amplifier with a voltage gain:

$$\frac{\Delta V_{out}}{\Delta V_{in}} = -\beta_F \cdot \frac{R_C}{R_B}$$

- Top make our circuit work as a practical linear amplifier, we have to make sure the BJT always in forward-active mode.

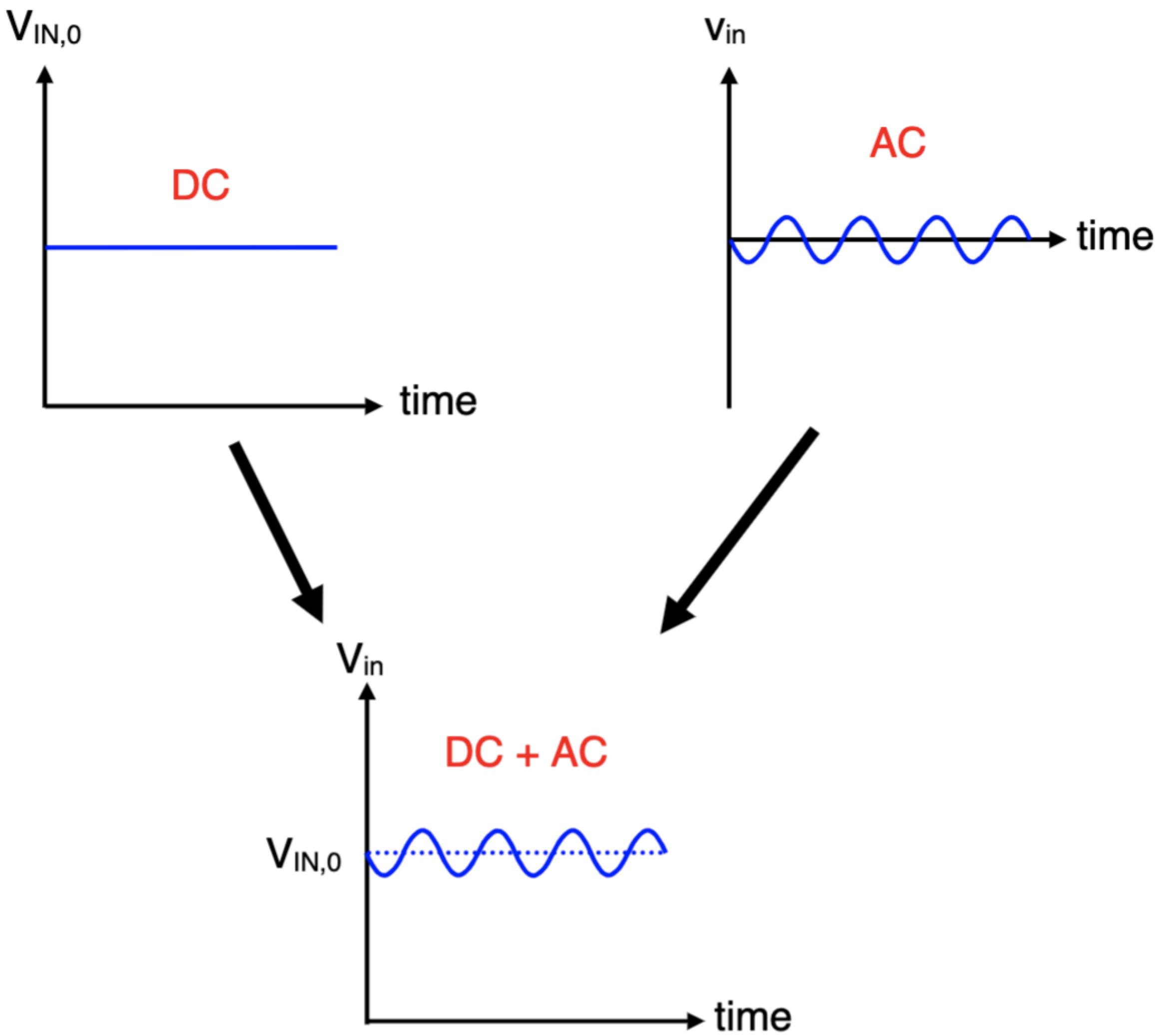
5.2: Example_2



- What we are going to do is add another DC voltage source $V_{IN,0}$ and AC source v_{in} to compose the V_{in}:

$$V_{in} = V_{IN,0} + v_{in}$$

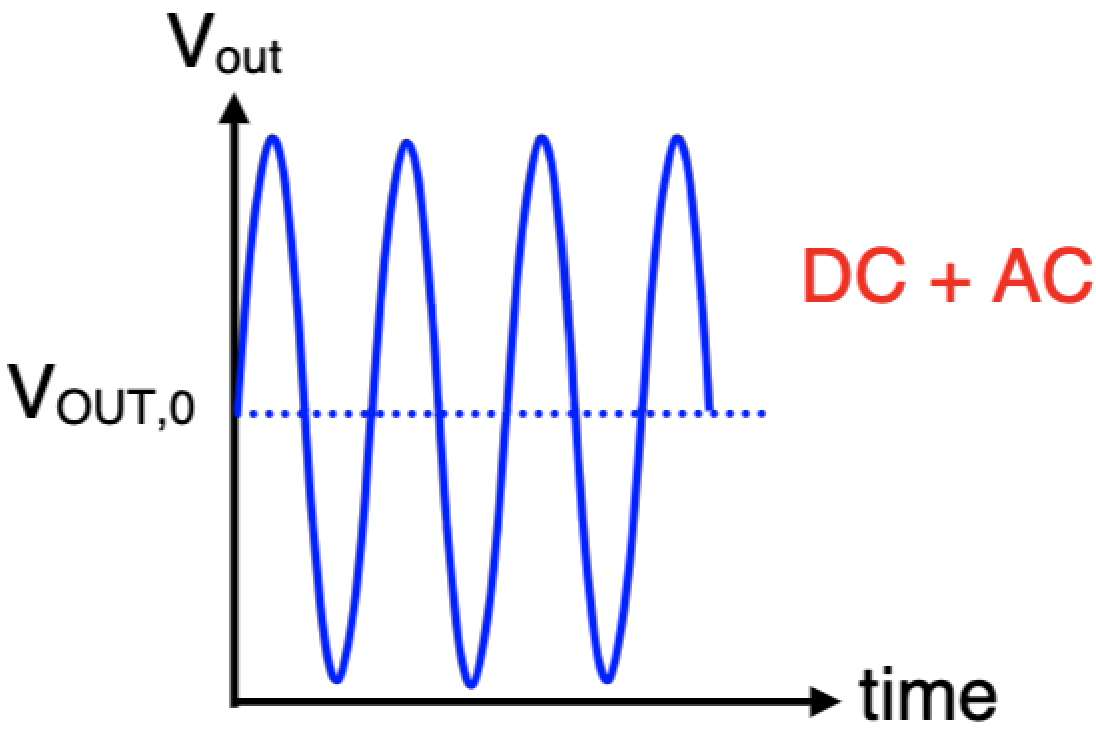
- The DC voltage source $V_{IN,0}$ is used to bias the circuit so that forward-active mode can remain, so the $V_{IN,0} often referred as the **bias voltage**.



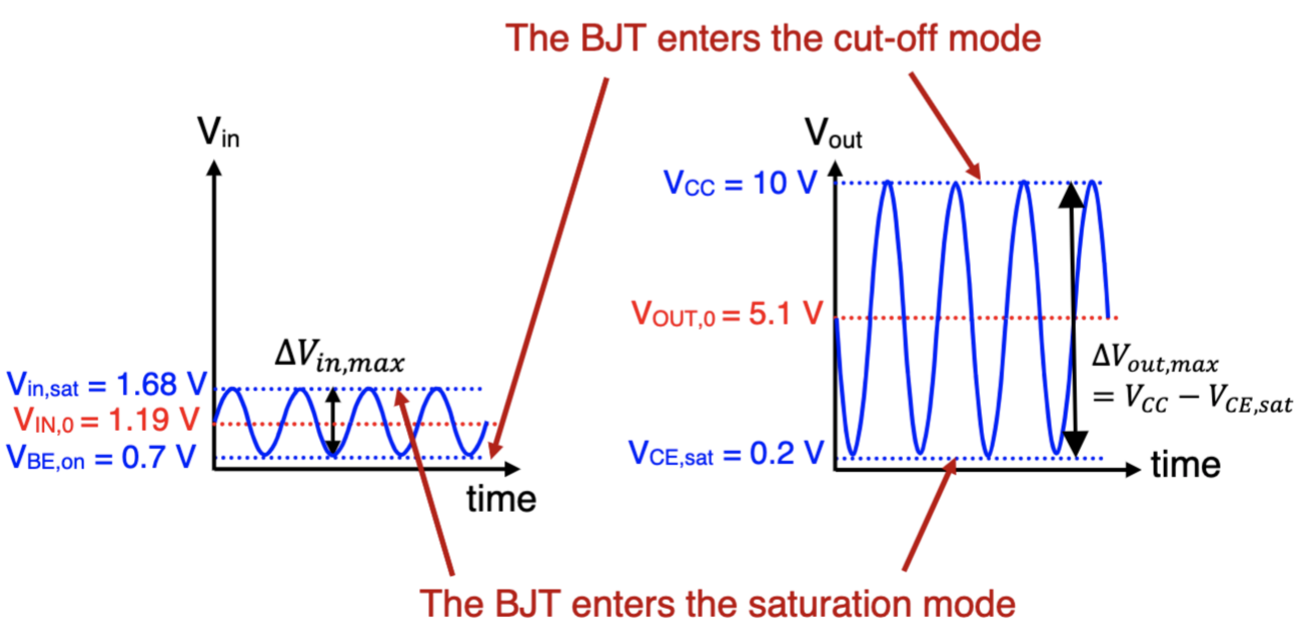
- If we replace V_{in} by $V_{in} = V_{ON,0} + v_{in}$:

$$\begin{aligned} V_{out} &= V_{CC} - \beta_F \cdot \frac{R_C}{R_B} \cdot (V_{IN,0} - V_{BE,on}) - \beta_F \cdot \frac{R_C}{R_B} \cdot v_{in} \\ &= V_{OUT,0} + v_{out} \end{aligned}$$

- $V_{out,0}$ is the DC components of the output.
- v_{out} is the AC signal.
- The '0' means the AC signal swings around zero as mean value:



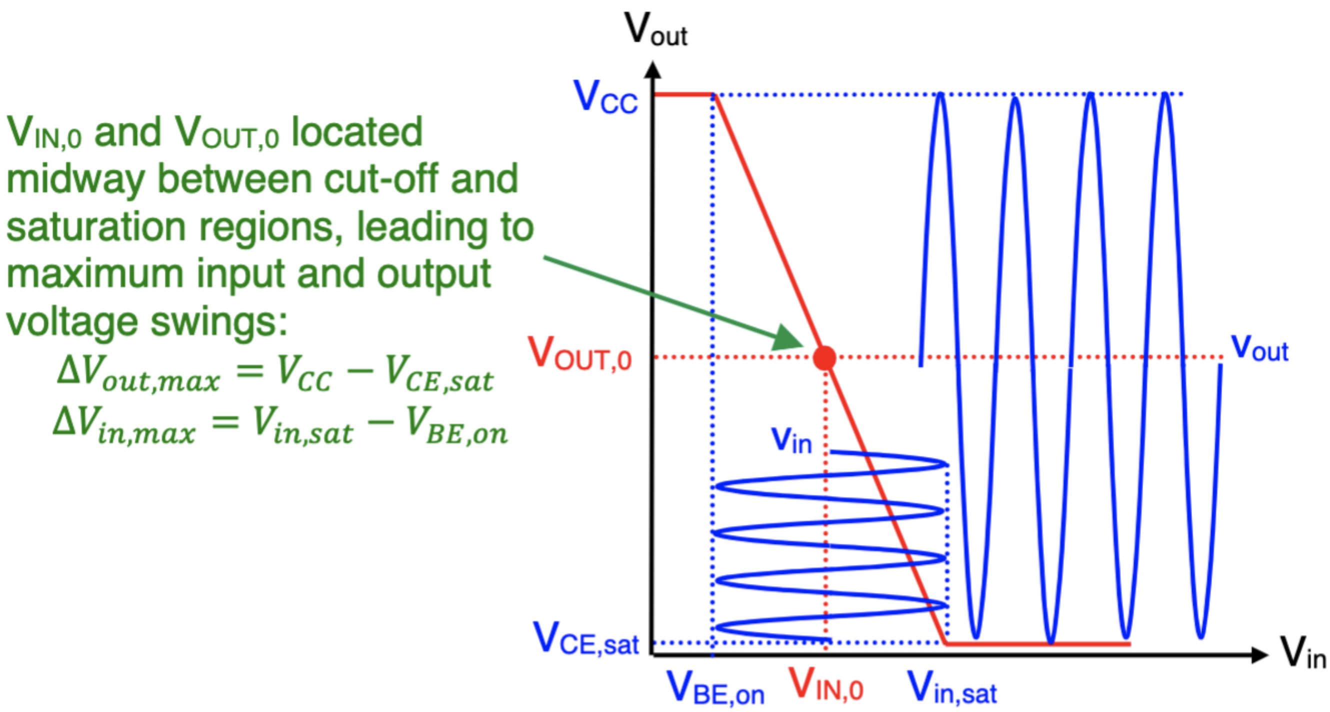
- The DC voltage $V_{IN,0}$ and $V_{OUT,0}$ are the *bias voltages*.
- To design the value of bias voltages, we need know the **maximum output voltage swing,** $\Delta V_{out,max}$, which is the maximum peak-to-peak amplitude of the AC output voltages v_{out} that make sure no distortion. The same for v_{in}.
- We can see the effective voltage swing from the graph below:



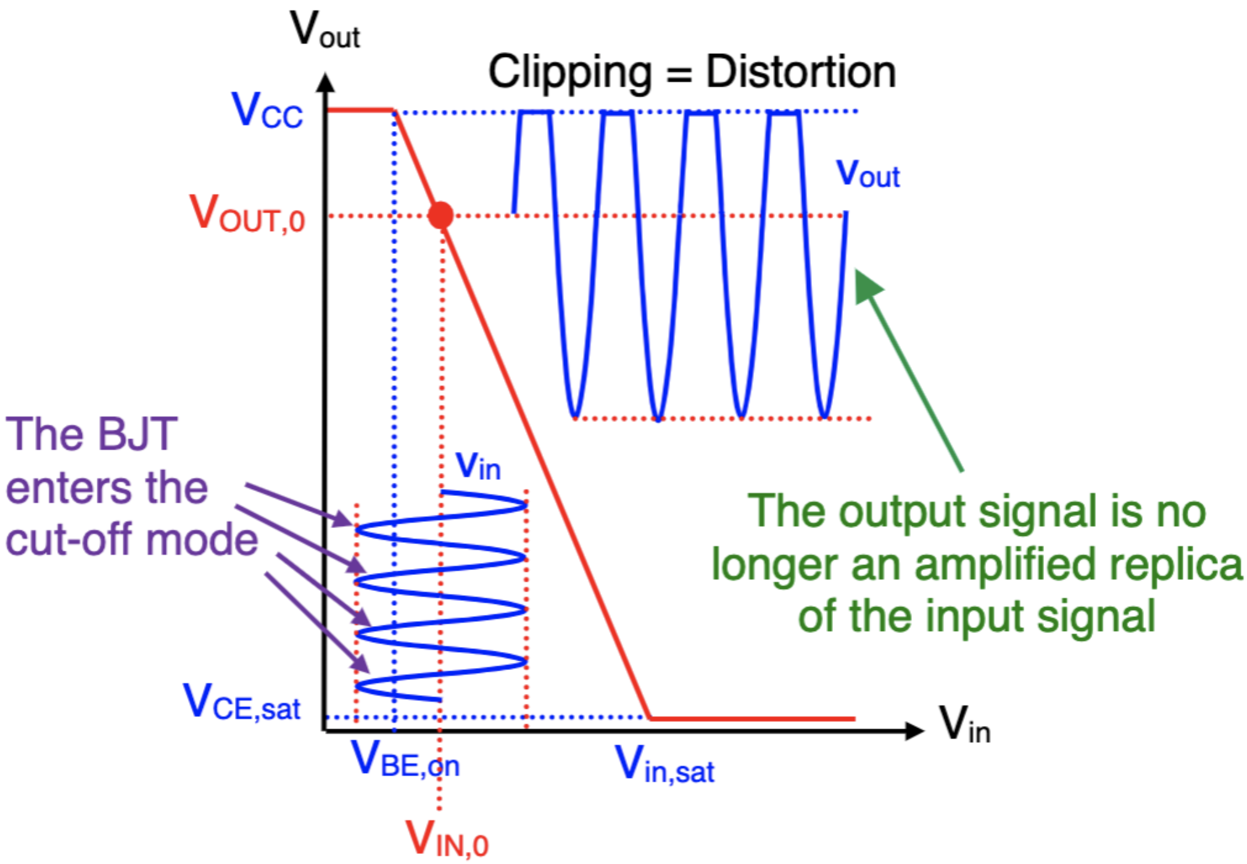
- In this circuit, in order to maximum the maximum output voltage swing, we have to ensure that $V_{OUT,0}$ is located at the midway of the V_{CC} and $V_{CE,sat}$:

$$V_{OUT,0} = \frac{V_{CC} + V_{CE,sat}}{2}$$

- Same for the $V_{IN,0}$.
- The final result will be:



- For the bad choose of bias voltages, distortion (clipping) will occur:



Clipping = Distortion
Vout
VCC
VOUT,0
vout
The BJT enters the cut-off mode
vin
The output signal is no longer an amplified replica of the input signal
VCE,sat
Vin
VBE,on
Vin,sat
VIN,0