CSE251: Electronic Devices and Circuits

Lecture: 20 - 22 – BJT

Prepared By:

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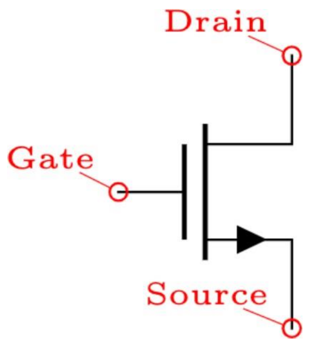
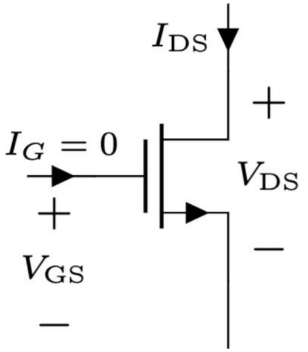
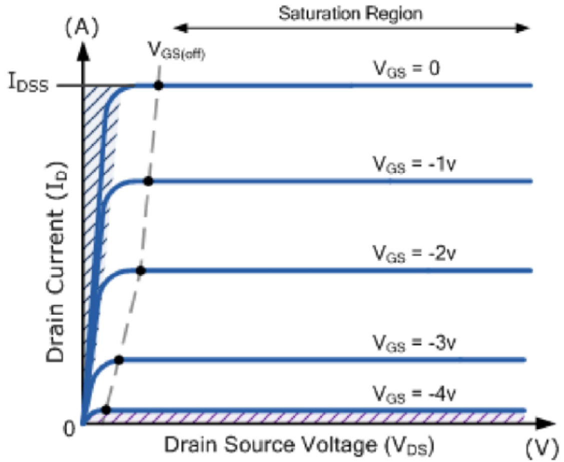
Transistors as Digital Switch

- Transistors are 3 terminal non-linear devices, can be used as switch
- 2 types – **Voltage Controlled**, **Current Controlled**
- **M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor (**MOSFET**) are voltage controlled
- Control, $\boldsymbol{C} = \boldsymbol{V_{GS}}$. The IV characteristics ($\boldsymbol{I_{DS}}$ vs $\boldsymbol{V_{DS}}$) depends on $\boldsymbol{V_{GS}}$
- Actual dependency is complex.
- Will start with a simple (but approximate) one – **S-Model** (Switch Model)

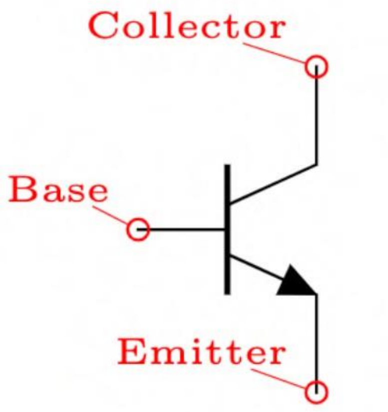


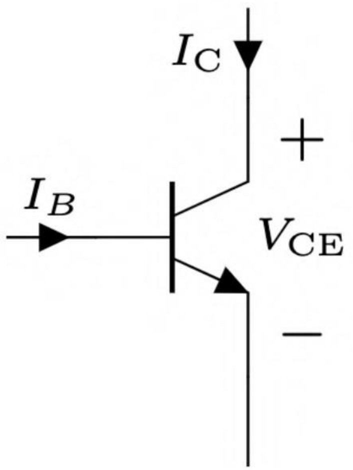


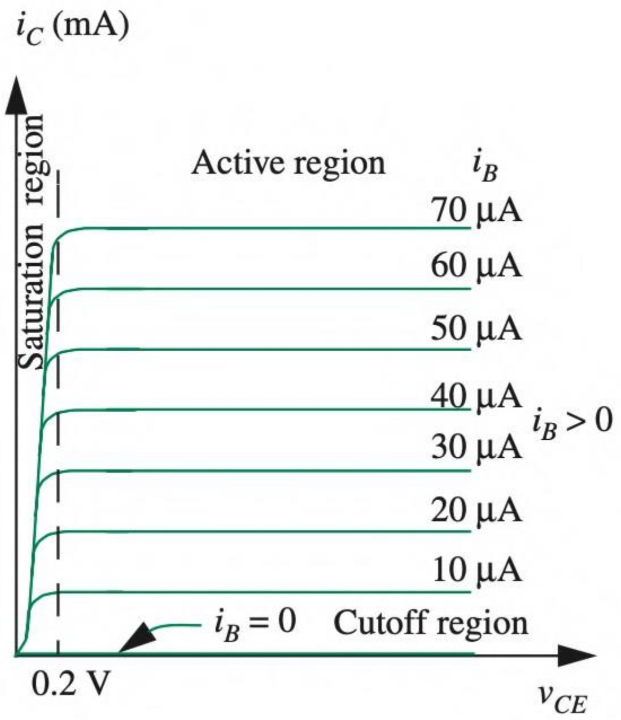


Bipolar Junction Transistor

- **Current-controlled** transistor, 3 terminals – Base, Emitter, Collector
- IV between C and E $(I_C\ vs\ V_{CE})$ is controlled by base current, $\boldsymbol{I_B}$
- IV is quite like MOSFET, but there are some differences
- We can use a S-model here too, but controlled by $\boldsymbol{I_B}$ (instead of $\boldsymbol{V_{GS}}$)

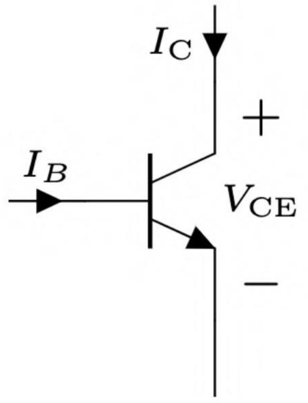






BJT vs MOSFET - Differences

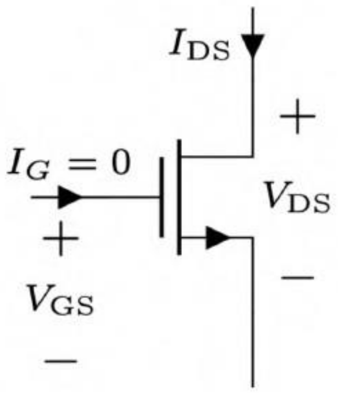
BJT



Current controlled, $\boldsymbol{I_B}$ controls ($\boldsymbol{I_C}$ vs $\boldsymbol{V_{CE}}$)

Base current, $\boldsymbol{I_B}$, is the control. Hence $I_E \neq I_C$, rather $\boldsymbol{I_E = I_C + I_B}$

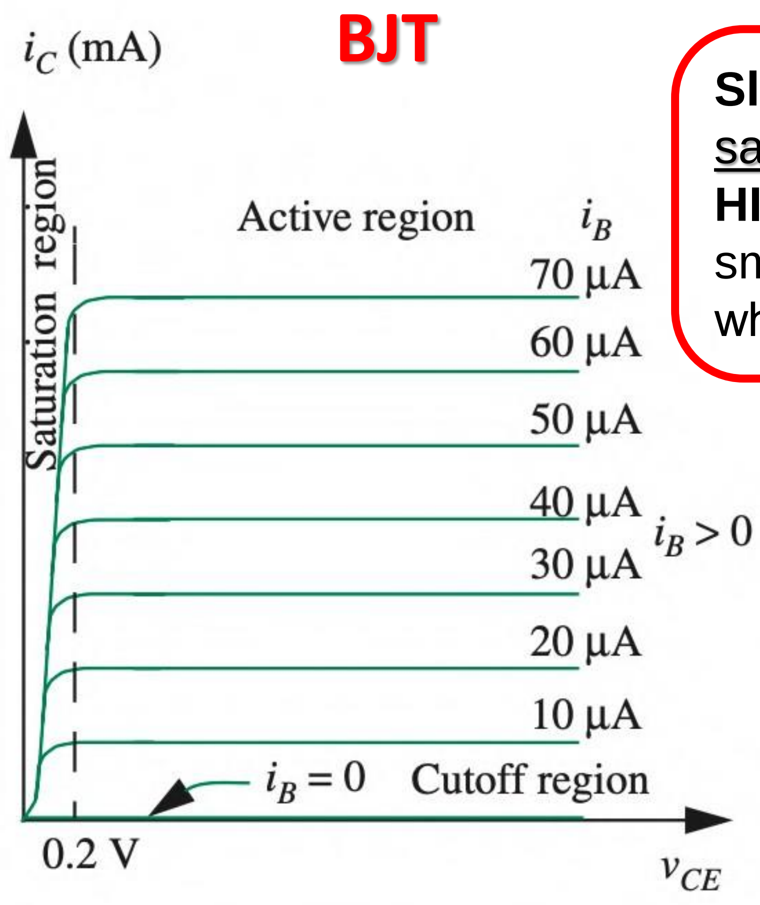
MOSFET



Voltage controlled, $\boldsymbol{V_{GS}}$ controls ($\boldsymbol{I_{DS}}$ vs $\boldsymbol{V_{DS}}$)

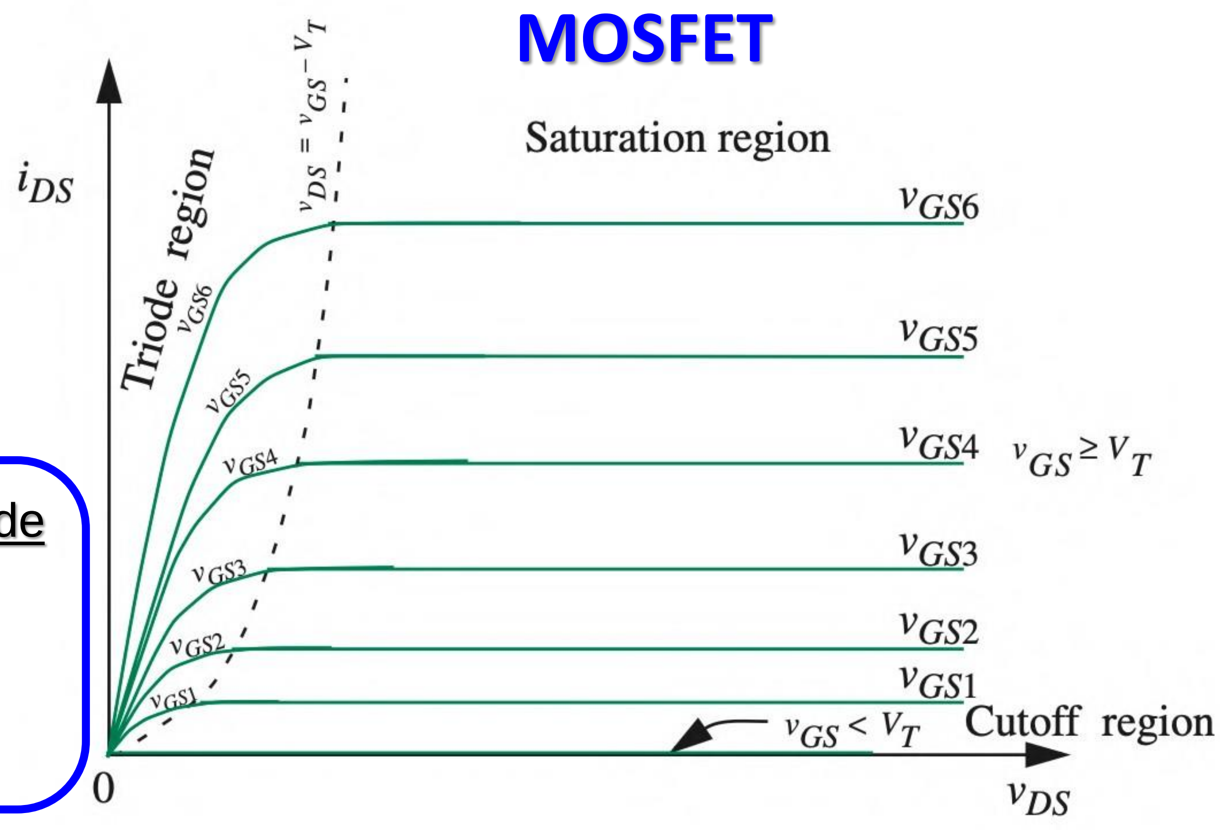
Gate current, $\boldsymbol{I_G}$, is always $\mathbf{0}$. Hence $I_S = I_D = I_{DS}$.

BJT vs MOSFET - Differences



Slope in the saturation region is **HIGH**, hence very small resistance when "**ON**"

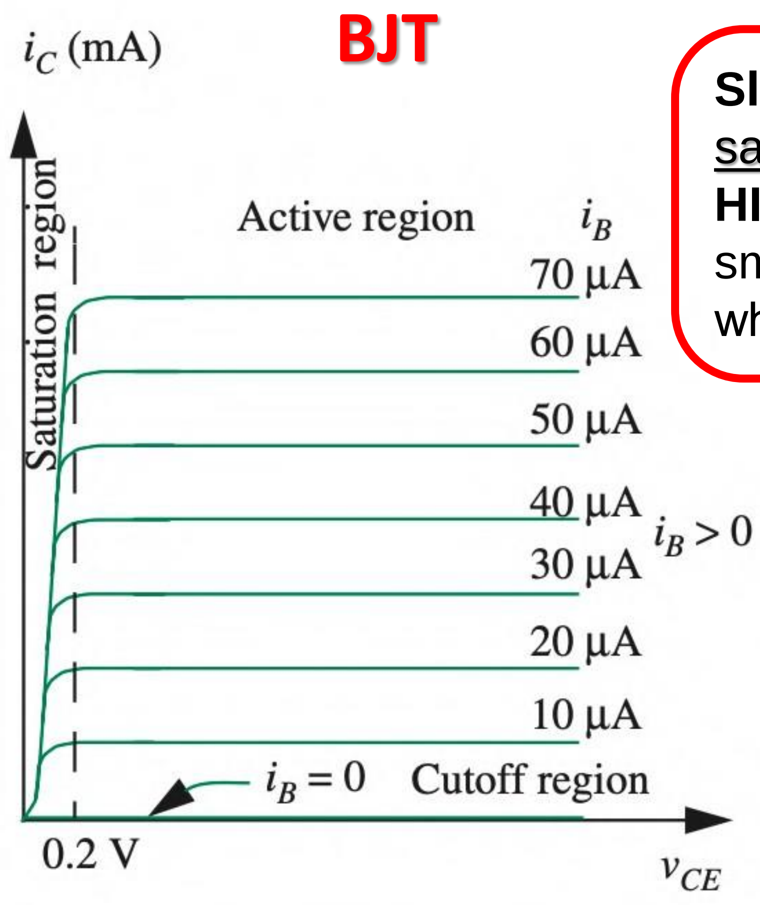
Slope in the Triode region is **LOW**, hence significant resistance when "**ON**"



Current in **active** region changes linearly with control $\boldsymbol{I_B}$.
Hence, $\boldsymbol{I_C \propto I_B}$

Current in **Saturation** region changes quadratically with control $\boldsymbol{V_{GS}}$.
Hence, $\boldsymbol{I_{DS} \propto V_{GS}^2}$

BJT vs MOSFET - Differences



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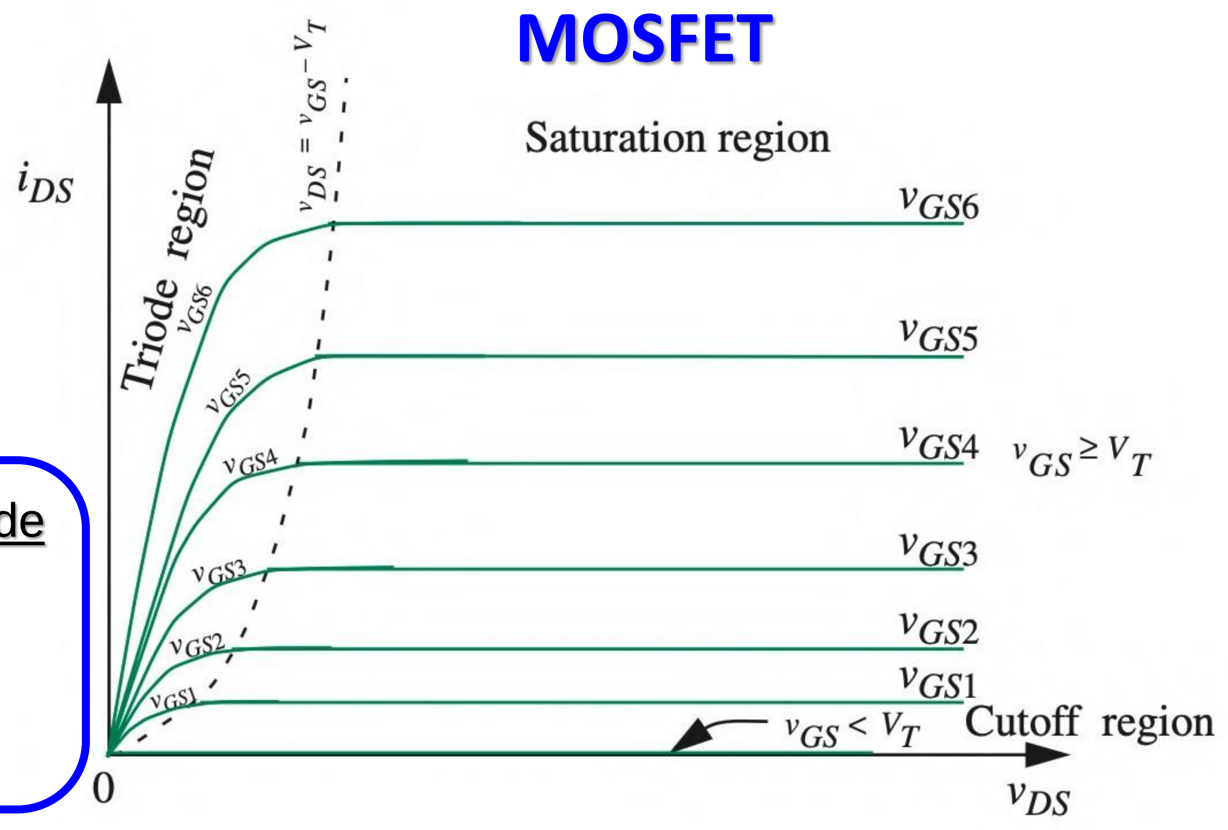

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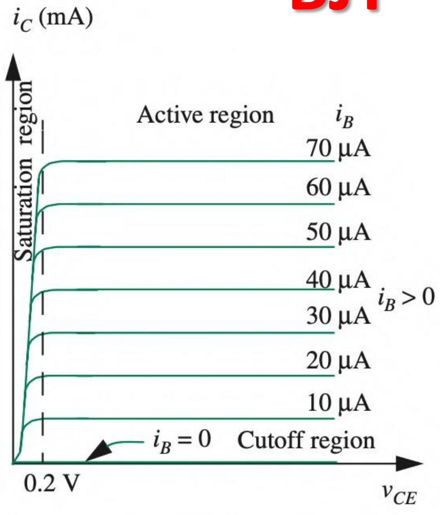
Hence, $\boldsymbol{I_C \propto I_B}$

Current in **Saturation** region changes quadratically with control $\boldsymbol{V_{GS}}$.
Hence, $\boldsymbol{I_{DS} \propto V_{GS}^2}$

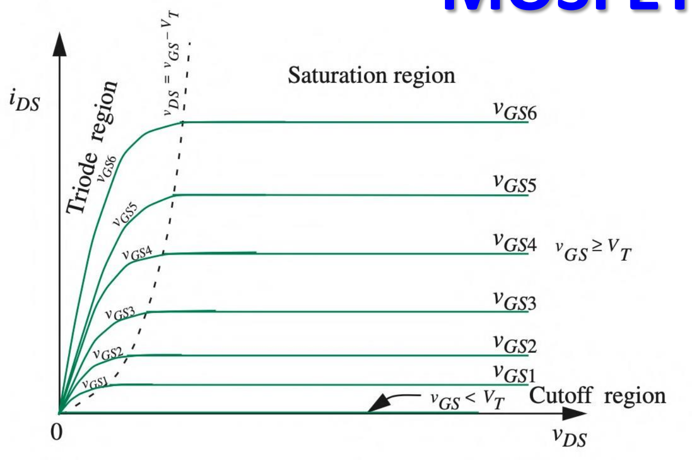
BJT vs MOSFET - Similarities

BJT



- **Saturation** mode for small $V_{CE} (< 0.2\ \mathrm{V})$
- Approximately Short circuit in **Saturation** mode (I_B **HIGH**)
- Open circuit in **Cutoff** mode ($I_B = 0$)
- Can use as a switch ⇒ S-Model!

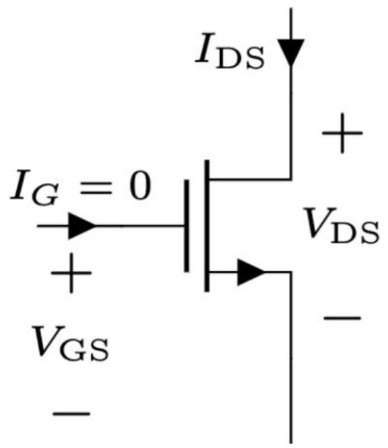
MOSFET

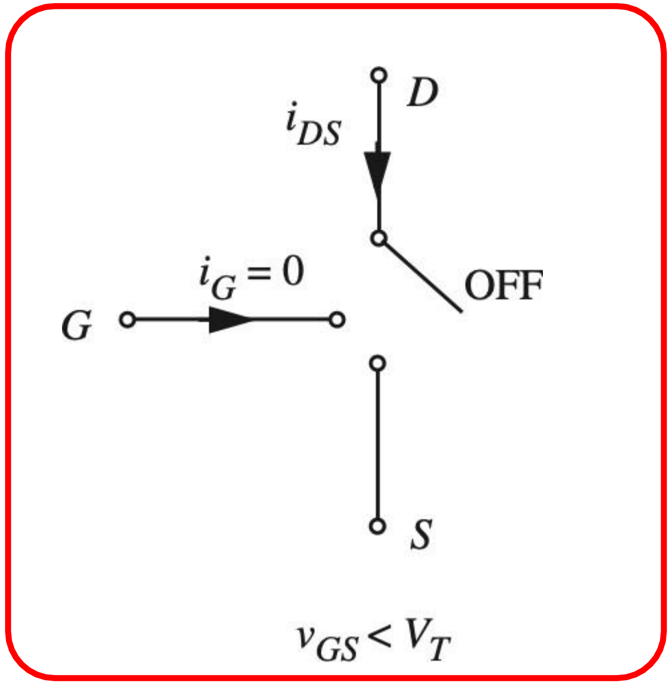


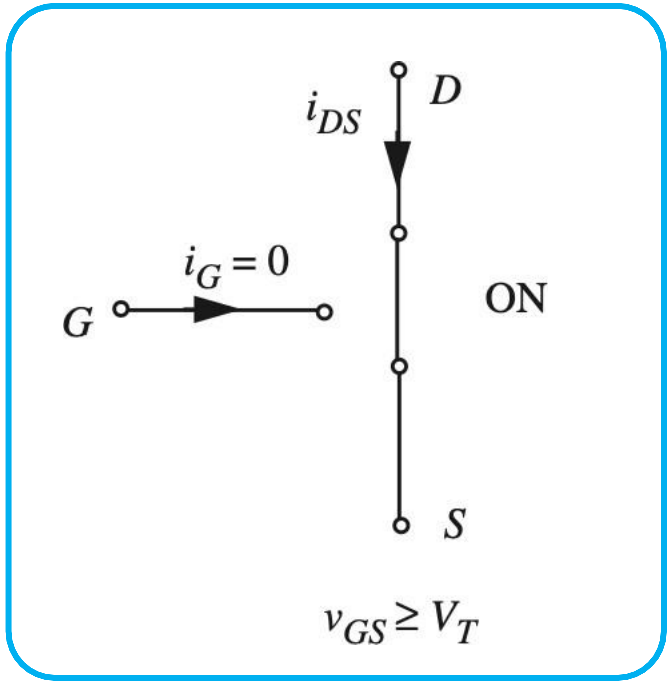
- **Triode** mode for small $V_{DS} (< V_{OV})$
- Approximately Short circuit in **Triode** mode (V_{GS} **HIGH**)
- Open circuit in **Cutoff** mode $\boldsymbol{(V_{GS} < V_T = 0)}$
- Can use as a switch ⇒ S-Model!

MOSFET S-Model

- The MOSFET (approximately) behaves like a switch
- C = V_{GS}. Here, $C = \text{“0”} \Rightarrow \boldsymbol{V_{GS} < V_T}$, and $C = \text{“1”} \Rightarrow \boldsymbol{V_{GS} > V_T}$



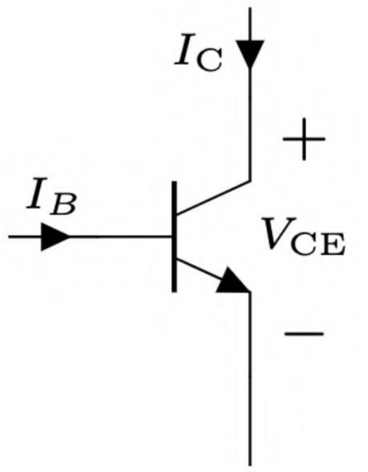


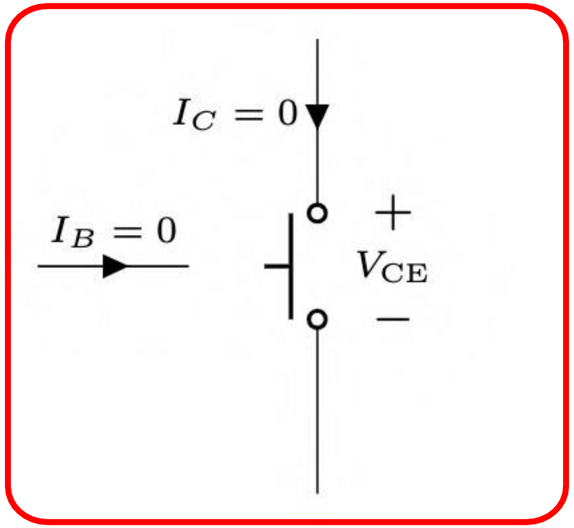


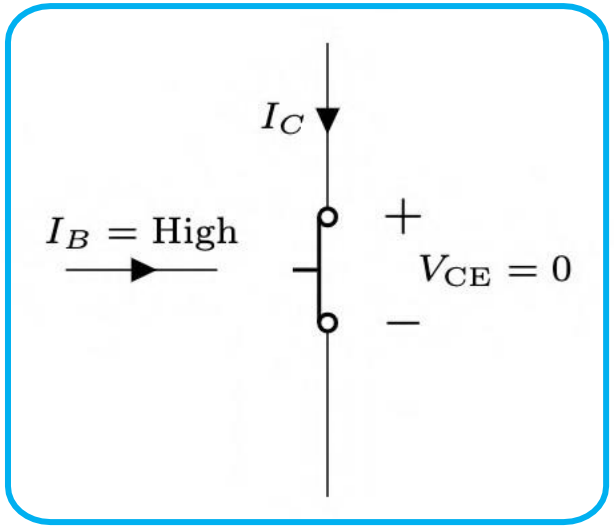
BJT S-Model

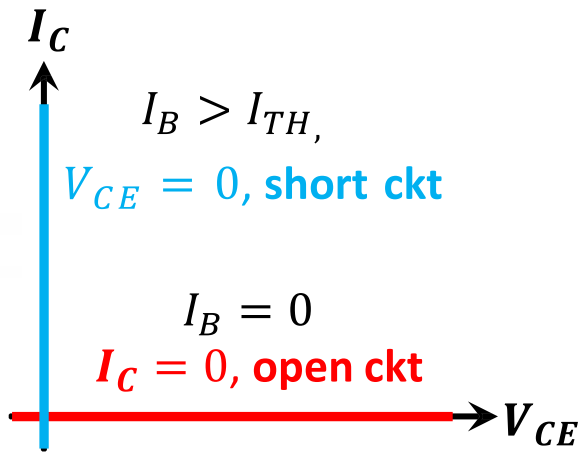
	Representation
Logic 0	$\boldsymbol{I_B = 0}$
Logic 1	$\boldsymbol{I_B > I_{TH}, I_B = HIGH}$

- The BJT (approximately) behaves like a switch
- C $= I_B$. Here, $C = \text{“0”} \Rightarrow \boldsymbol{I_B = 0}$, and $C = \text{“1”} \Rightarrow \boldsymbol{I_B > I_{TH}}$



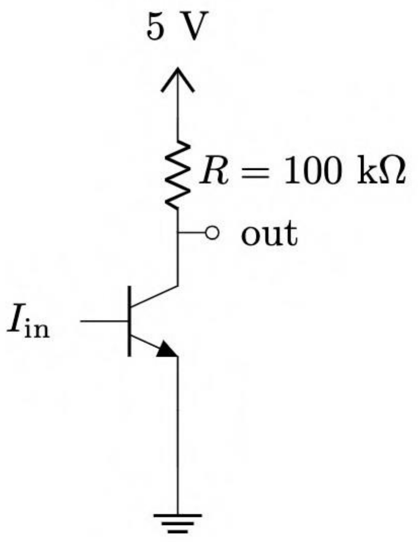




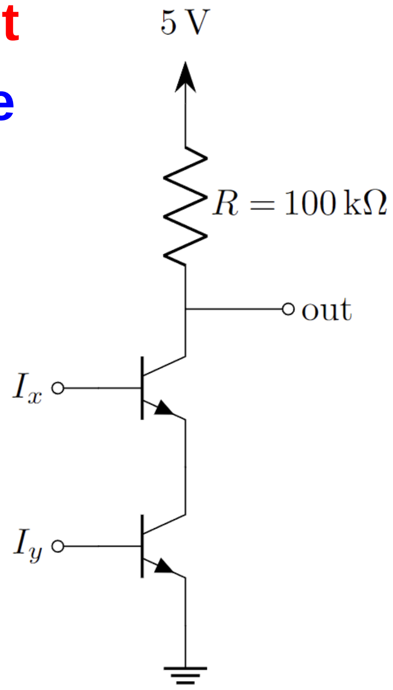


Current-Controlled Logic Gates using BJT

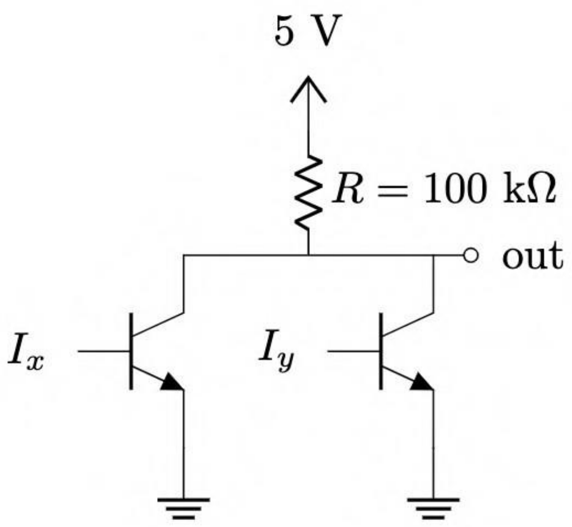
- Just replace switches with BJTs!
- Major problem: Cannot cascade! (Why?)
  - Input Logic Variable: **Current**
  - Output Logic Variable: **Voltage**



BJT Inverter (NOT Gate)



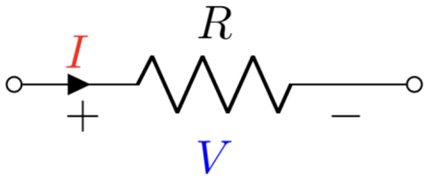
BJT NAND Gate



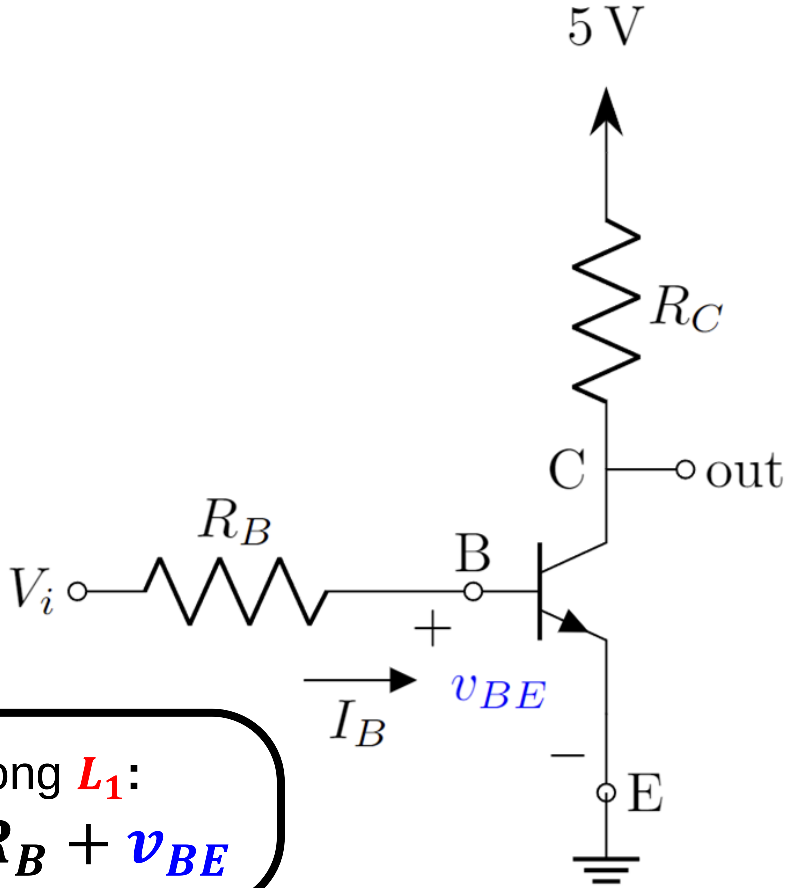
BJT NOR Gate

From Current Controlled to Voltage Controlled

How to convert current $\boldsymbol{I}$ into voltage $\boldsymbol{V}$?



$\boxed{\boldsymbol{V} = \boldsymbol{IR}}$



$$\boldsymbol{V_i = I_B R_B + v_{BE}}$$

$$\boldsymbol{I_B = \frac{V_i - v_{BE}}{R_B}}$$

$\boldsymbol{v_{BE}}$ depends on I_B.

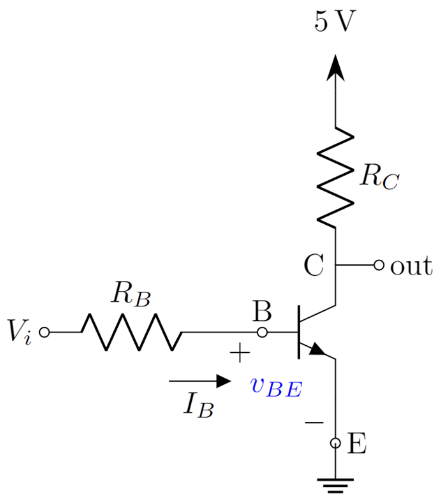
How?

KVL along $\boldsymbol{L_1}$**:**

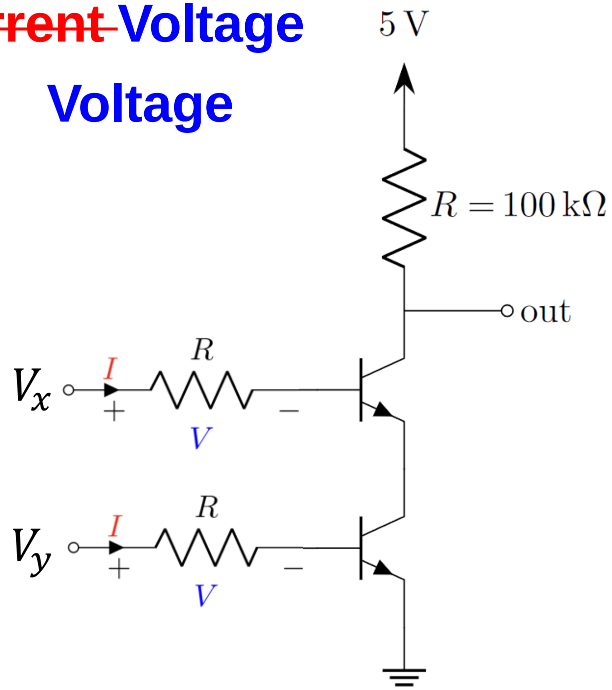
$$\boldsymbol{V_i = I_B R_B + v_{BE}}$$

Logic Gates using BJT

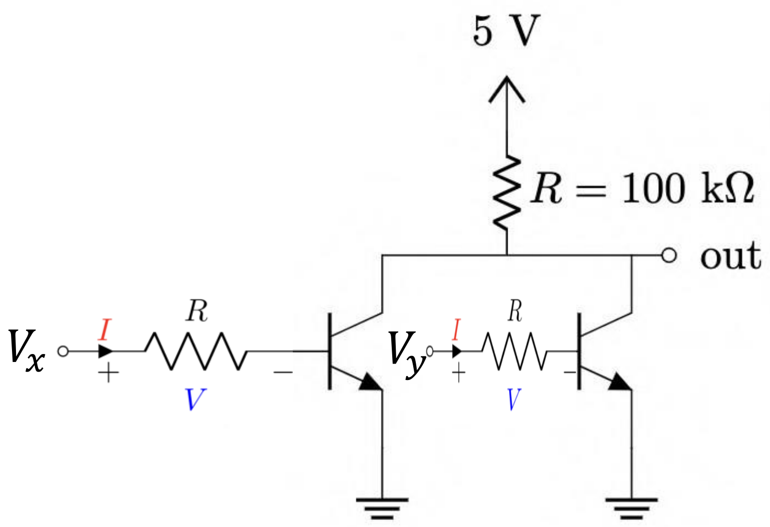
- Just replace switches with BJTs! **– and add a Resistor to the Base terminal**
- ~~Major problem: Cannot cascade! (Why?)~~ Can be cascaded.
    - Input Logic Variable: **~~Current~~ Voltage**
    - Output Logic Variable: **Voltage**



BJT Inverter (NOT Gate)



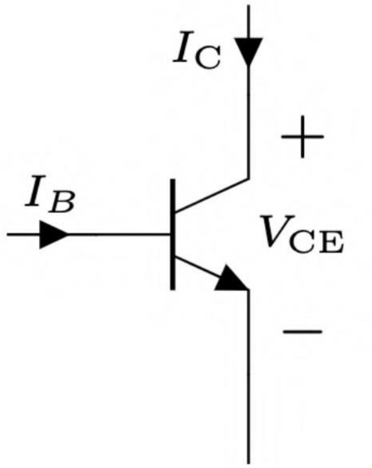
BJT NAND Gate

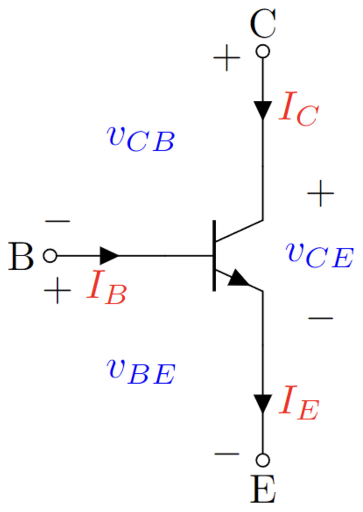


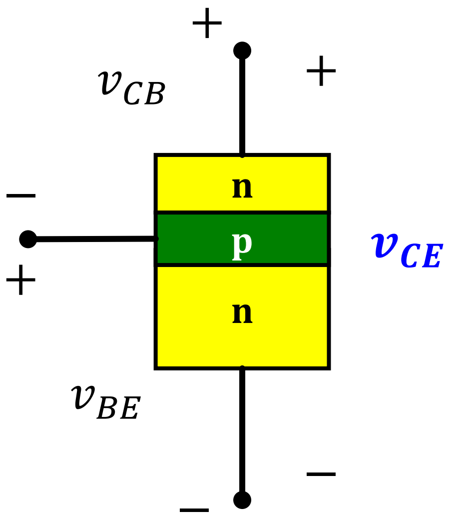
BJT NOR Gate

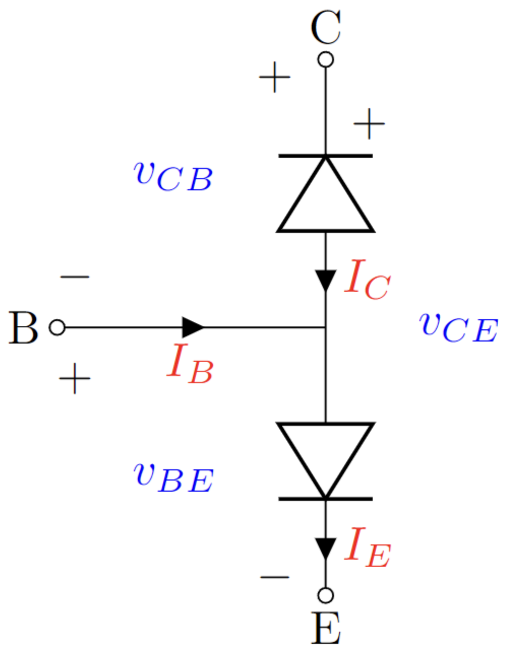
Parameters of BJT

A BJT can be thought of as two **“pn”** junctions placed back-to-back.







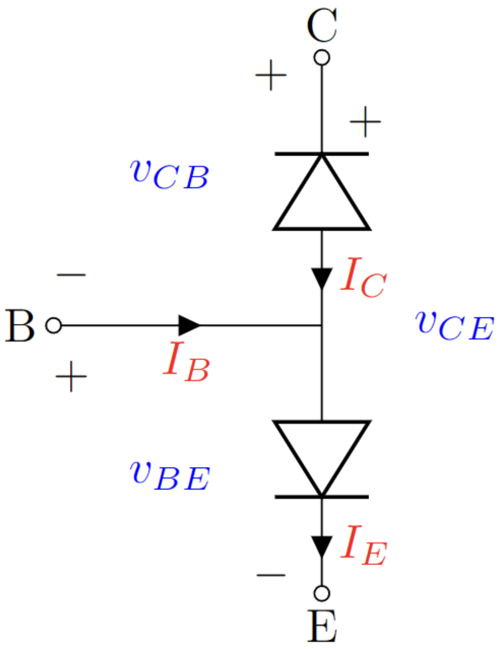


1st pn junction: Across **Base – Emitter**: Voltage v_{BE}

2nd pn junction: Across **Collector - Base**: Voltage v_{CB}

Parameters of BJT

A BJT can be thought of as two **"pn"** junctions placed back-to-back.



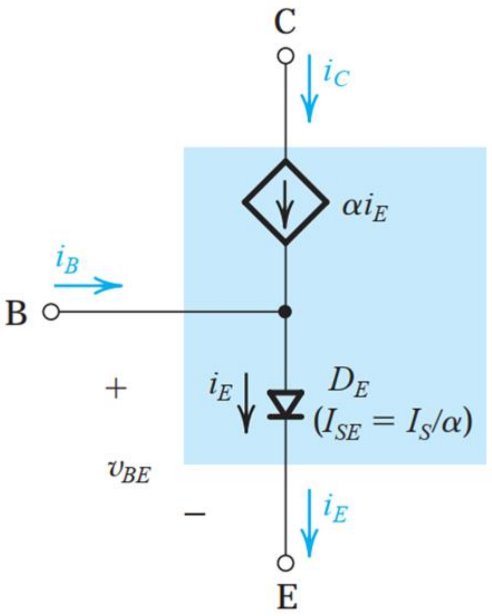
Modes	BE Junction	v_{BE}	CB Junction	v_{CB}	v_{CE}
Cut-off	Reverse Bias	$v_{BE} < 0.7$ V	Reverse Bias	$v_{CB} > -0.5$ V	
Active	Forward Bias	$v_{BE} = 0.7$ V	Reverse Bias	$v_{CB} > -0.5$ V	$v_{CE} > 0.2$ V
Saturation	Forward Bias	$v_{BE} = 0.7$ V	Forward Bias	$v_{CB} = -0.5$ V	$v_{CE} = 0.2$ V
Reverse Active	Reverse Bias	$v_{BE} < 0.6$ V	Forward Bias	$v_{CB} = -0.5$ V	$v_{CE} < 0.2$ V

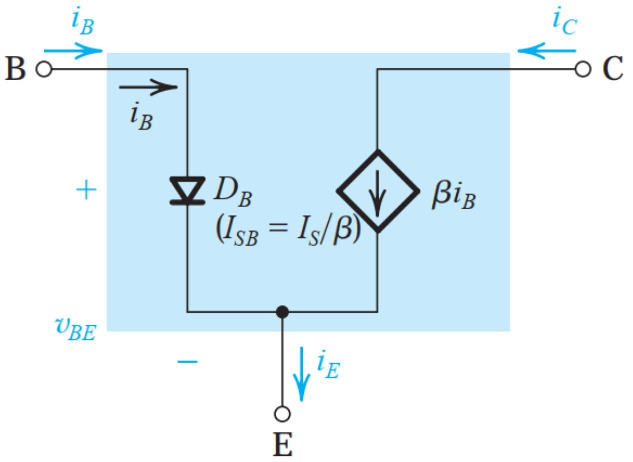
1st pn junction: Across **Base – Emitter**: Voltage $\boldsymbol{v_{BE}}$
2nd pn junction: Across **Collector - Base**: Voltage $\boldsymbol{v_{CB}}$

$$\boxed{v_{CE} = v_{CB} + v_{BE}}$$

Parameters of BJT: **Active Mode**

Equivalent circuit of an npn-BJT in **Active Mode**





Current relationships between the three currents in an npn BJT.

$$I_B + I_C = I_E$$

β: Common Emitter Current Gain
α: Common Base Current Gain

$$\boxed{\begin{aligned} I_C &= \beta I_B \\ I_C &= \alpha I_E \end{aligned}}$$

Only valid for active mode

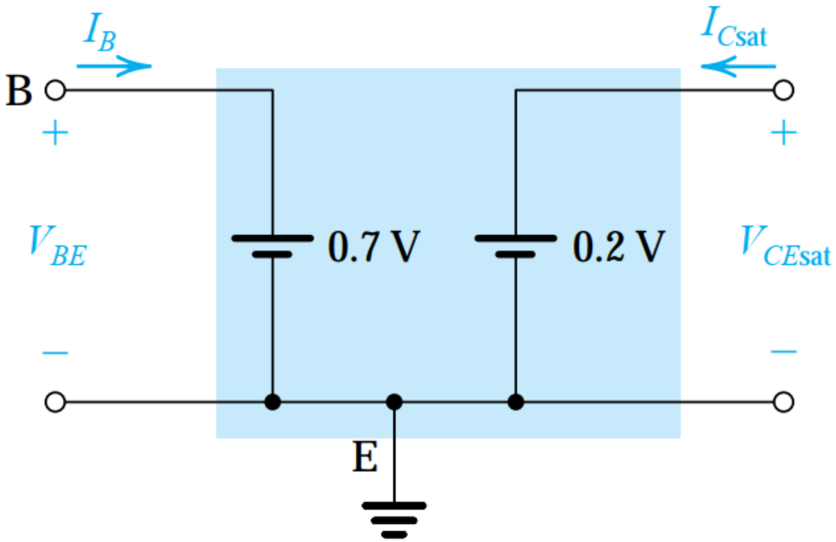
1st pn junction: Across **Base – Emitter**: Voltage $\boldsymbol{v_{BE}}$
2nd pn junction: Across **Collector - Base**: Voltage $\boldsymbol{v_{CB}}$

$$\boxed{v_{CE} = v_{CB} + v_{BE}}$$

Parameters of BJT: **Saturation Mode**

Equivalent circuit of an npn-BJT in **Saturation Mode**

Current relationships between the three currents in an npn BJT.



$$I_B + I_C = I_E$$

$$\boxed{\begin{array}{c} I_{C(sat)} < \beta I_B \\ I_C \neq \alpha I_E \end{array}}$$

β: Common Emitter Current Gain
α: Common Base Current Gain

Only valid for **Saturation** mode

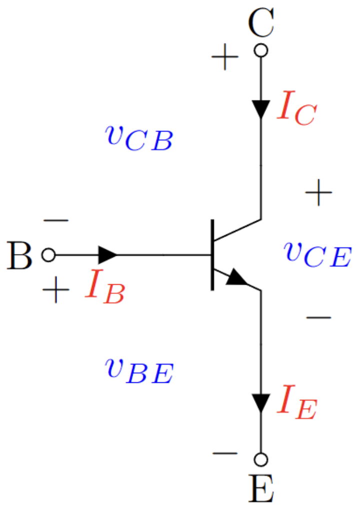
Figure 6.20 A simplified equivalent-circuit model of the saturated transistor.

1st pn junction: Across **Base – Emitter**: Voltage $\boldsymbol{v_{BE}}$
2nd pn junction: Across **Collector - Base**: Voltage $\boldsymbol{v_{CB}}$

$$v_{CE} = v_{CB} + v_{BE}$$

Parameters of BJT

A BJT can be thought of as two **"pn"** junctions placed back-to-back.



Modes	**Conditions!**
Cut-off	$v_{BE} < 0.7\ V$ and $v_{CB} > -0.5\ V$
Active	$v_{BE} = 0.7\ V$ and $v_{CE} > 0.2\ V$
Saturation	$v_{BE} = 0.7\ V$ and $v_{CE} = 0.2\ V$ and $\frac{I_C}{I_B} < \beta$
Reverse Active	$v_{BC} = 0.5\ V$ and $v_{EC} > 0.2\ V$

1st pn junction: Across **Base – Emitter**: Voltage v_{BE}
2nd pn junction: Across **Collector - Base**: Voltage v_{CB}

$$\boxed{v_{CE} = v_{CB} + v_{BE}}$$

Solving Circuits with ~~MOSFET~~ **BJT**

- Use **Method of Assumed State**!
- Three steps:
  - **Assume**: One of the modes (Cutoff, ~~Triode~~ Saturation, ~~Saturation~~ Active)
  - **Solve**: Use corresponding equation and KCL + KVL with currents
  - **Verify**: Check if the conditions of $\cancel{V_{GS}}$ $\boldsymbol{v_{BE}}$ and $\cancel{V_{DS}}$ $\boldsymbol{v_{CE}}$ are satisfied. If not, repeat.
- Might need to solve quadratic equation ($ax^2 + bx + c = 0$).
- If we get two roots, choose the one that's ***favorable*** to your assumption

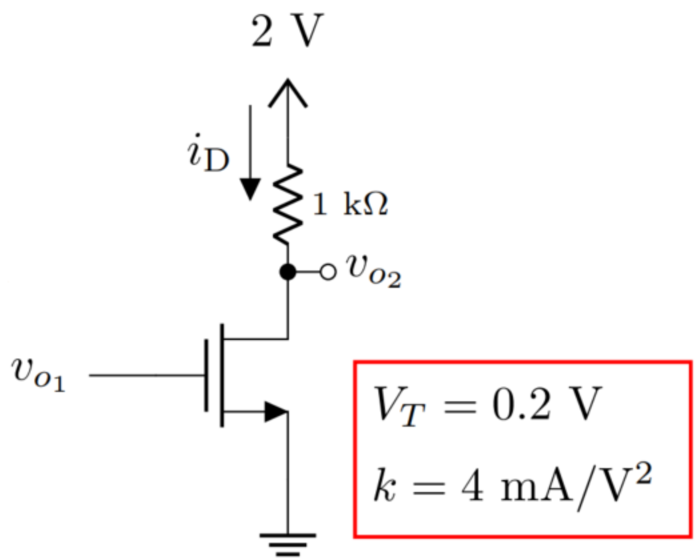
MOSFET Problem 1

Analyze the circuit to find $\boldsymbol{i_D}$ and $\boldsymbol{v_{o2}}$ using the Method of Assumed State. Here, the input of the MOSFET is $\boldsymbol{v_{o1} = 1\ V}$.

You must validate your assumptions.

Assume: One of the modes (Cutoff, Triode, Saturation)

Let the MOSFET be in **SATURATION**



$v_{o1} = 1$ V

Solve: corresponding equations:

Equation: $i_D = \frac{2 - v_{o2}}{1} = \frac{k}{2}(v_{o1} - V_T)^2$

Solving Equations →

$$v_{o2} = 2 - \frac{4}{2}(1 - 0.2)^2 \ \mathbf{V}$$

$$\boldsymbol{v_{o2} = (2 - 1.28\,)\mathrm{V} = 0.72}\ \mathrm{V}$$

Verify: For saturation condition → $\boldsymbol{v_{DS} > v_{GS} - V_T}$

Here, $v_{GS} - V_T = (1 - 0.2)\ \mathrm{V} = 0.8\ \mathrm{V}$

$v_{DS} = v_{o2} = 0.72\ \mathrm{V} \ngtr 0.8\ \mathrm{V}$

Assumption is Wrong!

MOSFET Problem 1

Analyze the circuit to find $\boldsymbol{i_D}$ and $\boldsymbol{v_{o2}}$ using the Method of Assumed State. Here, the input of the MOSFET is $\boldsymbol{v_{o1} = 1\,V}$.

You must validate your assumptions.

Assume:

Let the MOSFET be in **TRIODE**

Solve:

Equation: $i_D = \frac{2-v_{o2}}{1} = k\left(v_{o1} - V_T - \frac{v_{o2}}{2}\right)v_{o2}$

Solving Equations →

$$2 - v_{o2} = 4\left(0.8 - \frac{v_{o2}}{2}\right)v_{o2}$$
$$2v_{o2}^2 - 4.2v_{o2} + 2 = 0$$

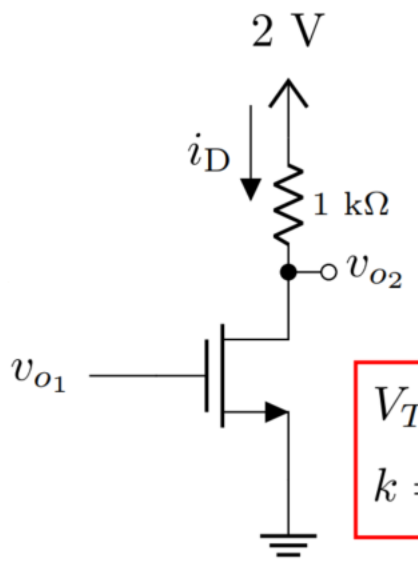
$$\boldsymbol{v_{o2}} = \cancel{\mathbf{1.37}\ \mathrm{V}} \text{ or } \mathbf{0.73}\ \mathrm{V}$$

Verify: For **triode** condition → $\boldsymbol{v_{DS} < v_{GS} - V_T}$

Here, $v_{GS} - V_T = (1 - 0.2)\ \mathrm{V} = 0.8\ \mathrm{V}$

$v_{DS} = v_{o2} = 0.73\ \mathrm{V} < 0.8\ \mathrm{V}$

Assumption is Correct!



$V_T = 0.2$ V

$k = 4$ mA/V^2

$v_{o1} = 1$ V

BJT Problem 1

Analyze the circuit to find $\boldsymbol{I_C}$ and $\boldsymbol{v_{out}}$ using the Method of Assumed State. Here, the input of the BJT is $\boldsymbol{V_i = 1\ V}$. You must validate your assumptions.

Assume:

Let the BJT be in **ACTIVE** mode

So, $v_{BE} = 0.7\ V$

$v_{CE} > 0.3$ V

Solve:

Equations: $\boldsymbol{I_B} = \frac{V_i - v_{BE}}{R_B} = \frac{1 - 0.7}{100}$ mA $= \mathbf{3\ \mu A}$

$\boldsymbol{I_C} = \beta I_B = 100 \times 3 \times 10^{-3}$ mA $= \mathbf{0.3\ mA}$

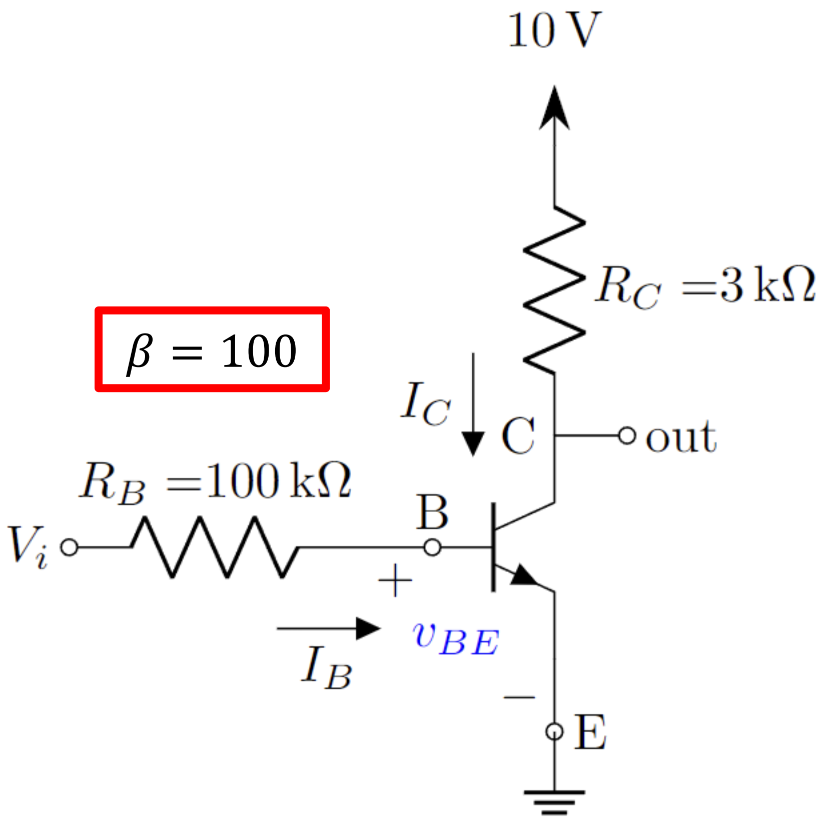
$\boldsymbol{v_{out}} = 10 - I_C R_C = (10 - 0.3 \times 3)$ V $= \mathbf{9.1\ V}$

Verify: For **ACTIVE** condition → $\boldsymbol{v_{CE} > 0.3}$ **V**

Here, $v_{CE} = v_{out} = 9.1$ V > 0.3 V

Assumption is Correct!

$\boxed{\beta = 100}$



BJT Problem 1

Analyze the circuit to find $\boldsymbol{I_C}$ and $\boldsymbol{v_{out}}$ using the Method of Assumed State. Here, the input of the BJT is $\boldsymbol{V_i = 5\ V}$. You must validate your assumptions.

Assume:

Let the BJT be in **ACTIVE** mode

So, $v_{BE} = 0.7\ V$

$v_{CE} > 0.2$ V

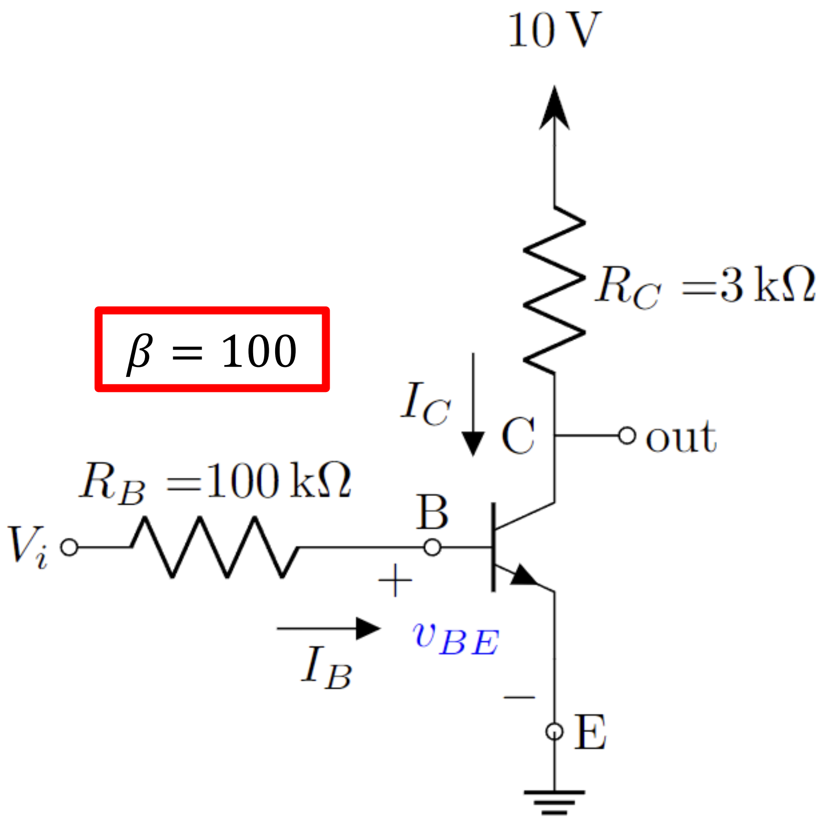
Solve:

Equations:

$$\boldsymbol{I_B} = \frac{V_i - v_{BE}}{R_B} = \frac{5 - 0.7}{100}\ \text{mA} = \mathbf{43\ \mu A}$$

$$\boldsymbol{I_C} = \beta I_B = 100 \times 43 \times 10^{-3}\ \text{mA} = \mathbf{4.3\ mA}$$

$$\boldsymbol{v_{out}} = 10 - I_C R_C = (10 - 4.3 \times 3\ )\ \text{V} = \mathbf{-2.9\ V}$$



Verify: For **ACTIVE** condition → $\boldsymbol{v_{CE} > 0.2\ V}$

Here, $v_{CE} = v_{out} = \mathbf{-2.9}\ \text{V} \not> 0.2\ \text{V}$

Assumption is Wrong!

BJT Problem 1

Analyze the circuit to find $\boldsymbol{I_C}$ and $\boldsymbol{v_{out}}$ using the Method of Assumed State. Here, the input of the BJT is $\boldsymbol{V_i = 5\ V}$. You must validate your assumptions.

Assume:

Let the BJT be in **Saturation** mode

So, $v_{BE} = 0.7\ V$ and $\frac{\boldsymbol{I_C}}{\boldsymbol{I_B}} < \boldsymbol{\beta}$

$v_{CE} = 0.2\ \text{V}$

Solve:

Equations: $\boldsymbol{I_B} = \frac{V_i - v_{BE}}{R_B} = \frac{5-0.7}{100}\ \text{mA} = \mathbf{43\ \mu A}$

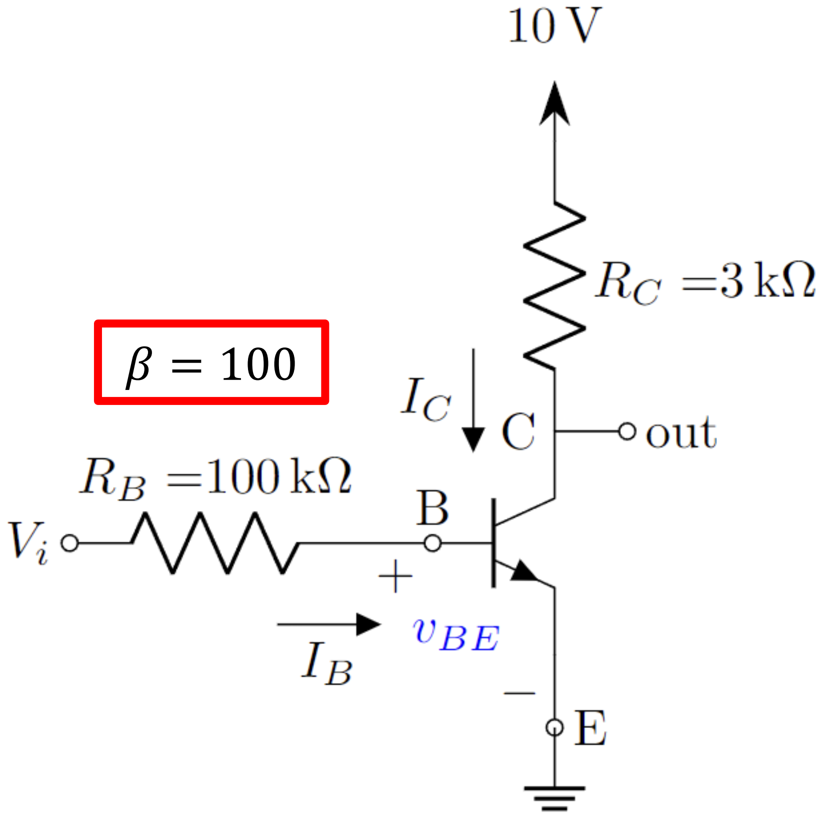
$$\boldsymbol{I_C} = \cancel{\beta I_B}\ \frac{10 - v_{CE}}{R_C} = \frac{10-0.2}{3}\text{mA} = \mathbf{3.27\ mA}$$

$$\boldsymbol{v_{out}} = v_{CE} = \mathbf{0.2\ V}$$

Verify: For **Saturation** condition → $\frac{\boldsymbol{I_C}}{\boldsymbol{I_B}} < \boldsymbol{\beta}$

Here, $\beta = 100$ $\frac{\boldsymbol{I_C}}{\boldsymbol{I_B}} = \frac{\mathbf{3.27}}{\mathbf{0.043}} = \mathbf{76 < 100}$

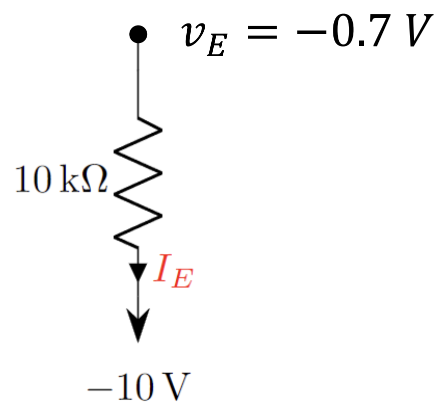
$\boxed{\beta = 100}$



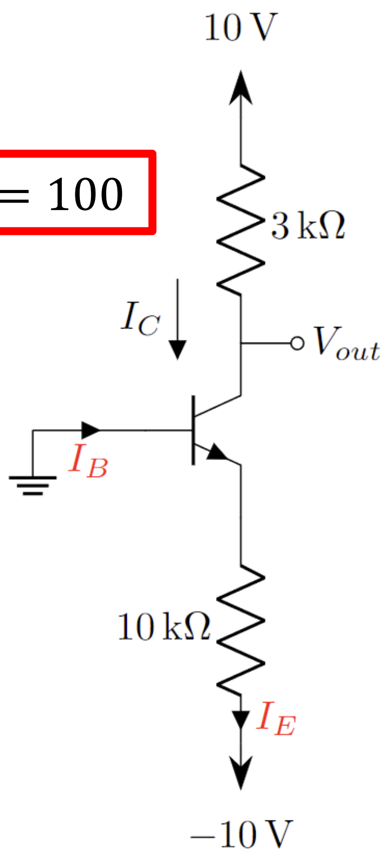
Assumption is Correct!

BJT Problem 2

Analyze the circuit to find $\boldsymbol{I_B, I_C, I_E}$ and $\boldsymbol{v_{out}}$ using the Method of Assumed State. You must validate your assumptions.



$\boxed{\beta = 100}$



Assume:

Let the BJT be in **Active** mode

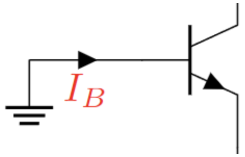
So, $v_{BE} = 0.7\ V$

$v_{CE} > 0.2$ V

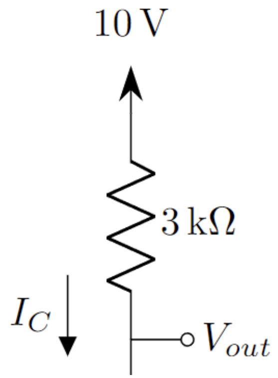
Solve:

Equations:

$$I_E = \frac{v_E - (-10)}{10} = \frac{-0.7+10}{10}\,\text{mA} = \mathbf{0.93\ mA}$$



$$\boldsymbol{I_B} = \frac{\mathbf{1}}{\boldsymbol{\beta}}\boldsymbol{I_C} = \frac{1}{\beta}\cdot\alpha\boldsymbol{I_E} = \frac{1}{\beta}\cdot\frac{\beta}{\beta+1}\boldsymbol{I_E} = \frac{1}{\beta+1}\boldsymbol{I_E} = \mathbf{9.21\ \mu A}$$



$$\boldsymbol{v_{out} = v_C = 10 - 3I_C = 10 - 3\beta I_B}$$

$$= \left(\mathbf{10 - 3\cdot 100\cdot 9.207\times 10^{-3}}\right)\mathbf{V}$$

$$= \mathbf{7.237\ V}$$

BJT Problem 2

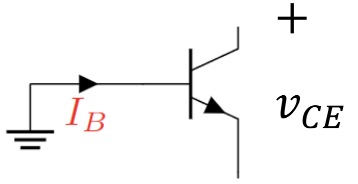
Analyze the circuit to find $\boldsymbol{I_B, I_C, I_E}$ and $\boldsymbol{v_{out}}$ using the Method of Assumed State. You must validate your assumptions.

Assume:

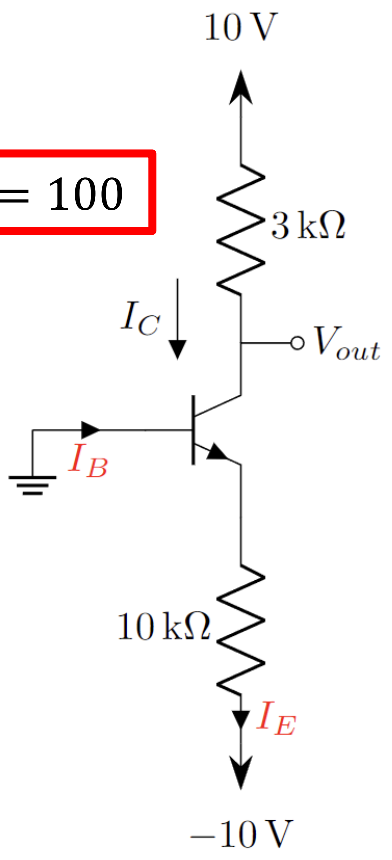
Let the BJT be in **Active** mode

So, $v_{BE} = 0.7\ V$

$v_{CE} > 0.2$ V



$\boxed{\beta = 100}$



Solve:

Equations: $\boldsymbol{I_E = 0.93\ \text{mA}}$

$\boldsymbol{I_B = 9.21\ \mu\text{A}}$

$\boldsymbol{v_{out} = v_C = 7.237\ \text{V}}$ $\boldsymbol{v_B = 0\ \text{V}}$ $\boldsymbol{v_E = -0.7\ \text{V}}$

Verify: For **ACTIVE** condition → $\boldsymbol{v_{CE} > 0.2\ \text{V}}$

Here, $v_{CE} = (7.237 + 0.7)\ \textbf{V} = \boldsymbol{7.937\ \text{V}} > 0.2\ \text{V}$

Assumption is Correct!