ECE 65: Components & Circuits Lab

Lecture 12

BJT Transfer function

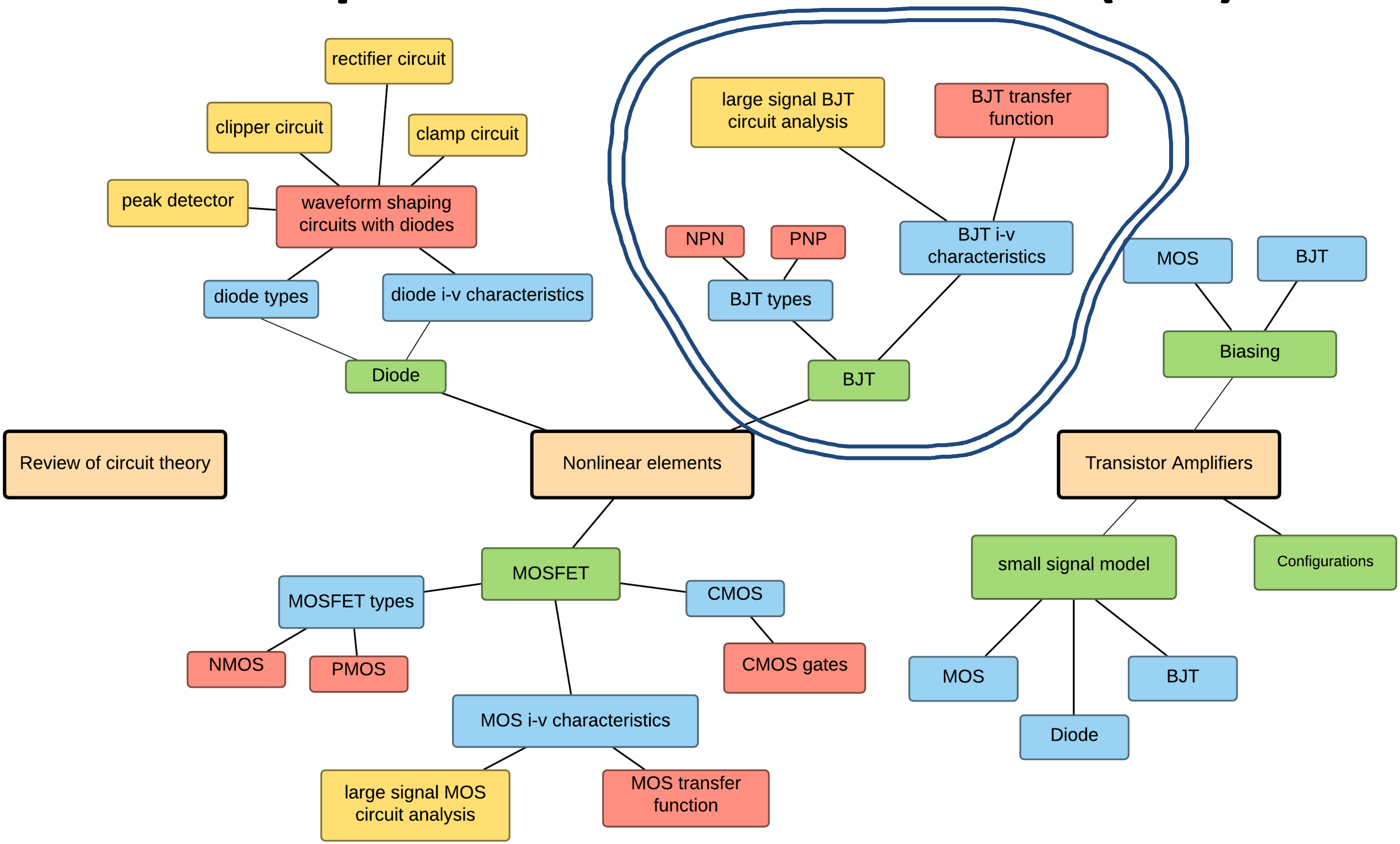
Reference notes: sections 3.2

Sedra & Smith (7th Ed): sections 6.1,6.4

Saharnaz Baghdadchi

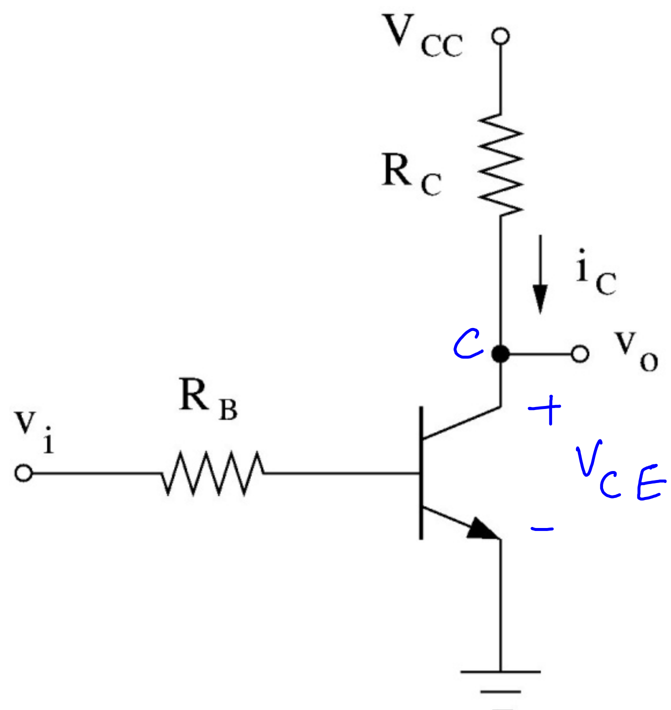
Course map

3. Bipolar Junction Transistor (BJT)



Discussion question: BJT Transfer Function

how would the output $v_o = v_{CE}$ change in terms of v_i?



BJT Transfer Function

BE KVL: $\underline{v_i = R_B i_B + v_{BE}}$

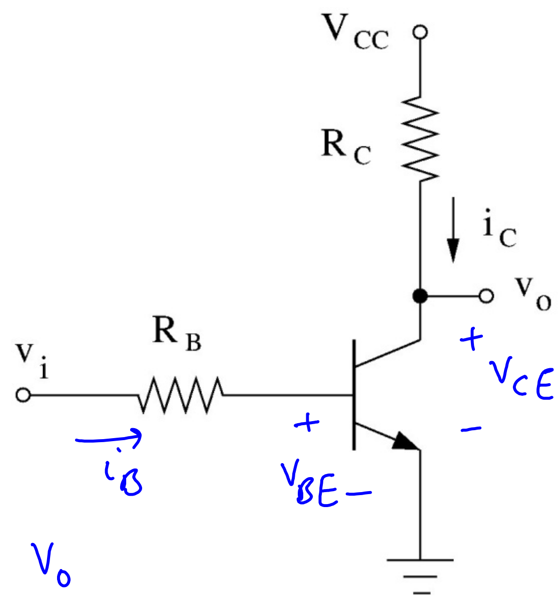
CE KVL: $\underline{V_{CC} = R_C i_C + v_{CE}}$

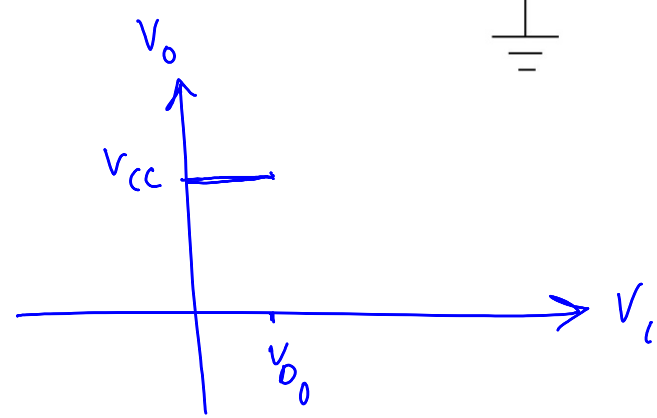
Case 1: BJT is in cut-off

$i_B = 0$, $V_{BE} < V_{D0}$, $i_C = 0$, $i_E = 0$

$V_i = V_{BE} < V_{D_0} \longrightarrow V_i < V_{D_0}$

$V_{CC} = R_C \times 0 + V_o \longrightarrow V_o = V_{CC}$





$\boxed{\text{For } V_i < V_{D_0}\text{, BJT is in cut-off, } V_o = V_{CC}}$

BJT Transfer Function

Case 2: BJT is ON, $v_{BE} = V_{D_0}$

$$i_B = \frac{v_i - v_{BE}}{R_B} = \frac{v_i - V_{D_0}}{R_B},$$

$$\boxed{v_{CE} = V_{CC} - R_C i_C}$$

$i_C = \beta i_B$, $v_{CE} \geq V_{D_0}$

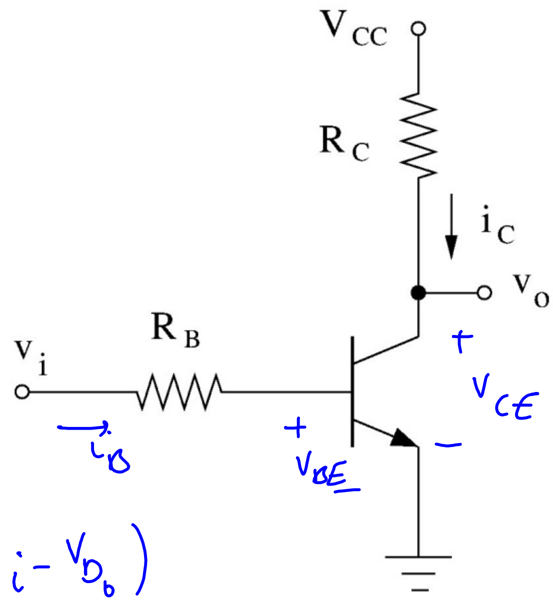
$\downarrow$

$$i_C = \frac{\beta}{R_B}(v_i - V_{D_0}), \quad v_{CE} = V_{CC} - \frac{\beta R_C}{R_B}(v_i - V_{D_0})$$

$$v_{CE} \geq V_{D_0} \longrightarrow v_i \leq V_{D_0} + \frac{V_{CC} - V_{D_0}}{\beta R_C / R_B}$$

$$v_o = \left(V_{CC} + \frac{\beta R_C}{R_B} V_{D_0}\right) - \frac{\beta R_C}{R_B} v_i$$

For $v_i \leq V_{D_0} + \dfrac{V_{CC} - V_{D_0}}{\beta R_C / R_B}$ the BJT is in active mode.



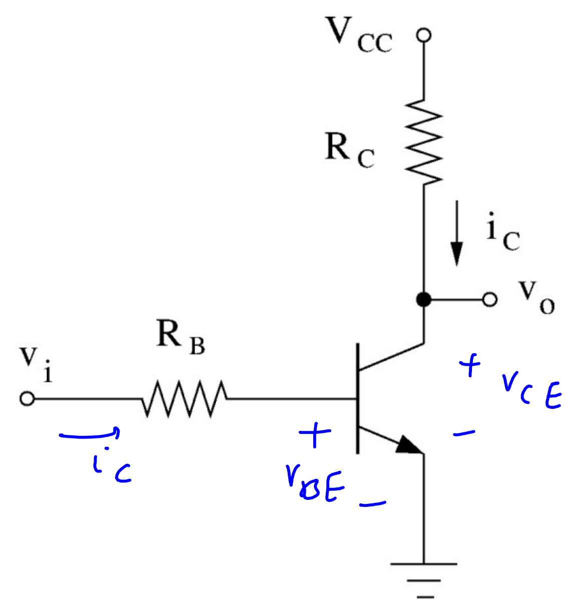
BJT Transfer Function

Case 3: BJT is in saturation.

$v_{BE} = V_{D_0}$, $\boxed{i_C < \beta i_B}$, $v_{CE} = V_{sat}$

$$i_B = \frac{v_i - v_{BE}}{R_B} ,$$

$$v_{CE} = V_{CC} - R_C i_C , \quad i_C = \frac{V_{CC} - V_{sat}}{R_C}$$



$$i_C < \beta i_B \longrightarrow \frac{V_{CC} - V_{sat}}{R_C} < \frac{\beta}{R_B}(v_i - V_{D_0})$$

$$v_i > V_{D_0} + \frac{V_{CC} - V_{sat}}{\beta R_C / R_B}$$

For $v_i > V_{D_0} + \dfrac{V_{CC} - V_{sat}}{\beta R_C / R_B}$, BJT is in saturation

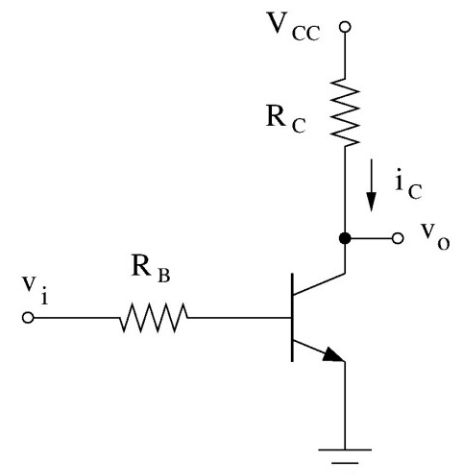
$v_o = V_{sat}$

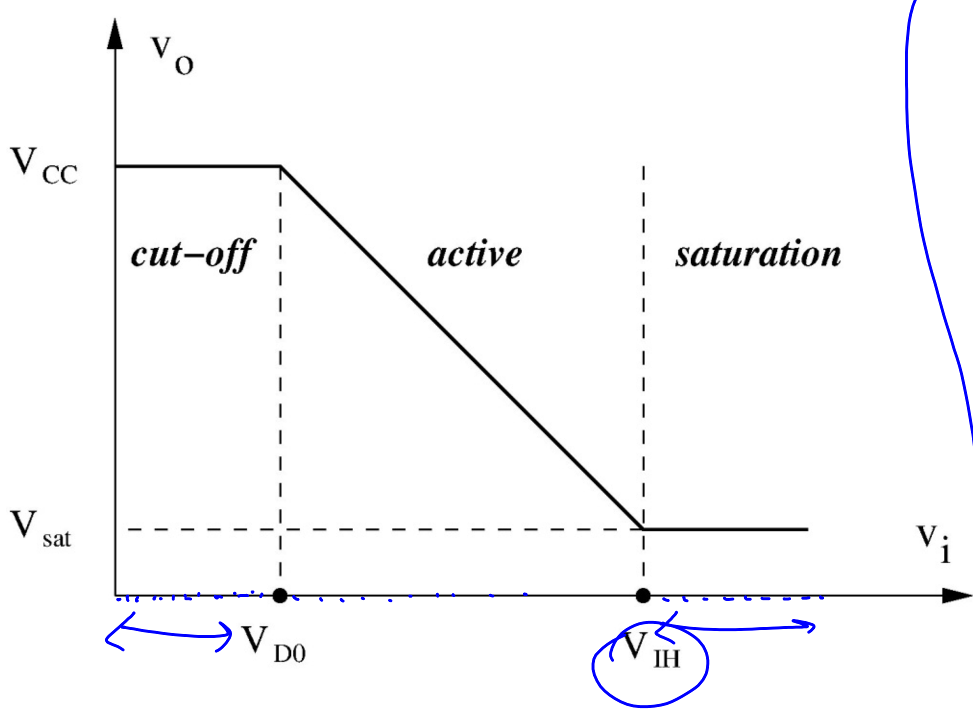
BJT Transfer Function

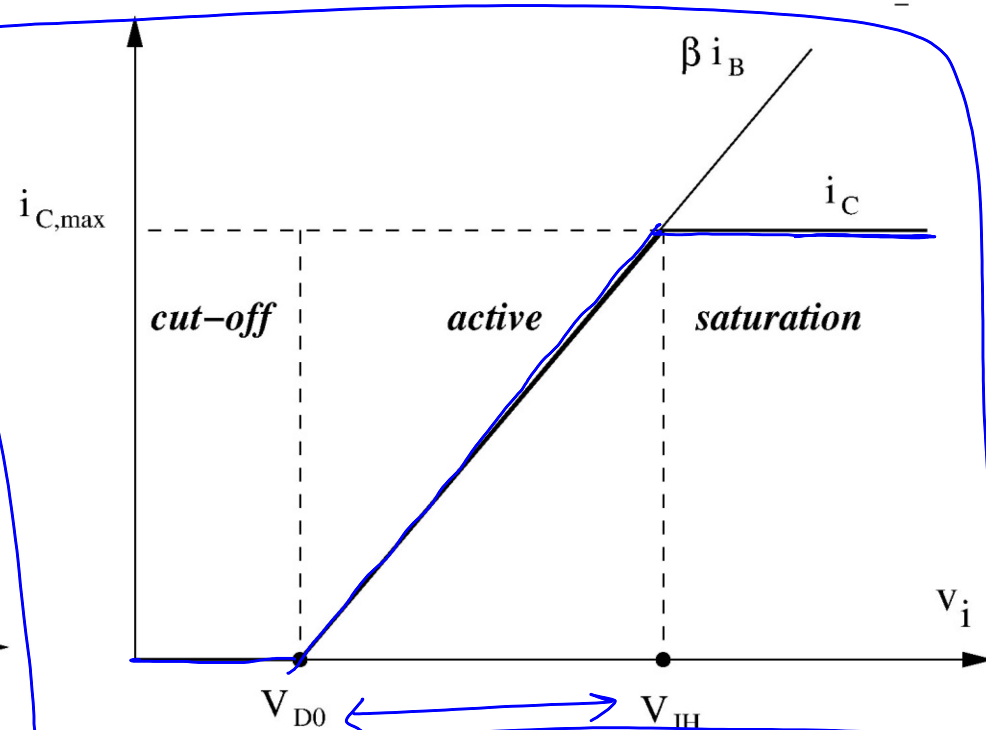
$$v_i < V_{D0} \quad \rightarrow \text{BJT in Cutoff}$$

$$V_{D0} \le v_i \le V_{D0} + \frac{V_{CC} - V_{D0}}{\beta R_C / R_B} \quad \rightarrow \text{BJT in active}$$

$$V_{D0} + \frac{V_{CC} - V_{sat}}{\beta R_C / R_B} < v_i \quad \rightarrow \text{BJT in deep saturation}$$







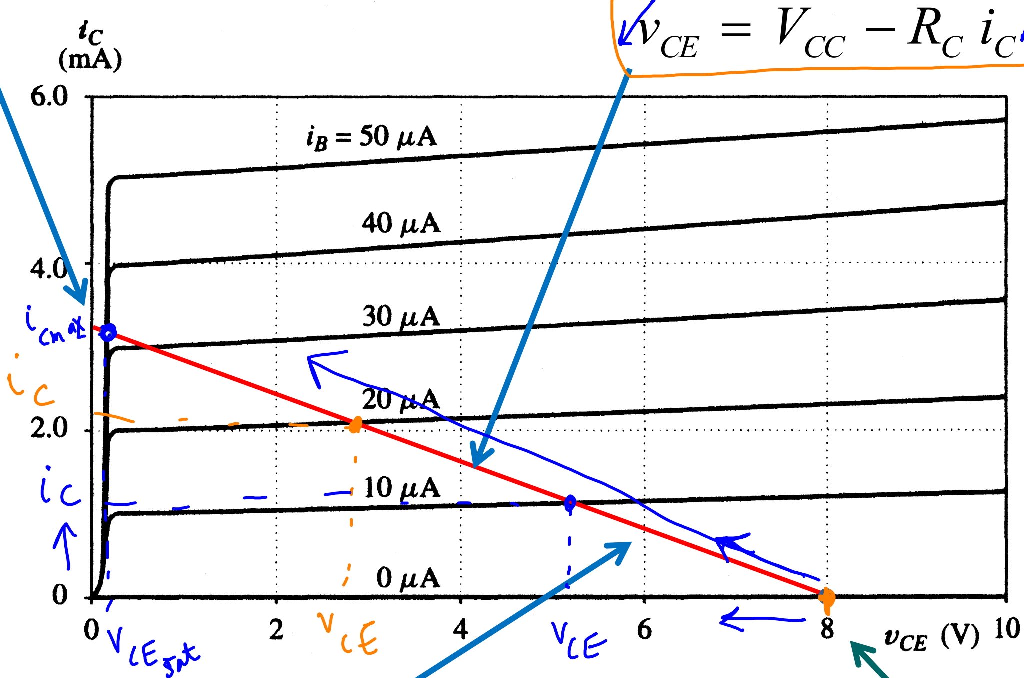
BJT transfer function on the load line

Saturation : $V_{IH} < v_i$

i_B increases but i_C unchanged

Load Line (CE - KVL)

$$v_{CE} = V_{CC} - R_C\, i_C$$

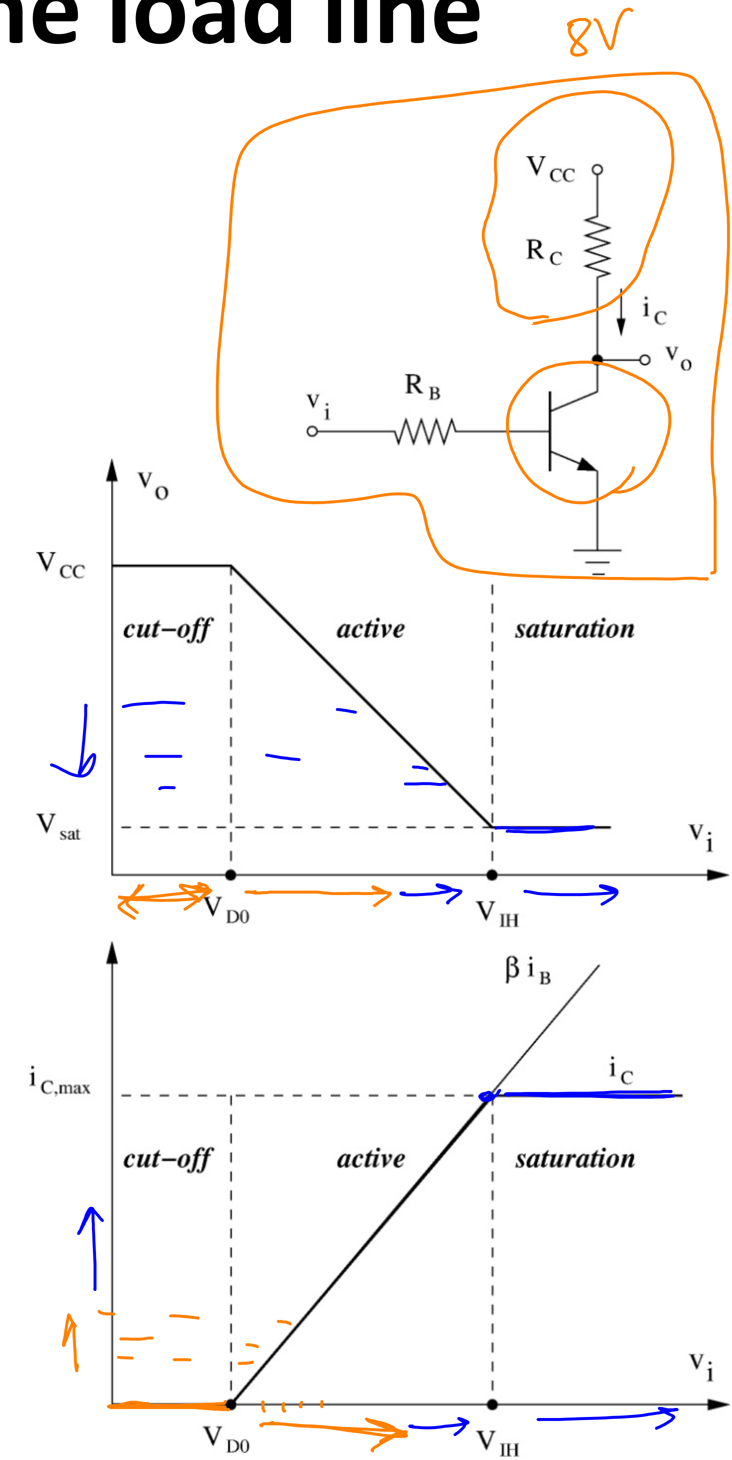


Active : $V_{D0} \le v_i \le V_{IH}$

i_B & i_C increase together

Cut – off :

$v_i < V_{D0}$



BJT β varies substantially

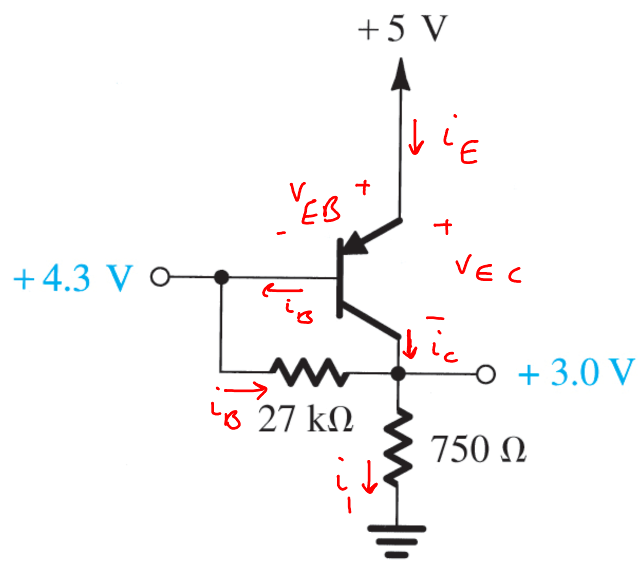
Transistor β depends on many factors:

- Strongly depends on temperature (9% increase per ^oC)
- Depends on i_C (not constant as assumed in the model)
- β of similarly manufactured BJT can vary (manufacturer spec sheet typically gives a range as well as an average value for β)
- β_{min} is an important parameter. For example, to ensure operation in deep saturation for all similar model BJTs, we need to set $i_C / i_B < \beta_{min}$

Lecture 12 reading quiz

A few measurements on the below circuit produces the labeled voltages.

Find the value of β (Assume $V_{D0} = 0.7V$).



$v_{EB} = v_E - v_B = 5V - 4.3V = 0.7V \longrightarrow$ BJT is ON

$v_{EC} = v_E - v_C = 5V - 3V = 2V > 0.7$

$\Downarrow$

BJT is in active mode

$\rightarrow i_C = \beta i_B$, $\boxed{i_1 = i_C + i_B}$

$i_1 = \dfrac{3V}{750\Omega} = 4mA \Rightarrow \boxed{i_1 = 4mA}$

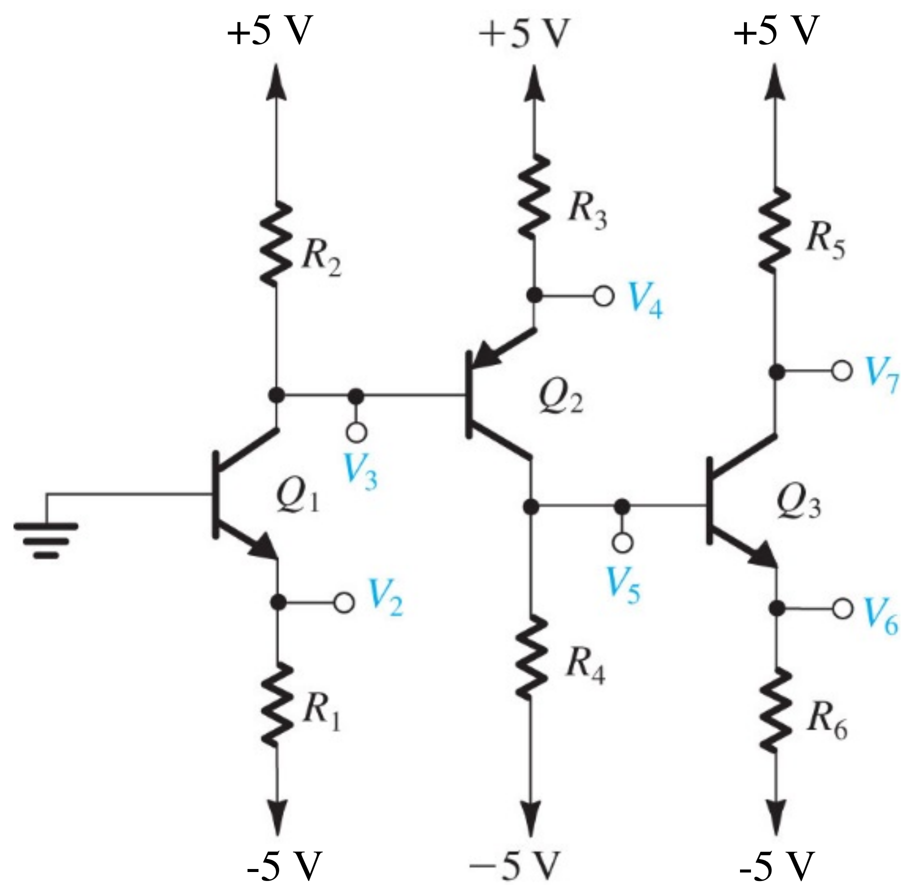
$i_B = \dfrac{4.3V - 3V}{27k\Omega} = 48\mu A \Rightarrow \boxed{i_B = 48\mu A}$

$i_1 = i_B + \beta i_B \Rightarrow i_1 = (1+\beta)\, i_B \Rightarrow 4mA = (1+\beta)\, 48\mu A$

$\Rightarrow \boxed{\beta = 82.3}$

Discussion question 2.

Using $\beta = \infty$, design the following circuit so that the transistors operate in the active region and the collector currents in Q_1, Q_2, and Q_3 are 2 mA, 2 mA, and 4 mA, respectively, and $V_3 = 0$, $V_5 = -4\ V$, and $V_7 = 2\ V$.



$V_3 = 0\,V$ & $i_{C_1} = 2\,mA$

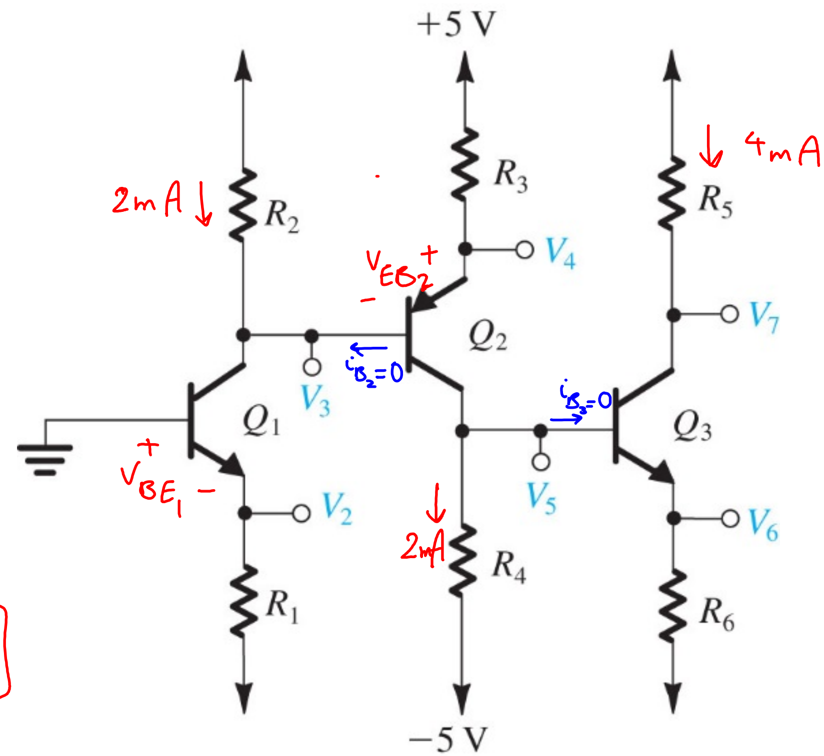
$$\frac{5V - 0V}{R_2} = 2\,mA \longrightarrow \boxed{R_2 = 2.5\,k\Omega}$$

Q_1 is ON $\longrightarrow V_{BE_1} = V_{B_1} - V_{E_1} = 0.7$

$\longrightarrow V_2 = -0.7V$

$\beta = \infty \longrightarrow i_{C_1} = i_{E_1} = 2\,mA$

$$R_1 = \frac{V_2 - (-5)}{2\,mA} = \frac{-0.7 + 5}{2\,mA} \longrightarrow \boxed{R_1 = 2.15\,k\Omega}$$



$$R_4 = \frac{V_5 - (-5V)}{2\,mA} = \frac{-4V + 5V}{2\,mA} \longrightarrow \boxed{R_4 = 0.5\,k\Omega}$$

Q_2 is ON $\longrightarrow V_{EB_2} = V_{E_2} - V_{B_2} = 0.7V \longrightarrow V_4 = 0.7V + 0 \longrightarrow V_4 = 0.7V$

$\beta = \infty \longrightarrow i_{C_2} = i_{E_2} = 2\,mA$

$$R_3 = \frac{5V - V_4}{2\,mA} = \frac{5V - 0.7}{2\,mA} = \frac{4.3V}{2\,mA} \longrightarrow \boxed{R_3 = 2.15\,k\Omega}$$

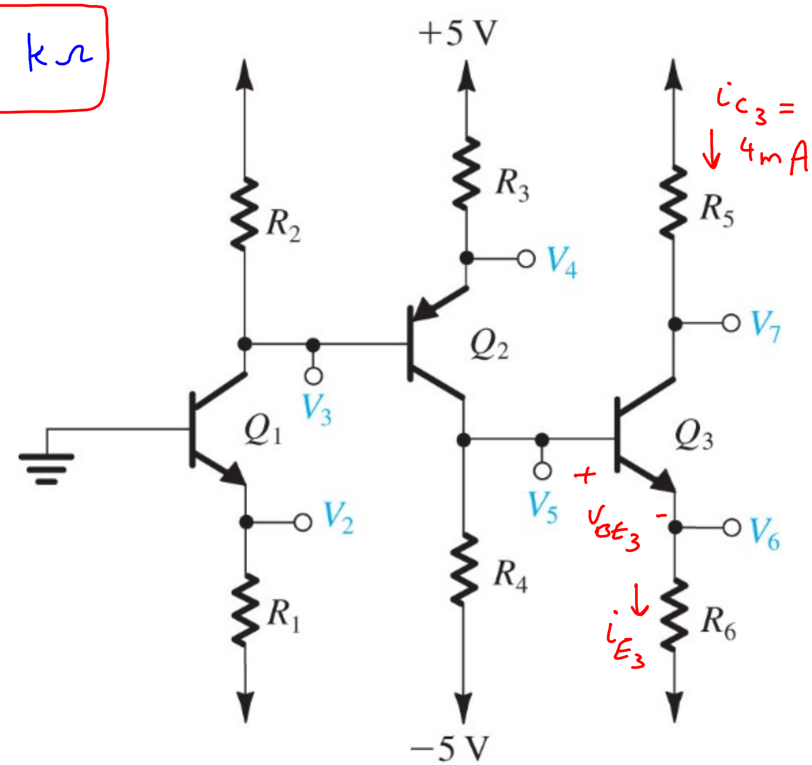
$$R_5 = \frac{5V - V_7}{4mA} = \frac{5V - 2V}{4mA} \longrightarrow \boxed{R_5 = 0.75\ k\Omega}$$

$$Q_3 \text{ is ON} \longrightarrow V_{BE_3} = V_5 - V_6 = 0.7\ V$$

$$\longrightarrow V_6 = -4.7\ V$$

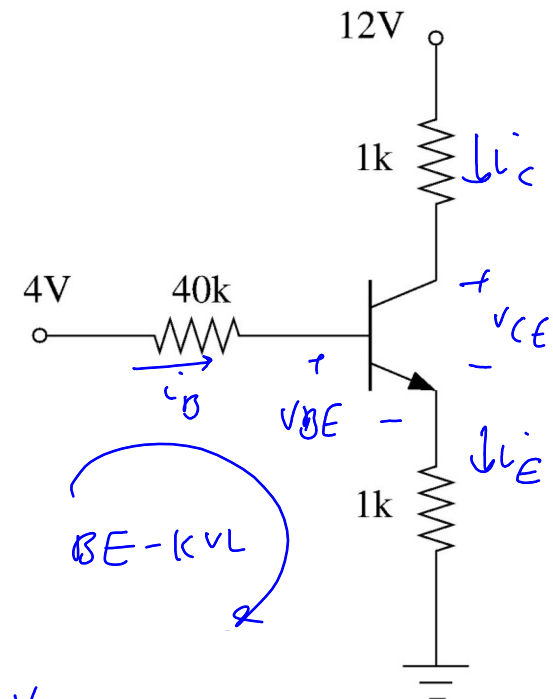
$$\beta = \infty \longrightarrow i_{C_3} = i_{E_3} = 4\ mA$$

$$R_6 = \frac{-4.7 - (-5)}{4mA} \longrightarrow \boxed{R_6 = 75\ \Omega}$$



Discussion question 2.

Find the transistor parameters in this BJT circuit. ($\beta = 100$, $V_{D0} = 0.7V$, $V_{sat} = 0.2\ V$).



Assume BJT is in cut off, $i_B = 0$, $i_C = 0$, $i_E = 0$

$V_{BE} < 0.7V$

BE-KVL:

$$\boxed{4V = 40k \times i_B + V_{BE} + 1k \times i_E}$$

if $i_B = i_E = 0 \longrightarrow V_{BE} = 4V > 0.7 \longrightarrow$ BJT is ON

Assume BJT is in active mode: $i_C = \beta i_B$, $V_{CE} \geq V_{D0}$, $V_{BE} = 0.7V$

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

$4V = 40k \times i_B + 0.7 + 1k\,(101)\, i_B$

$\boxed{i_B = 23.4\ \mu A}$, $\boxed{i_E = 2.36\ mA}$, $\boxed{i_C = 2.34\ mA}$

CE KVL:

$$12V = 1k \times i_C + V_{CE} + 1k \times i_E$$

$$12V = 1k \times 2.34mA + V_{CE} + 1k \times 2.36mA$$

$$\longrightarrow V_{CE} = 7.3V > 0.7V$$

BJT is in active mode.