CSE251: Electronic Devices and Circuits

Lecture: 18 - 20 – BJT

Prepared By:

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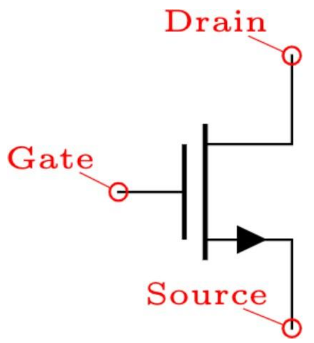
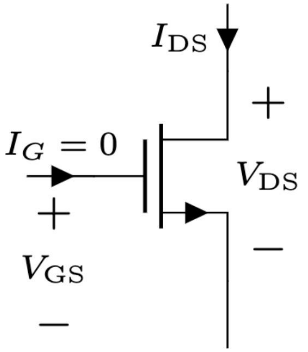
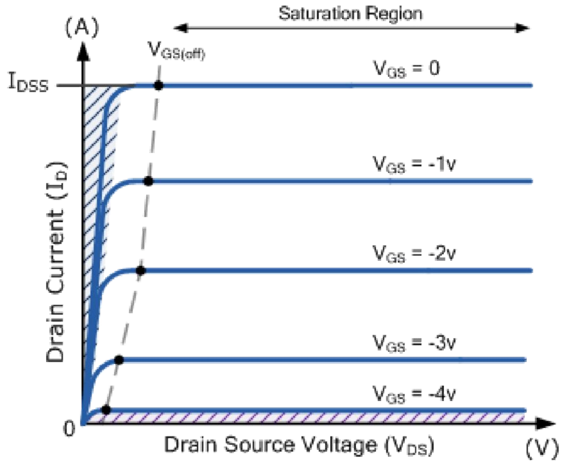
Transistors as Digital Switch

- 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, $C = V_{GS}$. The IV characteristics (I_{DS} vs V_{DS}) depends on V_{GS}
- Actual dependency is complex.
- Will start with a simple (but approximate) one – **S-Model** (Switch Model)

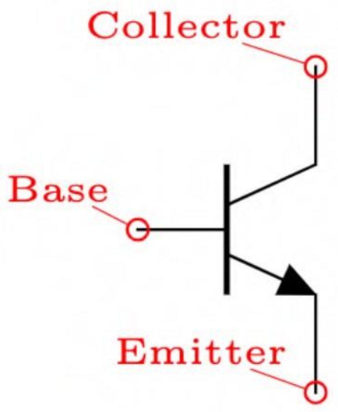


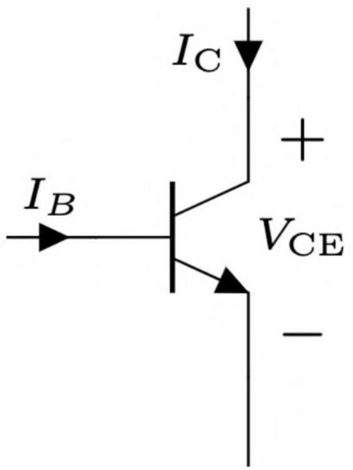


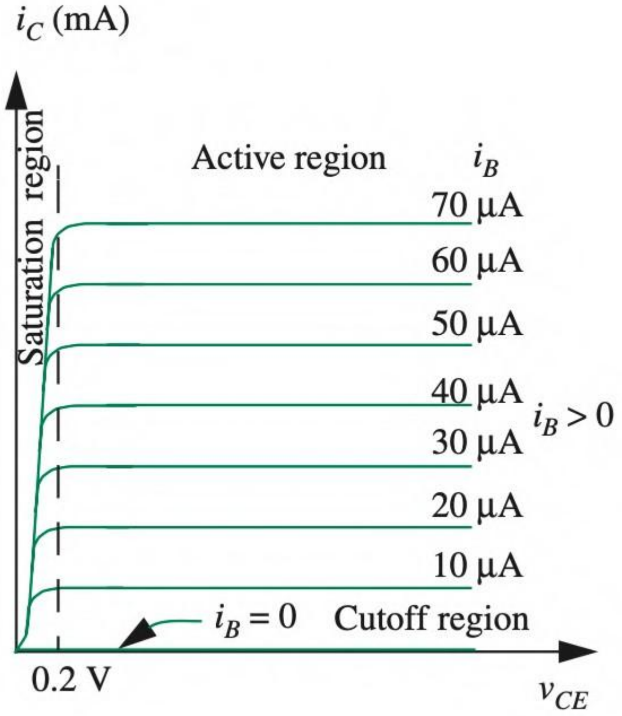


Bipolar Junction Transistor

- **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 $\boldsymbol{V_{GS}}$)

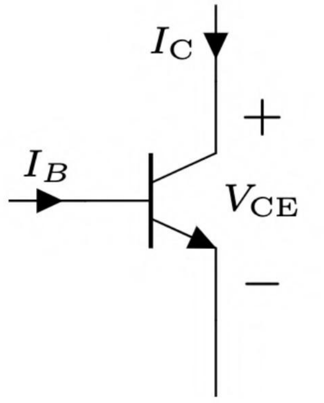






BJT vs MOSFET - Differences

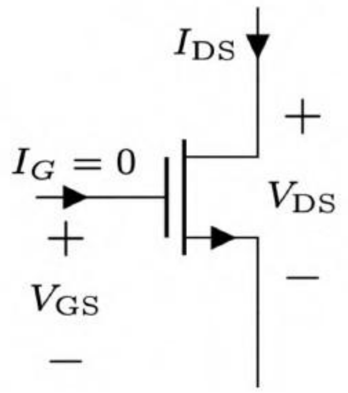
BJT



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

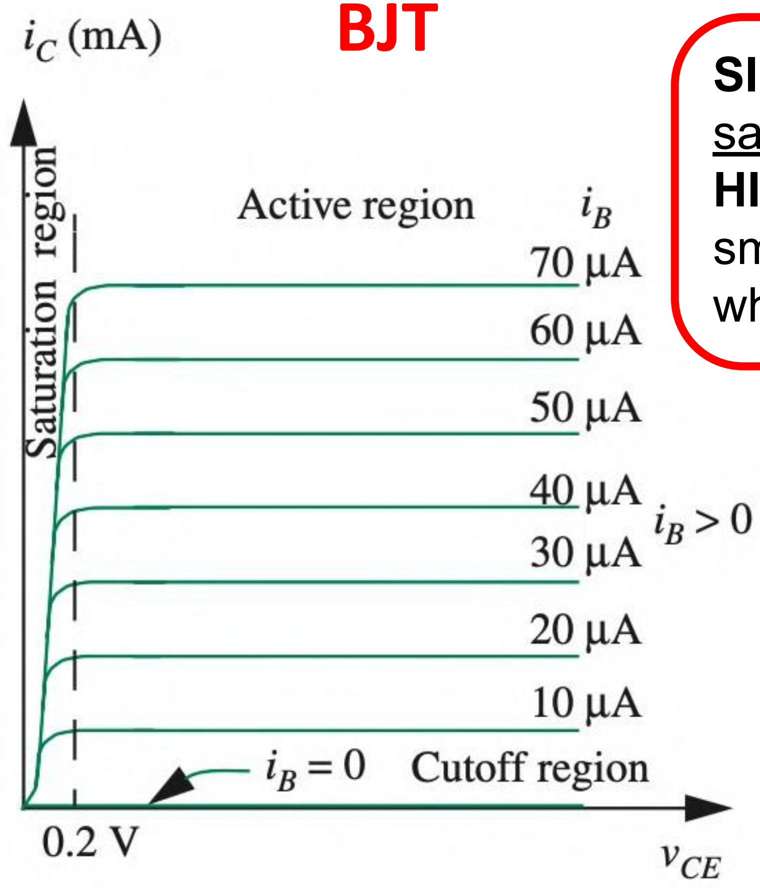


Voltage controlled, $\boldsymbol{V_{GS}}$ controls ($\boldsymbol{I_{DS}}$ vs $\boldsymbol{V_{DS}}$)

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

BJT vs MOSFET - Differences

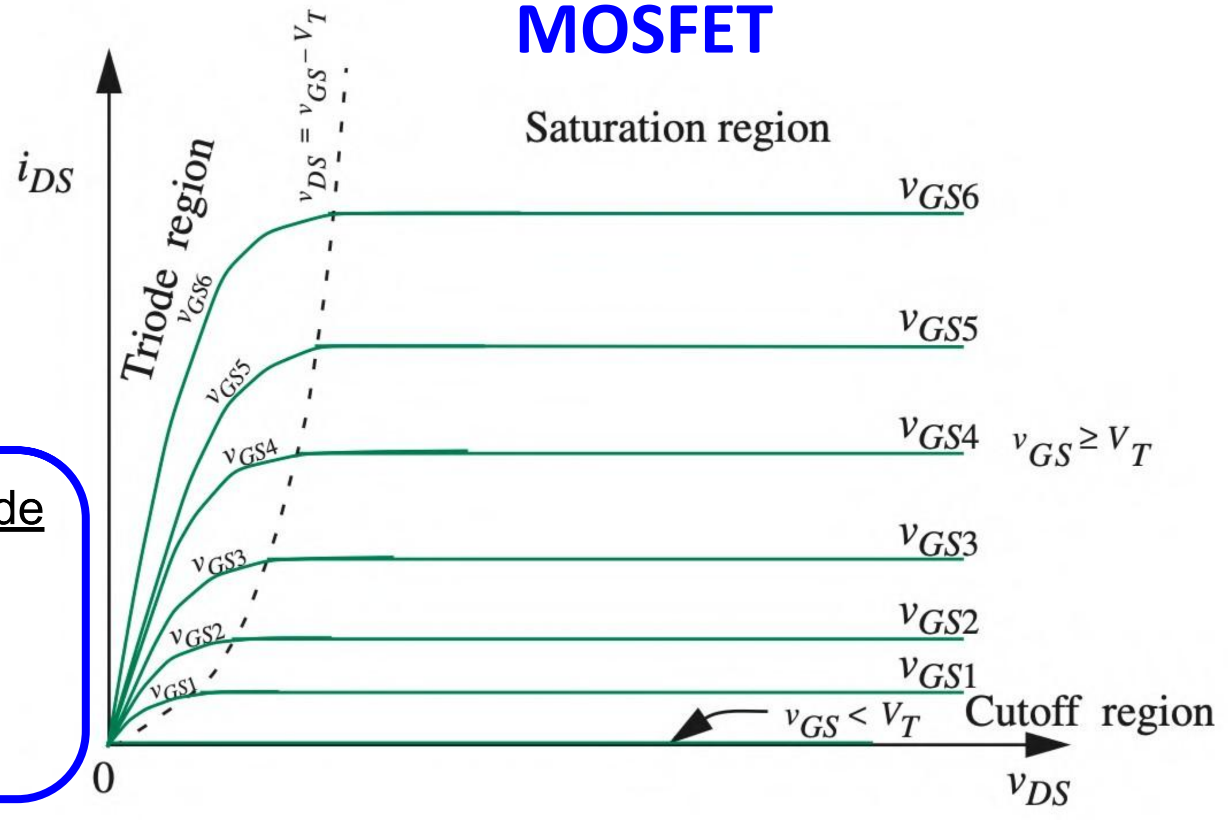
BJT



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

Slope in the <u>Triode</u> region is **LOW**, hence significant resistance when "**ON**"

MOSFET

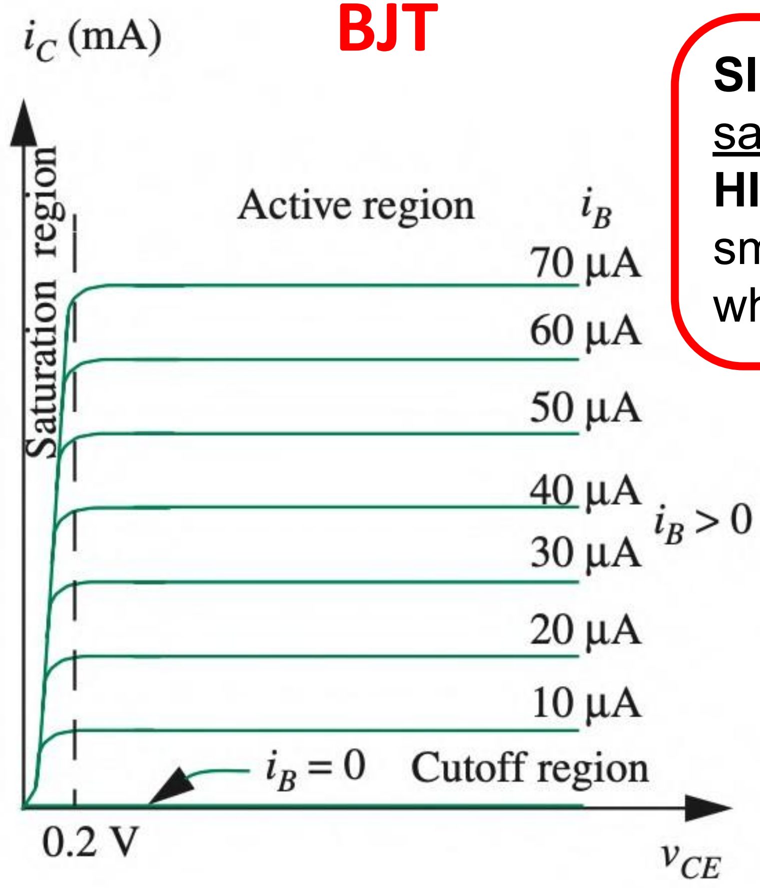


Current in **active** region changes linearly with control I_B.
Hence, $I_C \propto I_B$

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

BJT vs MOSFET - Differences

BJT



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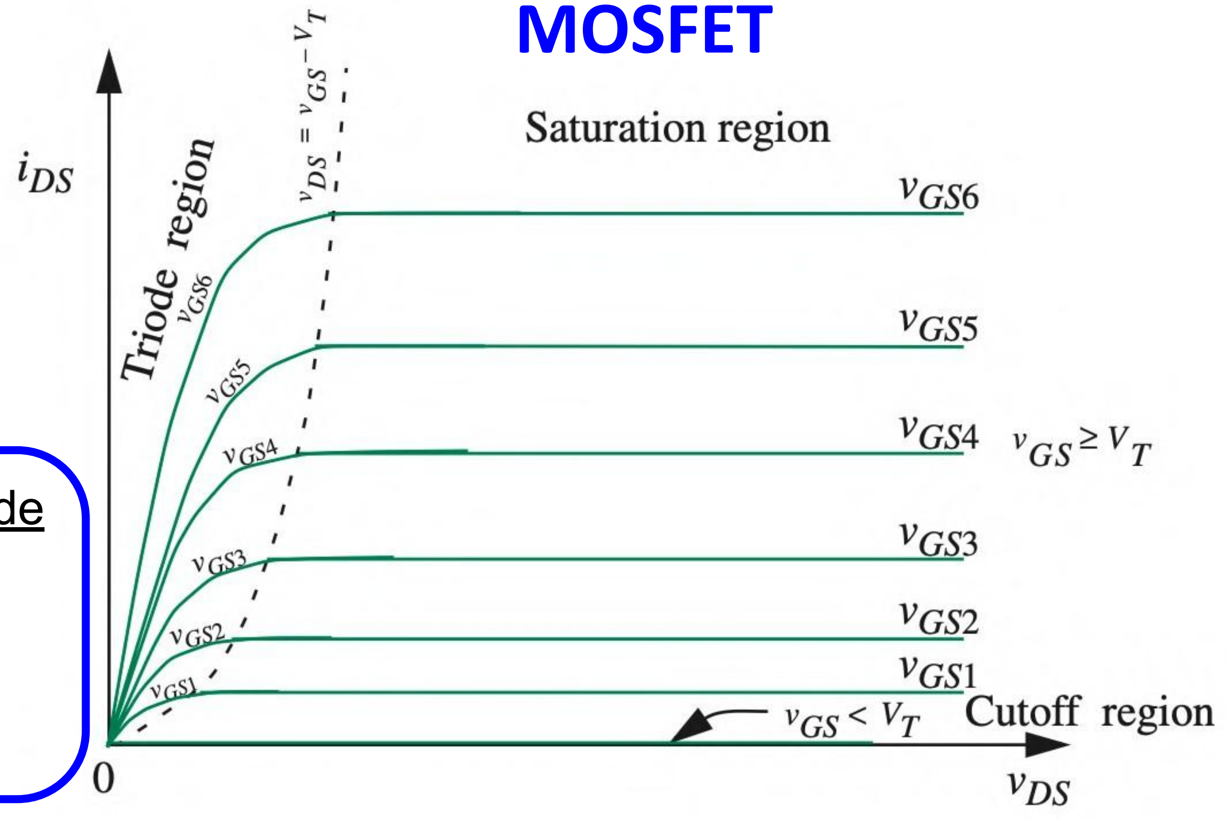
MOSFET



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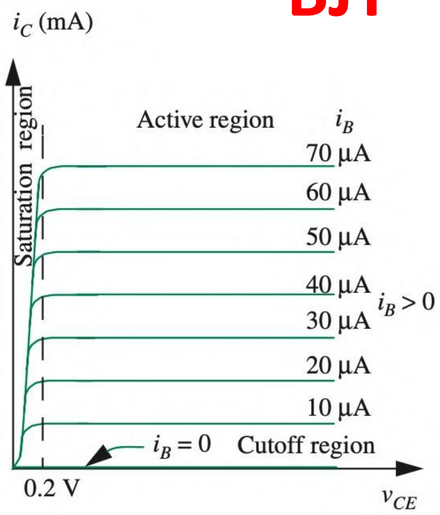
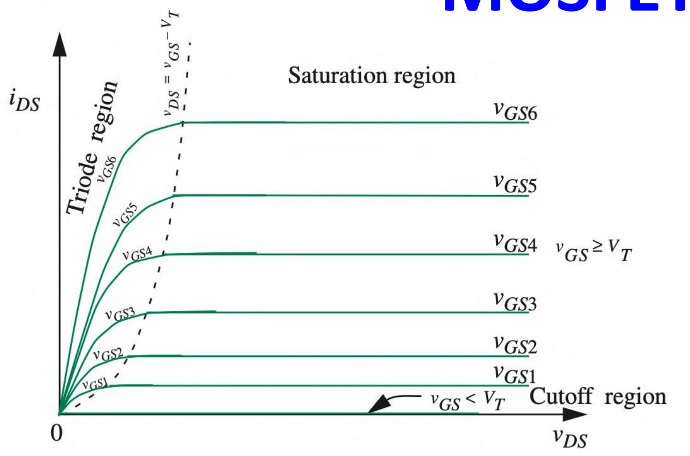
Hence, $I_{DS} \propto V_{GS}^2$

BJT vs MOSFET - Similarities

BJT



MOSFET

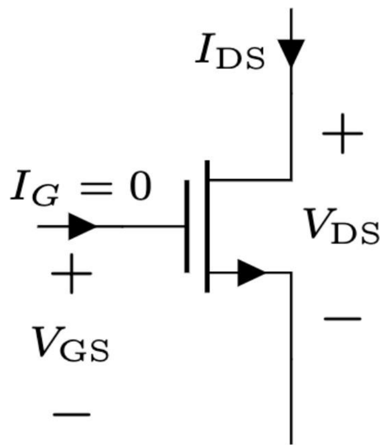


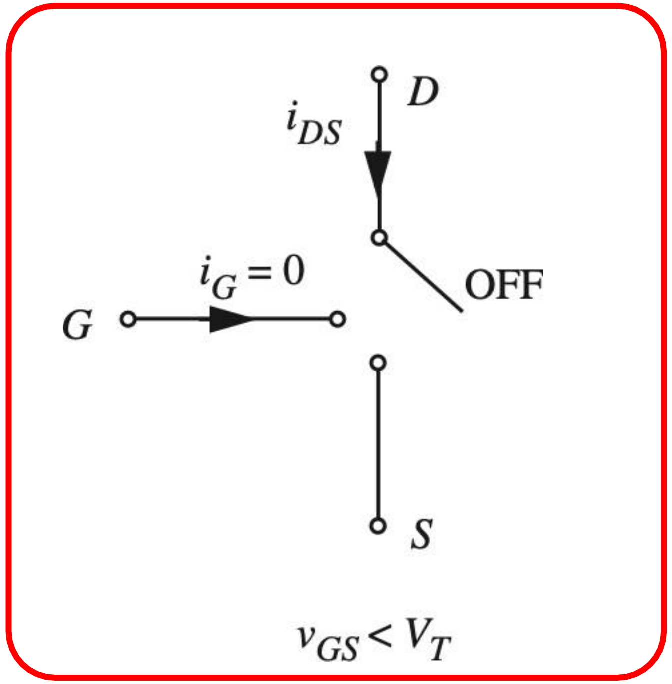
- **Saturation** mode for small $V_{CE} (< 0.2\text{ V})$
- Approximately Short circuit in **Saturation** mode (I_B **HIGH**)
- Open circuit in **Cutoff** mode ($I_B = 0$)
- Can use as a switch ⇒ S-Model!

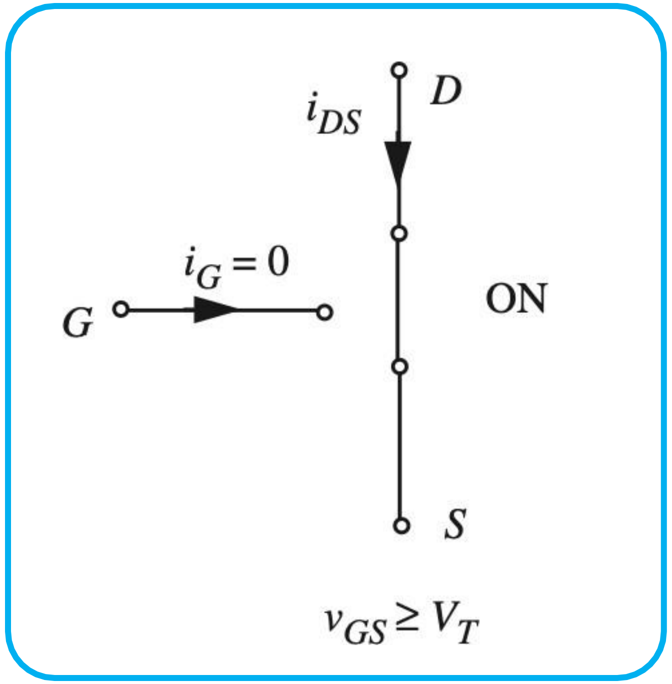
- **Triode** mode for small $V_{DS} (< V_{OV})$
- Approximately Short circuit in **Triode** mode (V_{GS} **HIGH**)
- Open circuit in **Cutoff** mode $\boldsymbol{(V_{GS} < V_T = 0)}$
- Can use as a switch ⇒ S-Model!

MOSFET S-Model

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



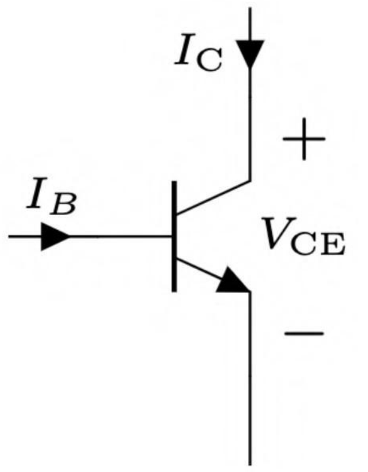


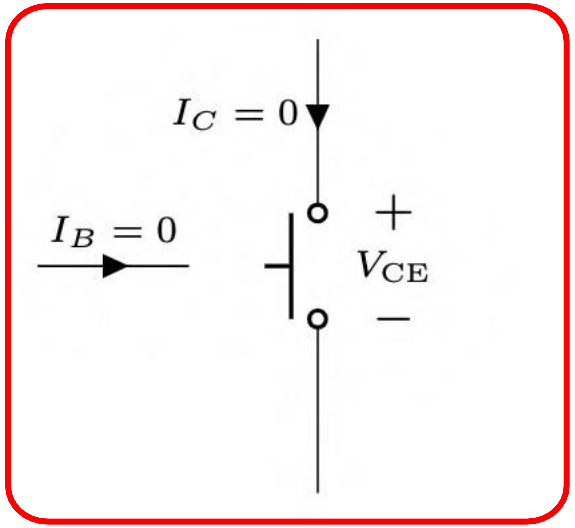


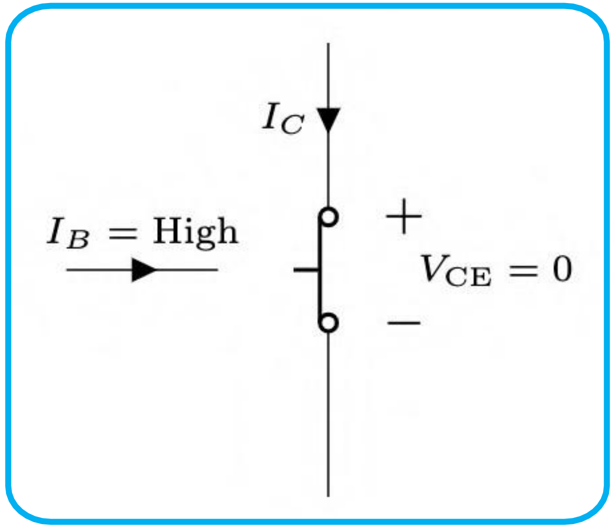
BJT S-Model

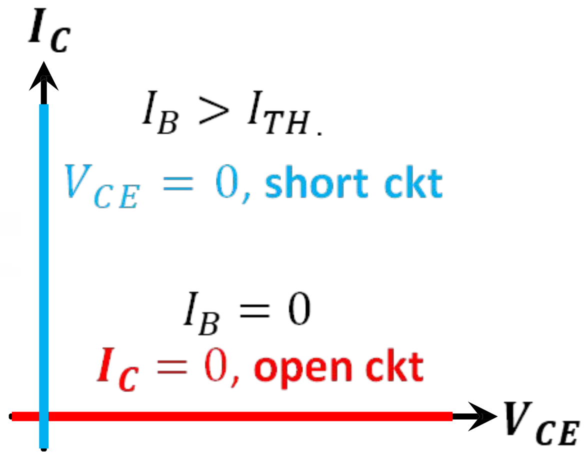
	Representation
Logic 0	
Logic 1	

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



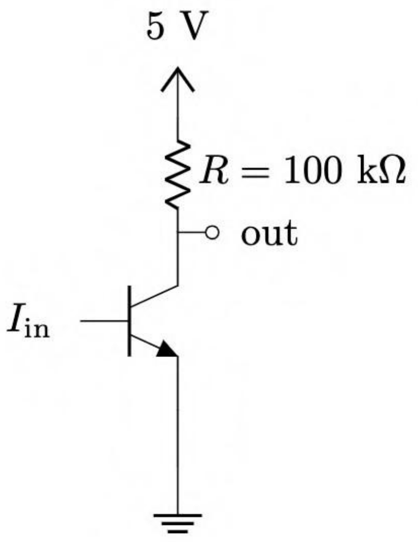




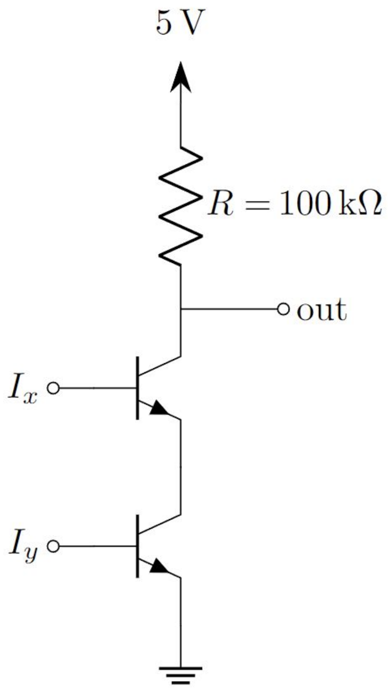


Current-Controlled Logic Gates using BJT

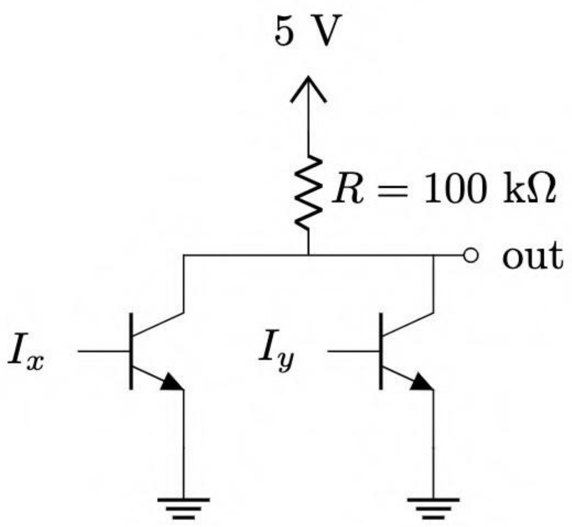
- Just replace switches with BJTs!
- Major problem: Cannot cascade! (Why?)
  - Input Logic Variable: **Current**
  - Output Logic Variable: **Voltage**



BJT Inverter (NOT Gate)



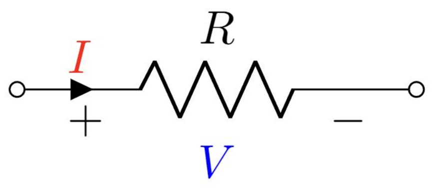
BJT NAND Gate



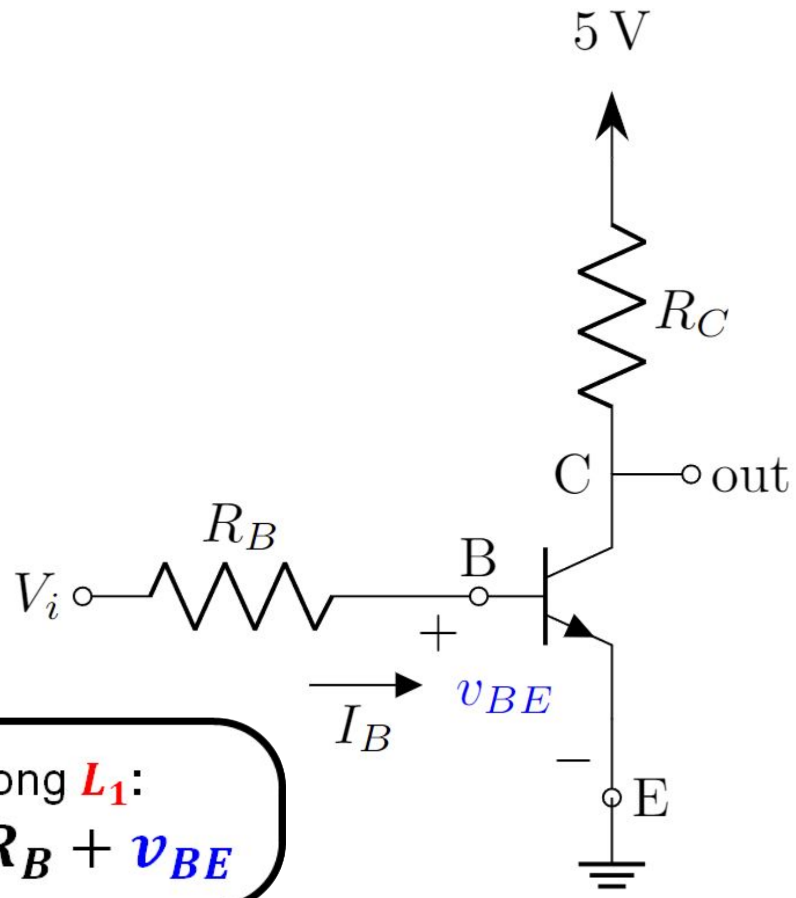
BJT NOR Gate

From Current Controlled to Voltage Controlled

How to convert current I into voltage V?



$$\boxed{V = IR}$$



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

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

KVL along L_1:
$V_i = I_B R_B + v_{BE}$

v_{BE} depends on I_B.

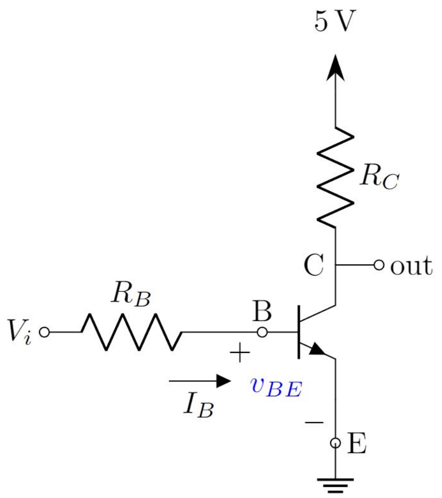
How?

Logic Gates using BJT

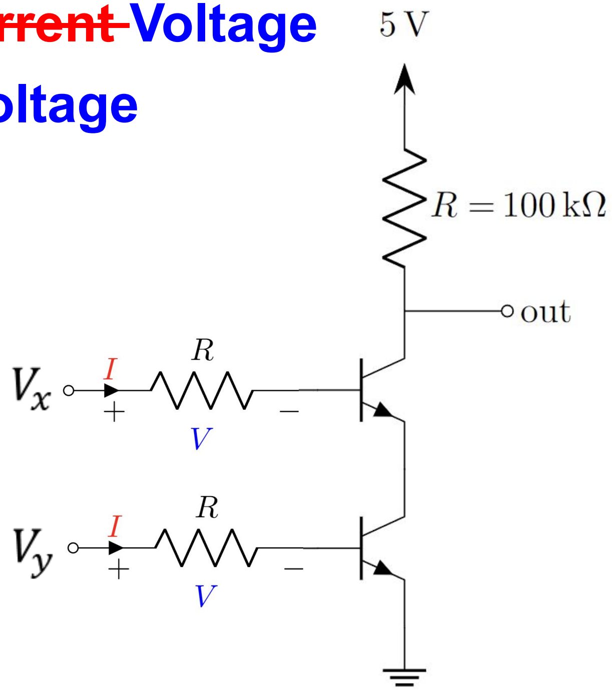
- Just replace switches with BJTs! **– and add a Resistor to the Base terminal**

~~• Major problem: Cannot cascade! (Why?)~~ Can be cascaded.

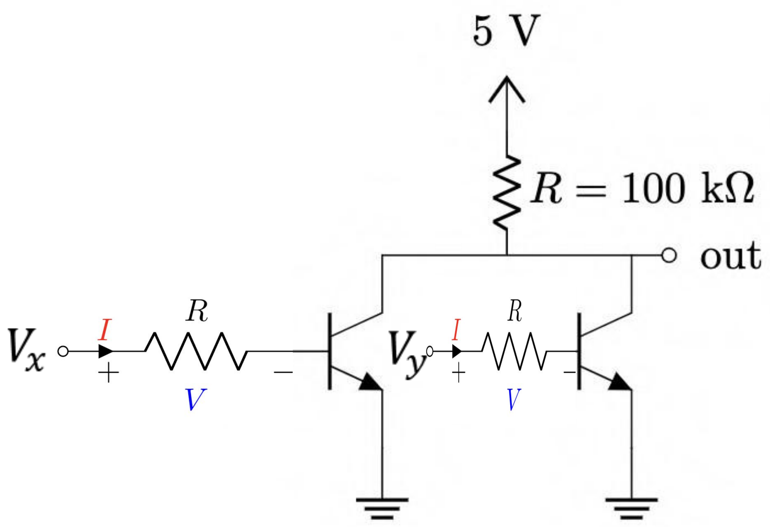
  - Input Logic Variable: ~~**Current**~~ **Voltage**
  - Output Logic Variable: **Voltage**



BJT Inverter (NOT Gate)



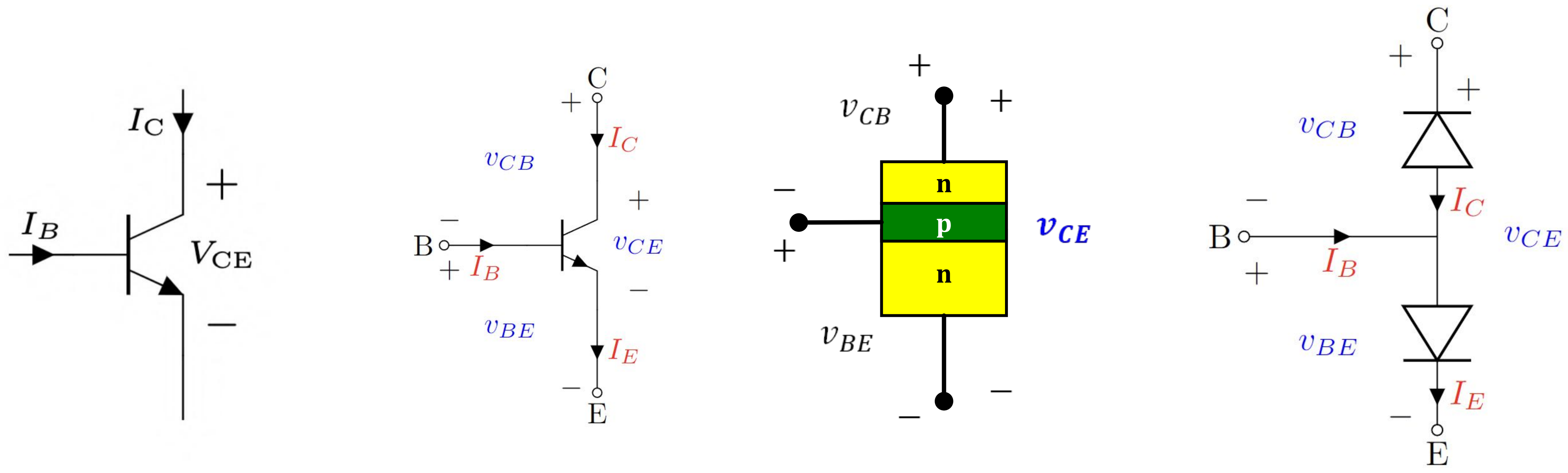
BJT NAND Gate



BJT NOR Gate

Parameters of BJT

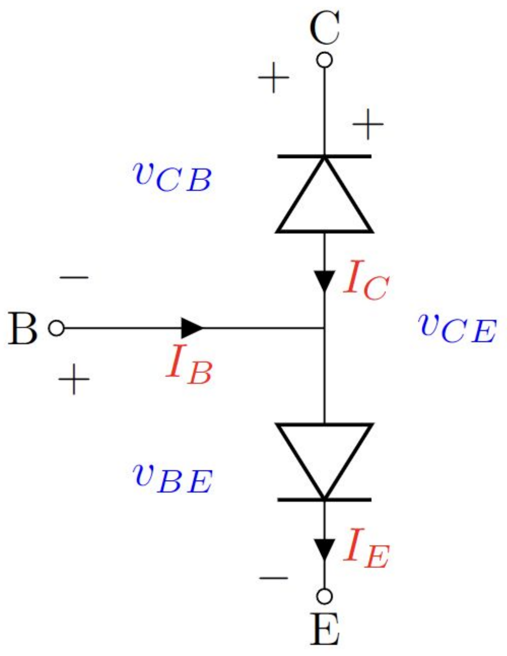
A BJT can be thought of as two **"pn"** junctions placed back-to-back.



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

Parameters of BJT

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



Modes	BE Junction		CB Junction		
Cut-off	Reverse Bias		Reverse Bias		
Active	Forward Bias		Reverse Bias		
Saturation	Forward Bias		Forward Bias		
Reverse Active	Reverse Bias		Forward Bias		

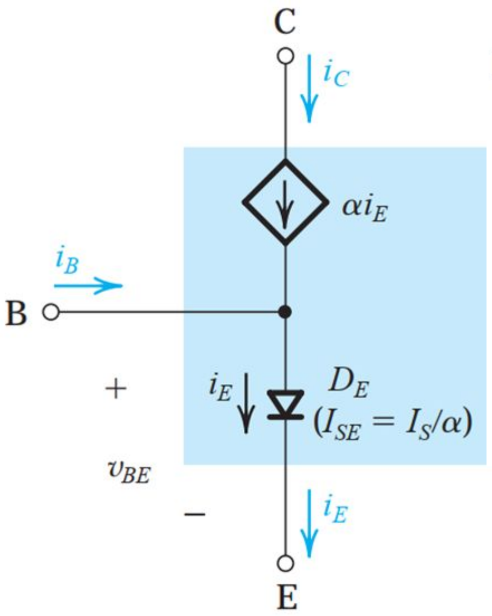
1st pn junction: Across **Base – Emitter**: Voltage $\boldsymbol{v_{BE}}$
2nd pn junction: Across **Collector - Base**: Voltage $\boldsymbol{v_{CB}}$

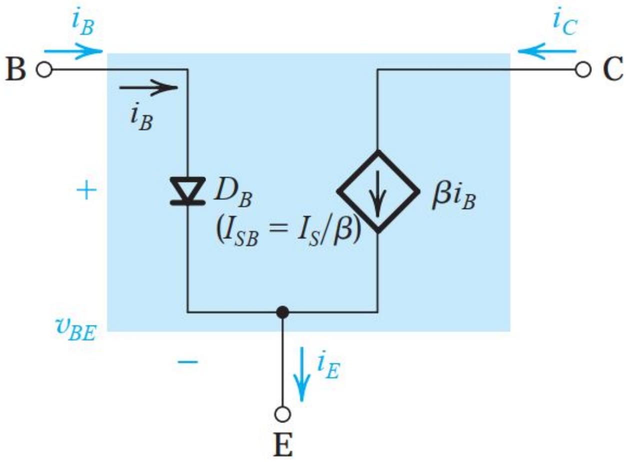
$$\boxed{v_{CE} = v_{CB} + v_{BE}}$$

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

$$\boxed{I_C = \beta I_B \qquad I_C = \alpha I_E}$$

Only valid for active mode

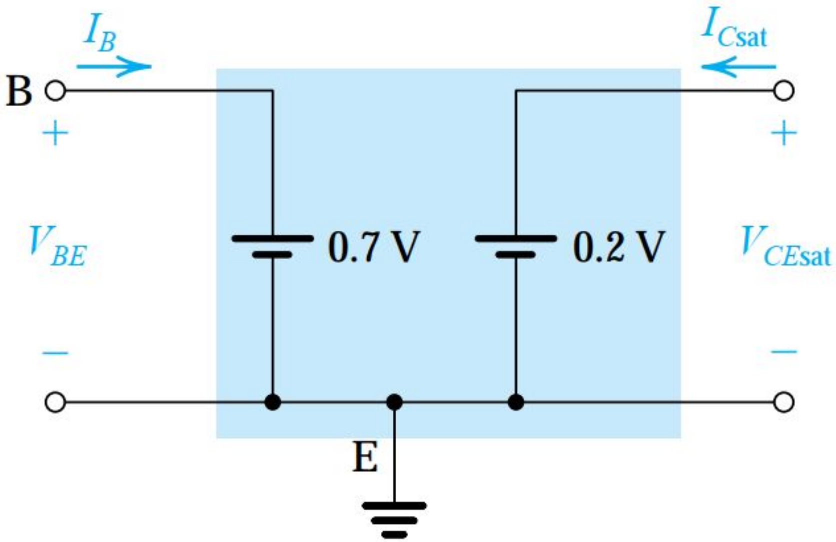
1st pn junction: Across **Base – Emitter**: Voltage $\boldsymbol{v_{BE}}$
2nd pn junction: Across **Collector - Base**: Voltage $\boldsymbol{v_{CB}}$

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

Parameters of BJT: **Saturation Mode**

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

Current relationships between the three currents in an npn BJT.



$I_B + I_C = I_E$

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

$$\boxed{I_{C(sat)} < \beta I_B \qquad I_C \neq \alpha I_E}$$

Only valid for **Saturation** mode

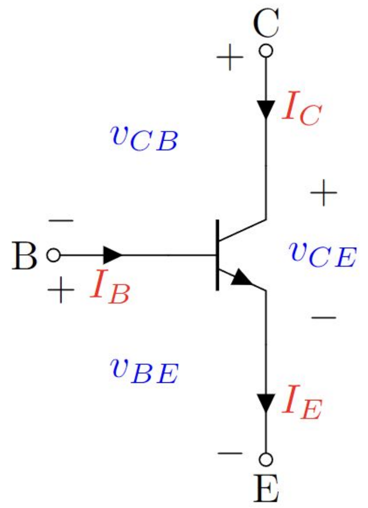
Figure 6.20 A simplified equivalent-circuit model of the saturated transistor.

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	
Active	
Saturation	
Reverse Active	

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**

Solve: corresponding equations:

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

Solving Equations →

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

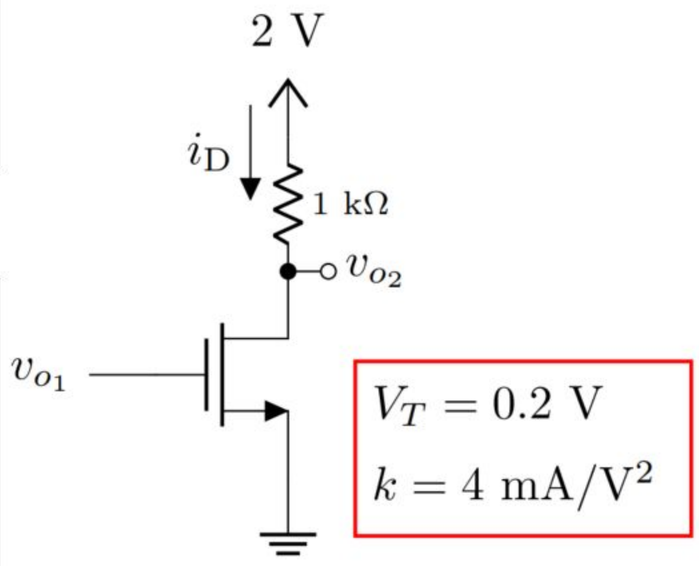
$$\boldsymbol{v_{o2}} = (\mathbf{2 - 1.28}\ )\mathbf{V} = \mathbf{0.72}\ \mathrm{V}$$

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!



$v_{o1} = 1\ \mathrm{V}$

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**

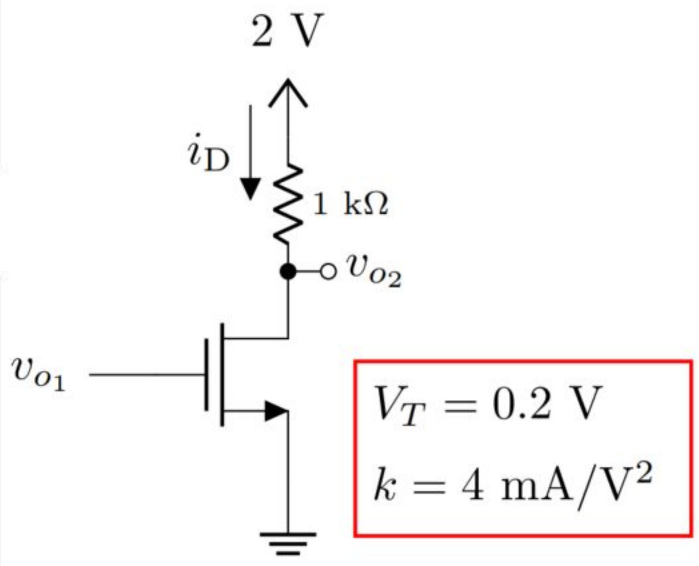
Solve:

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

Solving Equations →

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

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



$v_{o1} = 1\,\mathrm{V}$

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!

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, $v_{BE} = 0.7\ V$

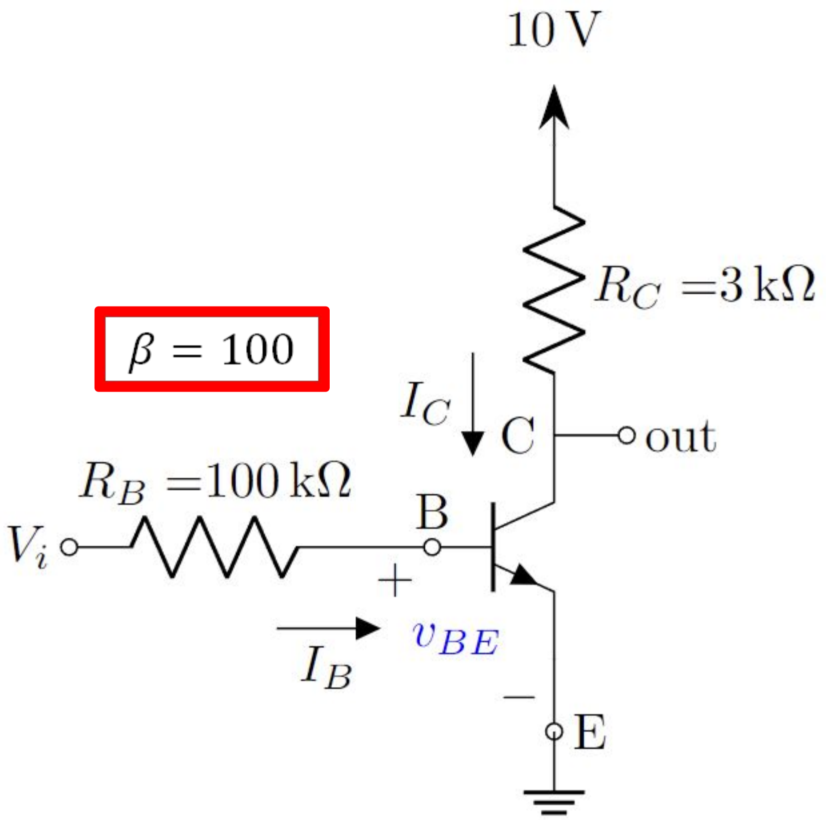
$v_{CE} > 0.3\ \mathrm{V}$

Solve:

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

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

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



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

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

Assumption is Correct!

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, $v_{BE} = 0.7\ V$

$v_{CE} > 0.2\ \mathrm{V}$

Solve:

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

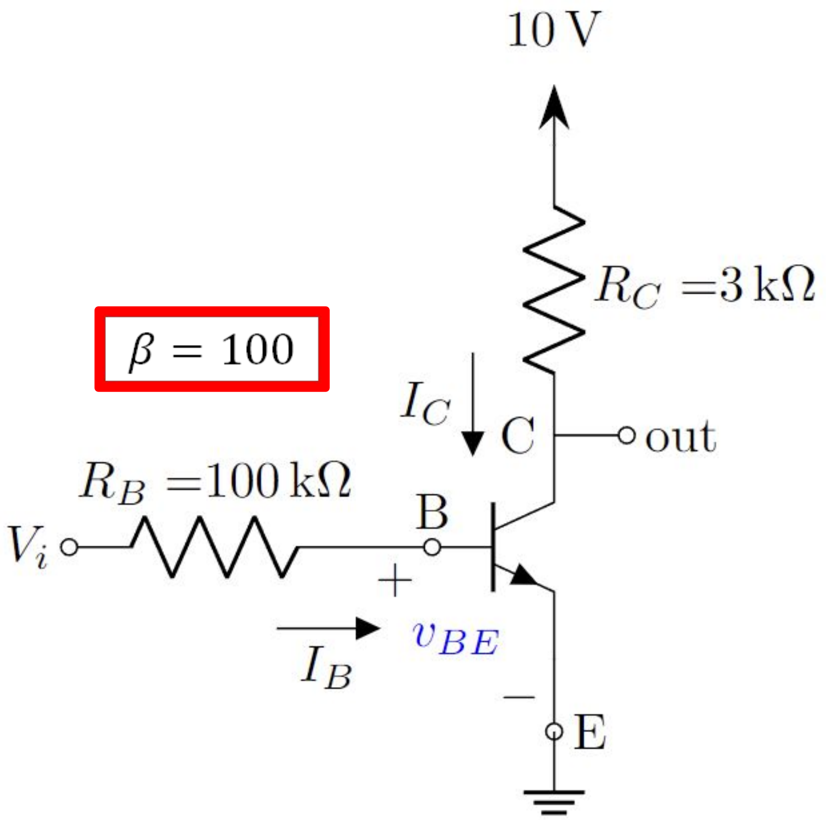
$$\boldsymbol{I_C} = \beta I_B = 100 \times 43 \times 10^{-3}\ \mathrm{mA} = \mathbf{4.3\ mA}$$

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

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

Here, $v_{CE} = v_{out} = \mathbf{-2.9}\ \mathrm{V} \ngtr 0.2\ \mathrm{V}$

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

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

Solve:

Equations:

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

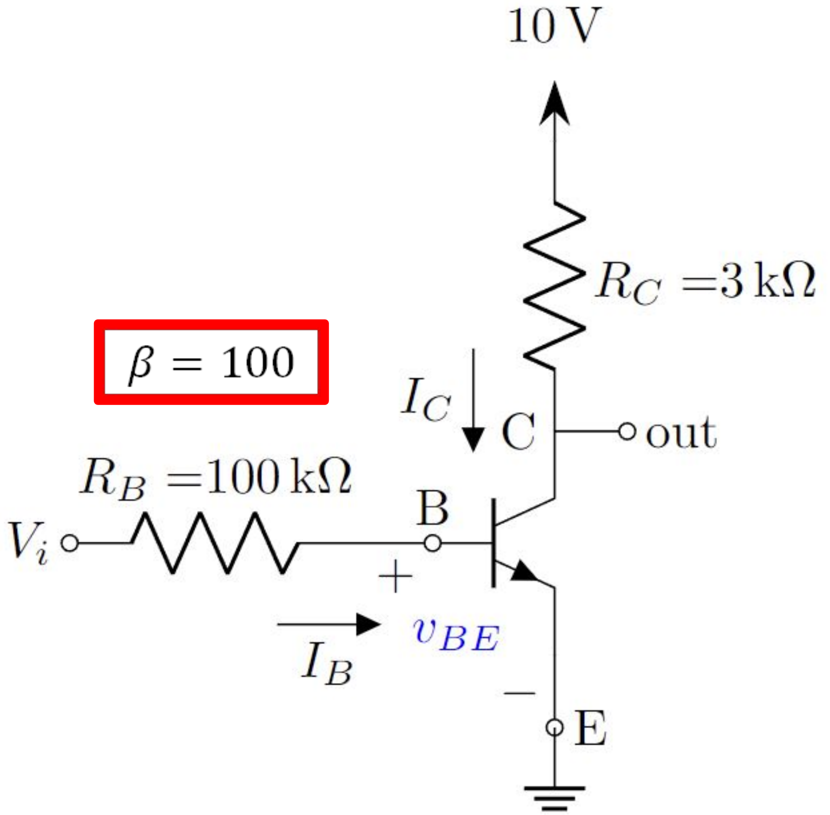
$$\boldsymbol{I_C} = \cancel{\beta I_B}\ \frac{10-v_{CE}}{R_C} = \frac{10-0.2}{3}\mathrm{mA} = \mathbf{3.27\ mA}$$

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

Verify: For **Saturation** condition $\rightarrow \dfrac{\boldsymbol{I_C}}{\boldsymbol{I_B}} < \boldsymbol{\beta}$

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

$\boxed{\beta = 100}$



Assumption is Correct!

BJT Problem 2

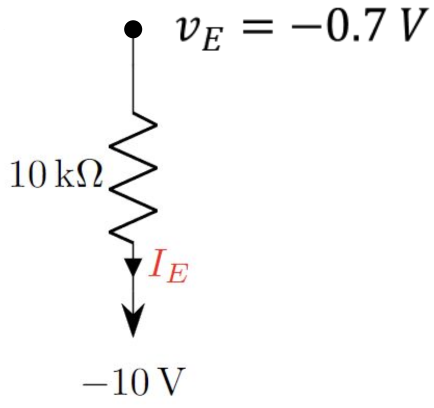
Analyze the circuit to find $\boldsymbol{I_B}, \boldsymbol{I_C}, \boldsymbol{I_E}$ and $\boldsymbol{v_{out}}$ using the Method of Assumed State. You must validate your assumptions.

Assume:

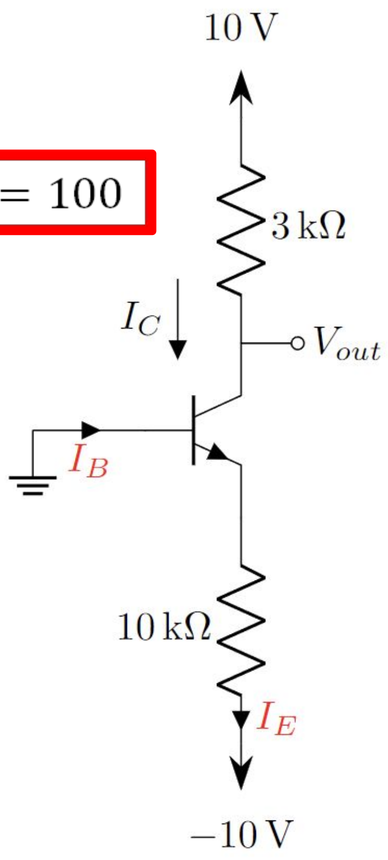
Let the BJT be in **Active** mode

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

$v_{CE} > 0.2\ \mathrm{V}$



$\beta = 100$

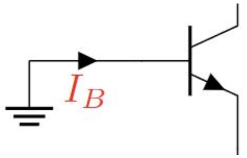


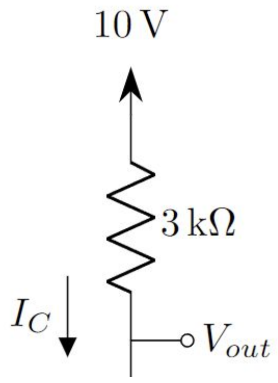
Solve:

Equations:

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

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





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

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

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

BJT Problem 2

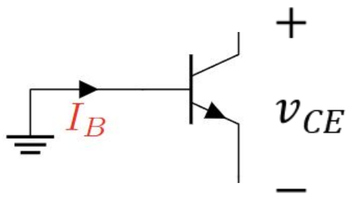
Analyze the circuit to find $\boldsymbol{I_B}, \boldsymbol{I_C}, \boldsymbol{I_E}$ and $\boldsymbol{v_{out}}$ using the Method of Assumed State. You must validate your assumptions.

Assume:

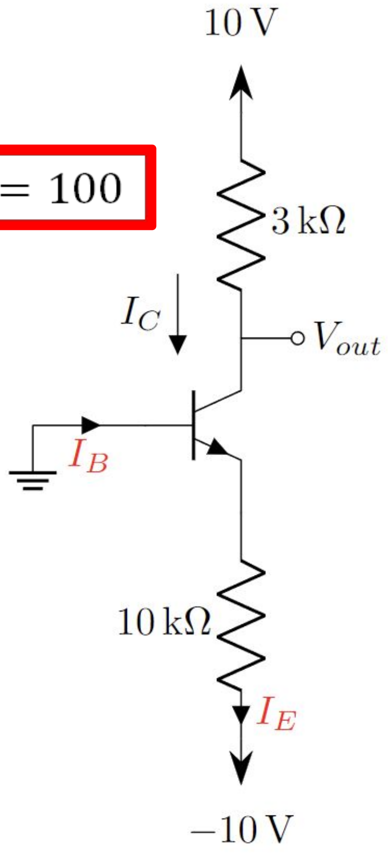
Let the BJT be in **Active** mode

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

$v_{CE} > 0.2\ \mathrm{V}$



$\boxed{\beta = 100}$



Solve:

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

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

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

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

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

Assumption is Correct!