

CSE251: Electronic Devices and Circuits

Lecture: 20 - 22 – BJT

Prepared By:

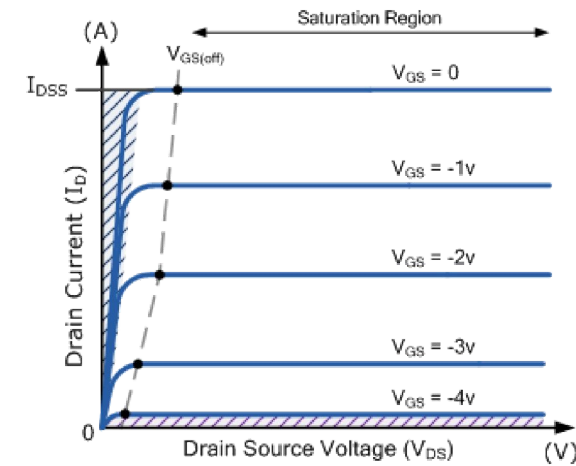
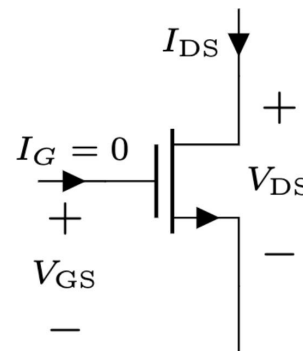
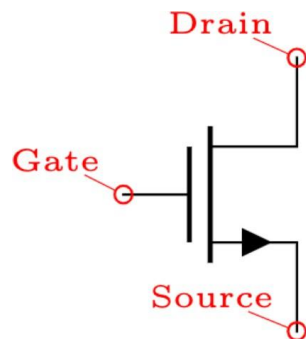
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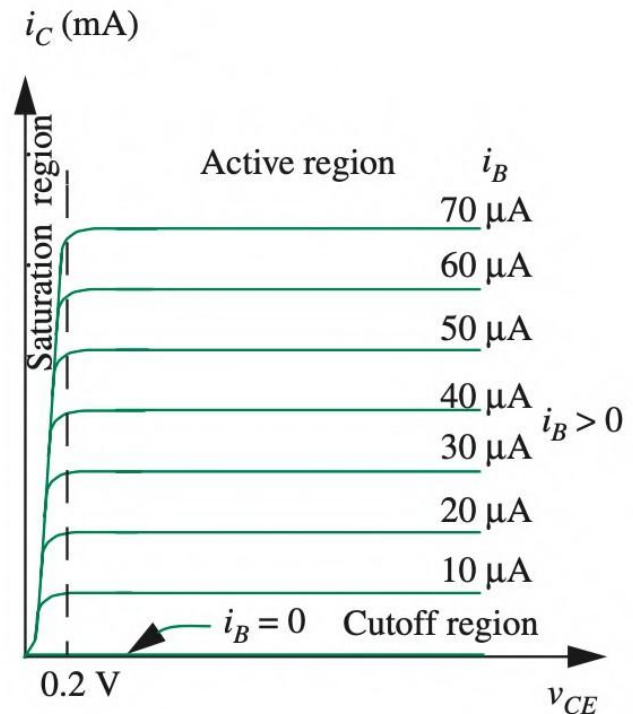
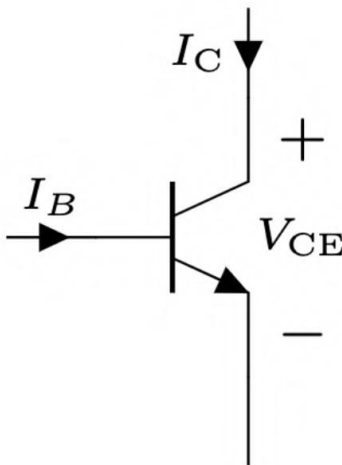
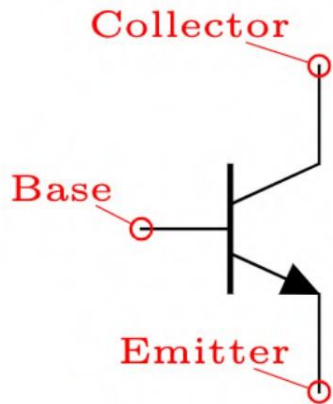
Transistors as Digital Switch

- 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, $C = V_{GS}$. 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)



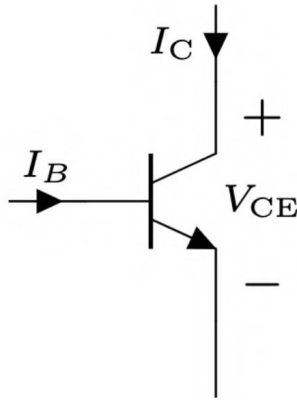
Bipolar Junction Transistor

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



BJT vs MOSFET - Differences

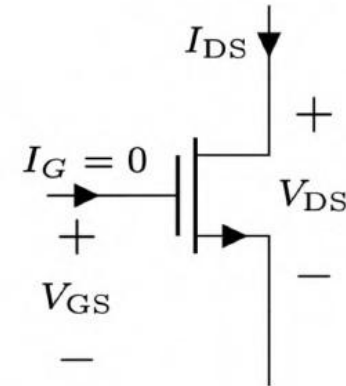
BJT



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

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

MOSFET

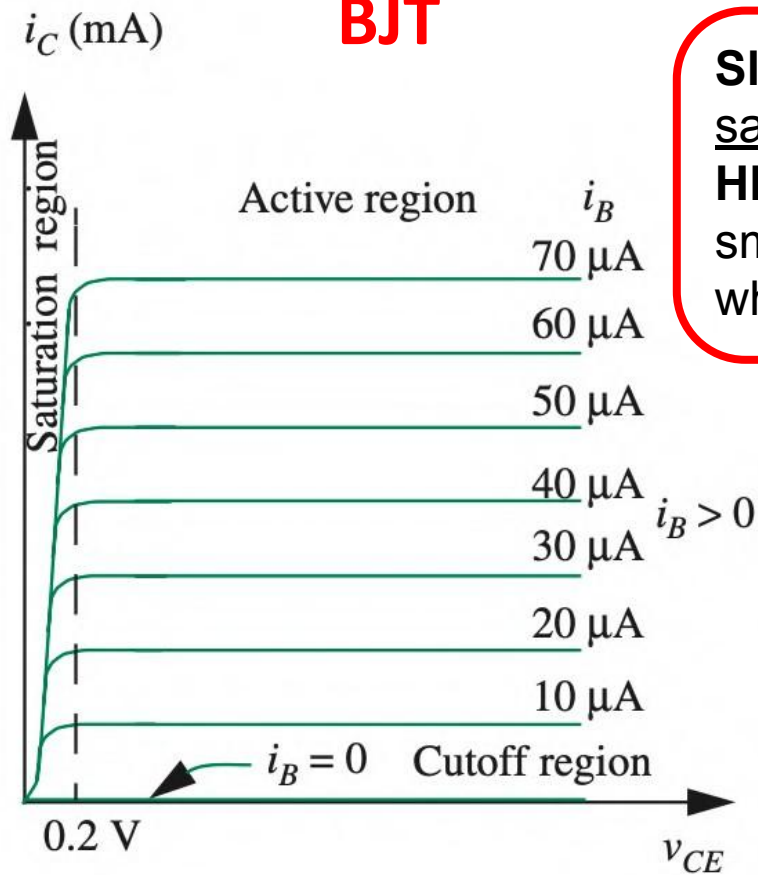


Voltage controlled, V_{GS} controls (I_{DS} vs V_{DS})

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

BJT vs MOSFET - Differences

BJT

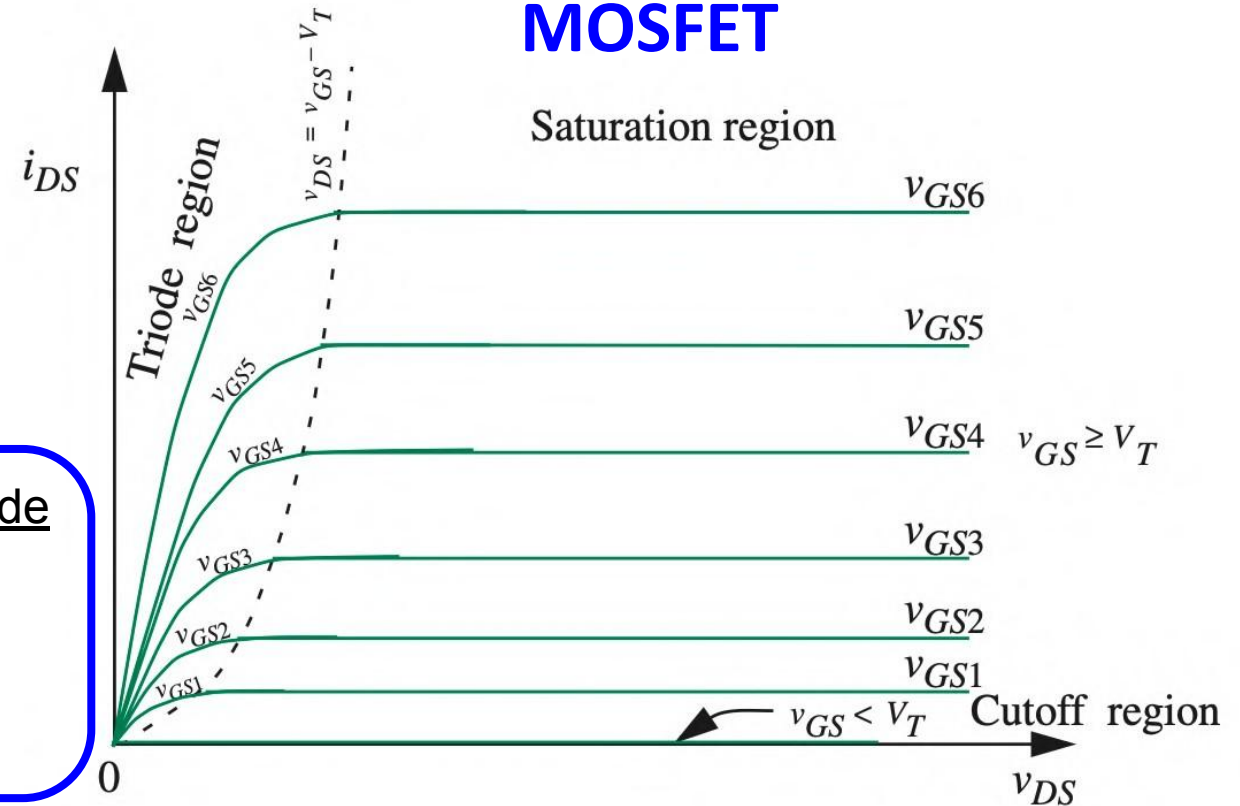


Slope in the saturation region is **HIGH**, hence very small resistance when "ON"

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

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

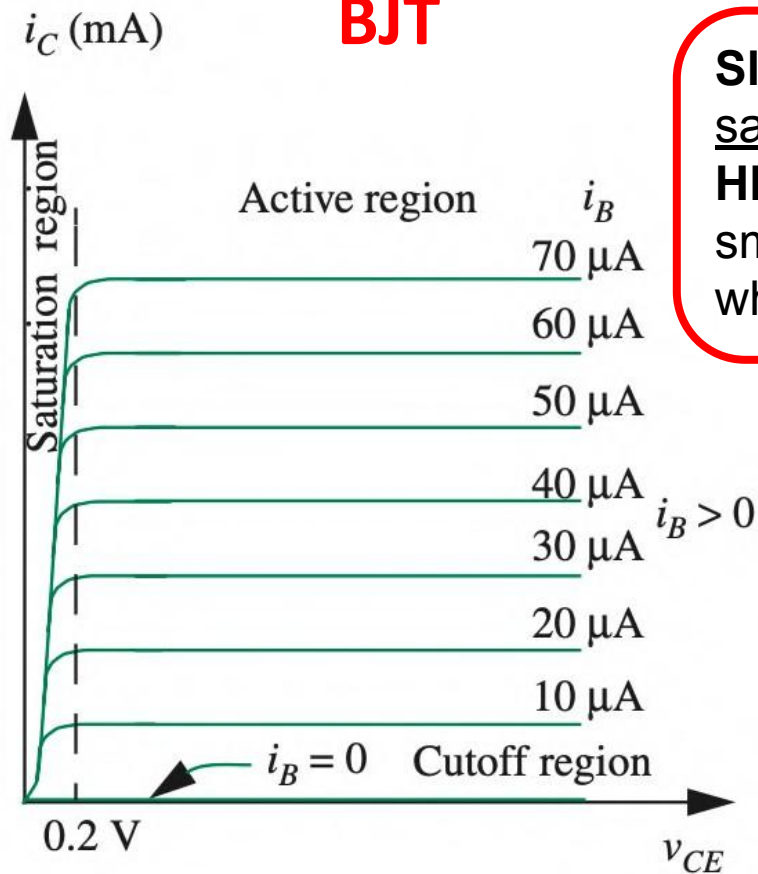
MOSFET



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

BJT vs MOSFET - Differences

BJT

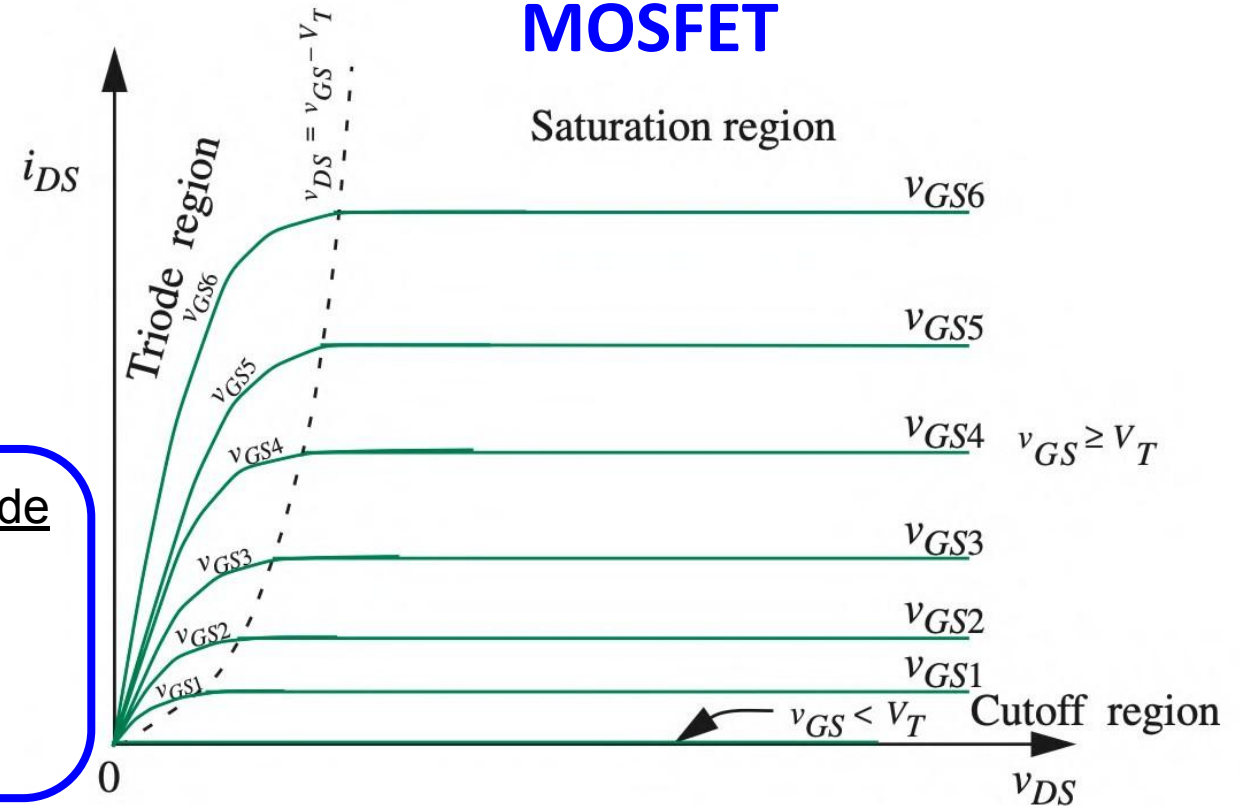


Slope in the saturation region is **HIGH**, hence very small resistance when “ON”

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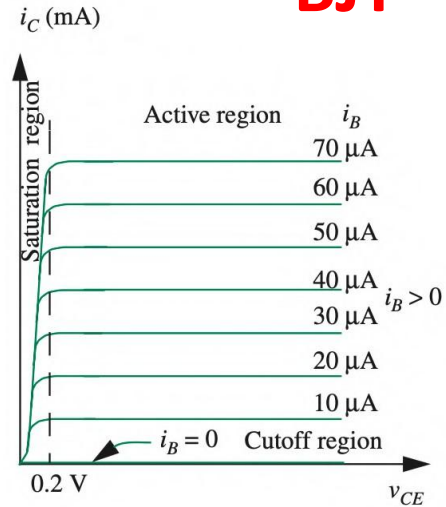
MOSFET



Current in **Saturation** region changes quadratically with control V_{GS} .
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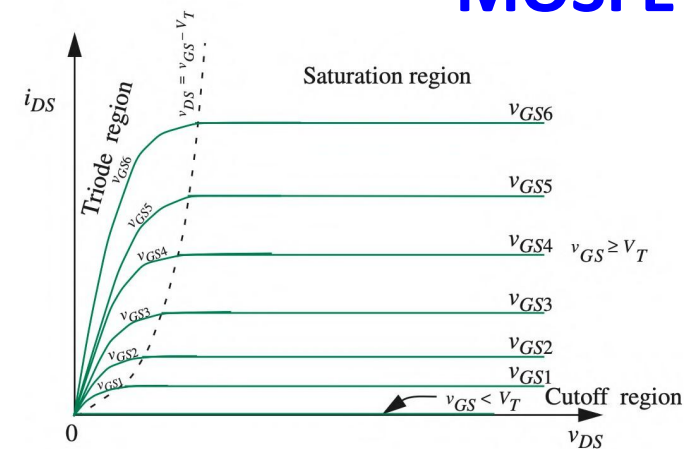
BJT vs MOSFET - Similarities

BJT



- **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 \Rightarrow S-Model!

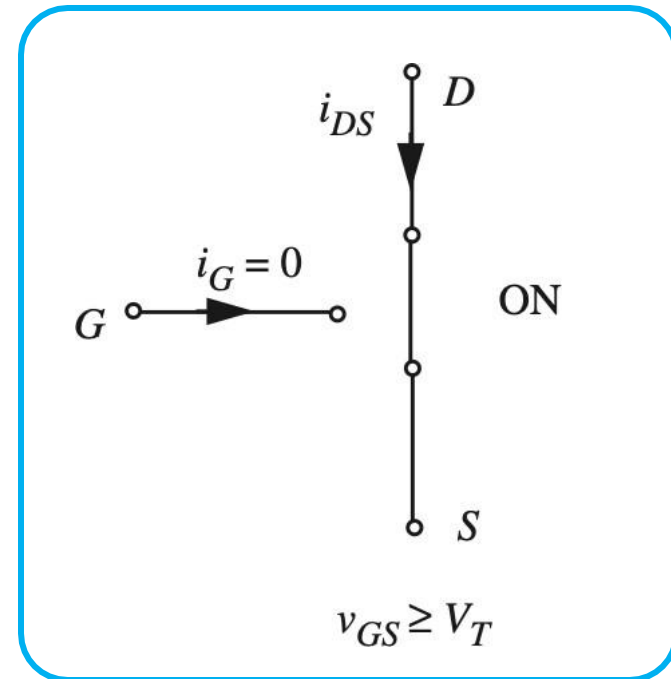
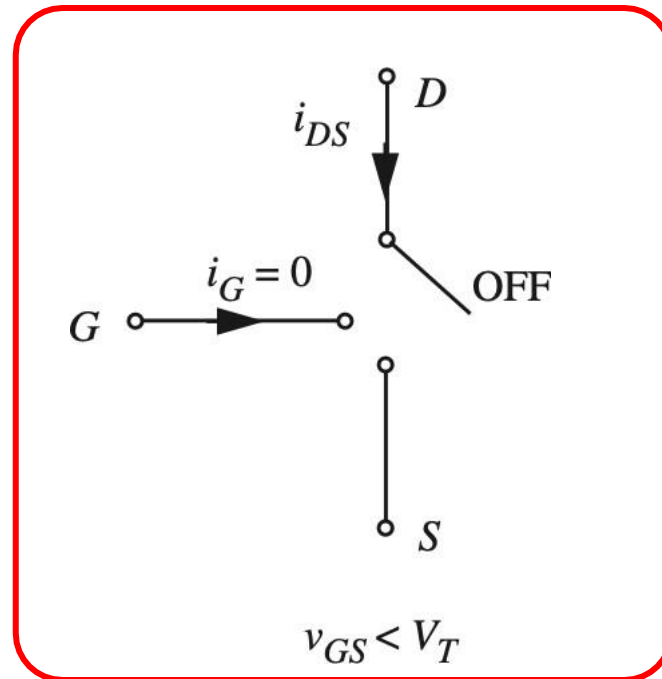
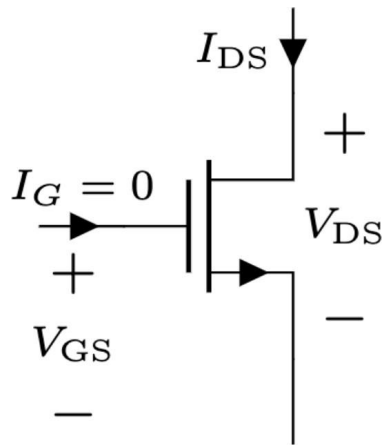
MOSFET



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

MOSFET S-Model

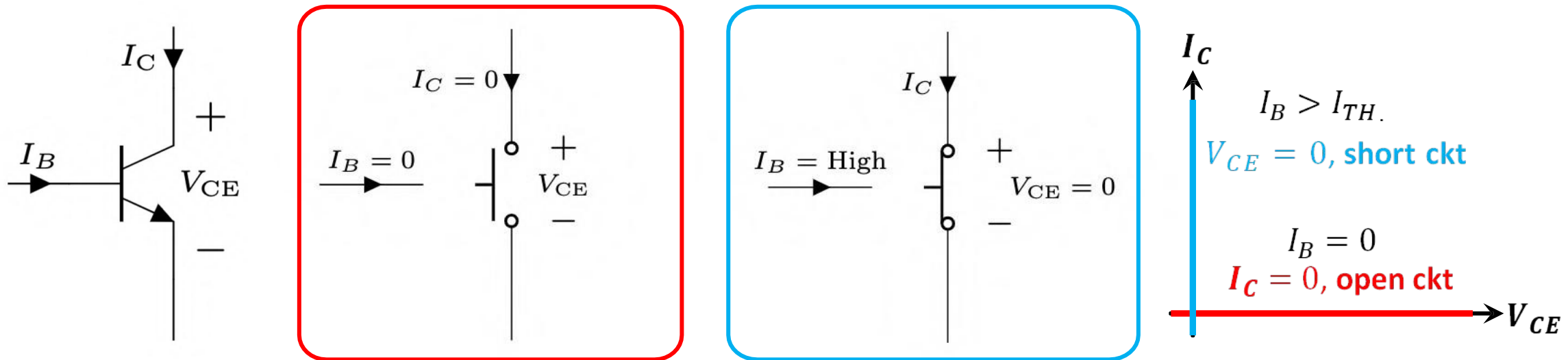
- The MOSFET (approximately) behaves like a switch
- $C = V_{GS}$. Here, $C = \text{"0"} \Rightarrow V_{GS} < V_T$, and $C = \text{"1"} \Rightarrow V_{GS} > V_T$



BJT S-Model

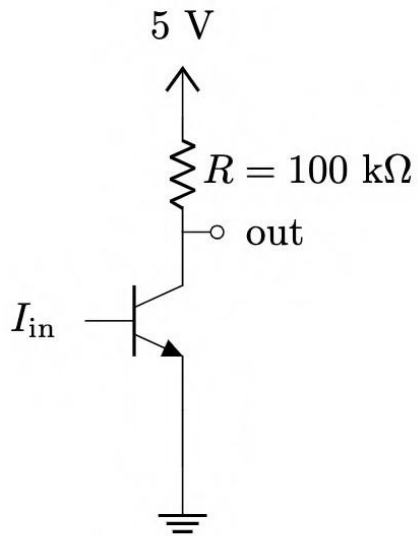
	Representation
Logic 0	
Logic 1	

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

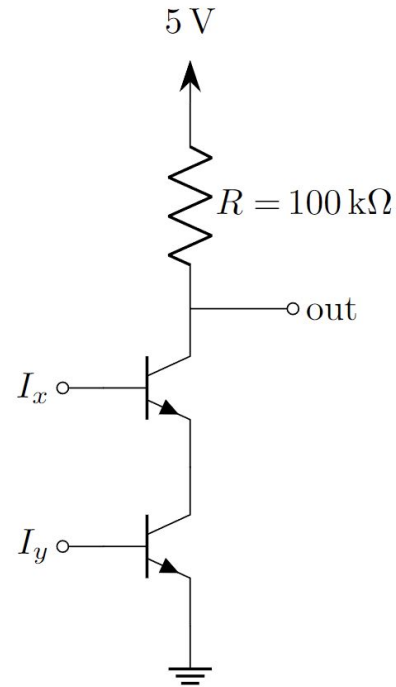


Current-Controlled Logic Gates using BJT

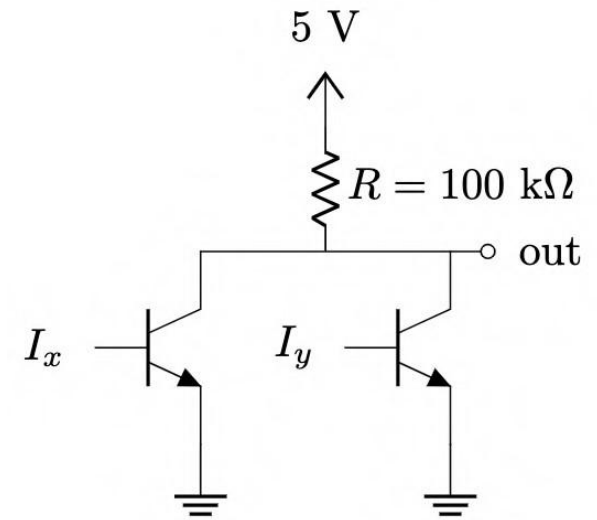
- Just replace switches with BJTs!
- Major problem: Cannot cascade! (Why?)
 - Input Logic Variable: **Current**
 - Output Logic Variable: **Voltage**



BJT Inverter (NOT Gate)



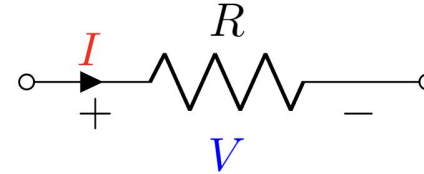
BJT NAND Gate



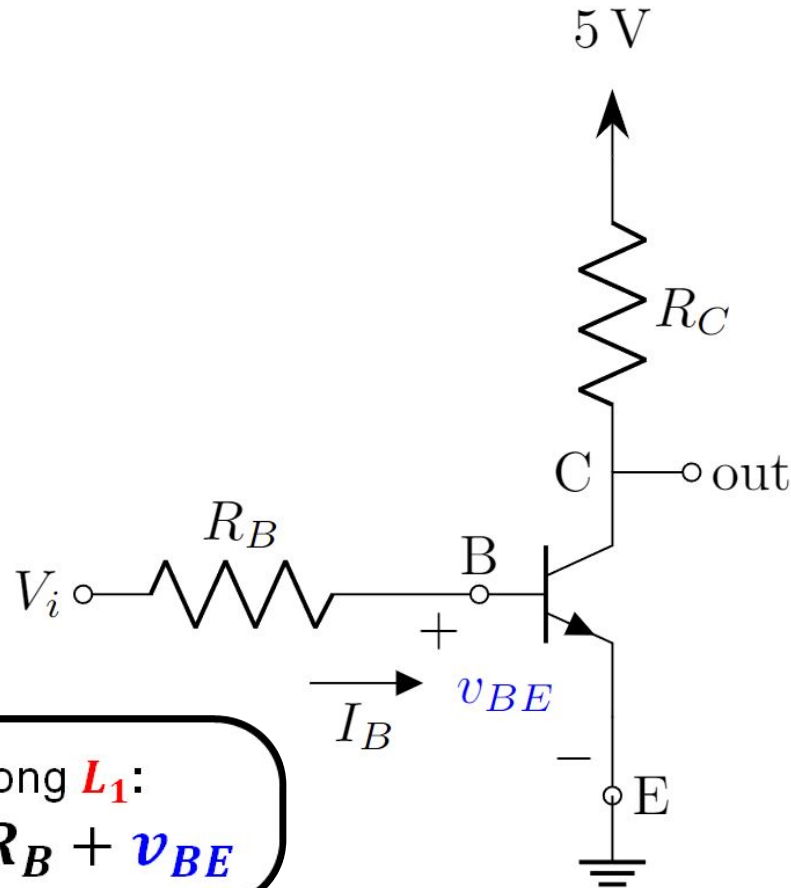
BJT NOR Gate

From Current Controlled to Voltage Controlled

How to convert current I into voltage V ?



$$V = IR$$



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

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

v_{BE} depends on I_B .

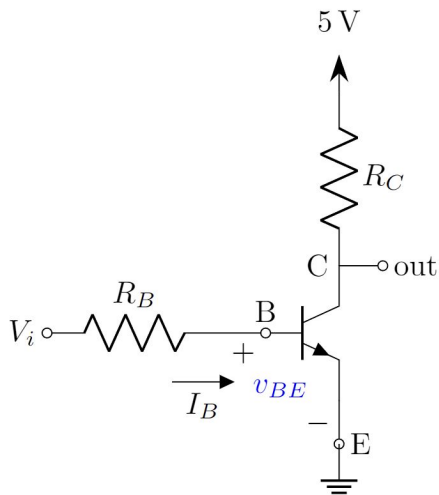
How?

KVL along L_1 :

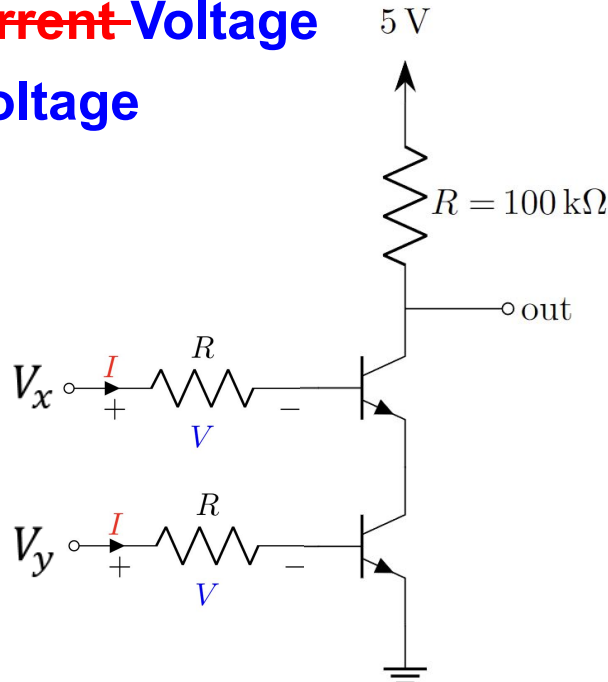
$$V_i = I_B R_B + v_{BE}$$

Logic Gates using BJT

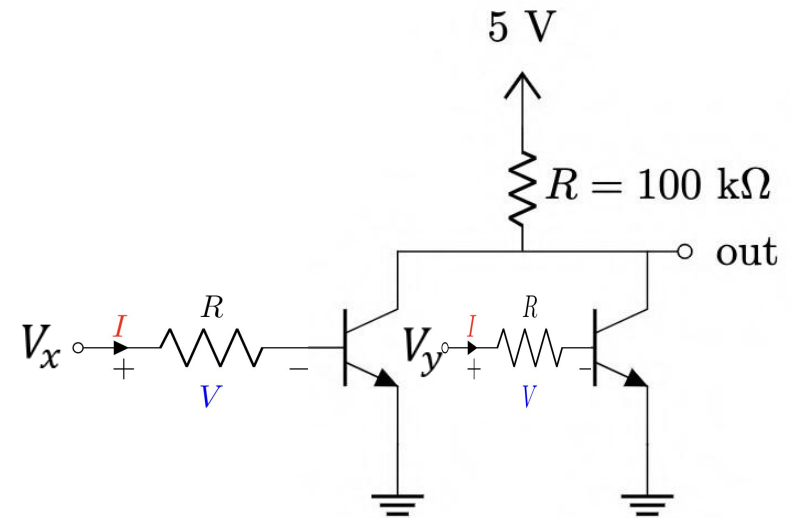
- Just replace switches with BJTs! – **and add a Resistor to the Base terminal**
- ~~Major problem: Cannot cascade! (Why?)~~ Can be cascaded.
 - Input Logic Variable: **Current-Voltage**
 - Output Logic Variable: **Voltage**



BJT Inverter (NOT Gate)



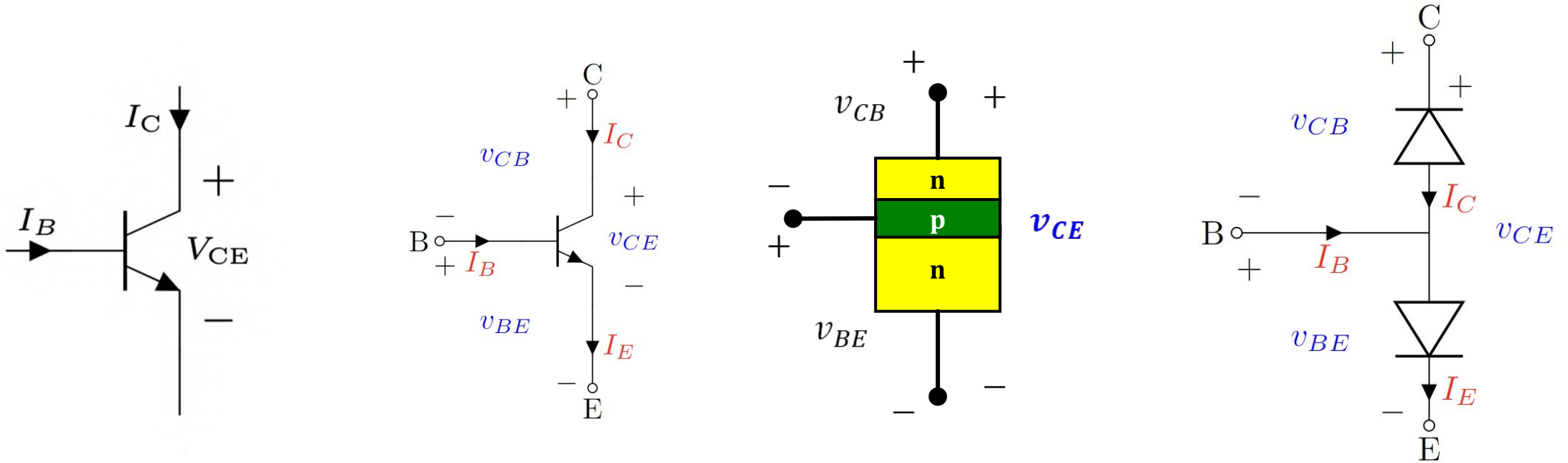
BJT NAND Gate



BJT NOR Gate

Parameters of BJT

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

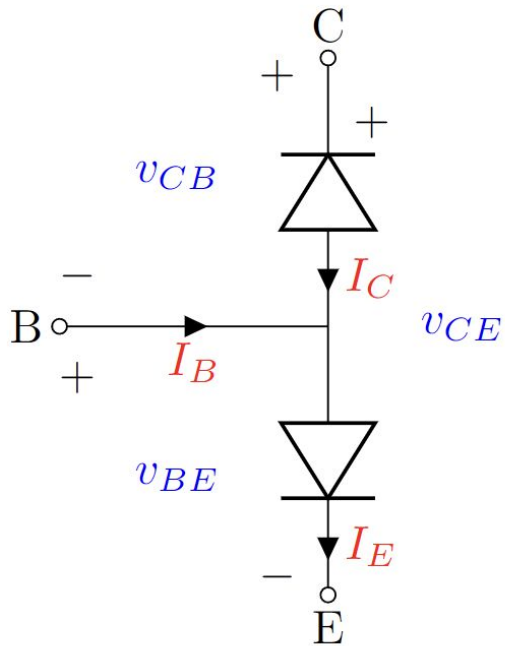


1st pn junction: Across **Base – Emitter**: Voltage v_{BE}

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.



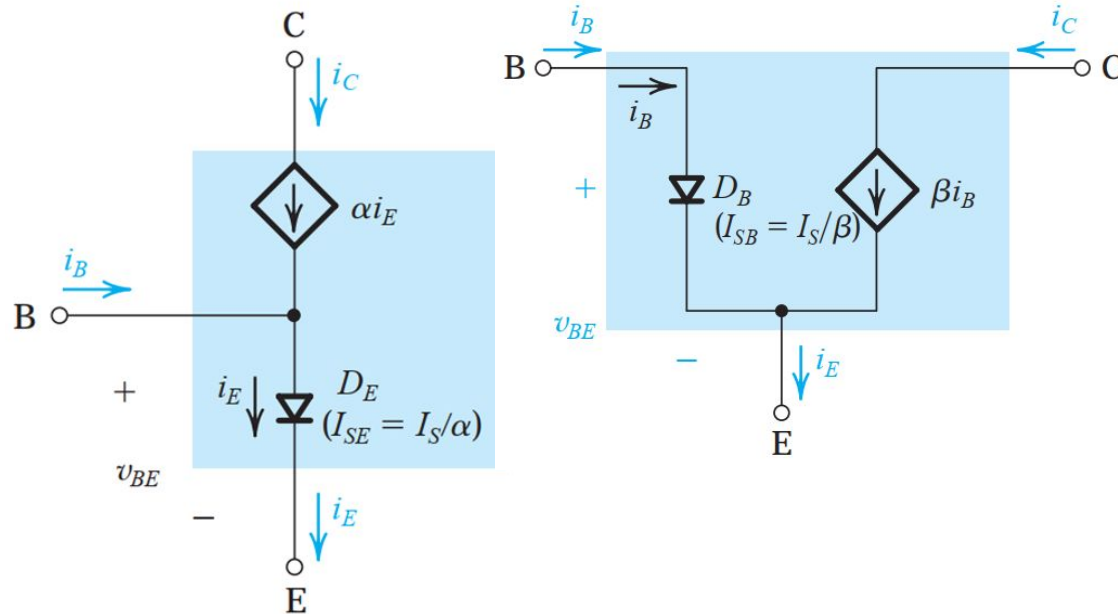
Modes	BE Junction		CB Junction		
Cut-off	Reverse Bias		Reverse Bias		
Active	Forward Bias		Reverse Bias		
Saturation	Forward Bias		Forward Bias		
Reverse Active	Reverse Bias		Forward Bias		

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

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

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

$$I_C = \beta I_B$$

$$I_C = \alpha I_E$$

Only valid for active mode

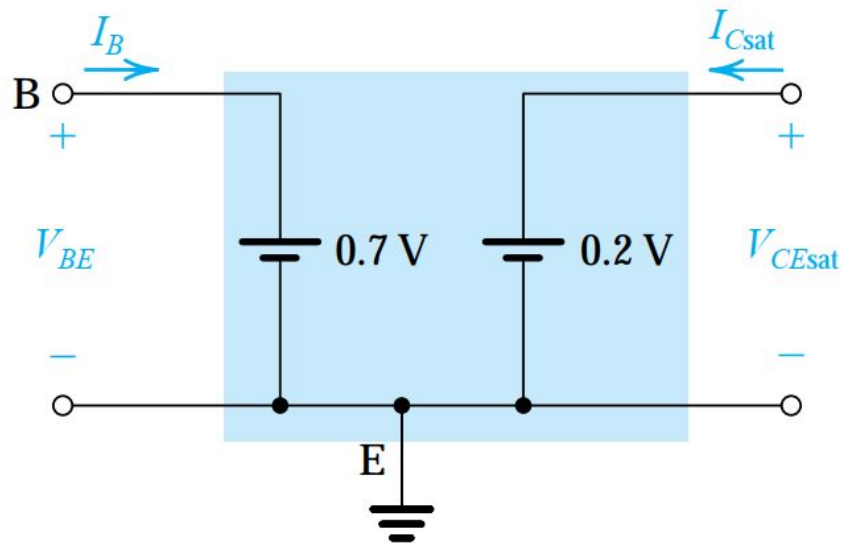
1st pn junction: Across **Base – Emitter**: Voltage v_{BE}

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

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

Parameters of BJT: Saturation Mode

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



Current relationships between the three currents in an npn BJT.

$$I_B + I_C = I_E$$

$$I_{C(sat)} < \beta I_B$$

$$I_C \neq \alpha I_E$$

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

Only valid for **Saturation** mode

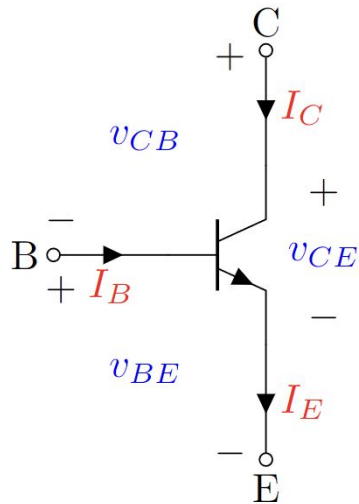
Figure 6.20 A simplified equivalent-circuit model of the saturated transistor.

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

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

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 V_{GS} v_{BE} and V_{DS} 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 i_D and v_{o2} using the Method of Assumed State. Here, the input of the MOSFET is $v_{o1} = 1\text{ V}$.

You must validate your assumptions.

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

Let the MOSFET be in **SATURATION**

Solve: corresponding equations:

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

Solving Equations \rightarrow

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

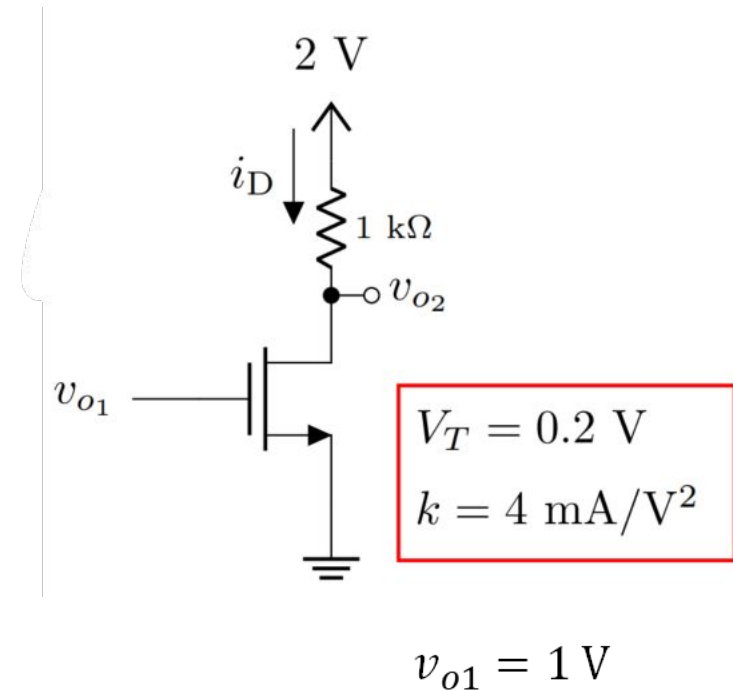
$$v_{o2} = (2 - 1.28) \text{ V} = 0.72 \text{ V}$$

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

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

$$v_{DS} = v_{o2} = 0.72 \text{ V} \not> 0.8 \text{ V}$$

Assumption is Wrong!



MOSFET Problem 1

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

You must validate your assumptions.

Assume:

Let the MOSFET be in **TRIODE**

Solve:

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

Solving Equations \rightarrow

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

$$2v_{o2}^2 - 4.2v_{o2} + 2 = 0$$

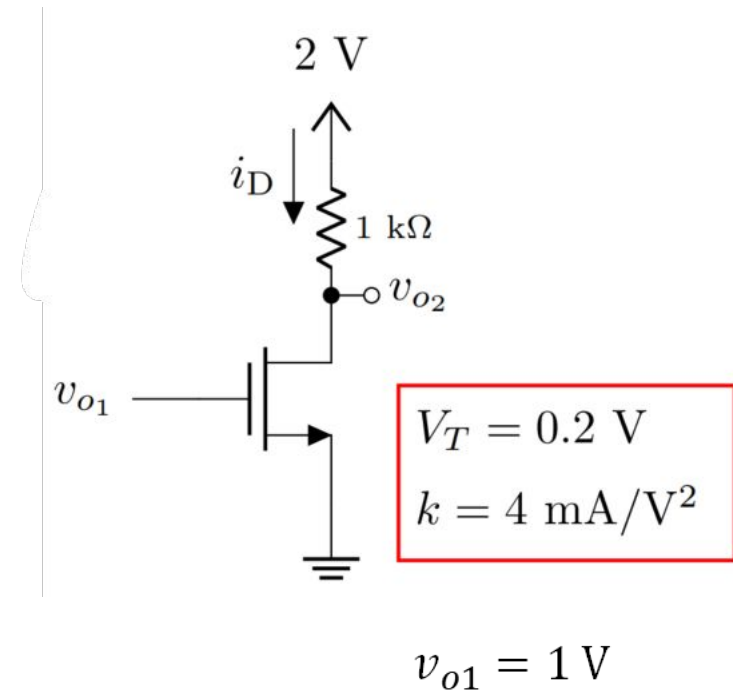
$$v_{o2} = \cancel{1.37\text{ V}} \text{ or } 0.73\text{ V}$$

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

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

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

Assumption is Correct!



BJT Problem 1

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

Assume:

Let the BJT be in **ACTIVE** mode

So, $v_{BE} = 0.7\text{ V}$
 $v_{CE} > 0.3\text{ V}$

Solve:

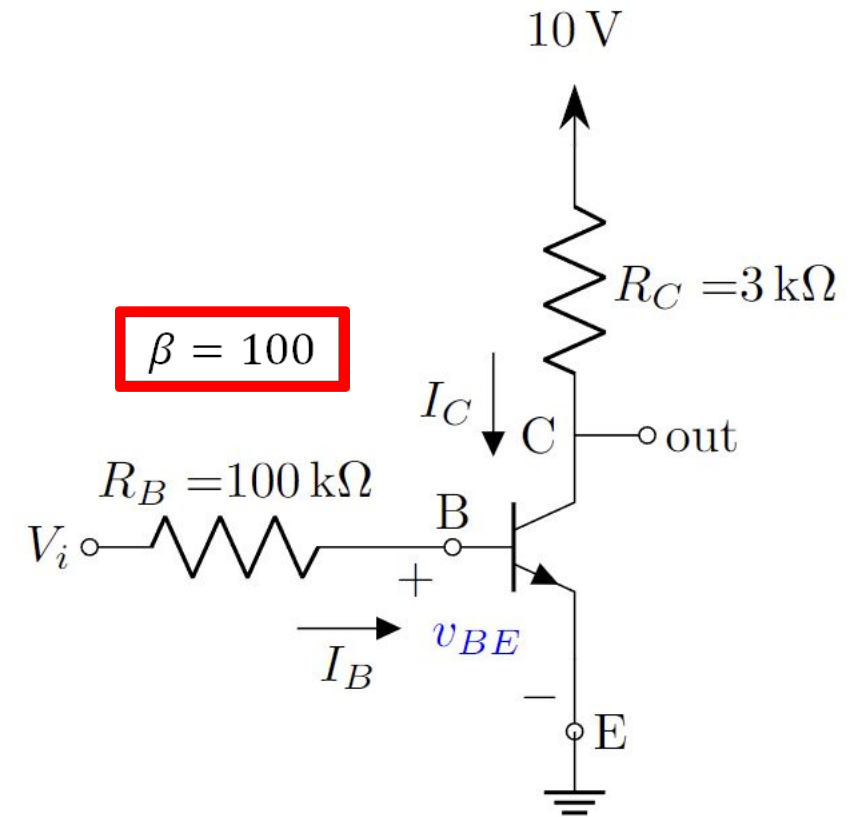
Equations:

$$I_B = \frac{V_i - v_{BE}}{R_B} = \frac{1 - 0.7}{100} \text{ mA} = 3\text{ }\mu\text{A}$$
$$I_C = \beta I_B = 100 \times 3 \times 10^{-3} \text{ mA} = 0.3\text{ mA}$$
$$v_{out} = 10 - I_C R_C = (10 - 0.3 \times 3) \text{ V} = 9.1\text{ V}$$

Verify: For **ACTIVE** condition $\rightarrow v_{CE} > 0.3\text{ V}$

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

Assumption is Correct!



BJT Problem 1

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

Assume:

Let the BJT be in **ACTIVE** mode

So, $v_{BE} = 0.7\text{ V}$
 $v_{CE} > 0.2\text{ V}$

Solve:

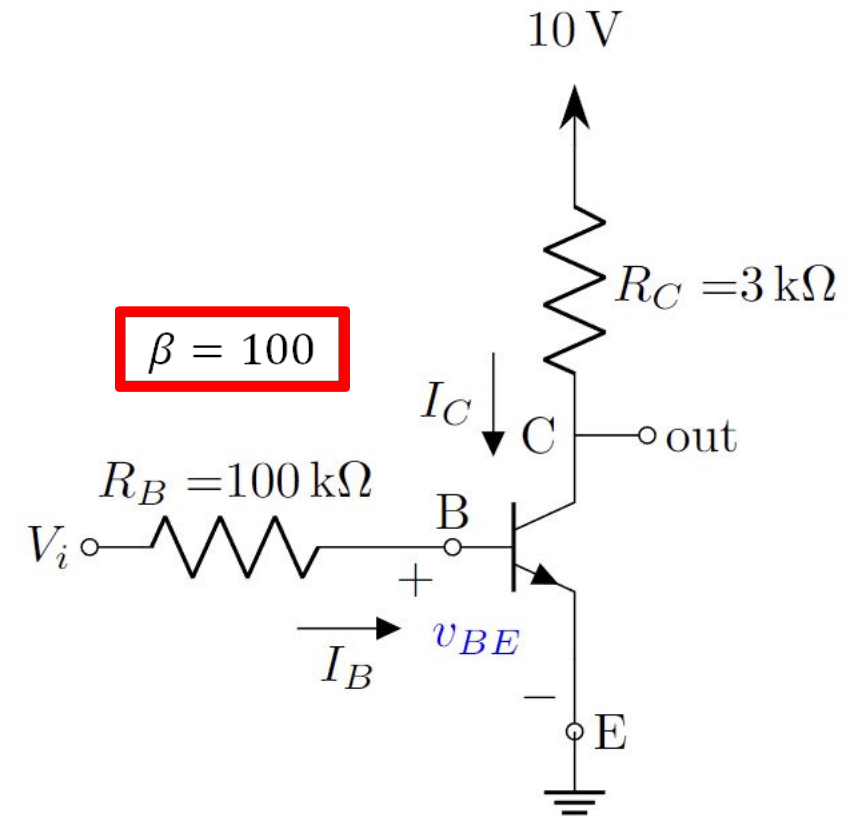
Equations:

$$I_B = \frac{V_i - v_{BE}}{R_B} = \frac{5 - 0.7}{100} \text{ mA} = 43 \mu\text{A}$$
$$I_C = \beta I_B = 100 \times 43 \times 10^{-3} \text{ mA} = 4.3 \text{ mA}$$
$$v_{out} = 10 - I_C R_C = (10 - 4.3 \times 3) \text{ V} = -2.9 \text{ V}$$

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

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

Assumption is Wrong!



BJT Problem 1

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

Assume:

Let the BJT be in **Saturation** mode

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

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

Solve:

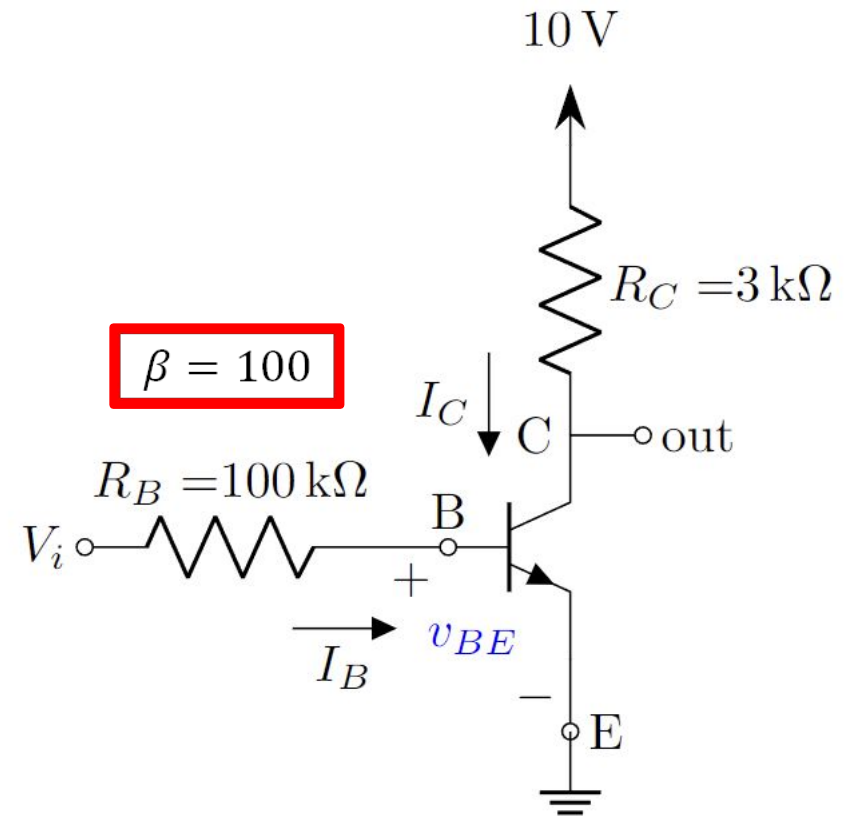
Equations:
$$I_B = \frac{V_i - v_{BE}}{R_B} = \frac{5 - 0.7}{100} \text{ mA} = 43\text{ }\mu\text{A}$$

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

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

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

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



Assumption is Correct!

BJT Problem 2

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

Assume:

Let the BJT be in **Active** mode

So,

$$v_{BE} = 0.7 \text{ V}$$

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

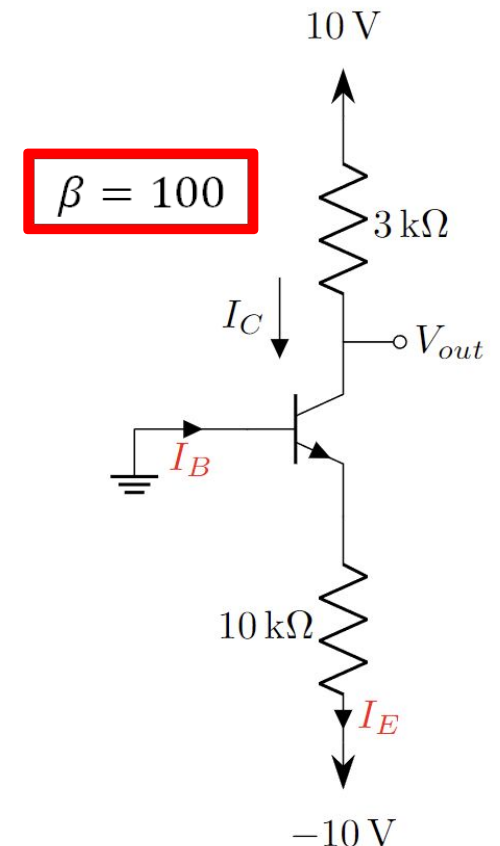
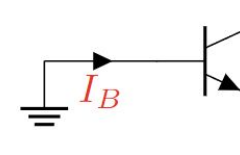
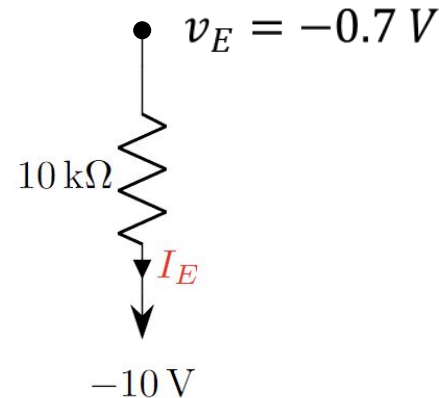
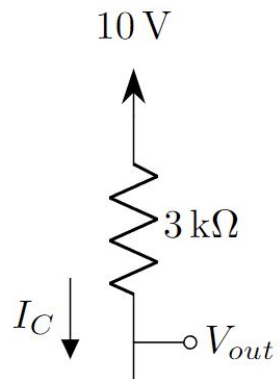
Solve:

Equations:

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

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

$$\begin{aligned} v_{out} = v_C &= 10 - 3I_C = 10 - 3\beta I_B \\ &= (10 - 3 \cdot 100 \cdot 9.207 \times 10^{-3}) \text{ V} \\ &= \mathbf{7.237 \text{ V}} \end{aligned}$$



BJT Problem 2

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

Assume:

Let the BJT be in **Active** mode

So, $v_{BE} = 0.7 \text{ V}$
 $v_{CE} > 0.2 \text{ V}$

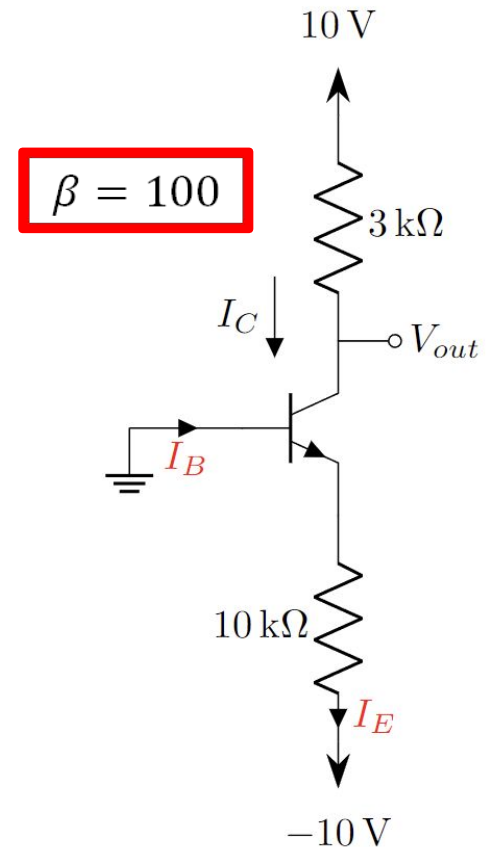
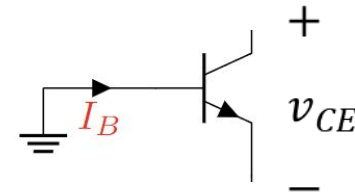
Solve:

Equations:

$$I_E = 0.93 \text{ mA}$$

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

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



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

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

Assumption is Correct!