# EE2013

# NON-LINEAR CIRCUIT ANALYSIS

## LECTURE 14: THE BJT

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Coordinator: Prof. Pádraig Cantillon-Murphy

# LECTURE SCHEDULE

Thursdays 11am-1pm
(with short break)

Back to usual this Thursday, 3rd March

# LECTURE NOTES

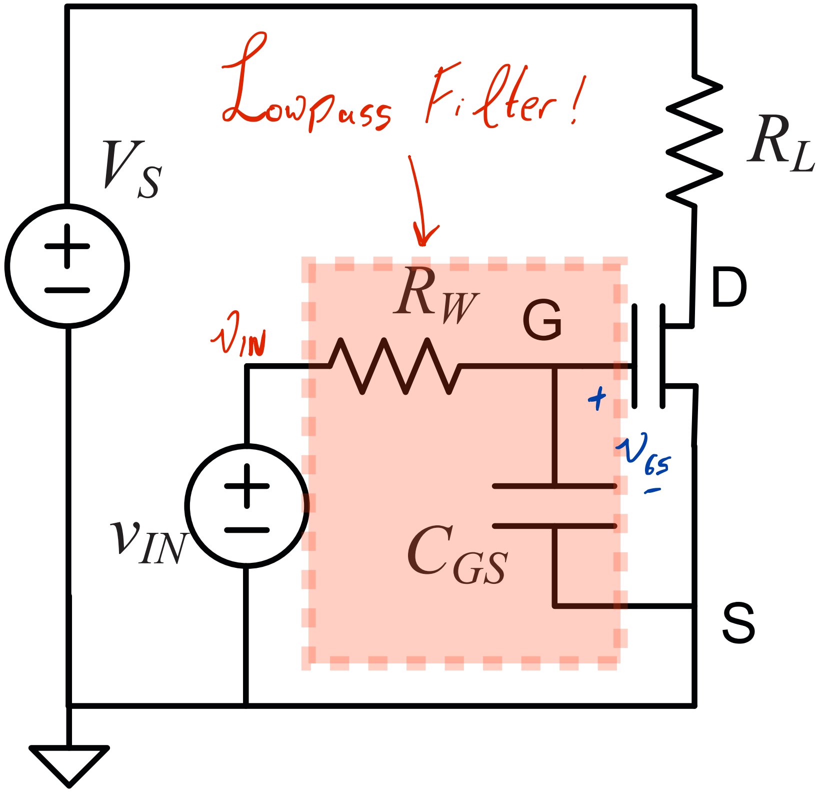
https://www.jaeger.ie/ee2013/lec14
Uploaded after lecture takes place

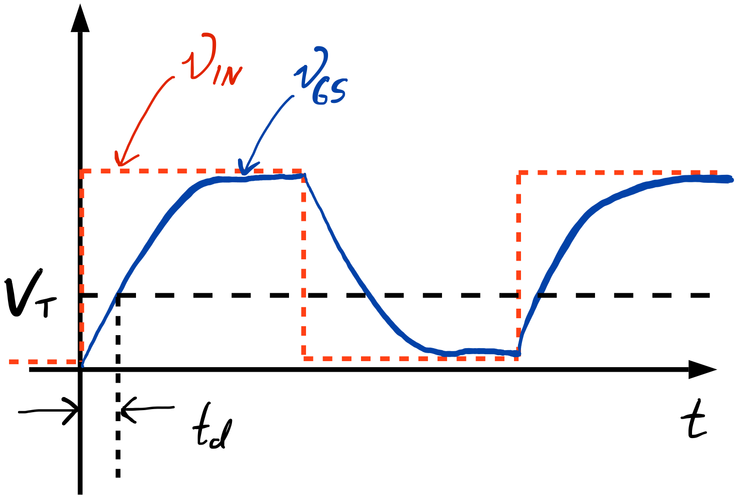
# QUESTIONS?

Just ask whenever it comes to you!
OR:
anthony.wall@mcci.ie on Email, Teams or Canvas

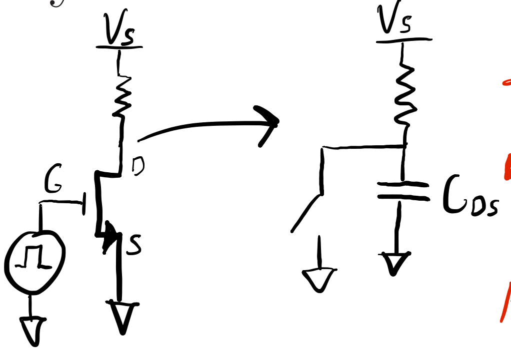
## 1 Review from last time

The MOSFET gate capacitance can have a significant impact on the response of the device in switching applications. For a MOSFET with a threshold voltage, $V_T$, $C_{GS}$ can result in measurable delay on turn-on. A typical power MOSFET might have $C_{GS} \approx$ 1-10 nF so that even for circuits switching in the kHz range with significant input resistance, delays at turn-on will inevitably occur.





As well as $C_{GS}$, there is also significant capacitance between the MOSFET drain and source, $C_{DS}$, which leads to dynamic power dissipation on switching. In a simple digital logic inverter operating at 50% duty cycle, the total power losses given below includes both dynamic and static dissipation.



$$\mathcal{E}_D = \frac{1}{2} C_{DS} V_s^2$$

2x per Cycle

f times per Second

$$P_{Dyn} = C_{DS} V_s^2 f$$

Total Power Dissipation:

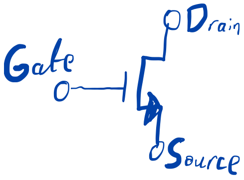
$$P_D = P_{STATIC} + P_{DYN}$$

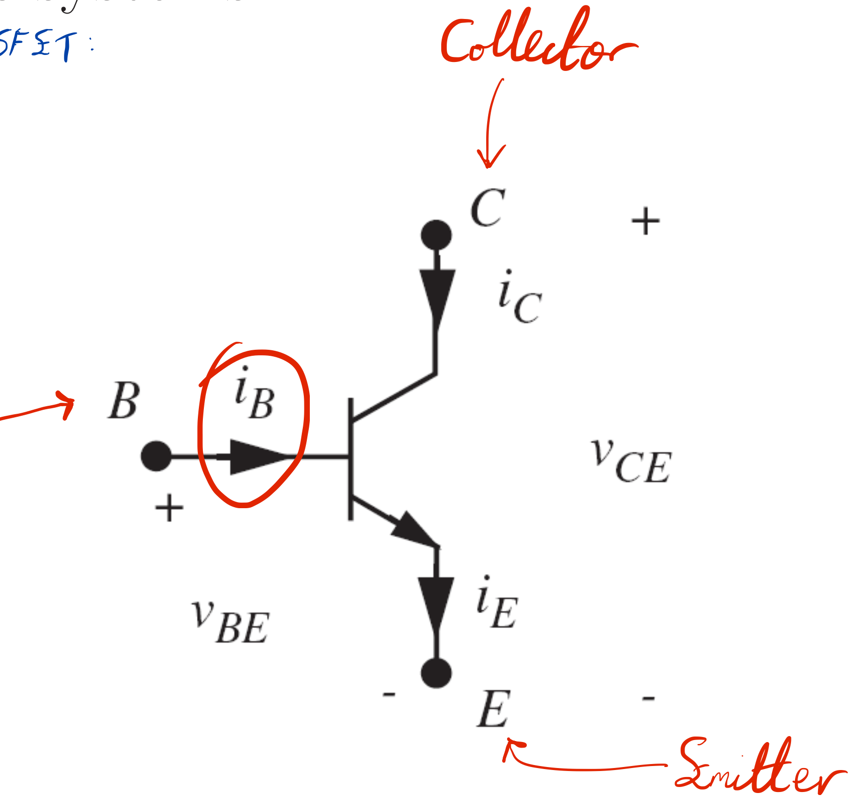
$$P_D = \frac{V_s^2}{2(R_L + R_{ON})} + C_{DS} V_s^2 f$$

# 2 The Bipolar Junction Transistor (BJT)

A second type of transistor is the bipolar junction transistor. Its circuit symbol and large-signal model are shown here. It finds application in demanding analogue circuits, especially for very-high-frequency applications, such as radio-frequency circuits for wireless systems.

Remember MOSFET:





CIRCUIT SYMBOL FOR BJT

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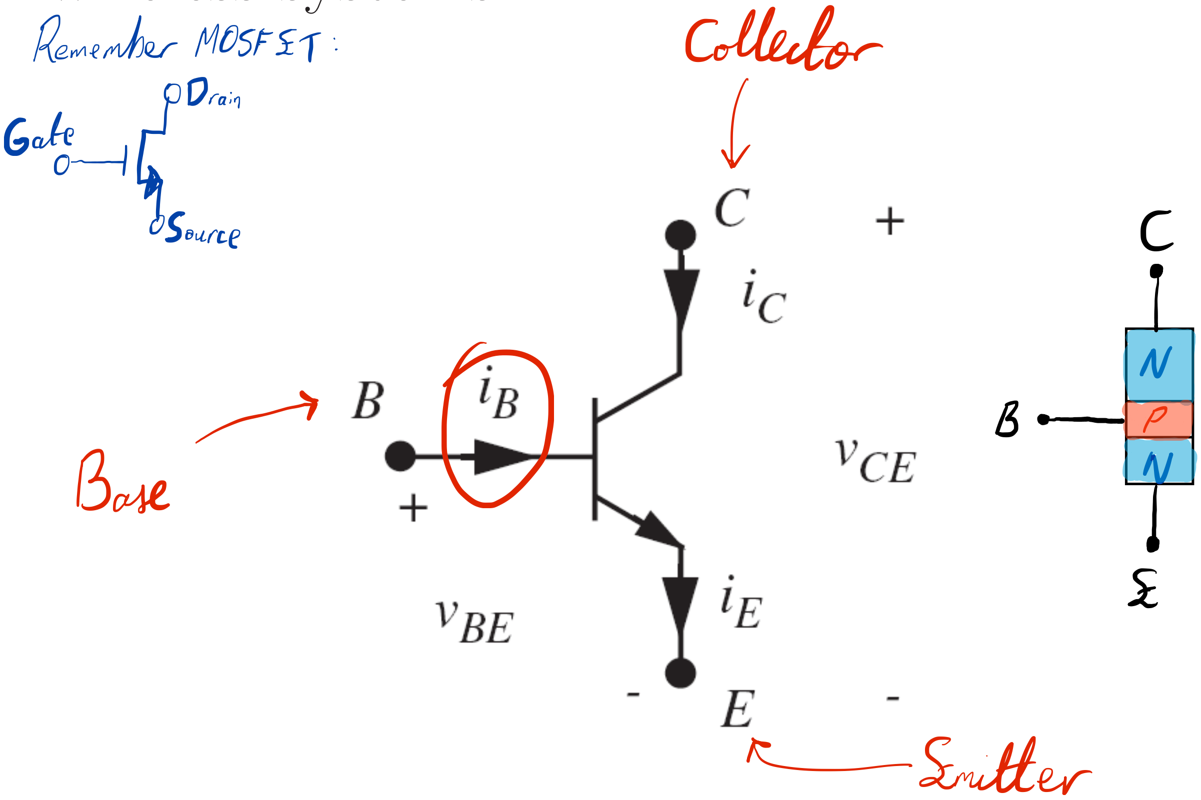
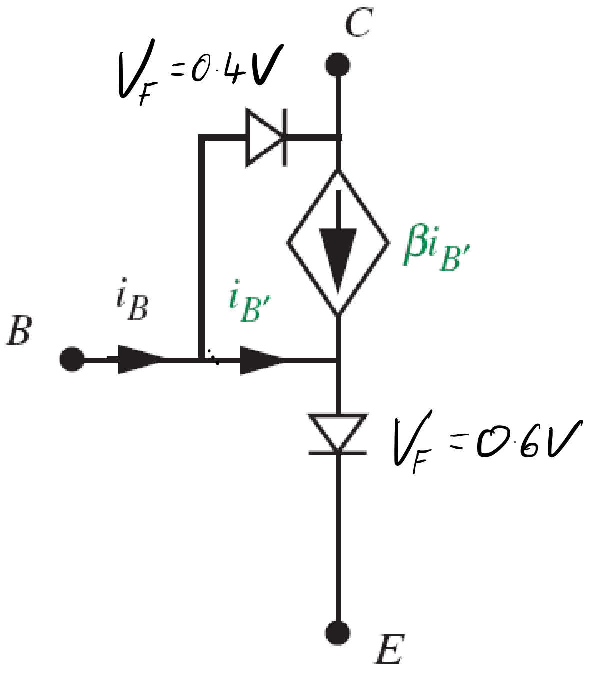
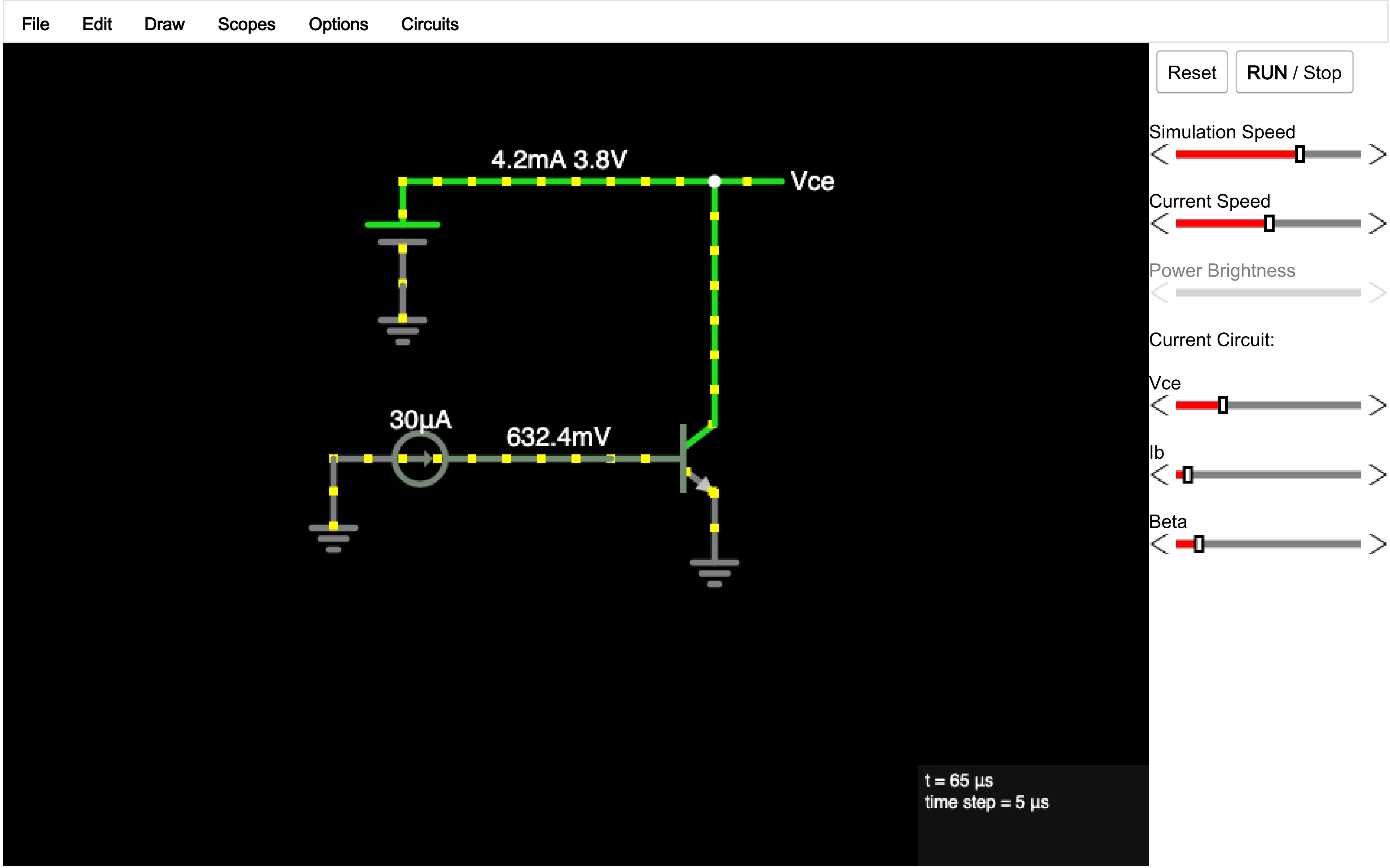




CIRCUIT SYMBOL FOR BJT

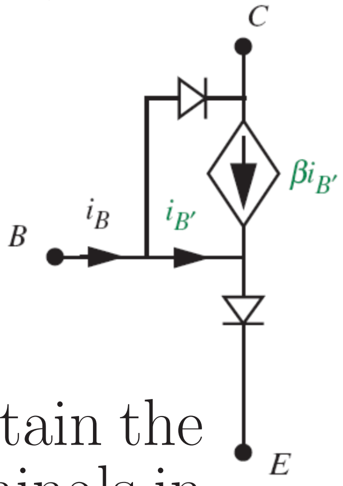
LARGE SIGNAL MODEL



```
t = 65 µs
time step = 5 µs
```

In the active region (where the device normally operates), the piecewise linear model for the BJT is as follows:

$$i_C = \begin{cases} \beta i_B & \text{if } i_B > 0 \text{ and } v_{CE} > v_{BE} - 0.4\text{V} \\ 0 & \text{otherwise} \end{cases}$$



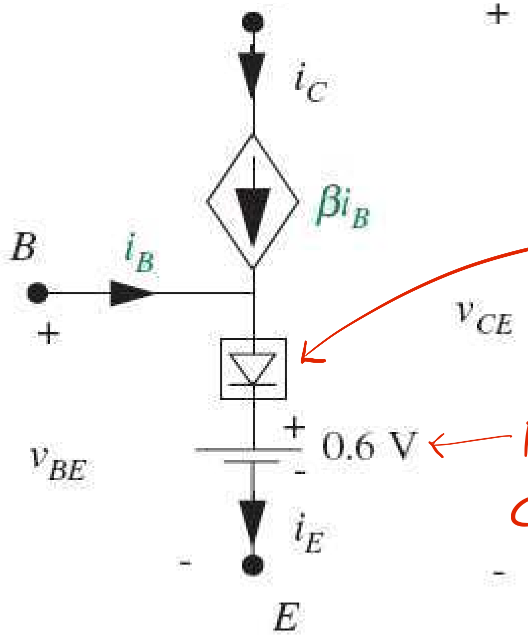
The second condition on $v_{CE}$ and $v_{BE}$ is necessary to maintain the internal diode between the base $(B)$ and collector $(C)$ terminals in reverse bias. Once this condition is satisfied, a simpler model can be used, shown below, where the internal potential drop across the base-emitter diode is approximately 0.6 V. The large signal model shown above only apply in the forward active region of operation.

$i_B \simeq i_B'$

$D_1$ Reverse Biased

$\Downarrow$

Ignore!



Ideal Diode
$V_F = 0$

$D_2$ forward Voltage
Captured by Voltage Source

SIMPLIFIED LARGE SIGNAL MODEL

The emitter (E) current, $i_E$, is given by KCL:

$$i_E = i_C + i_B$$

$$i_E = \beta i_B + i_B = i_B(\beta + 1)$$

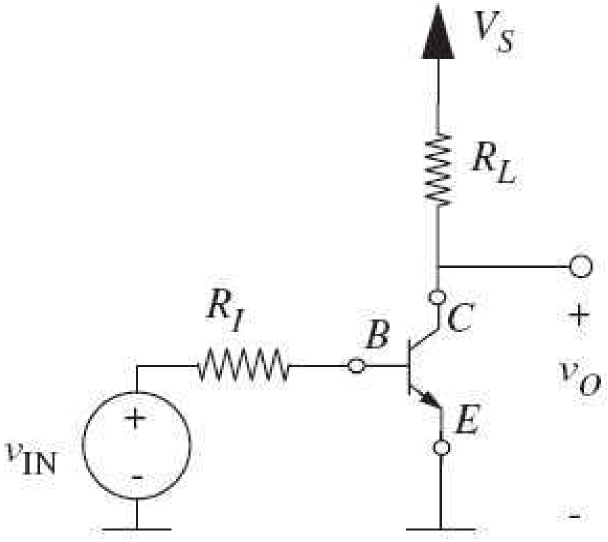
Usually $\beta >> 1$:

$$i_E \approx i_B(\beta)$$

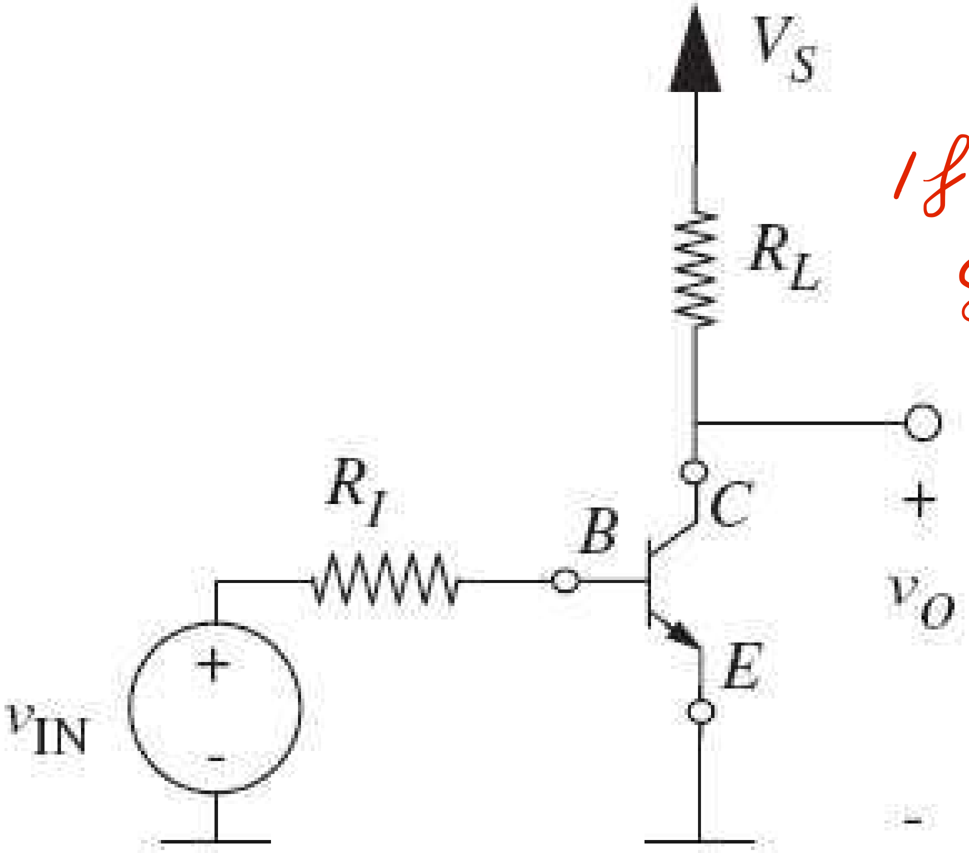
$$i_E \simeq i_C$$

## 3 The Common Emitter BJT Amplifier

The common emitter amplifier resembles the MOSFET common source amplified based on a BJT. This BJT amplifier configuration is called a common emitter amplifier since the emitter terminal of the BJT is common across the input and output ports. Using the piecewise-linear model for the BJT, we will determine the relationship between $v_O$ and $v_{IN}$, assuming that the BJT device is operating in its active region.

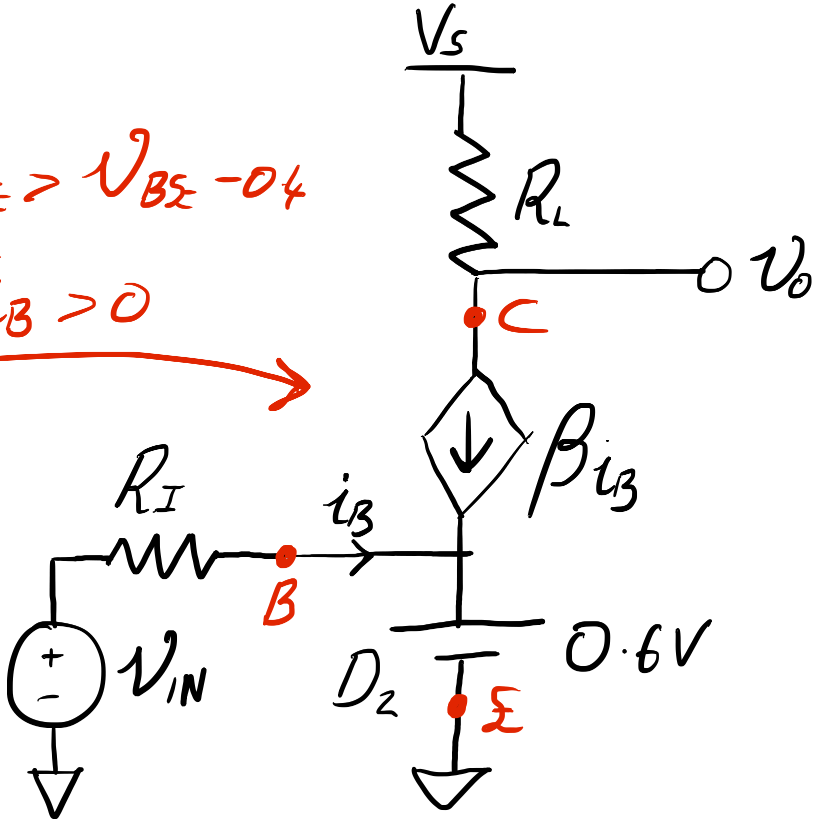


- If $v_{IN}$ ↑
- $V_{R_I}$ ↑ since $v_{BE}$ is constant
- $i_{R_I}$ ↑ (Ohm's law)
- $i_c$ ↑ since $i_c = \beta i_B$
- $v_{R_L}$ ⇑ due to $i_c$
- $v_o$ ⇓ due to $v_{R_L}$



If: $v_{CE} > v_{BE} - 0.4$

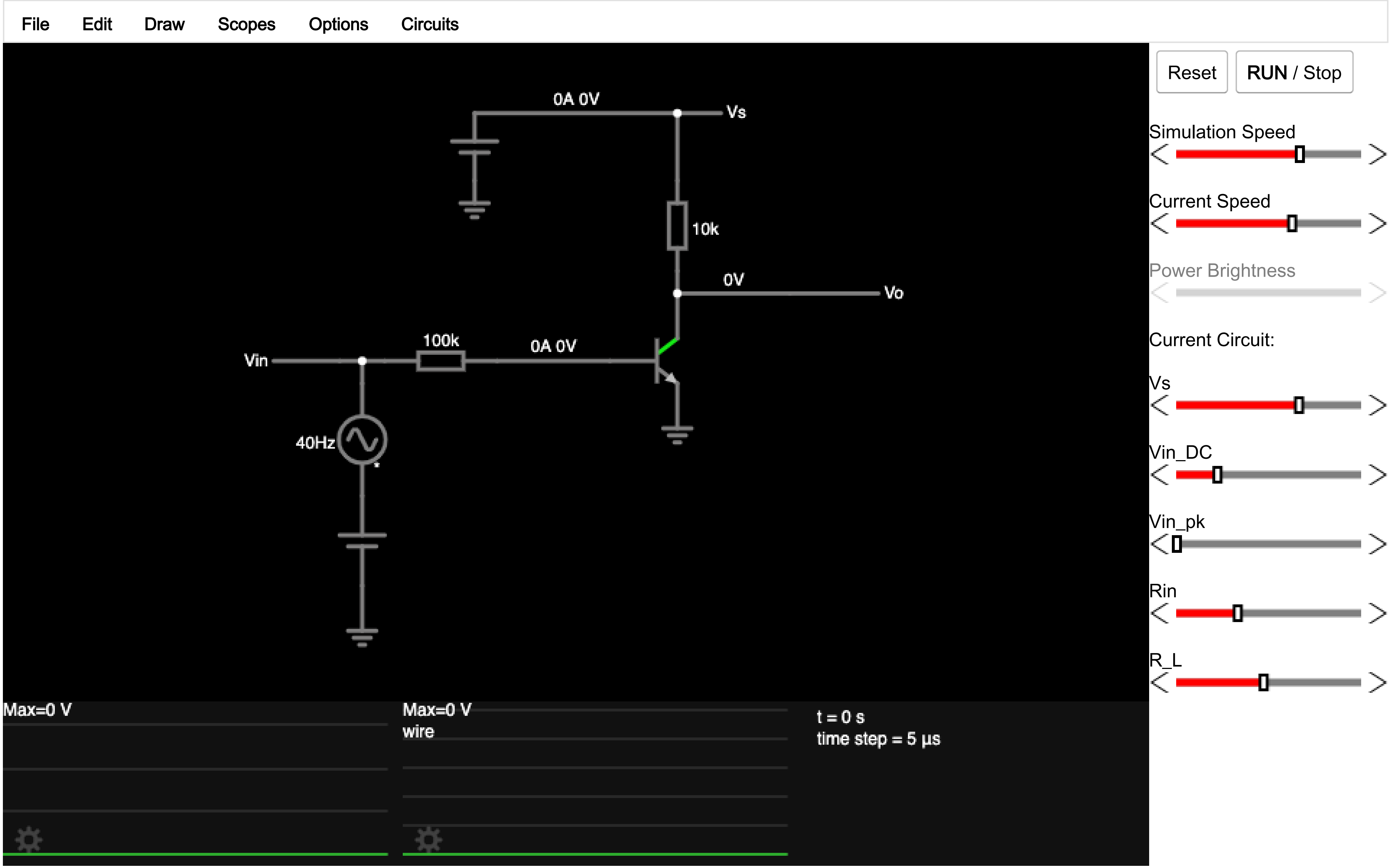
& $i_B > 0$



$$\Rightarrow v_{BE} \approx 0.6V \ \underline{\text{always}}$$

$$v_O = V_S - i_C R_L = V_S - (\beta i_B) R_L$$

$$v_O = V_S - \beta R_L \overset{i_B}{\boxed{\frac{(v_{IN} - 0.6)}{R_I}}}$$



Max=0 V

Max=0 V
wire

t = 0 s
time step = 5 µs

### 3.1 Numerical Example

We will analyse the common emitter amplifier for the following values; $R_I$ = 100 kΩ, $R_L$ = 10 kΩ, $\beta$ = 100, and $V_S$ = 10 V.

$$v_O = V_S - \beta R_L \frac{(v_{IN} - 0.6)}{R_I}$$

$$= 10 - (100)(10\times10^3)\frac{(v_{IN} - 0.6)}{100\times10^3}$$

$$= 10 - 10v_{IN} + 10(0.6)$$

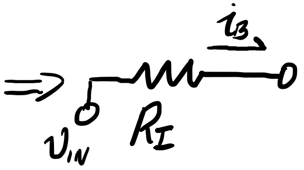
$$v_O = 16 \boxed{-} 10v_{IN}$$

Inverting!

$$v_O = 16 - 10v_{IN}$$

# Two Conditions for Active Region

① $i_B > 0 \Rightarrow$



$v_B \Rightarrow v_{R_I} > 0$

Remember $v_B = 0.6V$

$\rightarrow v_{IN} > 0.6V$

②

For $v_{CE} > v_{BE} - 0.4$ V, we note that:

$$v_{CE} = v_O \qquad v_{BE} = 0.6 \text{ V}$$

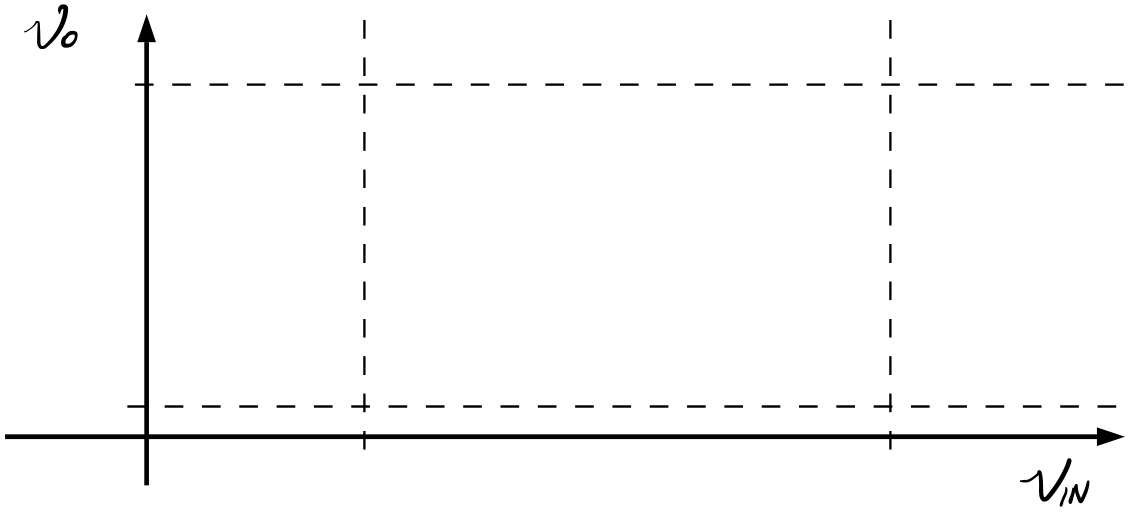
$v_o > 0.6 - 0.4$

$v_o > 0.2V$ $\rightarrow$ What $v_{IN}$ yields $v_o > 0.2V$?

$v_o = 16 - 10\,v_{IN}$

$0.2 < 16 - 10v_{IN}$

$v_{IN} > 1.58V$



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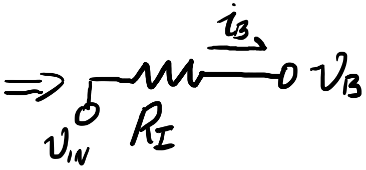

$\Rightarrow v_{R_I} > 0$

Remember $v_B = 0.6V$

$\rightarrow v_{IN} > 0.6V$

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For $v_{CE} > v_{BE} - 0.4$ V, we note that:

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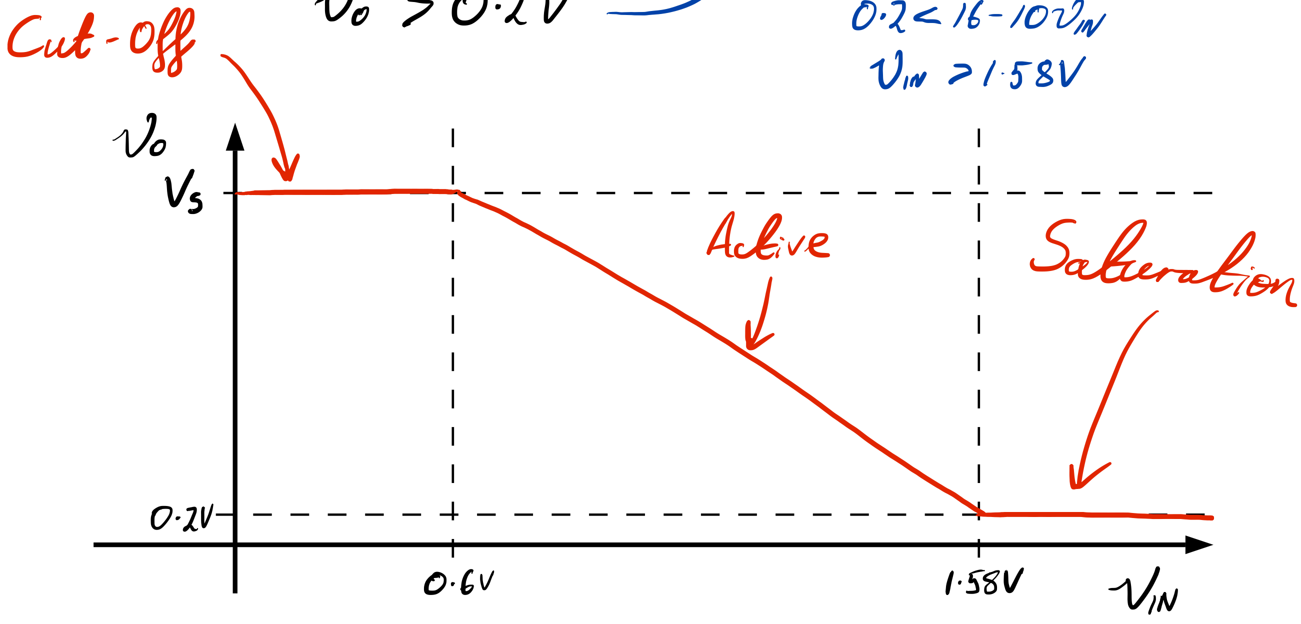
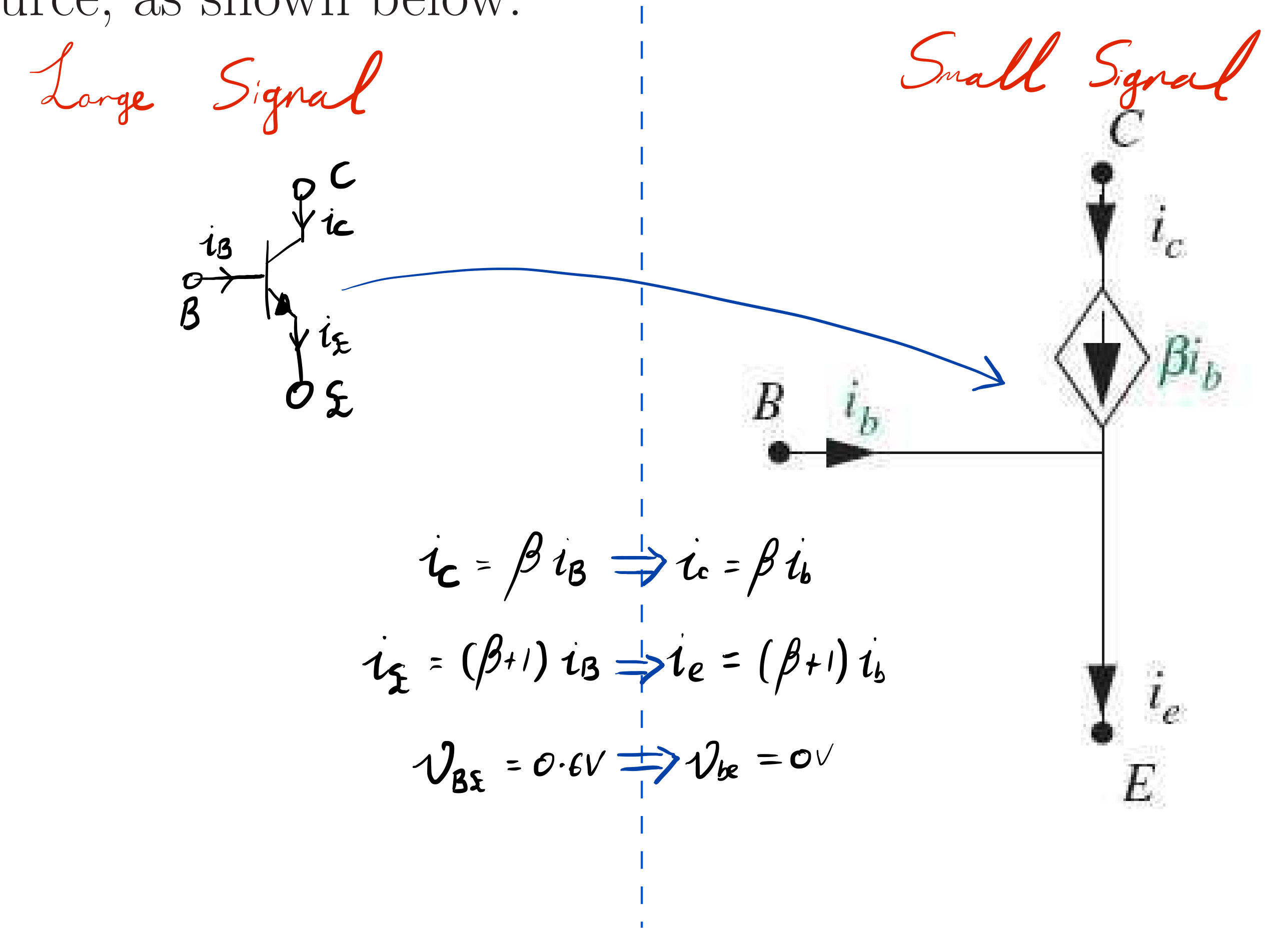


# 4 Small Signal Model for the BJT

For the small signal model of the BJT, the base-emitter diode can be replaced by a short circuit since we assume that the DC or bias conditions maintain it in forward bias. Therefore the small-signal model for the BJT is simply a linear current-controlled small signal source, as shown below.

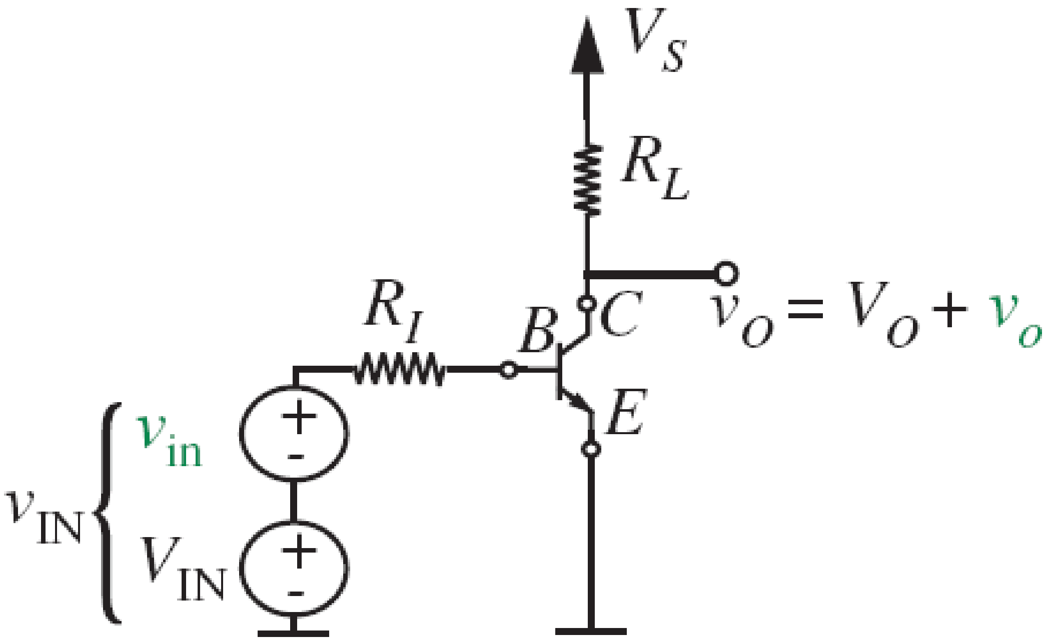


$$i_C = \beta i_B \Rightarrow i_c = \beta i_b$$

$$i_E = (\beta+1) i_B \Rightarrow i_e = (\beta+1) i_b$$

$$v_{BE} = 0.6V \Rightarrow v_{be} = 0V$$

To calculate the small-signal output voltage, $v_O$, replace the BJT with its small signal model and consider the small signal circuit.



The small signal model is shown below:

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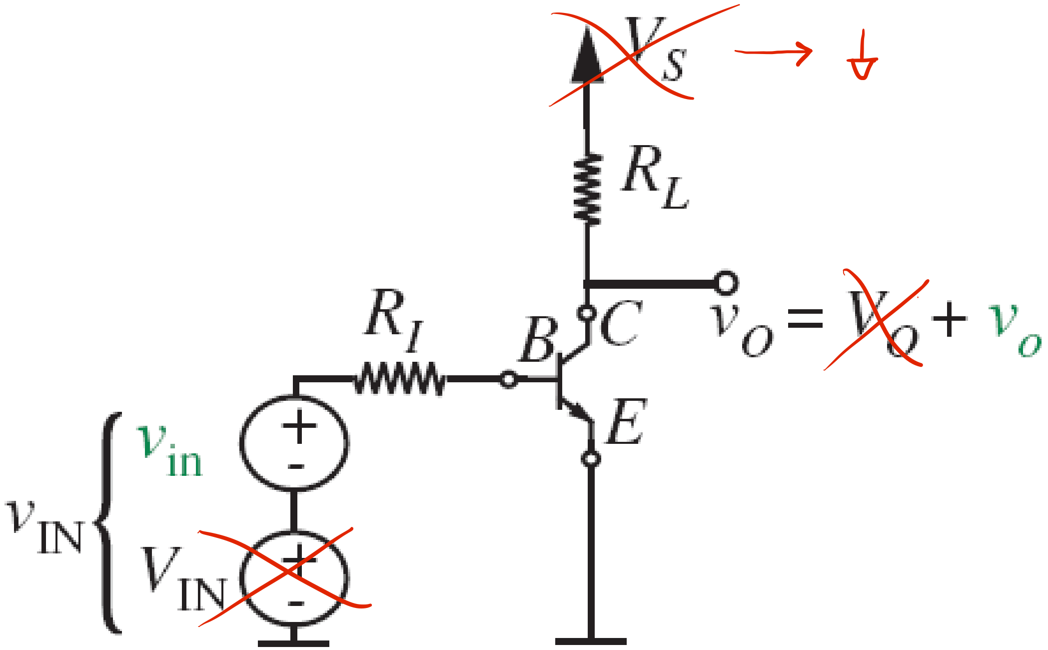

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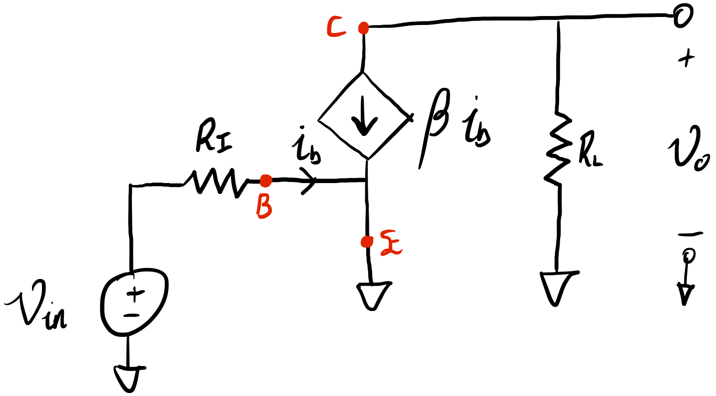

## 4.1 Example: Small Signal Gain of the Common Emitter Amplifier

We compute the small-signal gain ($v_o/v_{in}$) for the BJT common emitter amplifier, assuming that the amplifier operates in its active region. Again, $R_I = 100$ kΩ, $R_L = 10$ kΩ, $\beta = 100$, $V_S = 10$ V and the input bias voltage is chosen to be $V_{IN} = 1$ V.

Large Signal Reminder : $v_o = 16 - 10\,v_{IN} = 16 - 10 = 6V$ ✓ Active !

$$v_o = V_S - \beta R_L \frac{(v_{IN} - 0.6)}{R_I}$$

$$v_o = -i_c R_L =$$

$$v_o = -10 v_{in}$$

The linear small signal response of the common emitter amplifier makes it a good amplifier for high fidelity audio amplifier designs.

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Large Signal Reminder: $V_o = 16 - 10 V_{IN} = 16 - 10 = 6V$ ✓ Active!

$$v_o = \underset{=0}{\cancel{V_S}} - \beta R_L \frac{(v_{IN} - \overset{=0}{\cancel{0.6}})}{R_I}$$

$$v_o = -\beta \frac{R_L}{R_I} v_{in}$$

OR:

$$v_o = -i_c R_L = -\beta i_b R_L$$

$$v_o = -\beta \left(\frac{v_{in}}{R_I}\right) R_L$$

Substitute above Values:

$$v_o = -100 \left(\frac{10}{100}\right) v_{in}$$

Inverting!

$$v_o = -10 v_{in}$$

The linear small signal response of the common emitter amplifier makes it a good amplifier for high fidelity audio amplifier designs.