ECE 205 “Electrical and Electronics Circuits”

Spring 2024 – LECTURE 26

MWF – 12:00pm

Prof. Umberto Ravaioli

2062 ECE Building

Lecture 26 – Summary

Learning Objectives

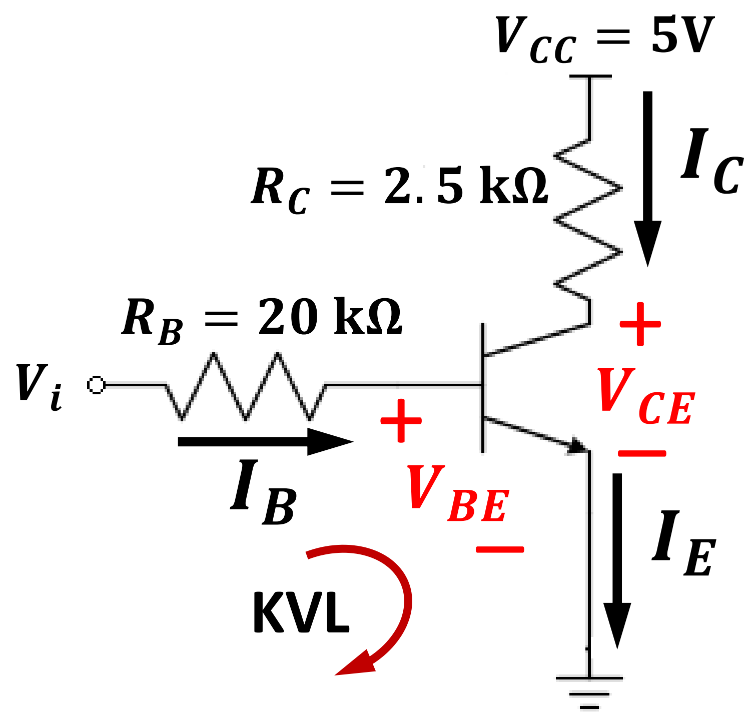
1. More BJT practice
2. Transistor as diode
3. Graphical use of *I-V* curves

Example 2: Find the BJT mode of operation

$$V_{BE}(\text{on}) = 0.7\text{V}$$

$$V_{CE}(\text{sat}) = 0.2\text{V}$$

$$\beta = 200$$



$(a)\ V_i = 0.5\text{V}$

$(b)\ V_i = 3.5\text{V}$

$$V_{BE}(\text{on}) = 0.7\text{V}$$

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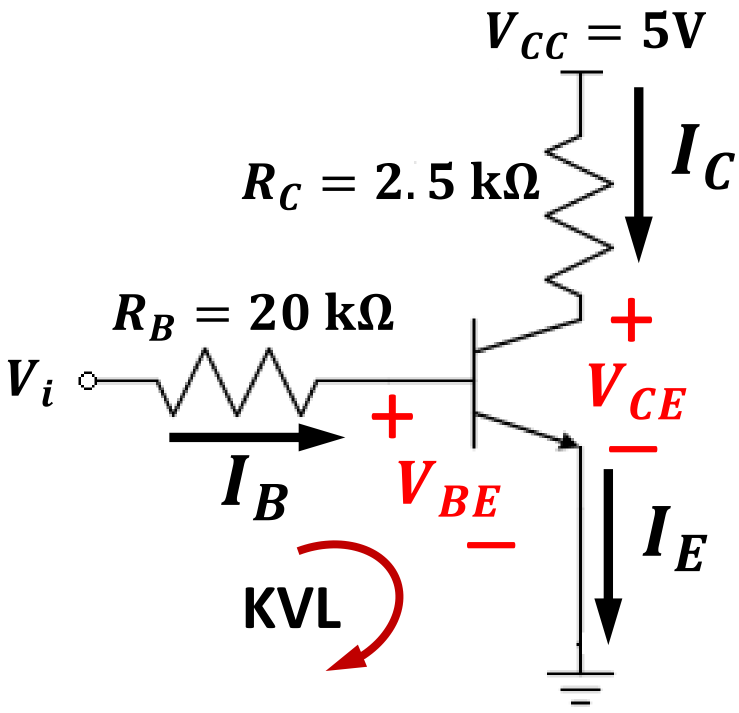
$$\beta = 200$$



$(a)\ V_i = 0.5\text{V}$

BJT is OFF since

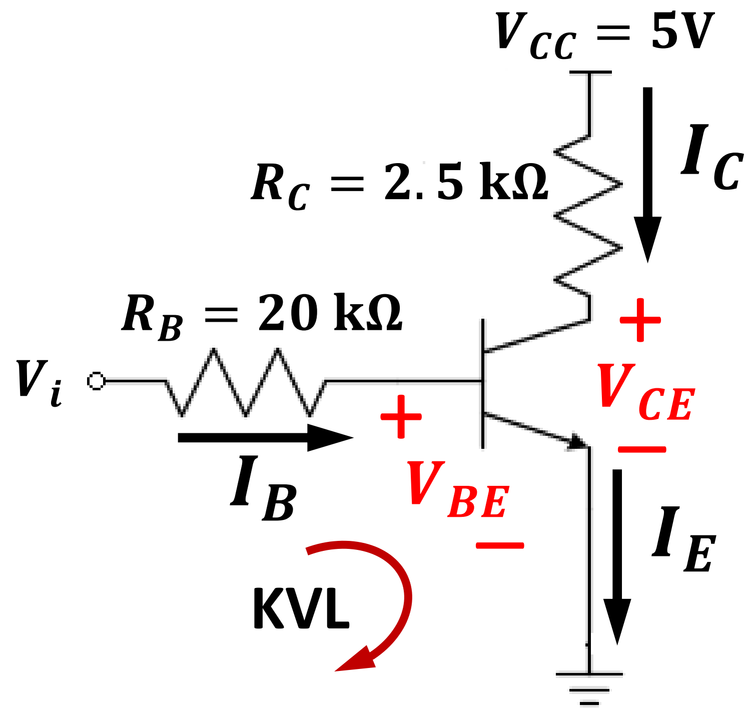
$$V_i < V_{BE}(\text{on})$$

Cut-off mode

$$V_{BE}(\text{on}) = 0.7\text{V}$$

$$V_{CE}(\text{sat}) = 0.2\text{V}$$

$$\beta = 200$$



$$(b)\ V_i = 3.5\text{V}$$

BJT is ON since $V_i > V_{BE}(\text{on})$

Assume forward active mode and check the collector behavior

KVL $-3.5 + I_B \times 20\text{k}\Omega + 0.7 = 0$

$$I_B = 0.14\text{mA}$$

$$I_C = \beta I_B = 200 \times 0.14 = 28\text{mA}$$

$$V_{BE}(\text{on}) = 0.7\text{V}$$

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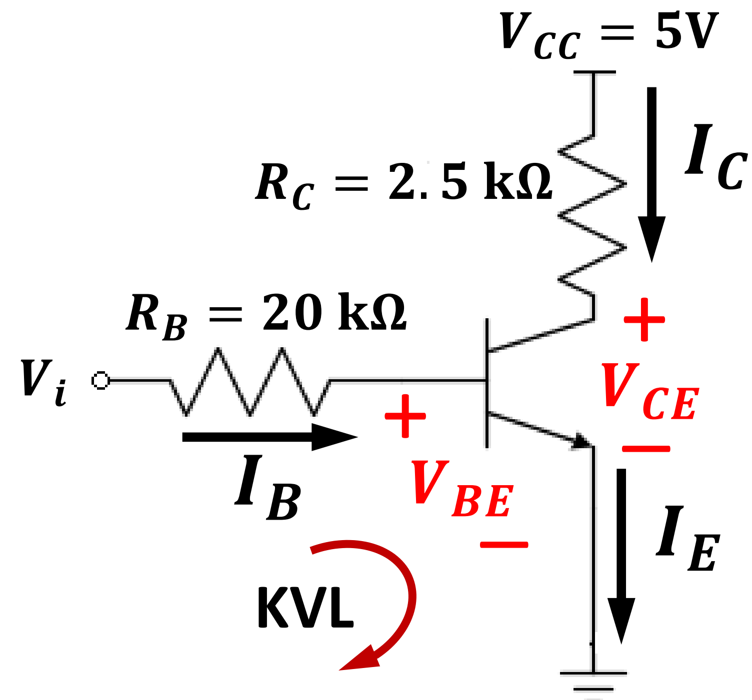

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Contradiction

$$V_{CE} = V_{CC} - I_C R_C = 5 - 28\text{m} \times 2.5\text{k} = -65\text{V} < 0.2\text{V}$$

$V_{BE}(\text{on}) = 0.7\text{V}$

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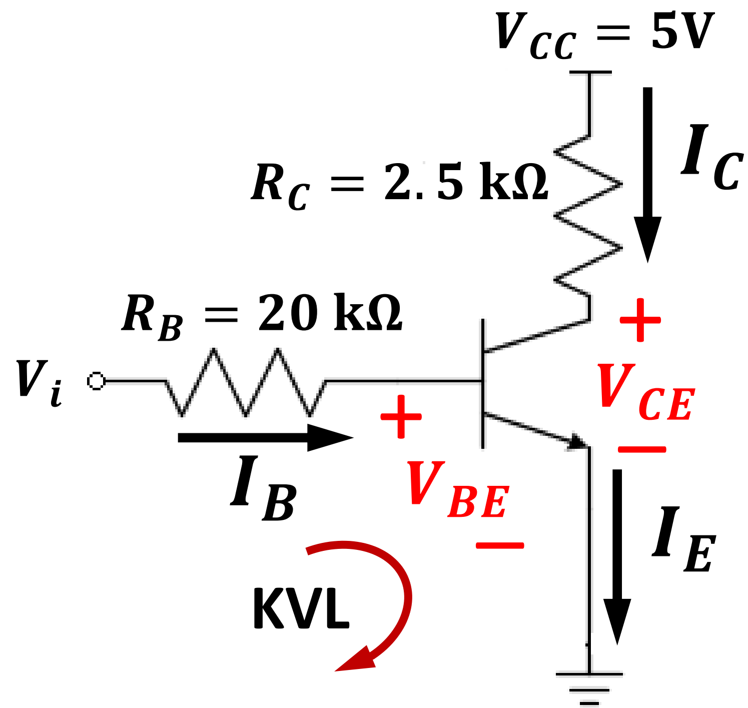

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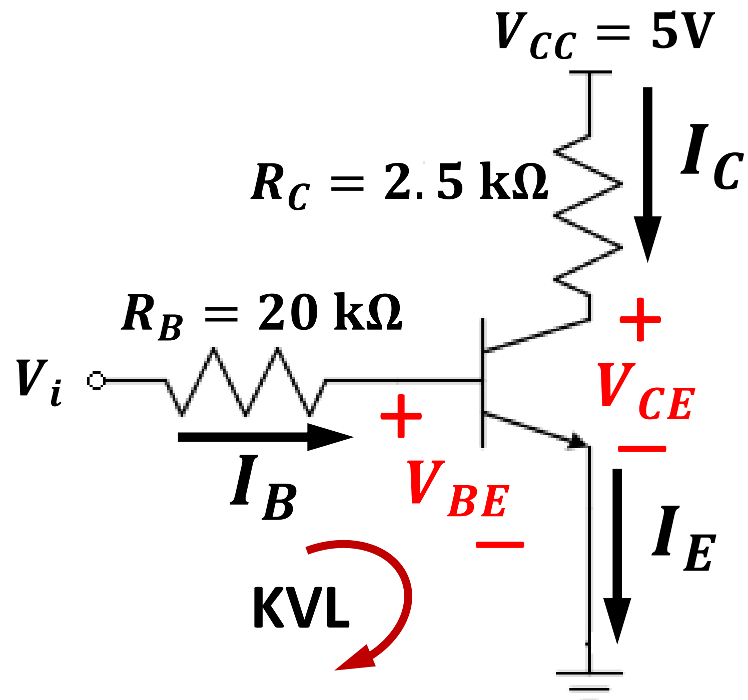
$V_{CE} = V_{CE}(\text{sat}) = 0.2\text{V}$ **Saturation mode**

$$V_{BE}(\text{on}) = 0.7\text{V}$$

$$V_{CE}(\text{sat}) = 0.2\text{V}$$

$$\beta = 200$$



$(b)\ V_i = 3.5\text{V}$

BJT is ON since $V_i > V_{BE}(\text{on})$

Let's find the collector current at onset of saturation

$$I_B = 0.14\text{mA}$$

$$I_C = \beta I_B = 28\text{mA}$$

Under Forward-Active assumption we had

$$V_{BE}(\text{on}) = 0.7\text{V}$$

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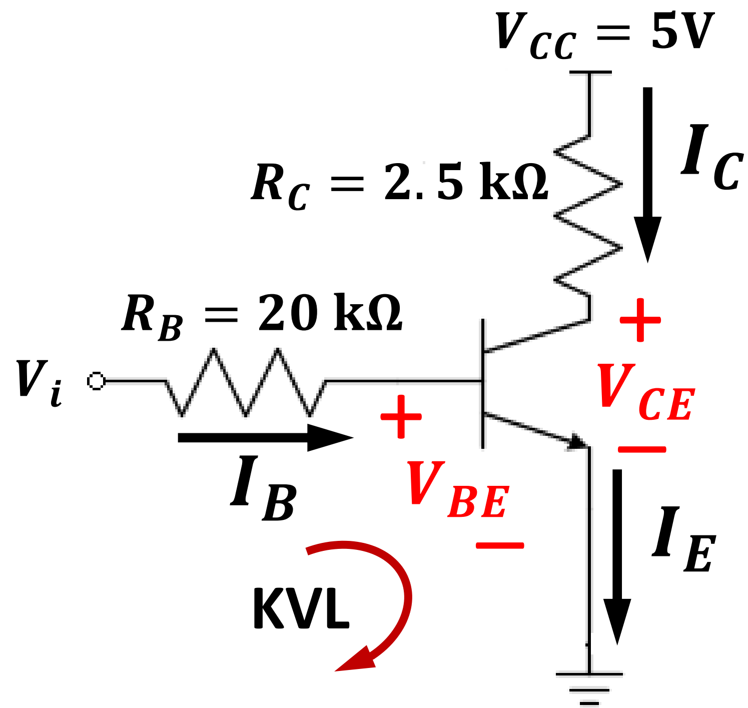

$$(b)\ V_i = 3.5\text{V}$$

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Let's find the collector current at onset of saturation

$$I_B = 0.14\text{mA} \qquad I_C = \beta I_B = 28\text{mA}$$

Under Forward-Active assumption we had

KVL $\quad 5 + (-I_C(\text{sat}) \times 2.5\text{k}\Omega) - V_{CE}(\text{sat}) = 0$

$$V_{BE}(\mathrm{on}) = 0.7\mathrm{V}$$

$$V_{CE}(\mathrm{sat}) = 0.2\mathrm{V}$$

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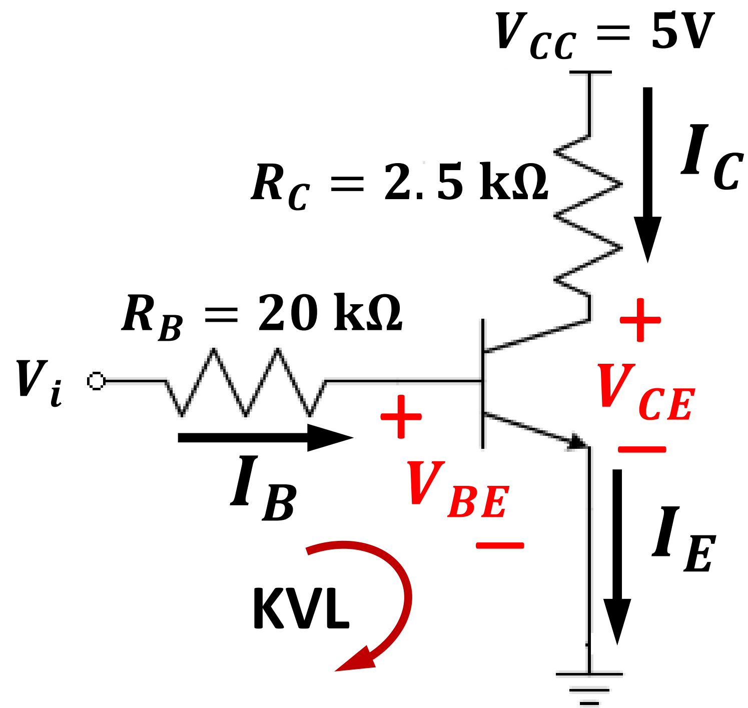

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KVL

$$5 + (-I_C(\mathrm{sat}) \times 2.5\mathrm{k\Omega}) - V_{CE}(\mathrm{sat}) = 0$$

$$I_C(\mathrm{sat}) = 4.8\mathrm{V}/2.5\mathrm{k\Omega} = 1.92\mathrm{mA} \ll \beta I_B$$

$$V_{BE}(\text{on}) = 0.7\text{V}$$

$$V_{CE}(\text{sat}) = 0.2\text{V}$$

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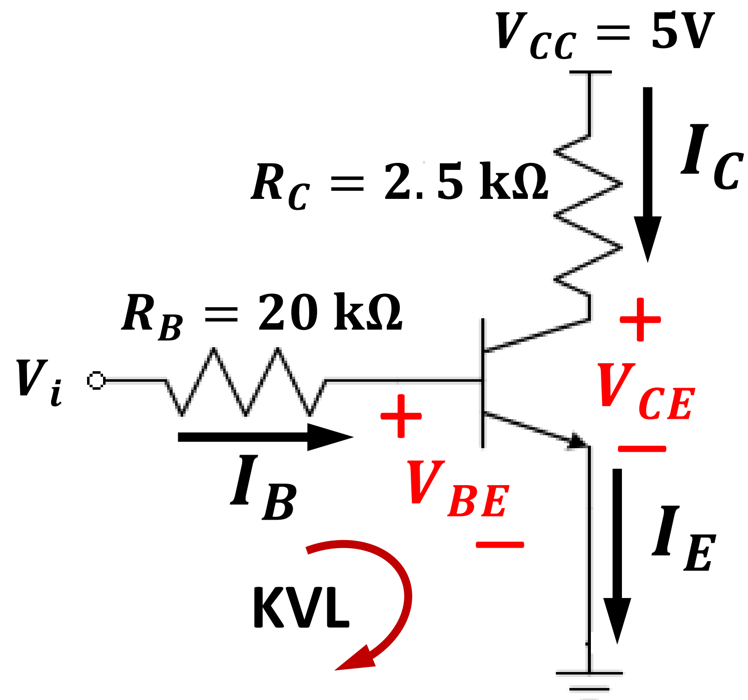

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Let's find the collector current at onset of saturation

$I_B = 0.14\text{mA}$ $\quad I_C = \beta I_B = 28\text{mA}$

Under Forward-Active assumption we had

KVL $\quad 5 + (-I_C(\text{sat}) \times 2.5\text{k}\Omega) - V_{CE}(\text{sat}) = 0$

$$I_C(\text{sat}) = 4.8\text{V}/2.5\text{k}\Omega = 1.92\text{mA} \ll \beta I_B$$

$V_{CE} = V_{CE}(\text{sat}) = 0.2\text{V}$ **Saturation mode**

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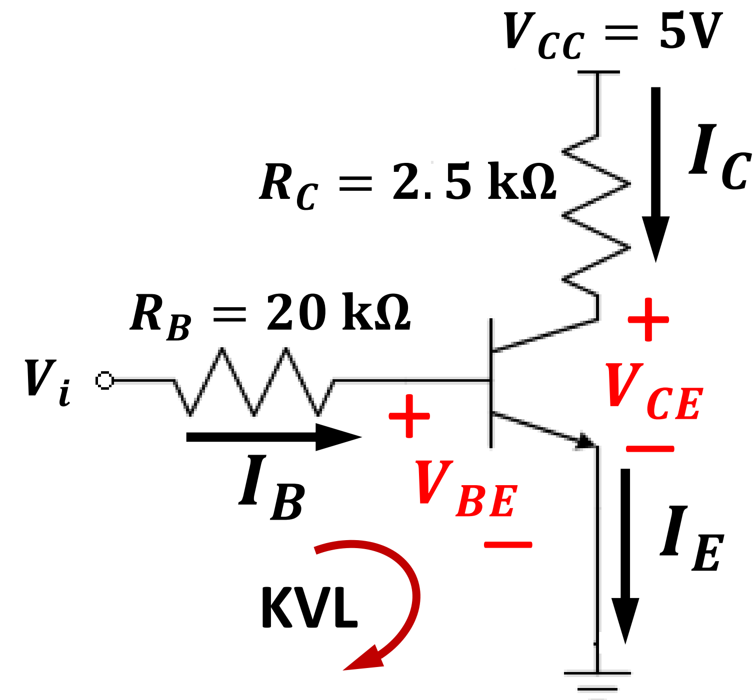


$$(b)\ V_i = 3.5\mathrm{V}$$

Let's find the base current at onset of saturation

$$I_B(\text{at onset of saturation}) = \frac{I_C(\mathrm{sat})}{\beta} = 9.6\ \mu\mathrm{A}$$

$$V_i(\text{at onset of saturation}) = 9.6\ \mu\mathrm{A} \times 20k\Omega + 0.7 = 0.892\mathrm{V}$$

The base current can be increased further, but the collector current remains at the saturation value $I_C(\mathrm{sat})$.

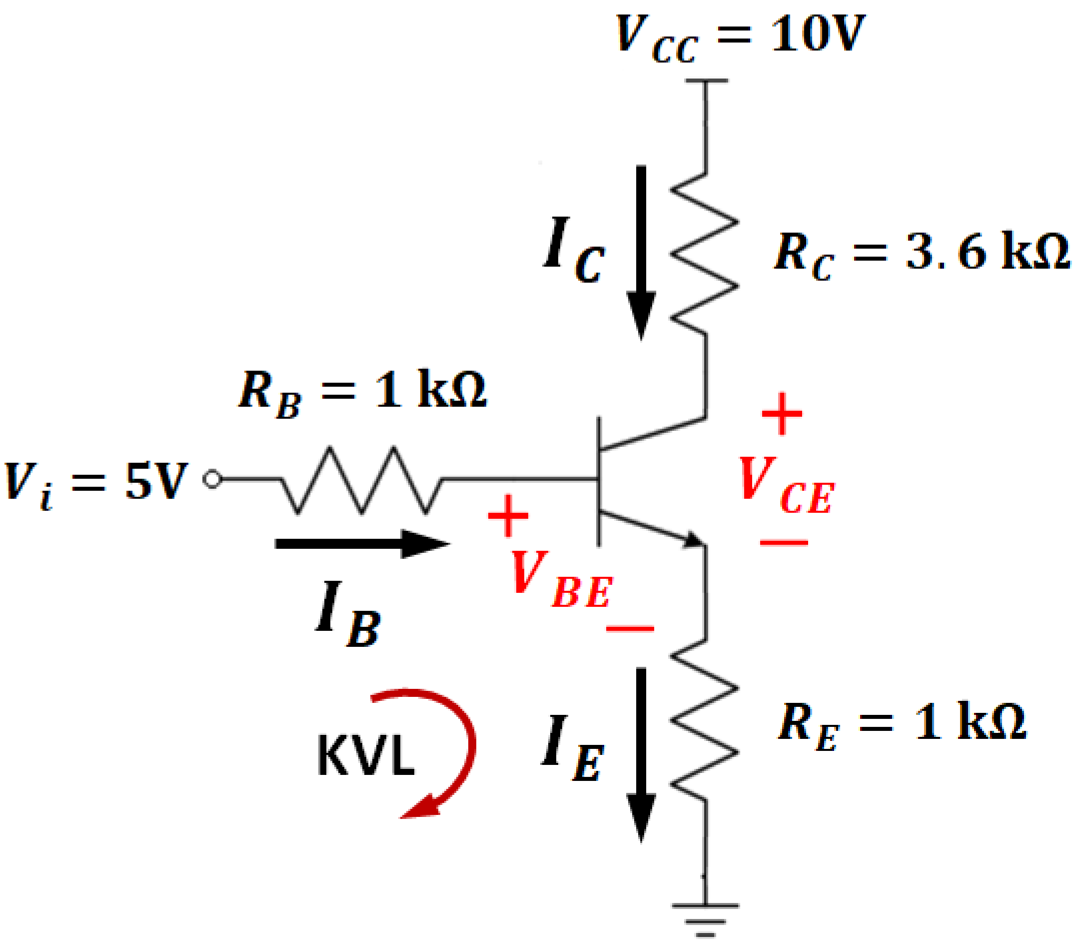
Example 3: BJT with emitter resistor

$$V_{BE}(\text{on}) = 0.7\text{V}$$

$$V_{CE}(\text{sat}) = 0.2\text{V}$$

$$\beta = 100$$

$$I_E = (\beta + 1)I_B$$



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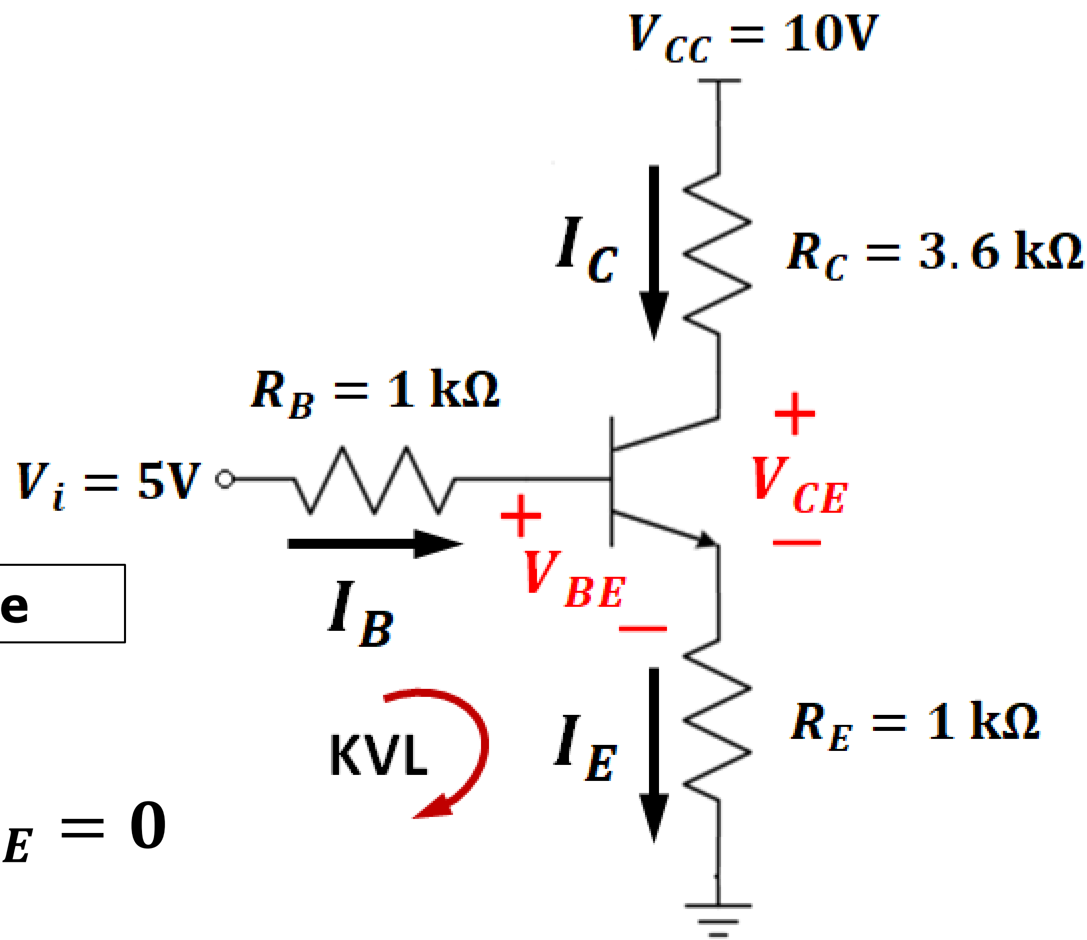

Assuming forward active mode

Base-emitter KVL

$$-V_i + I_B R_B + V_{BE} + I_E R_E = 0$$

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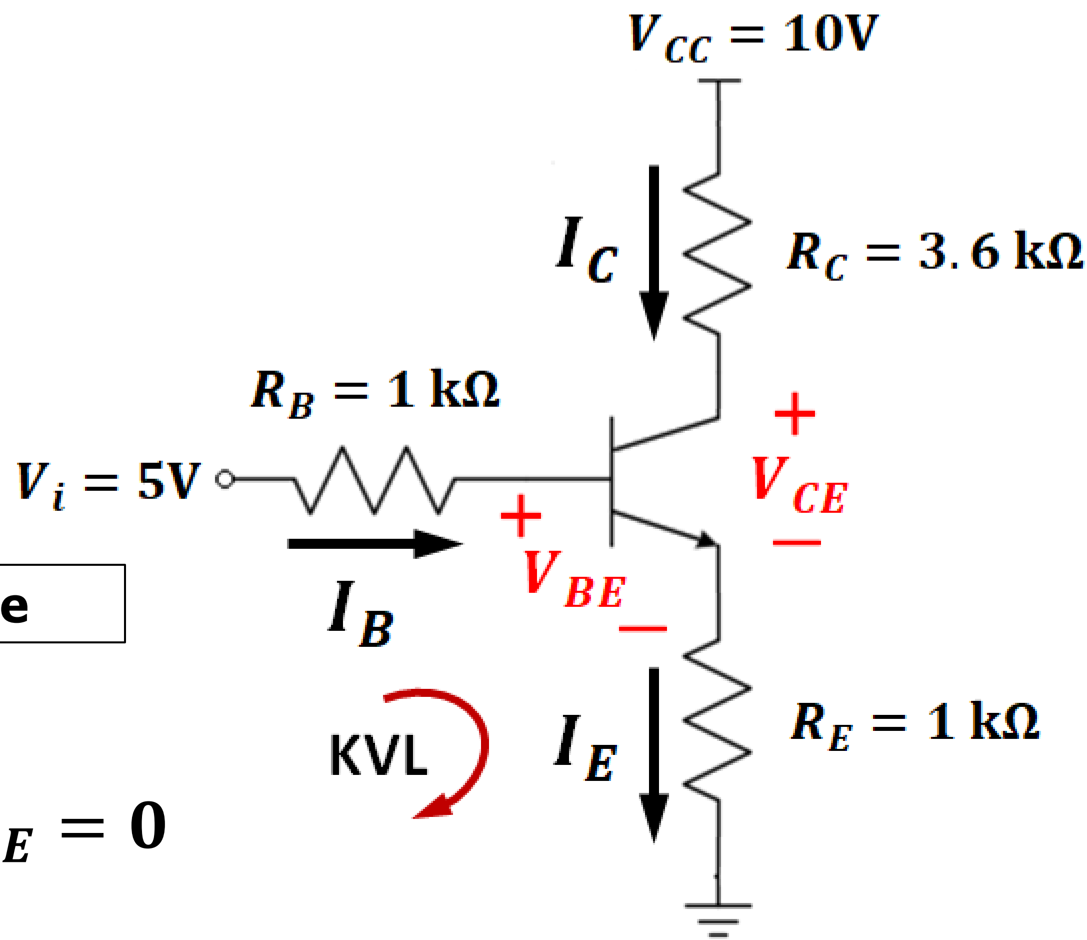


Assuming forward active mode

Base-emitter KVL

$$-V_i + I_B R_B + V_{BE} + I_E R_E = 0$$

$$-5 + I_B \times 1\text{k} + 0.7 + (\beta + 1)I_B \times 1\text{k} = 0$$

$$I_B = \frac{4.3}{1\text{k} + (\beta + 1)1\text{k}} = \frac{4.3}{102\text{k}} = 0.0422\text{mA} = 42.2\mu\text{A}$$

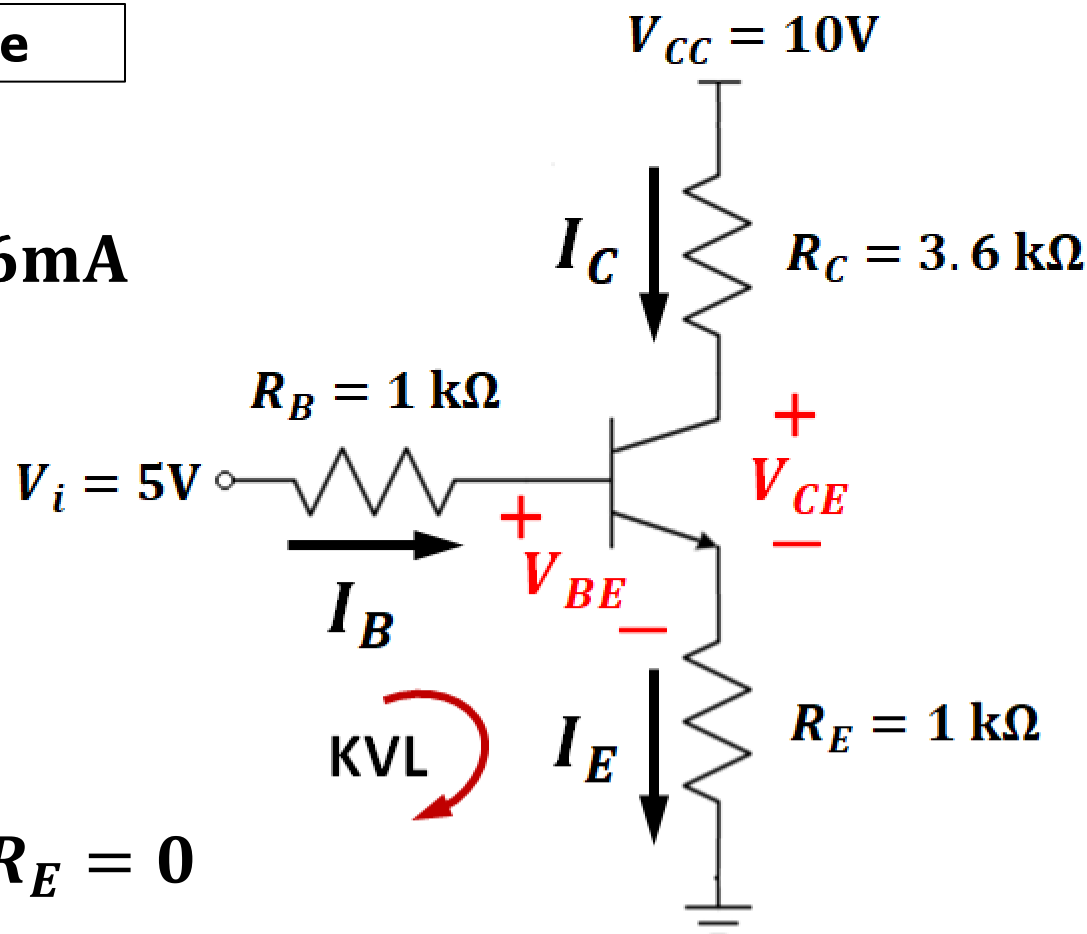
Example 3: BJT with emitter resistor

Assuming forward active mode

$$I_B = 0.0422\text{mA}$$

$$I_E = (\beta + 1)I_B = 4.26\text{mA}$$

$$I_C = \beta I_B = 4.22\text{mA}$$



Now, check for saturation

Collector-emitter KVL

$$-V_{CC} + I_C R_C + V_{CE} + I_E R_E = 0$$

Example 3: BJT with emitter resistor

Assuming forward active mode

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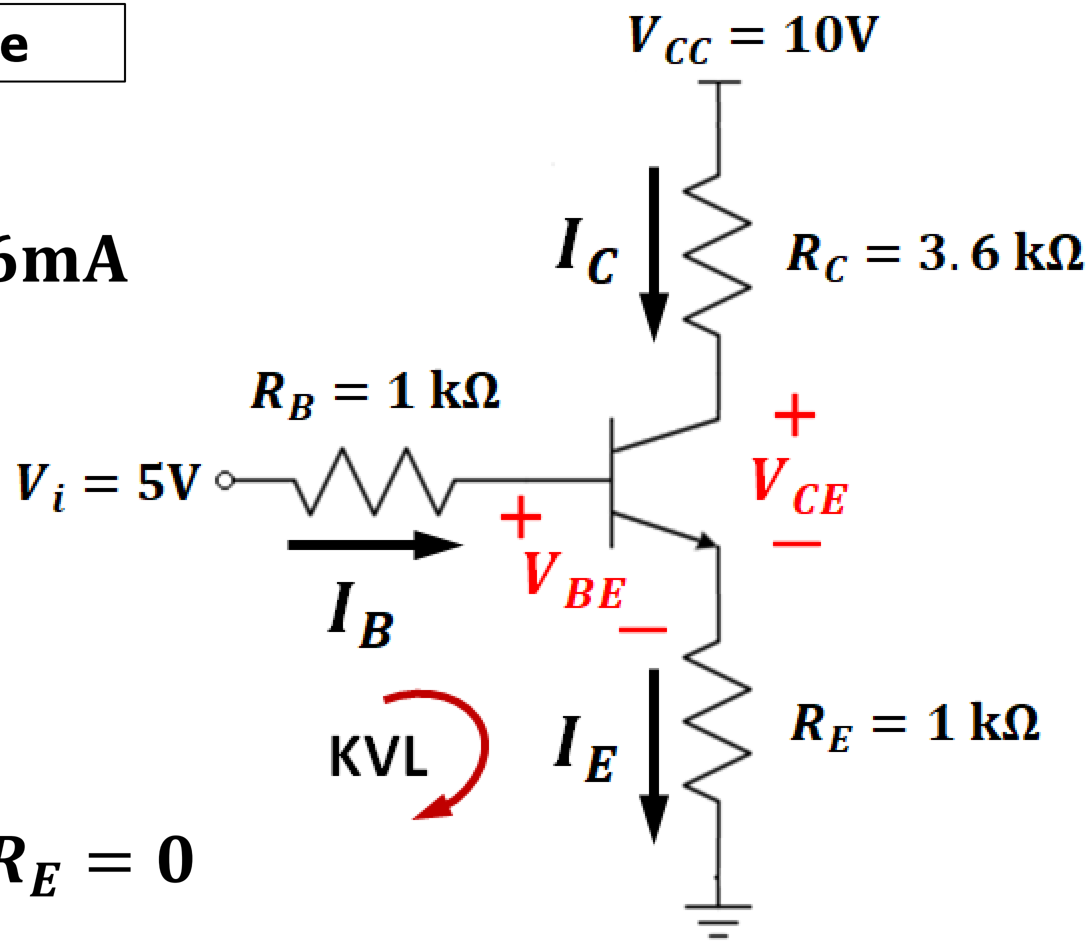

Now, check for saturation

Collector-emitter KVL

$$-V_{CC} + I_C R_C + V_{CE} + I_E R_E = 0$$

$$-10 + 4.22\text{m} \times 3.6\text{k} + V_{CE} + 4.26 \times 1\text{k} = 0$$

$$V_{CE} = 10 - 15.192 - 4.26 = -9.452\ \text{V} \ll V_{CE}(\text{sat})$$

Example 3: BJT with emitter resistor

Assuming forward active mode

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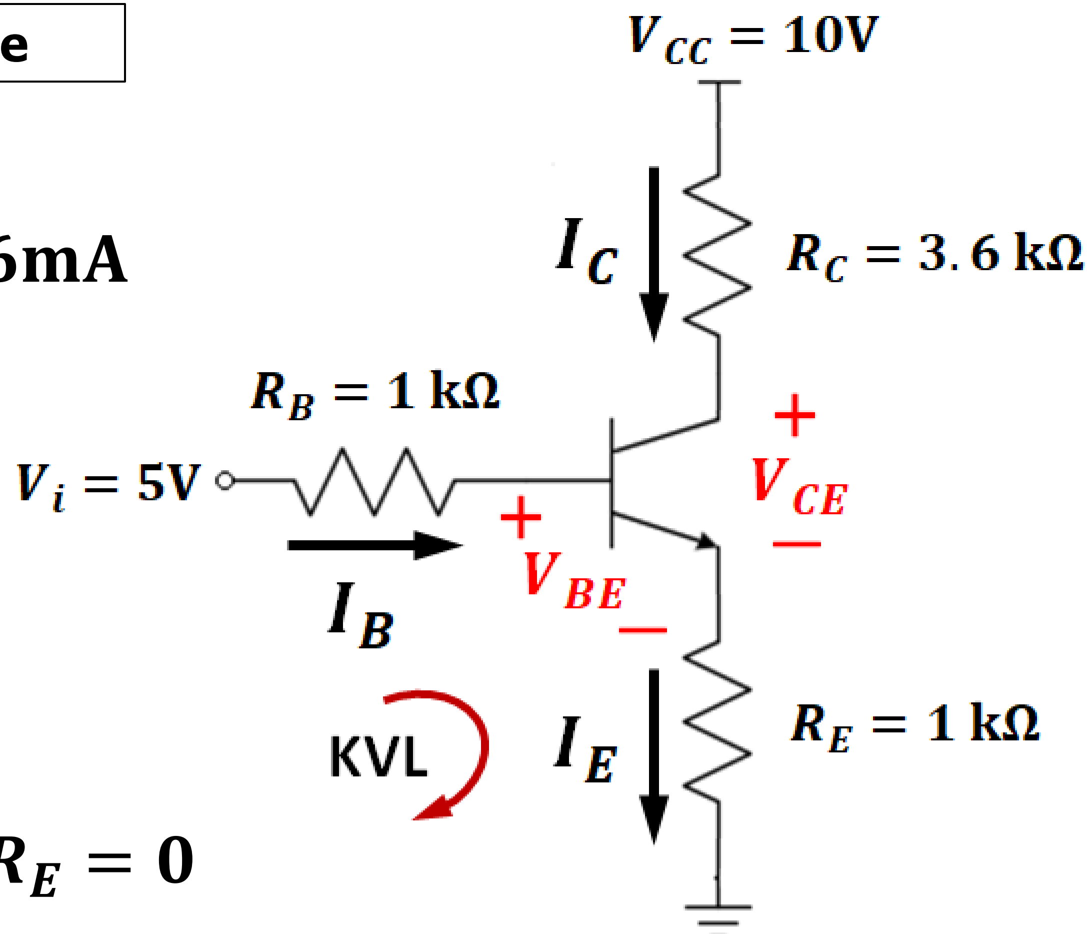

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$$V_{CE} = 10 - 15.192 - 4.26 = -9.452\ \text{V} \ll V_{CE}(\text{sat})$$

Assumption is invalid. ⇨ $V_{CE} = V_{CE}(\text{sat}) = 0.2\ \text{V}$

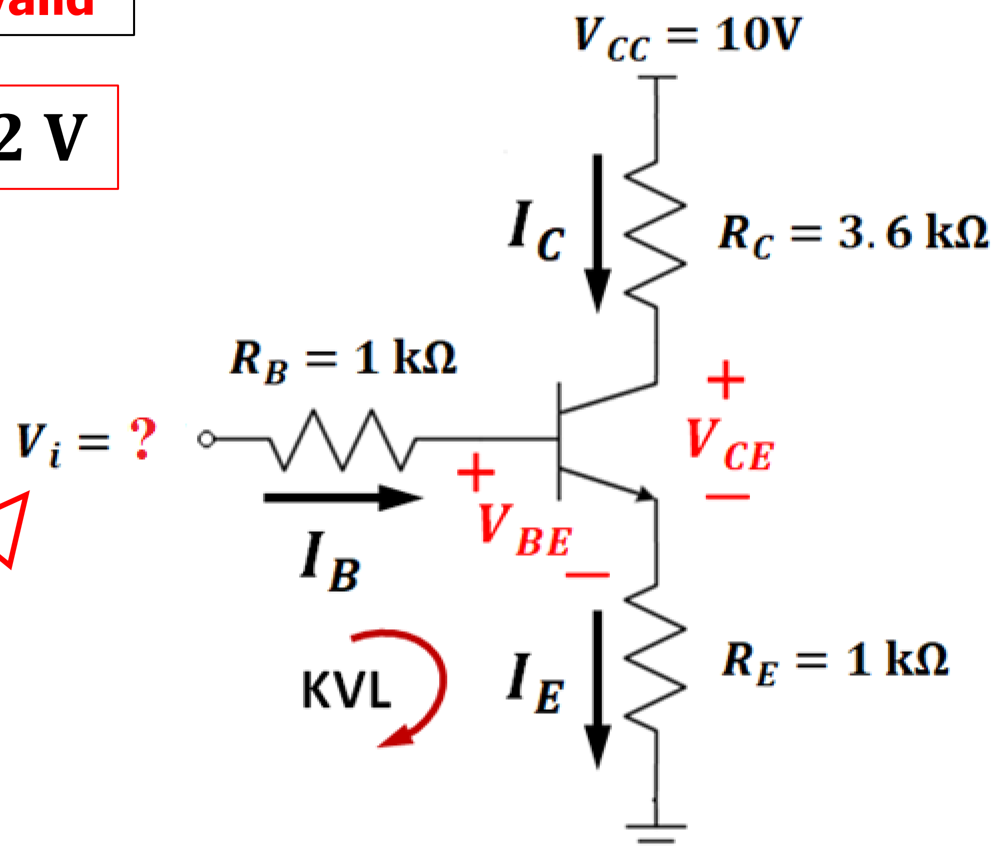
Previous results for currents are invalid

$$\Rightarrow \quad V_{CE} = V_{CE}(\text{sat}) = 0.2\ \text{V}$$

Remember

$$I_E = \frac{\beta + 1}{\beta} I_C = 1.01\, I_C$$

(valid up to onset of saturation)



Previous results for currents are invalid

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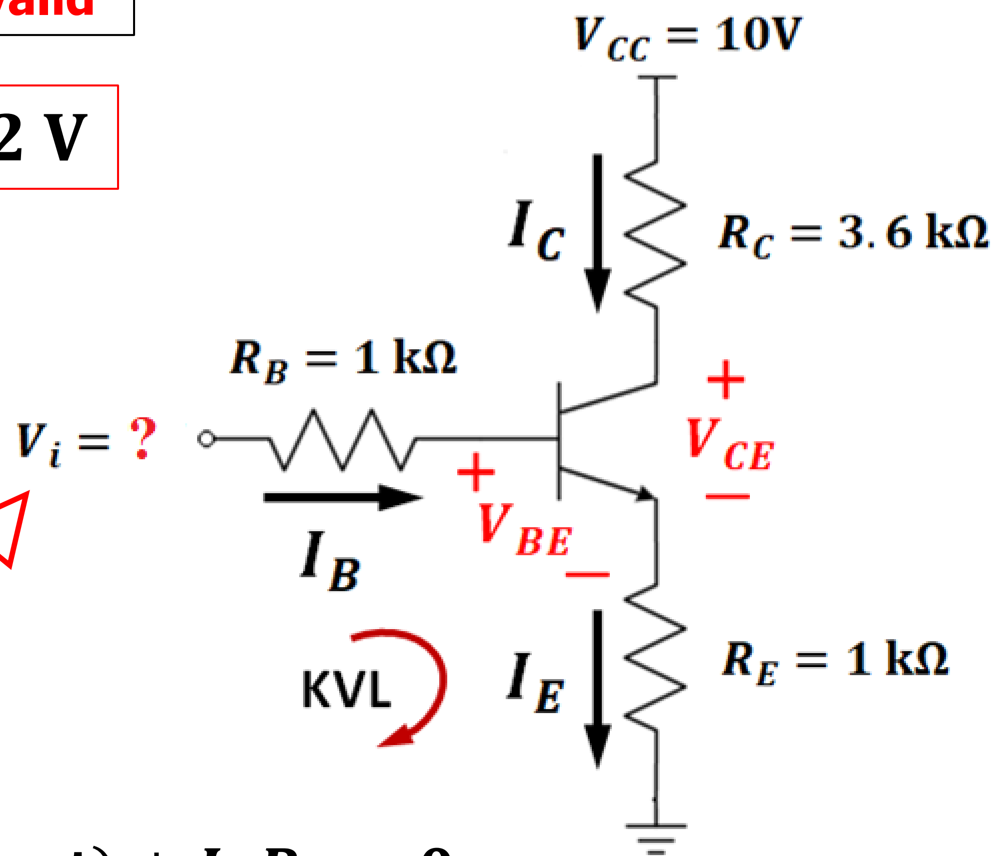


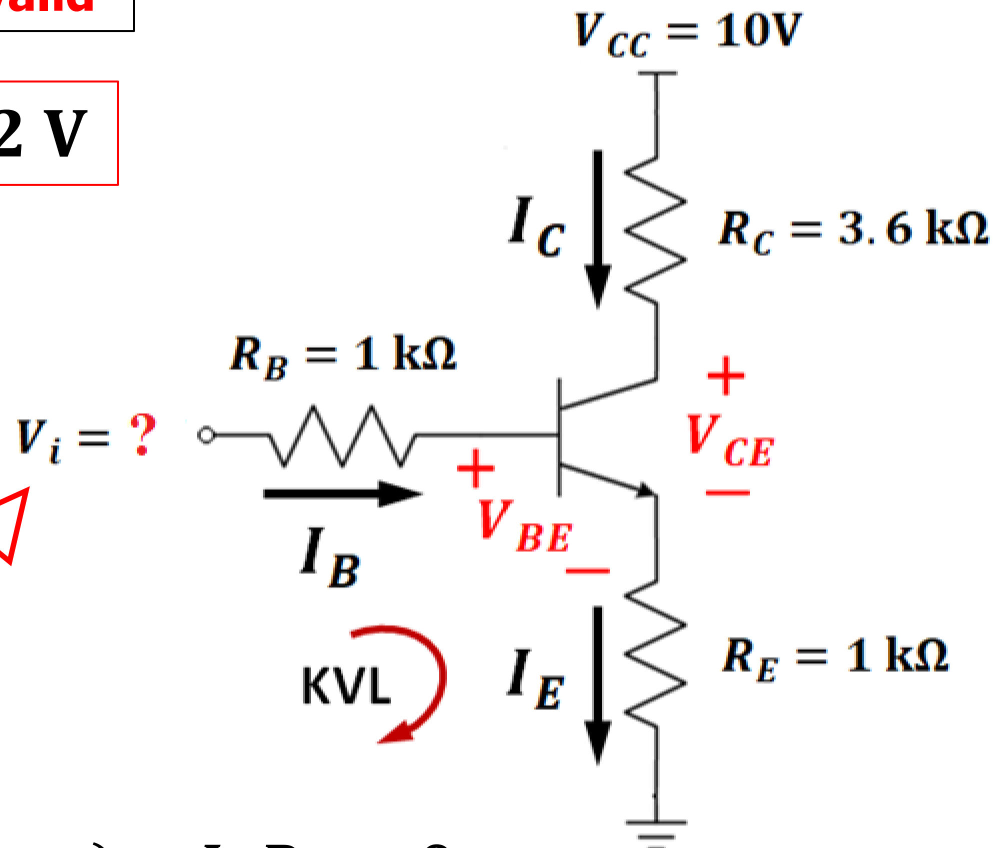
Recalculate collector-emitter KVL

$$-V_{CC} + I_C(\text{onsat})R_C + V_{CE}(\text{onsat}) + I_E R_E = 0$$

$$-10 + I_C(\text{onsat}) \times 3.6\text{k} + 0.2 + 1.01 \times I_C(\text{onsat}) \times 1\text{k} = 0$$

Previous results for currents are invalid

$$V_{CE} = V_{CE}(\text{sat}) = 0.2\ \text{V}$$



Remember

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$$-10 + I_C(\text{onsat}) \times 3.6\text{k} + 0.2 + 1.01 \times I_C(\text{onsat}) \times 1\text{k} = 0$$

$$I_C(\text{onsat}) = 9.8/4.61\text{k} = 2.13\ \text{mA}$$

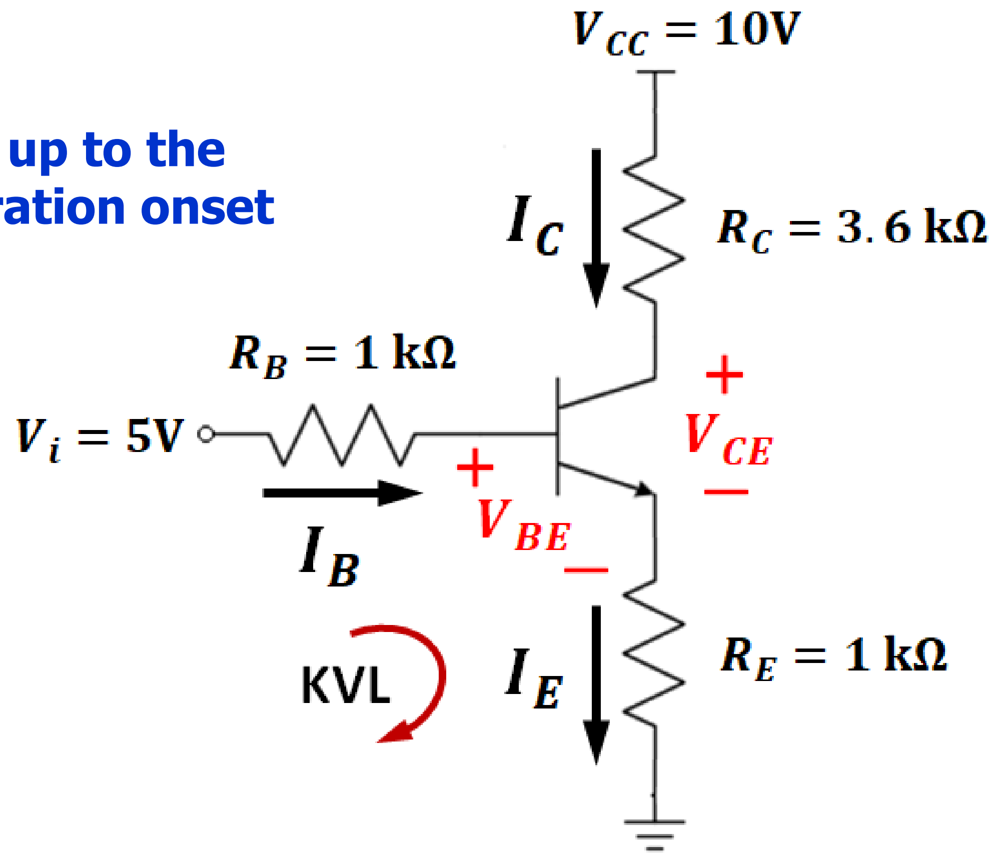
$$I_E(\text{onsat}) = 1.01\ I_C = 2.15\ \text{mA}$$

At onset of saturation

ATTENTION – Relevant for HW9-PL

$$I_E = \frac{\beta + 1}{\beta} I_C$$

is valid ONLY up to the point of saturation onset



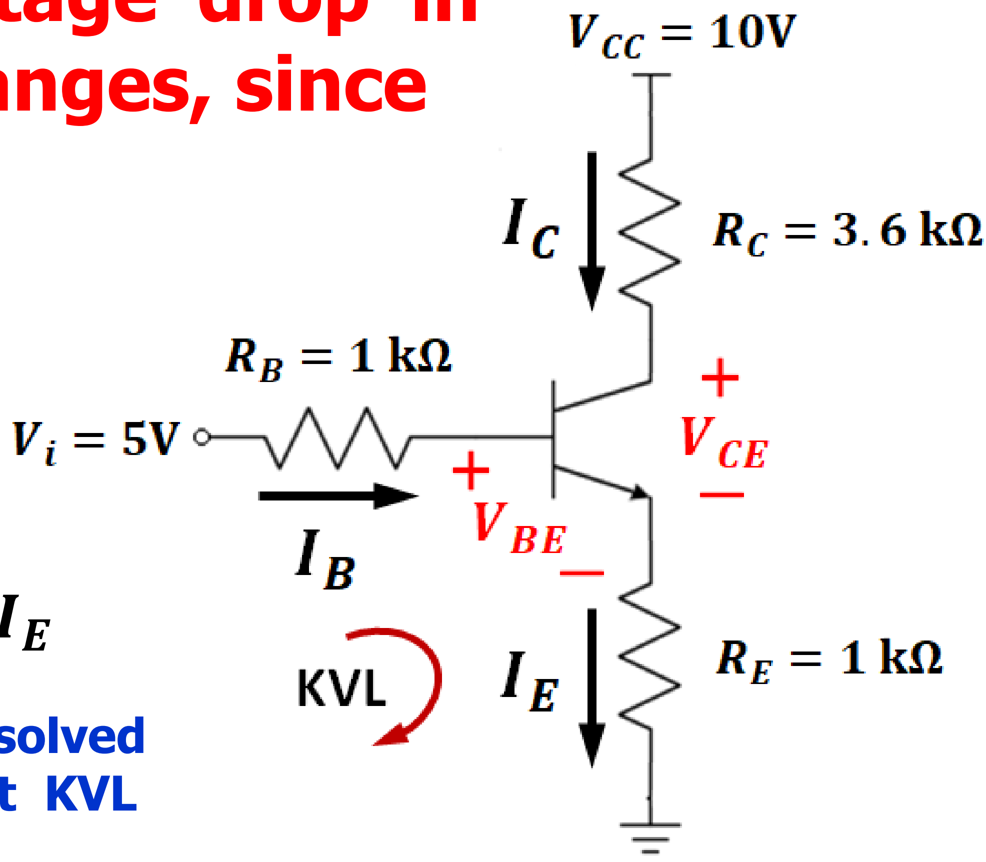
Deeper in saturation one must keep using

$$I_E = I_B + I_C$$

AGAIN: The derivations in the previous slide ARE NOT VALID in deeper saturation but only at the onset point where the device transitions from Forward-Active mode to Saturation mode

When the base current is increased beyond onset, the voltage drop in the emitter resistor changes, since

$$I_E = I_B + I_C$$



If we assume that the saturation $V_{CE}(\text{sat})$ remains at the value specified by the manufacturer throughout, in saturation

$$V_{CC} - V_{CE}(\text{sat}) = R_C I_C + R_E I_E$$

This equation has to be solved simultaneously with the base circuit KVL

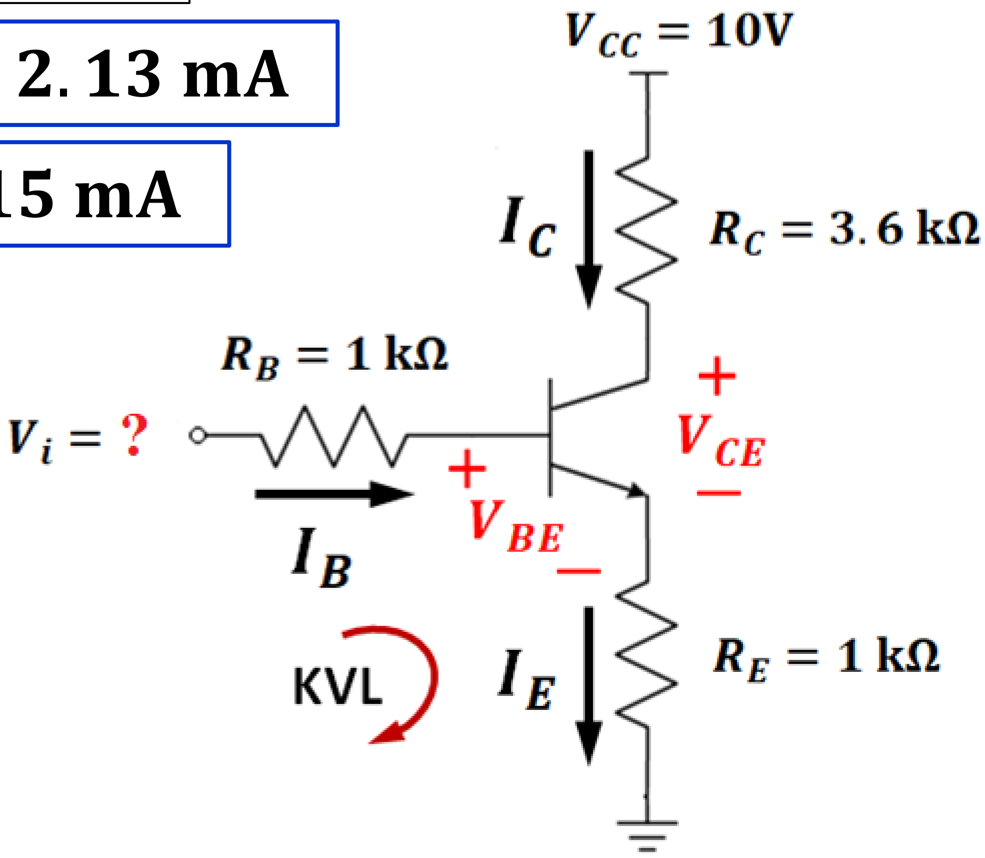
$$V_i - V_{BE} = R_B I_B + R_E I_E$$

Recalculated currents

$$I_C(\text{onsat}) = 9.8/4.61\text{k} = 2.13\text{ mA}$$

$$I_E(\text{onsat}) = 1.01\, I_C = 2.15\text{ mA}$$

Find base voltage at onset of saturation



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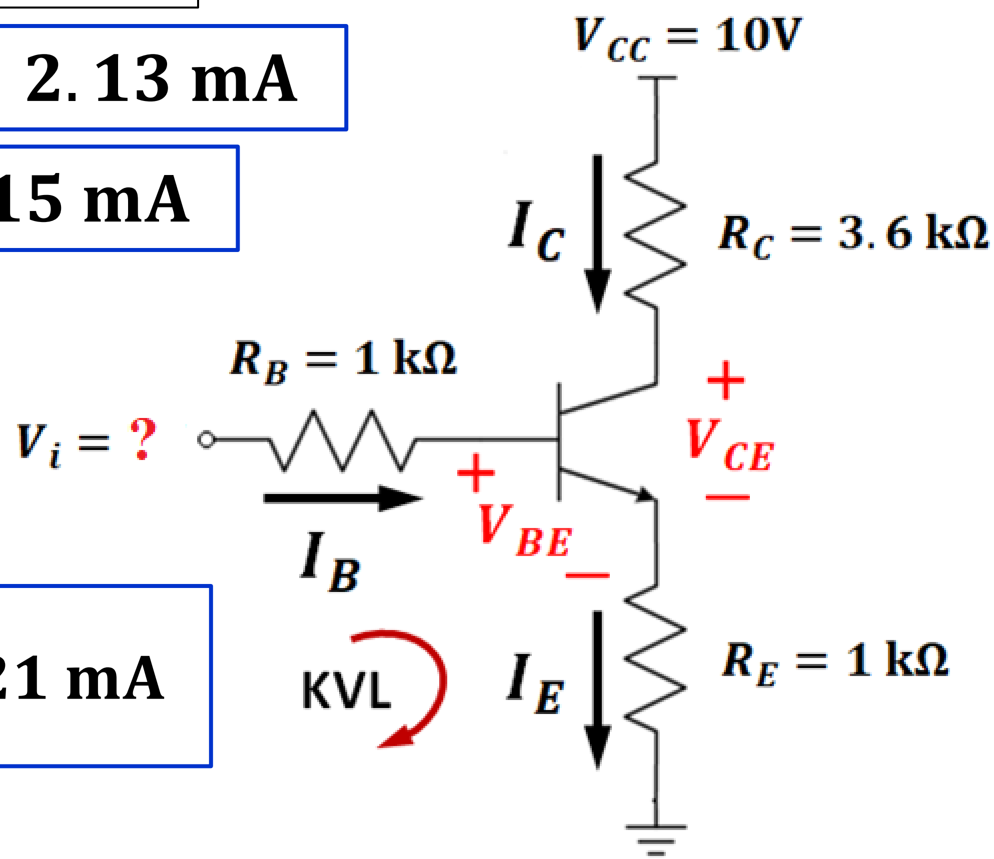
$$I_E(\text{onsat}) = 1.01\, I_C = 2.15\ \text{mA}$$

Find base voltage at onset of saturation

$$I_B(\text{onsat}) = \frac{I_C(\text{onsat})}{\beta} = 0.021\ \text{mA}$$



Recalculated currents

$$I_C(\text{onsat}) = 9.8/4.61\text{k} = 2.13\ \text{mA}$$

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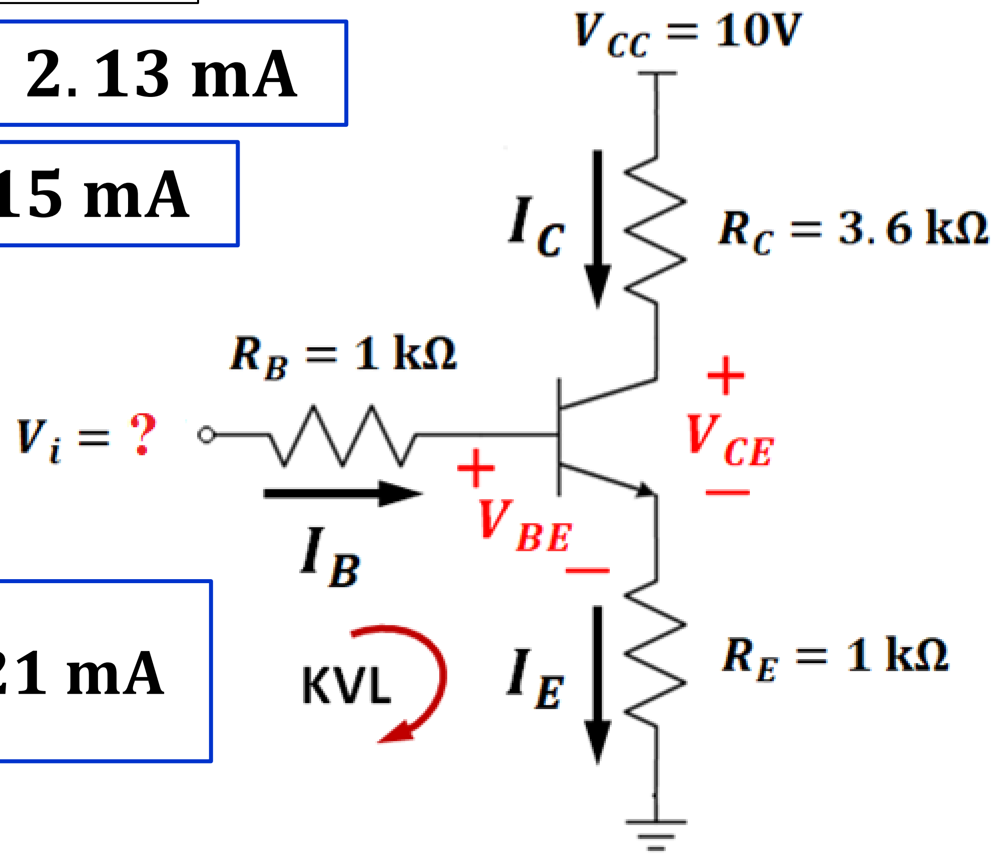
Find base voltage at onset of saturation



$$I_B(\text{onsat}) = \frac{I_C(\text{onsat})}{\beta} = 0.021\ \text{mA}$$

Base circuit KVL

$$-V_i(\text{onsat}) + I_B(\text{onsat})R_B + V_{BE} + I_E(\text{onsat})R_E = 0$$

$$V_i(\text{onsat}) = 0.021\text{m} \times 1\text{k} + 0.7 + 2.15\text{m} \times 1\text{k}$$

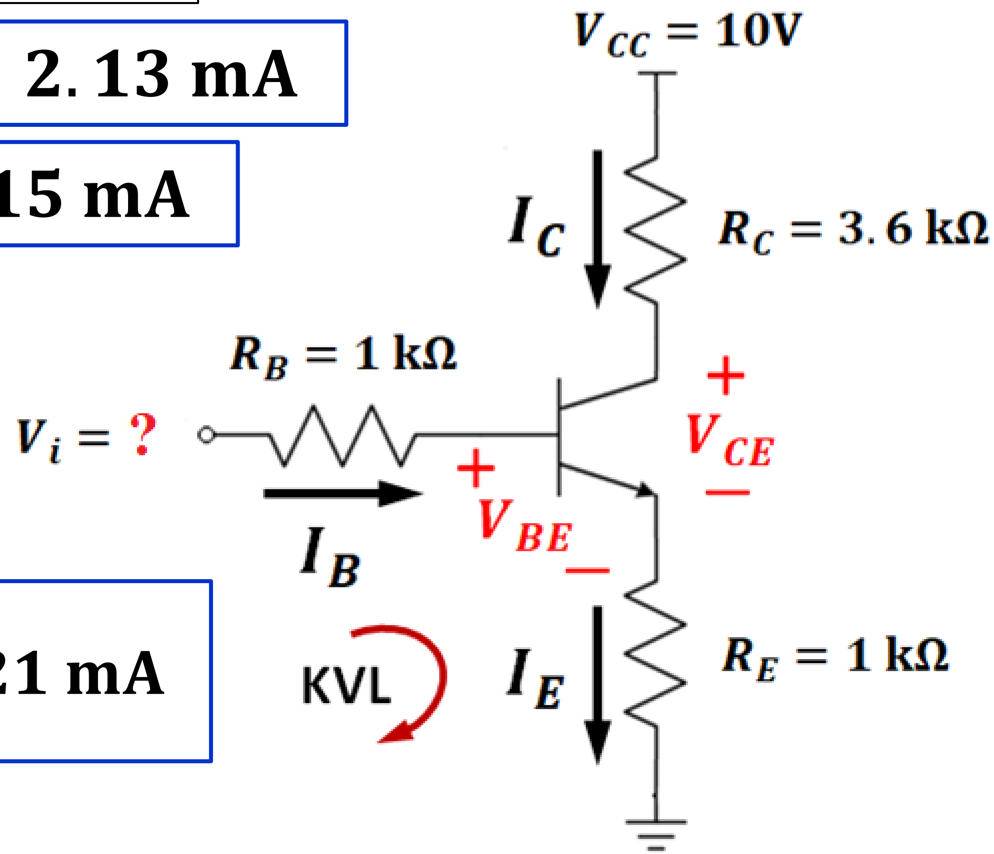
Recalculated currents

$$I_C(\text{onsat}) = 9.8/4.61\text{k} = 2.13\ \text{mA}$$

$$I_E(\text{onsat}) = 1.01\, I_C = 2.15\ \text{mA}$$

Find base voltage at onset of saturation

$$I_B(\text{onsat}) = \frac{I_C(\text{onsat})}{\beta} = 0.021\ \text{mA}$$



Base circuit KVL

$$-V_i(\text{onsat}) + I_B(\text{onsat})R_B + V_{BE} + I_E(\text{onsat})R_E = 0$$

$$V_i(\text{onsat}) = 0.021\text{m} \times 1\text{k} + 0.7 + 2.15\text{m} \times 1\text{k}$$

$$V_i(\text{onsat}) = 2.87\ \text{V}$$

At this input voltage on the base resistor, the BJT starts saturating

Resistor on emitter changes the saturation behavior

$$V_{BE}(\text{on}) \leq V_B < V_i(\text{onsat}) = 2.87\ \text{V}$$

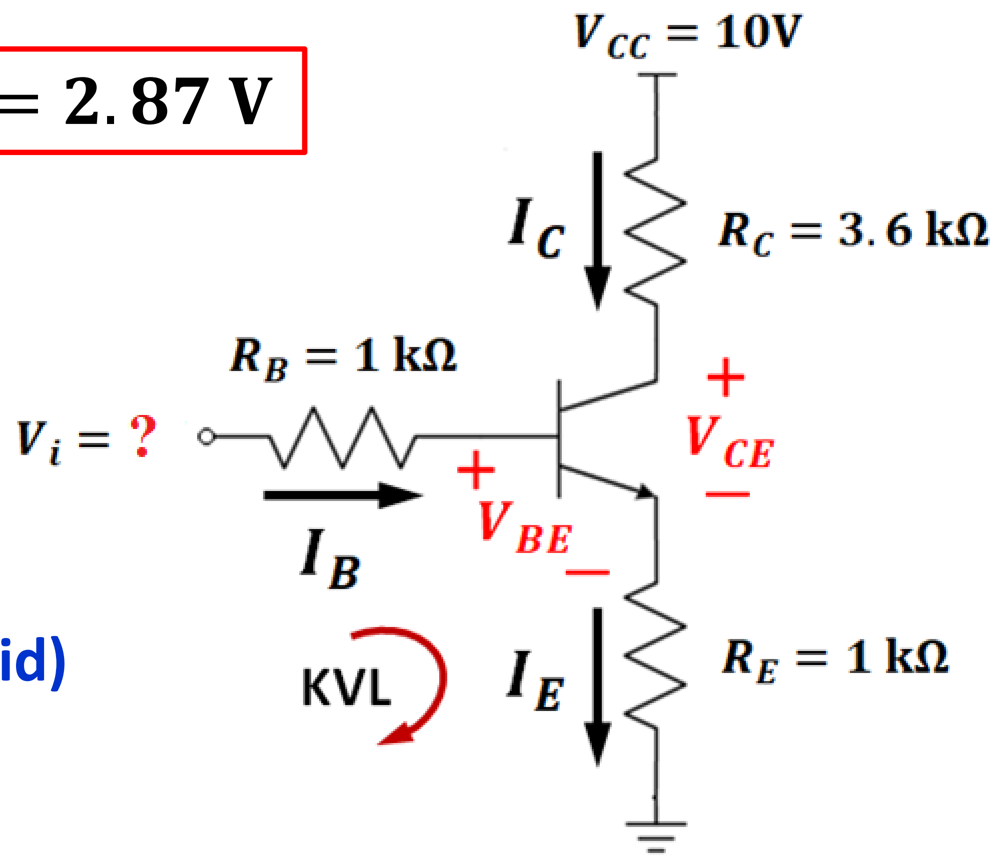
Forward-Active mode

$$V_B = V_i(\text{onsat}) = 2.87\ \text{V}$$

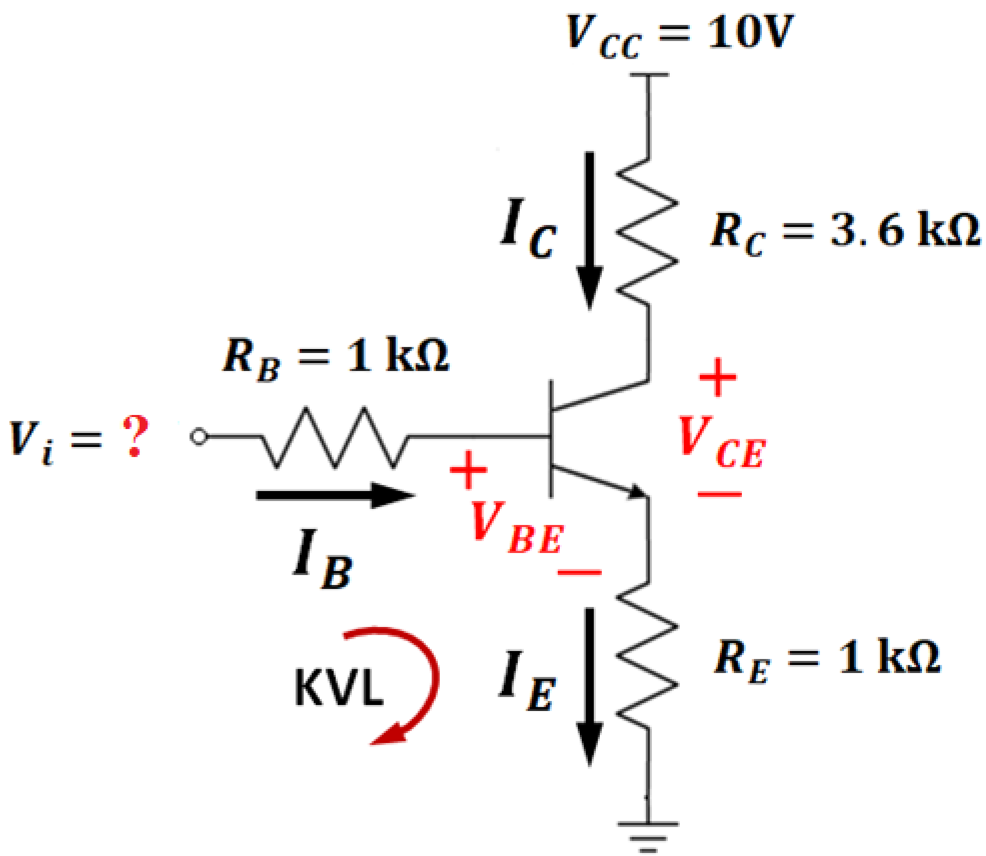
Onset of saturation
(FA mode equations are still valid)

$$V_B > V_i(\text{onsat}) = 2.87\ \text{V}$$

"*Deeper*" saturation
(FA mode equations are NOT valid)



In deeper saturation, collector current decreases somewhat



$V_{CC} = 10\ V$

$I_C R_C$

assume constant

$V_{CE} = V_{CE}(sat) = 0.2\ V$

$I_E R_E = (I_B + I_C) R_E$

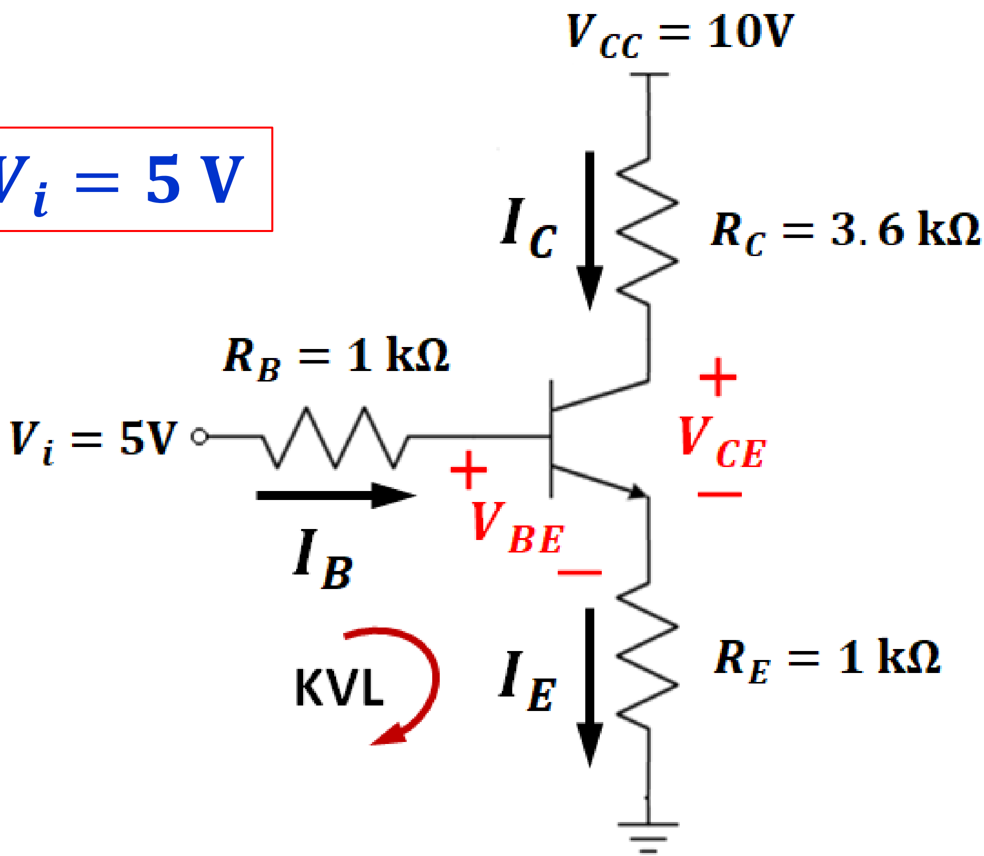
I_B keeps increasing in deeper saturation

$V_B > V_i(onsat) = 2.87\ V$

$I_C < I_C(onsat) = 2.13\ mA$

MUST SOLVE FOR COUPLED KVL's IN BASE AND COLLECTOR LOOPs

$V_i = 5\text{ V}$



$V_{CC} = 10\text{ V}$

$I_C R_C$

assume constant

$V_{CE} = V_{CE}(\text{sat}) = 0.2\text{ V}$

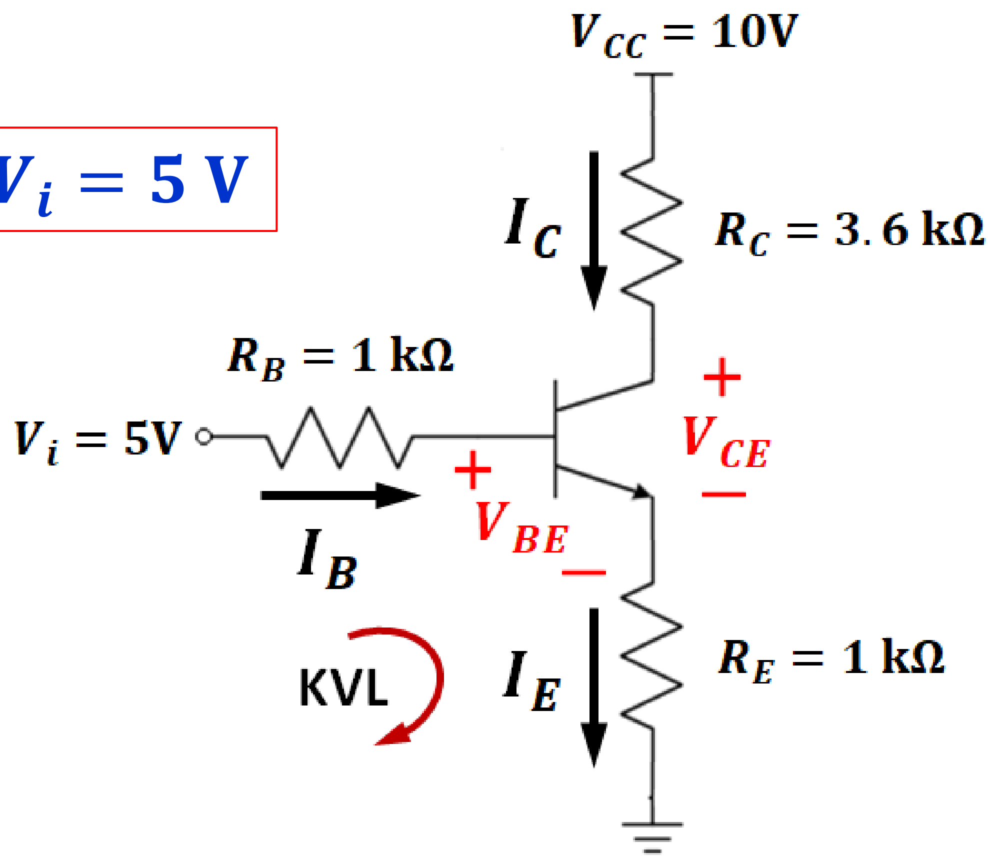
$I_E R_E = (I_B + I_C)R_E$

$$V_i = I_B R_B + V_{BE}\,(\text{on}) + I_E R_E$$

$$V_{CC} = I_C R_C + V_{CE}\,(\text{sat}) + I_E R_E$$

MUST SOLVE FOR COUPLED KVL's IN BASE AND COLLECTOR LOOPs

$V_i = 5\ \text{V}$



$V_{CC} = 10\ \text{V}$

$I_C R_C$

assume constant

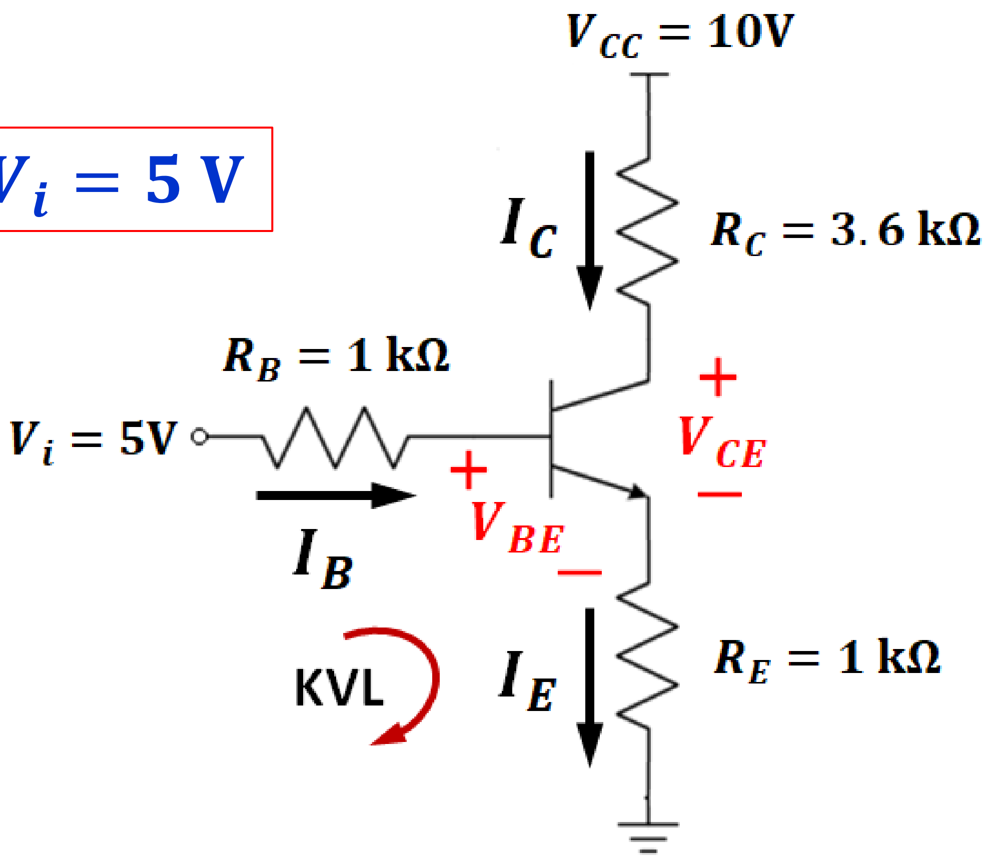
$V_{CE} = V_{CE}(\text{sat}) = 0.2\ \text{V}$

$I_E R_E = (I_B + I_C) R_E$

$$5 = 1\text{k}\, I_B + 0.7 + (I_B + I_C)1\text{k}$$

$$10 = 3.6\text{k}\ \ I_C + 0.2 + (I_B + I_C)1\text{k}$$

MUST SOLVE FOR COUPLED KVL's IN BASE AND COLLECTOR LOOPs



$V_i = 5\ \text{V}$

$V_{CC} = 10\ \text{V}$

$I_C R_C = 6.717\ \text{V}$

assume constant

$V_{CE} = V_{CE}(\text{sat}) = 0.2\ \text{V}$

$$I_E R_E = (I_B + I_C) R_E = 3.083\ \text{V}$$

$$2\text{k}\ I_B + 1\text{k}\ I_C = 4.3$$

$$1\text{k}\ I_B + 4.6\text{k}\ \ I_C = 9.8$$

$$I_B = 1.217\ \text{mA}$$

$$I_C = 1.866\ \text{mA}\ < I_C(\text{onsat})$$

$$I_C(\text{onsat}) = 2.13\ \text{mA}$$

RECAPITULATING: For BJT with added resistor on the emitter

To analyze deeper in saturation, one needs to solve the coupled KVL equations for base and collector loops with

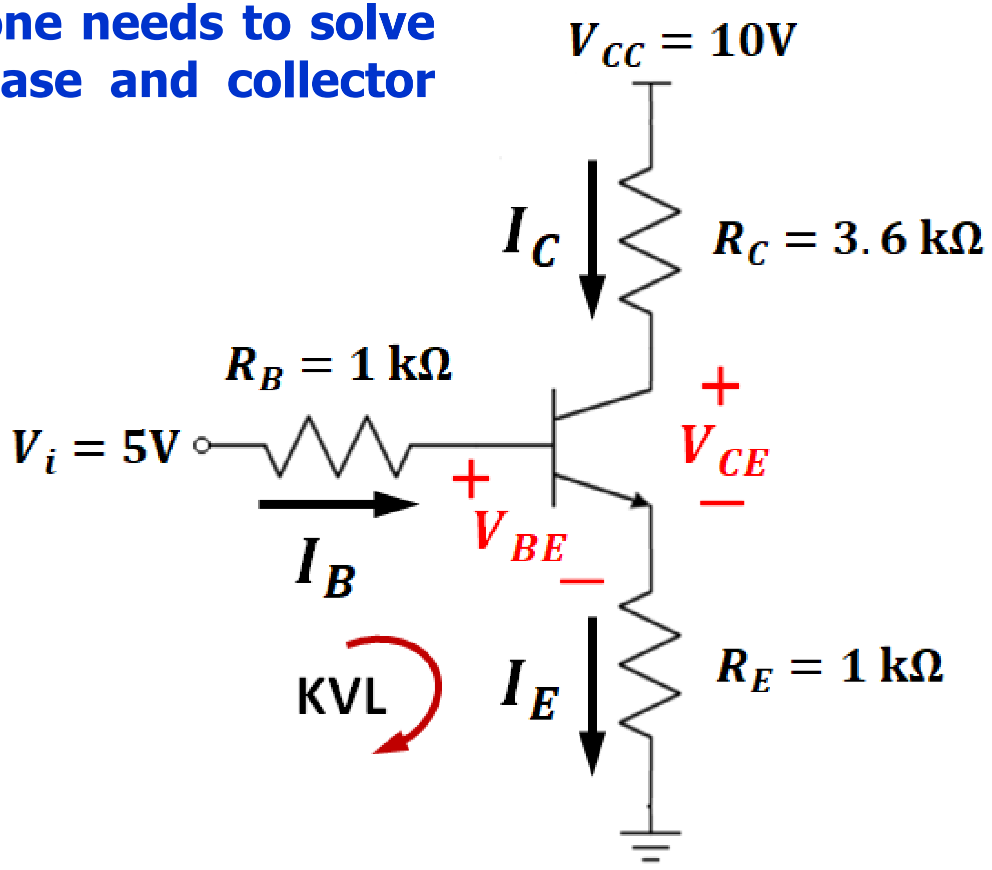
$$I_E = I_B + I_C$$

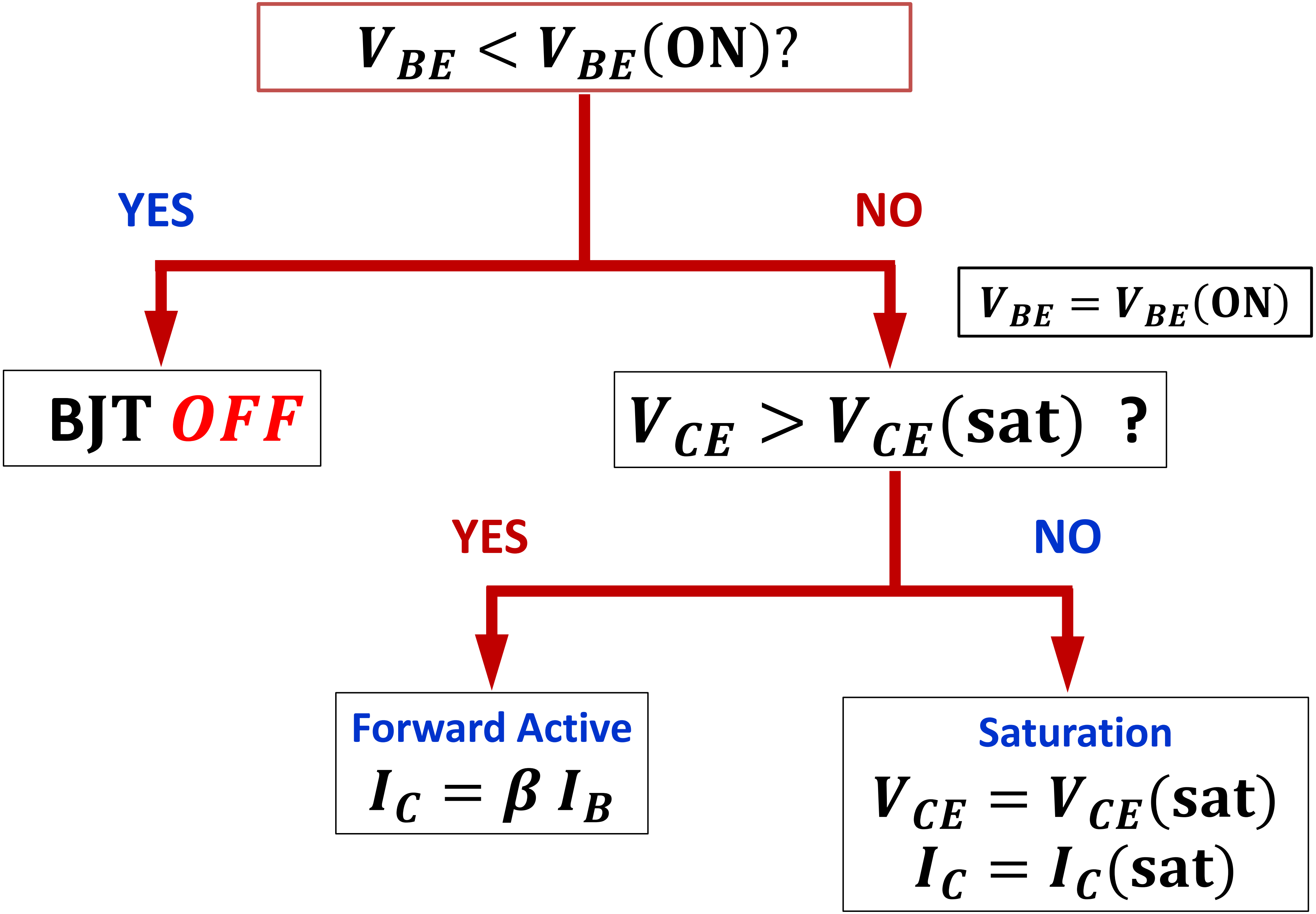
V_{CC} is fixed. Since I_E increases, I_C must decrease to maintain the collector KVL valid.

In our model we assume that V_{CE} remains fixed at $V_{CE}(\text{sat})$.

This is an approximation. As I_C decreases, $V_{CE}(\text{sat})$ decreases slowly toward zero.

Some even simpler models just set $V_{CE}(\text{sat}) = 0$.

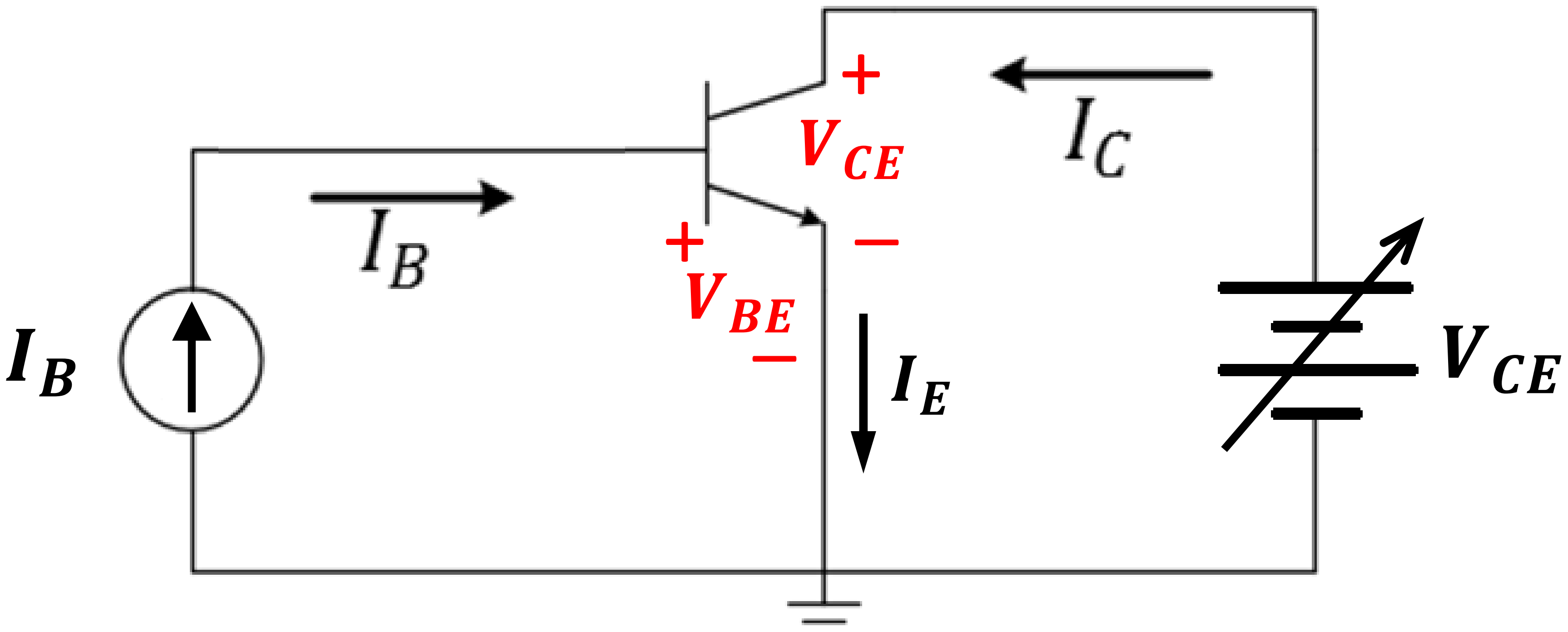




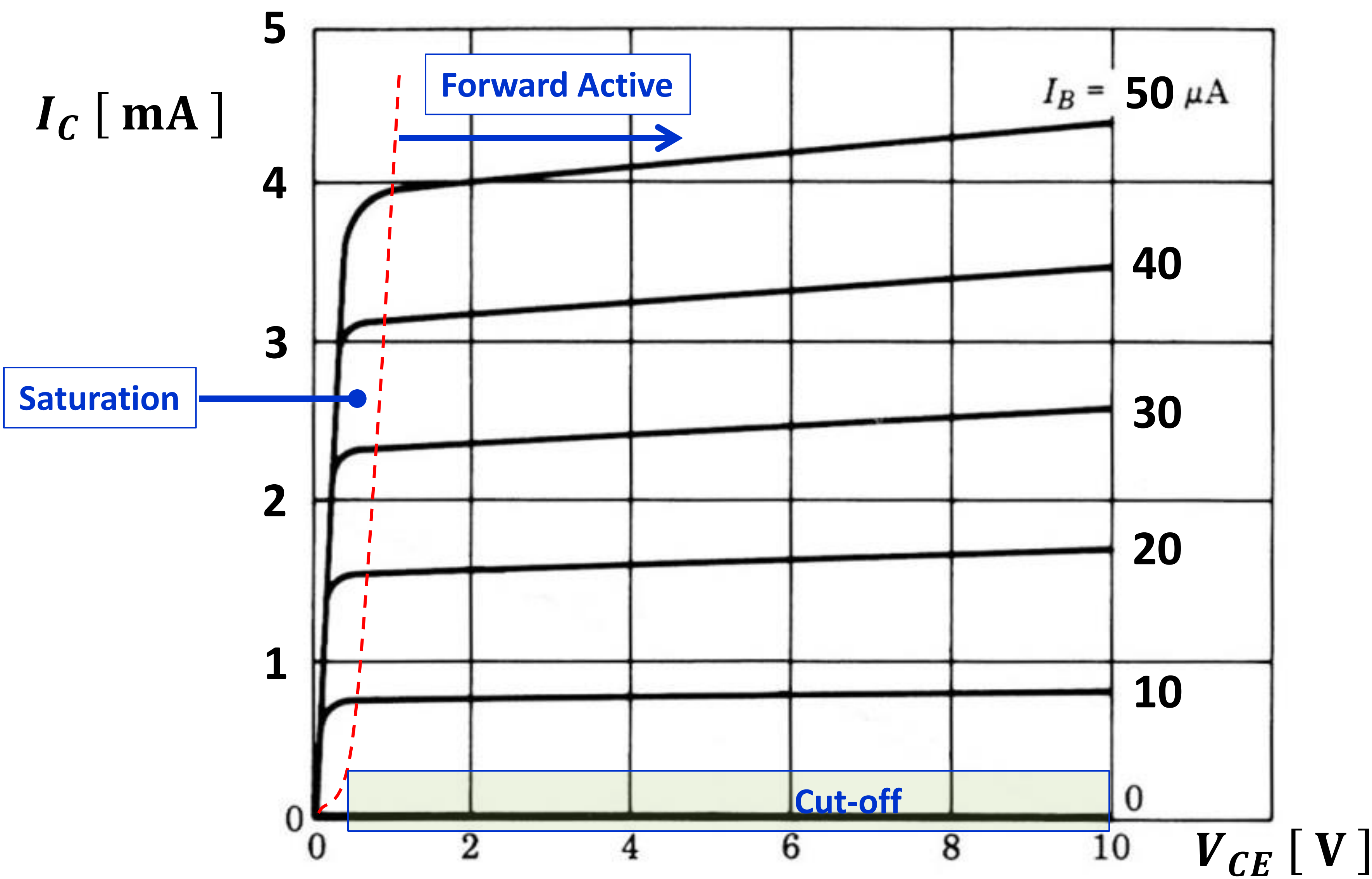
Emitter resistor complicates saturation analysis

BJT I-V curves are measured on actual devices

Measurements are made by ramping the V_{CE} at specific values of base current I_B



BJT *I*-*V* curves

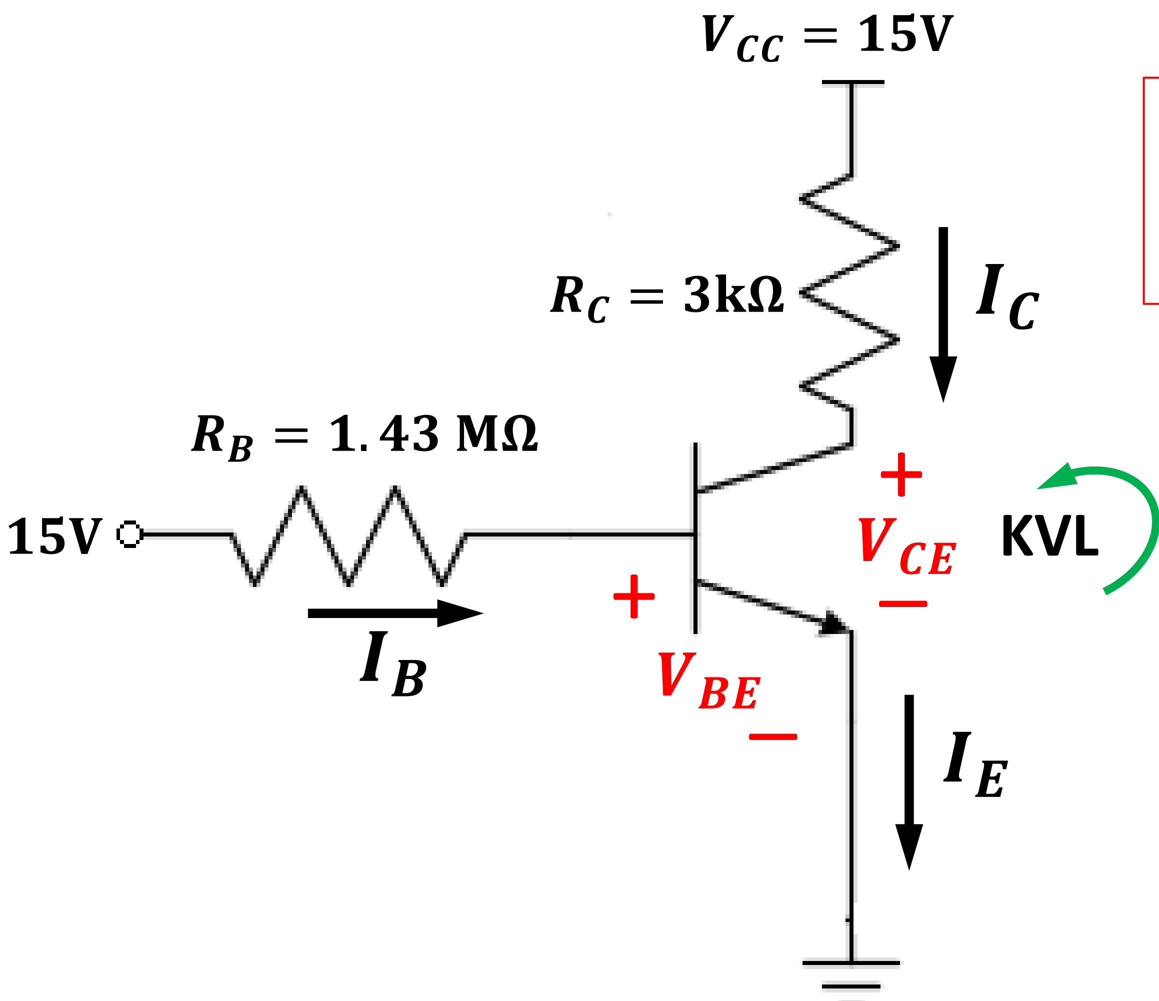


Example of graphical use of BJT I-V curves

$V_{BE}(\text{on}) = 0.7\text{V}$

$\beta = 100$

KVL $V_{CE} = V_{CC} - I_C R_C$



Let's write I_C as a function of V_{CE}

Example of graphical use of BJT I-V curves

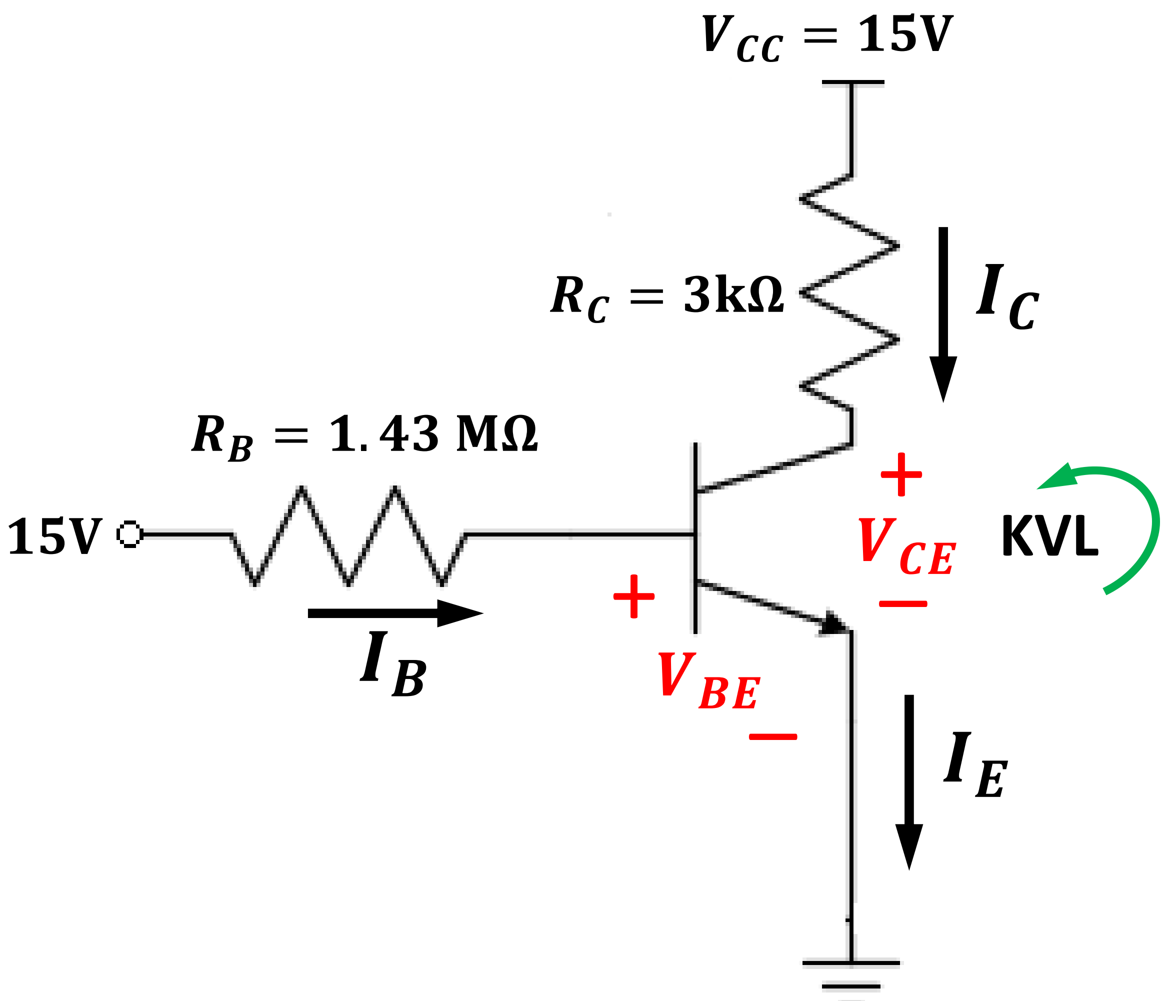
$$V_{BE}(\text{on}) = 0.7\text{V}$$

$$\beta = 100$$

KVL $$V_{CE} = V_{CC} - I_C R_C$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C}$$

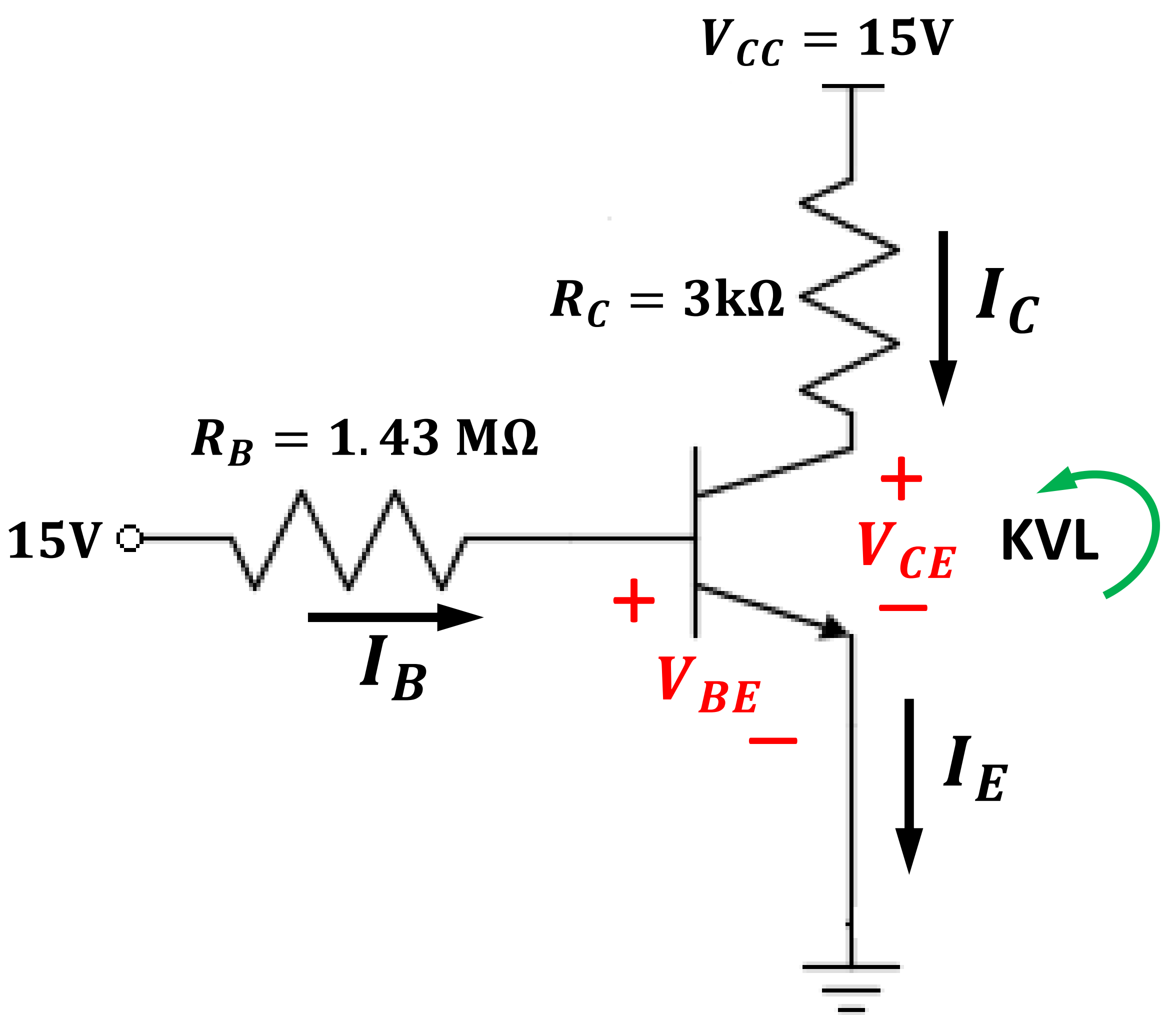
$$I_C = \frac{15 - V_{CE}}{3\text{k}\Omega}$$



Example of graphical use of BJT *I-V* curves

$V_{BE}(\text{on}) = 0.7\text{V}$

$\beta = 100$



KVL $V_{CE} = V_{CC} - I_C R_C$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C}$$

$$I_C = \frac{15 - V_{CE}}{3\text{k}\Omega}$$

$$I_C = 5\text{mA} - \frac{V_{CE}}{3\text{k}\Omega}$$

Equation of a straight line

V_{CE}	I_C
0V	5mA
15V	0mA

Example of graphical use of BJT I-V curves

$V_{BE}(\text{on}) = 0.7\text{V}$

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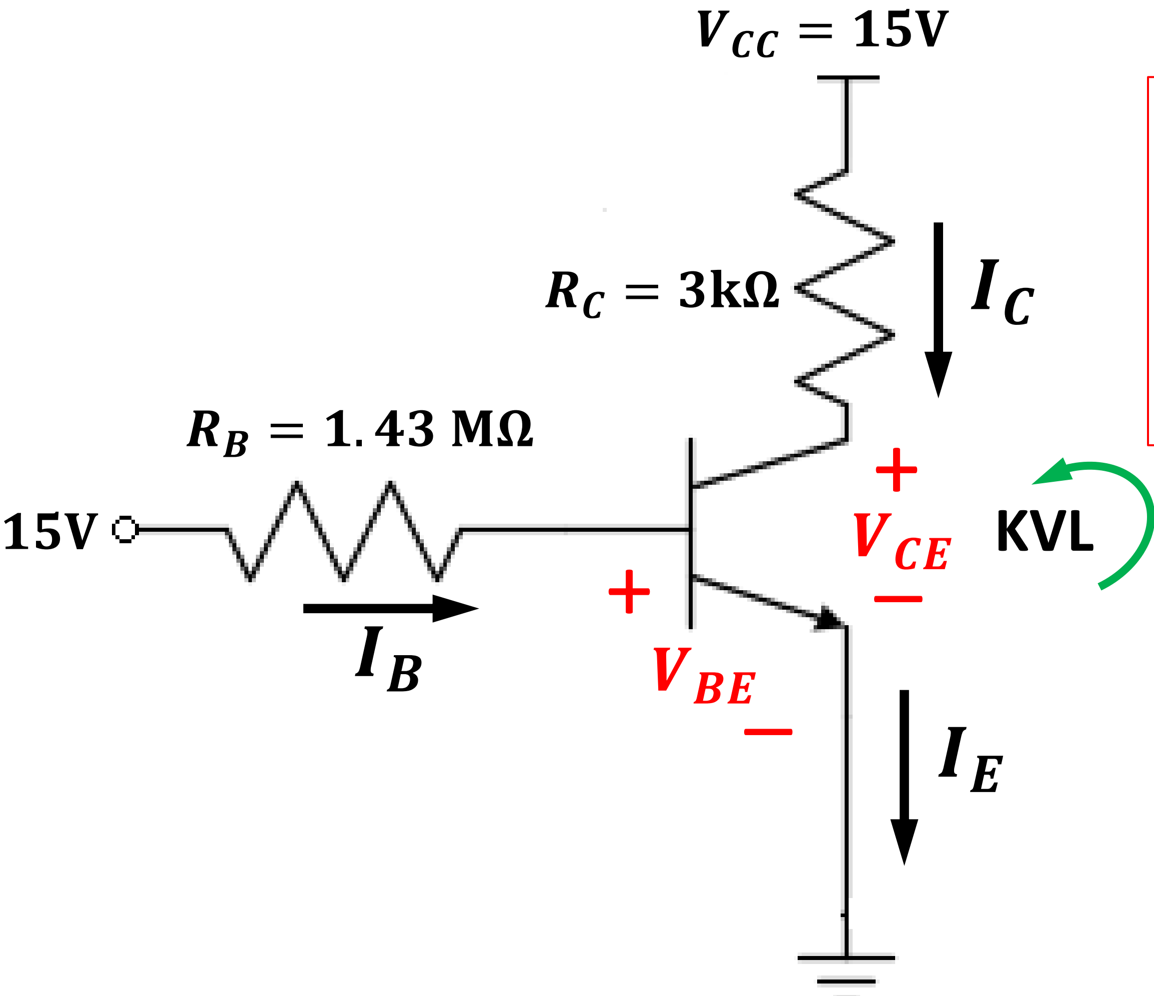
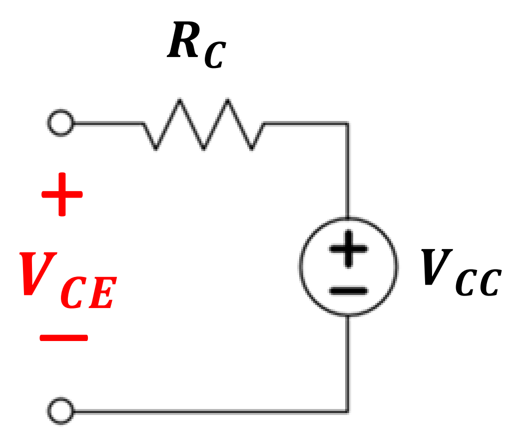
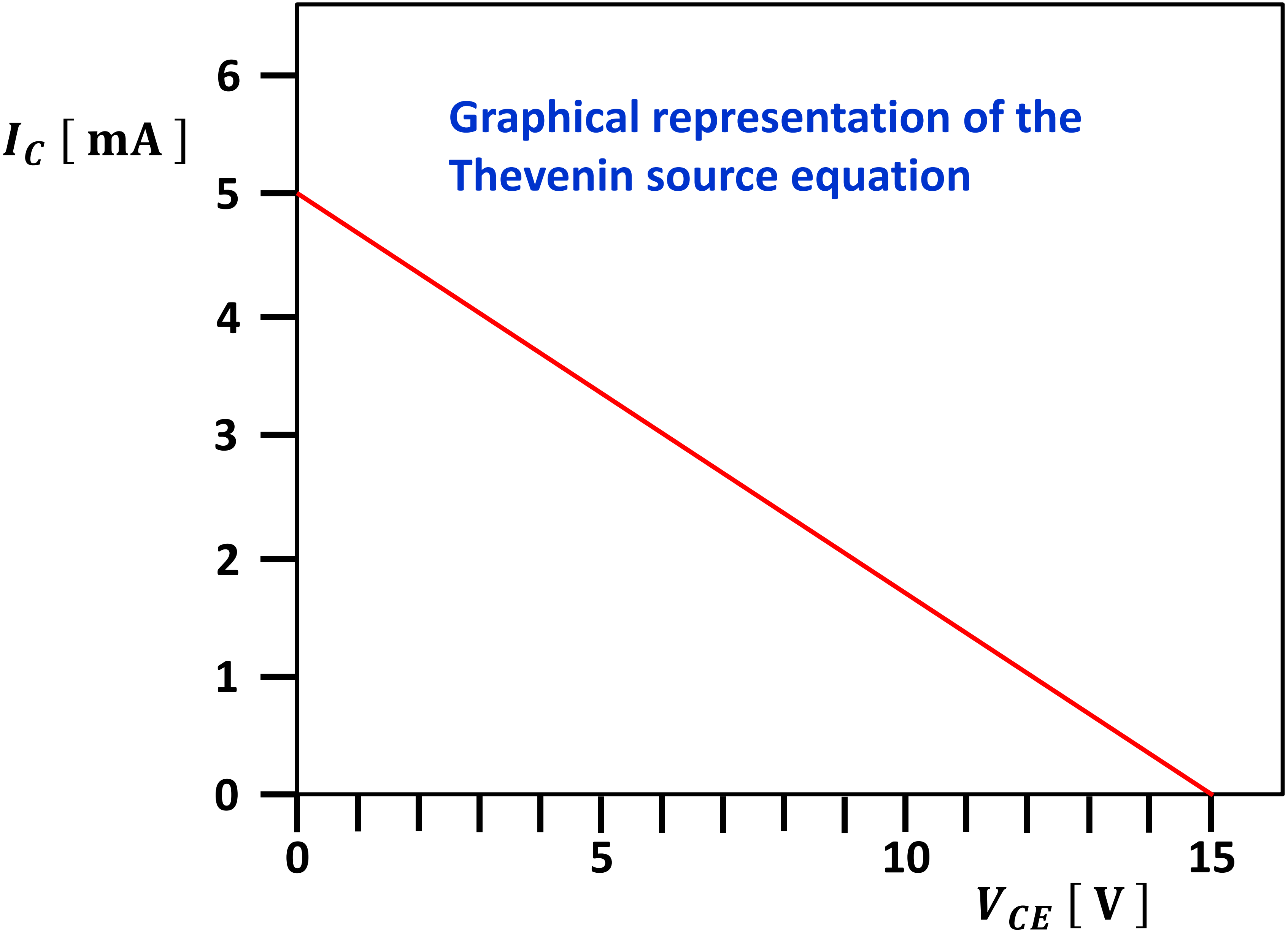
$$I_C = 5\text{mA} - \frac{V_{CE}}{3\text{k}\Omega}$$



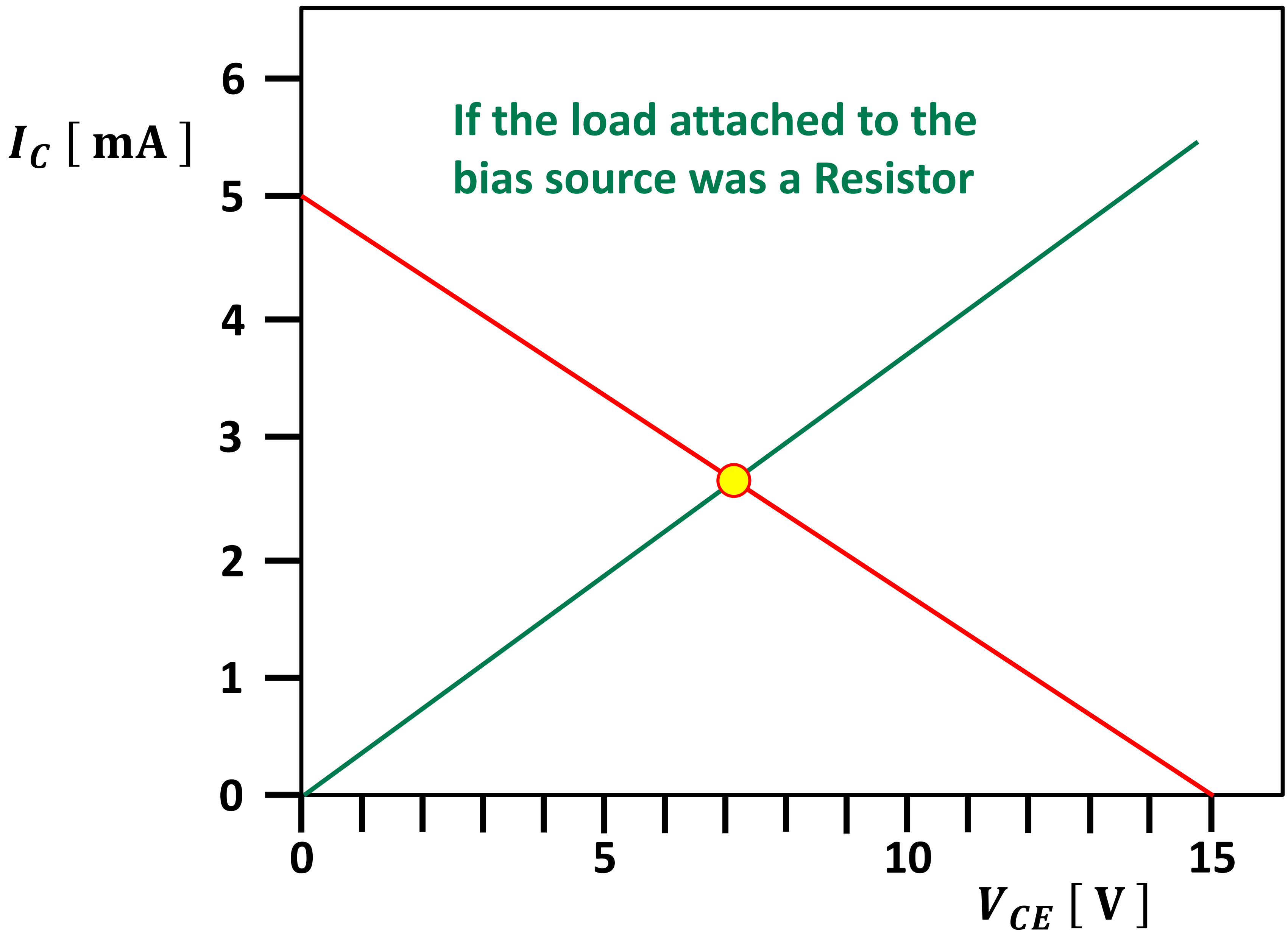
This equation just describes the collector biasing network as a Thevenin source. Here, V_{CE} and I_C depend on the behavior of the BJT, which is a non-linear load



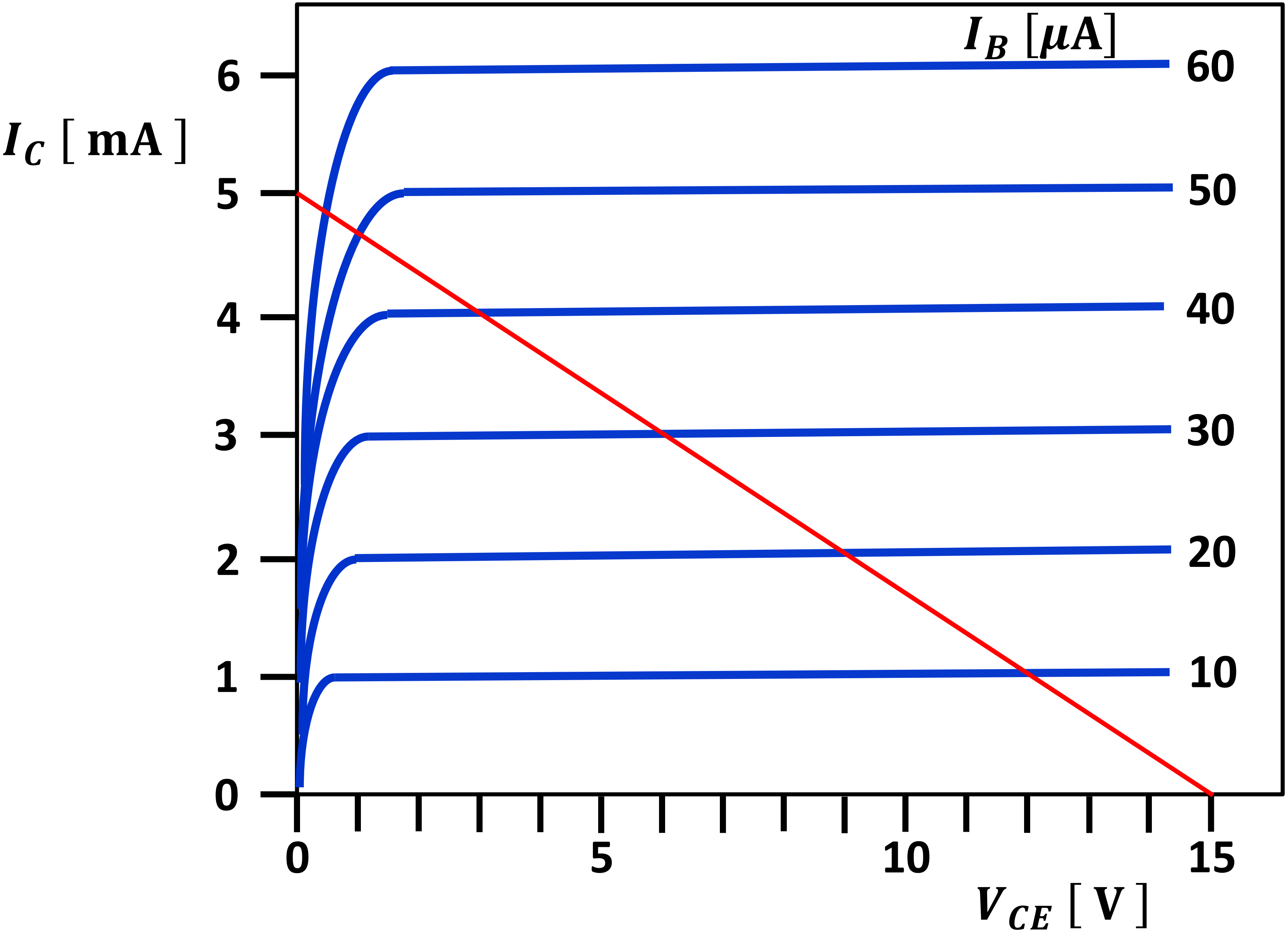
Example of graphical use of BJT I-V curves



Example of graphical use of BJT I-V curves



Example of graphical use of BJT I-V curves

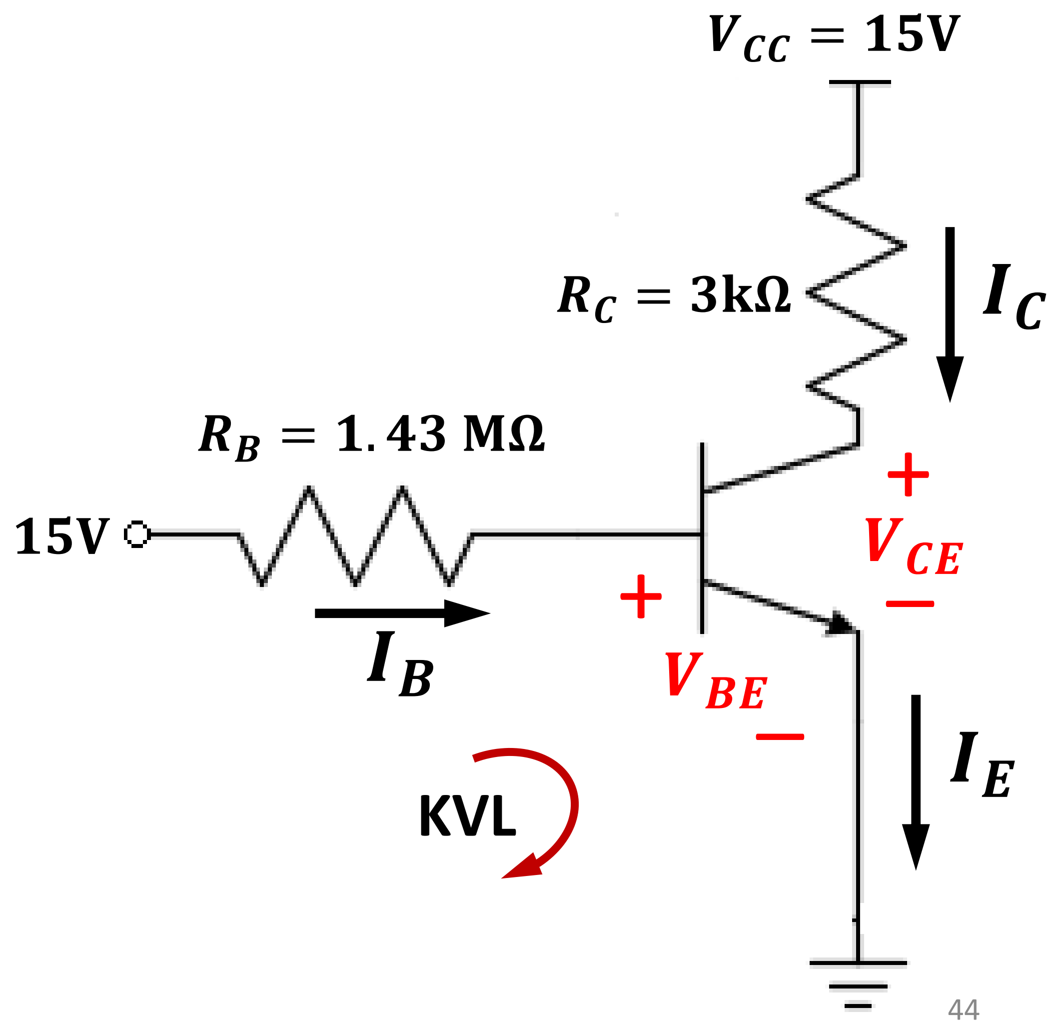


Example of graphical use of BJT I-V curves

$V_{BE}(\text{on}) = 0.7\text{V}$

$\beta = 100$

Let's examine the Base circuit:



Example of graphical use of BJT I-V curves

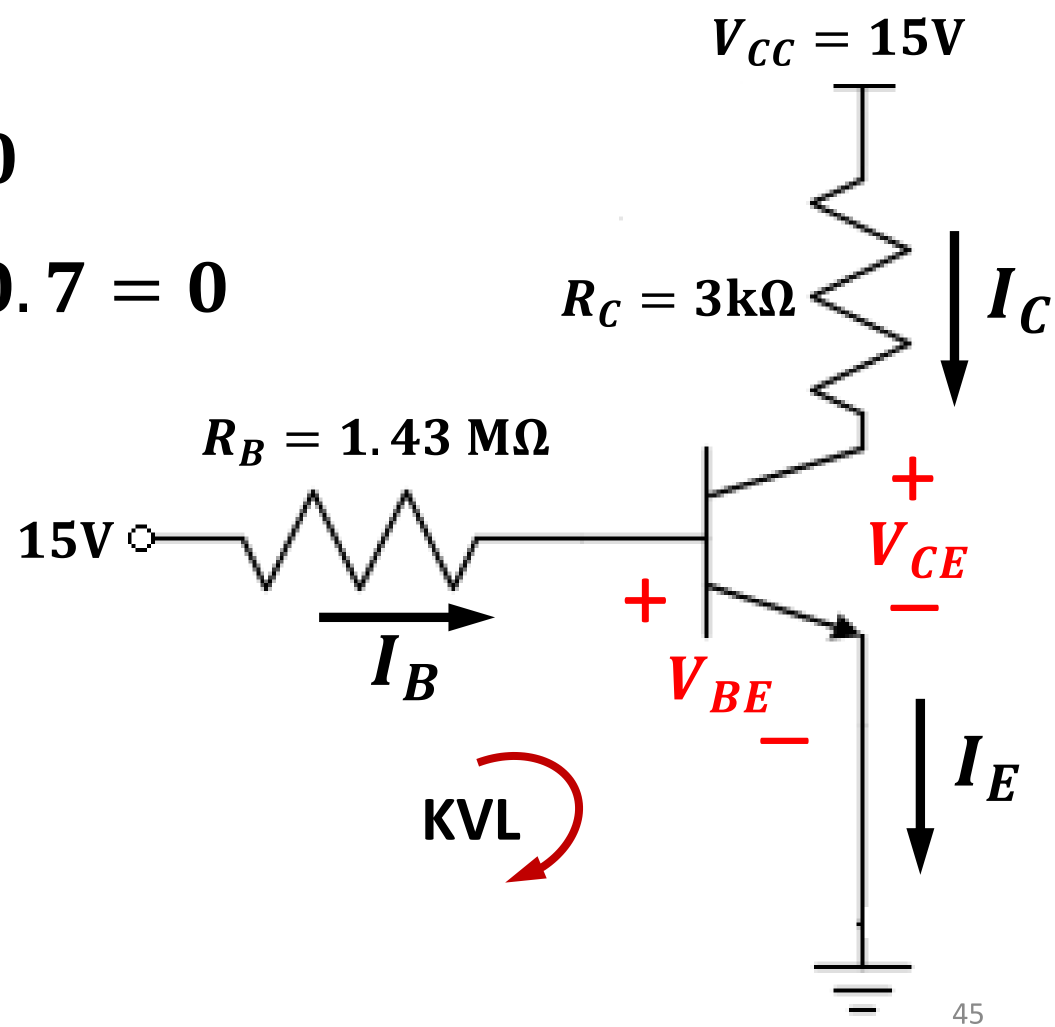
$V_{BE}(\text{on}) = 0.7\text{V}$

$\beta = 100$

Let's examine the Base circuit:

$$-15 + I_B R_B + V_{BE} = 0$$

$$-15 + 1.43\text{M} \times I_B + 0.7 = 0$$



Example of graphical use of BJT I-V curves

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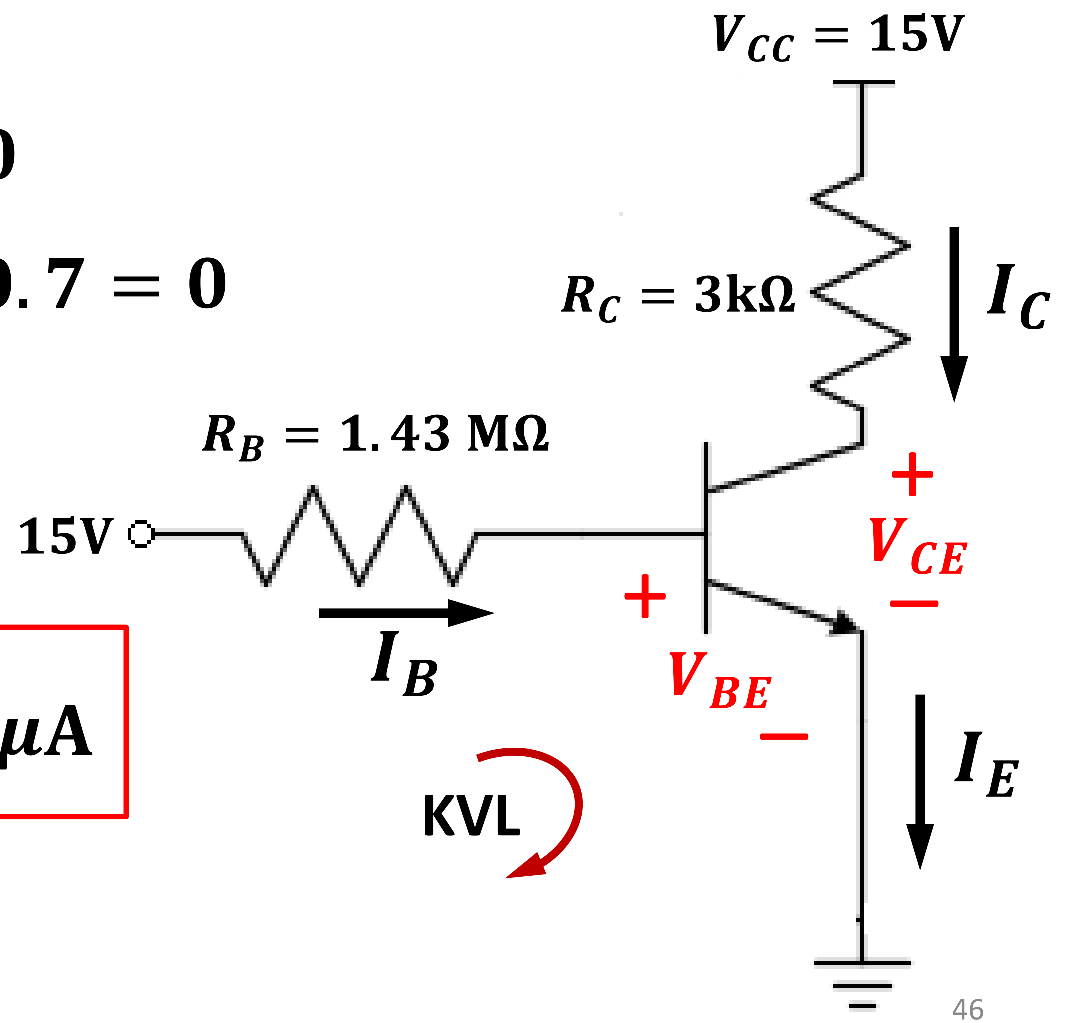
$$I_B = \frac{14.3}{1.43 \times 10^6} = 10\mu\text{A}$$



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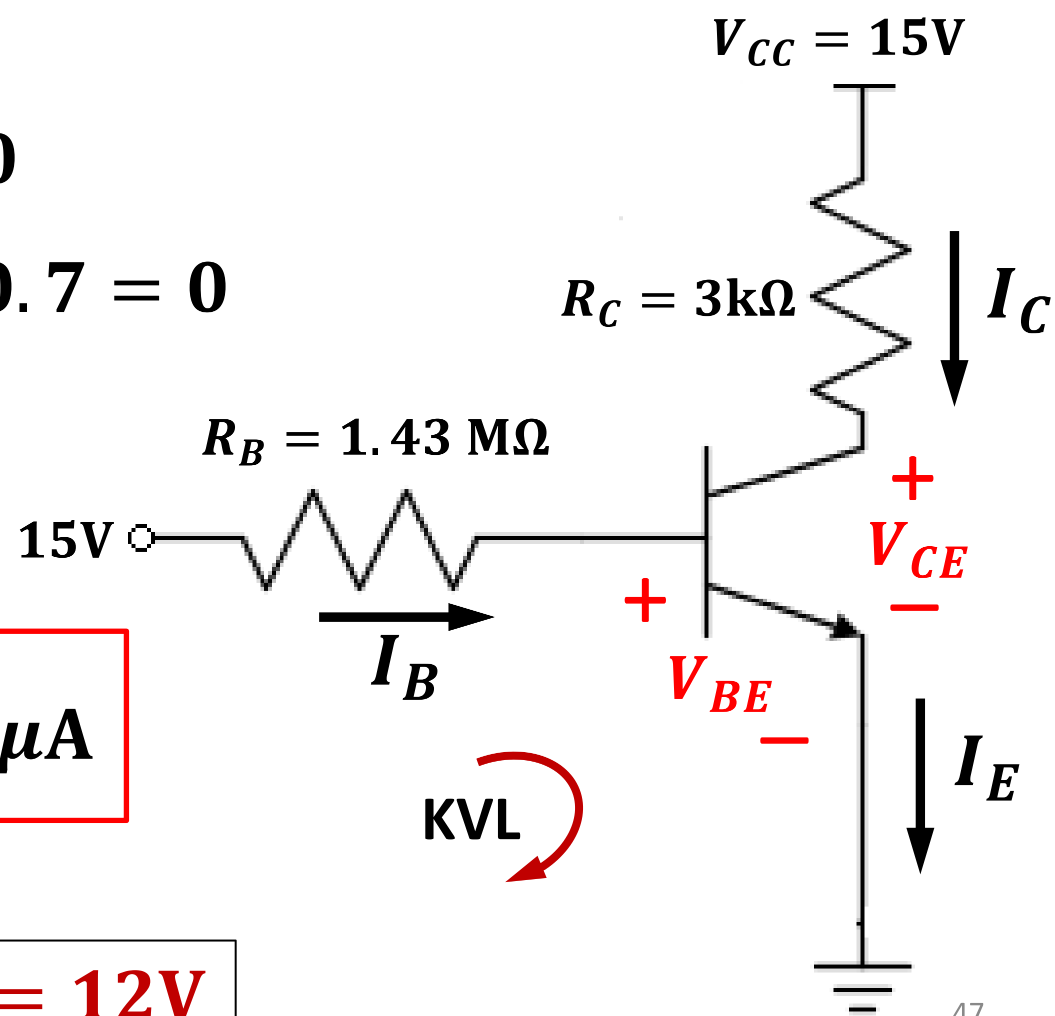
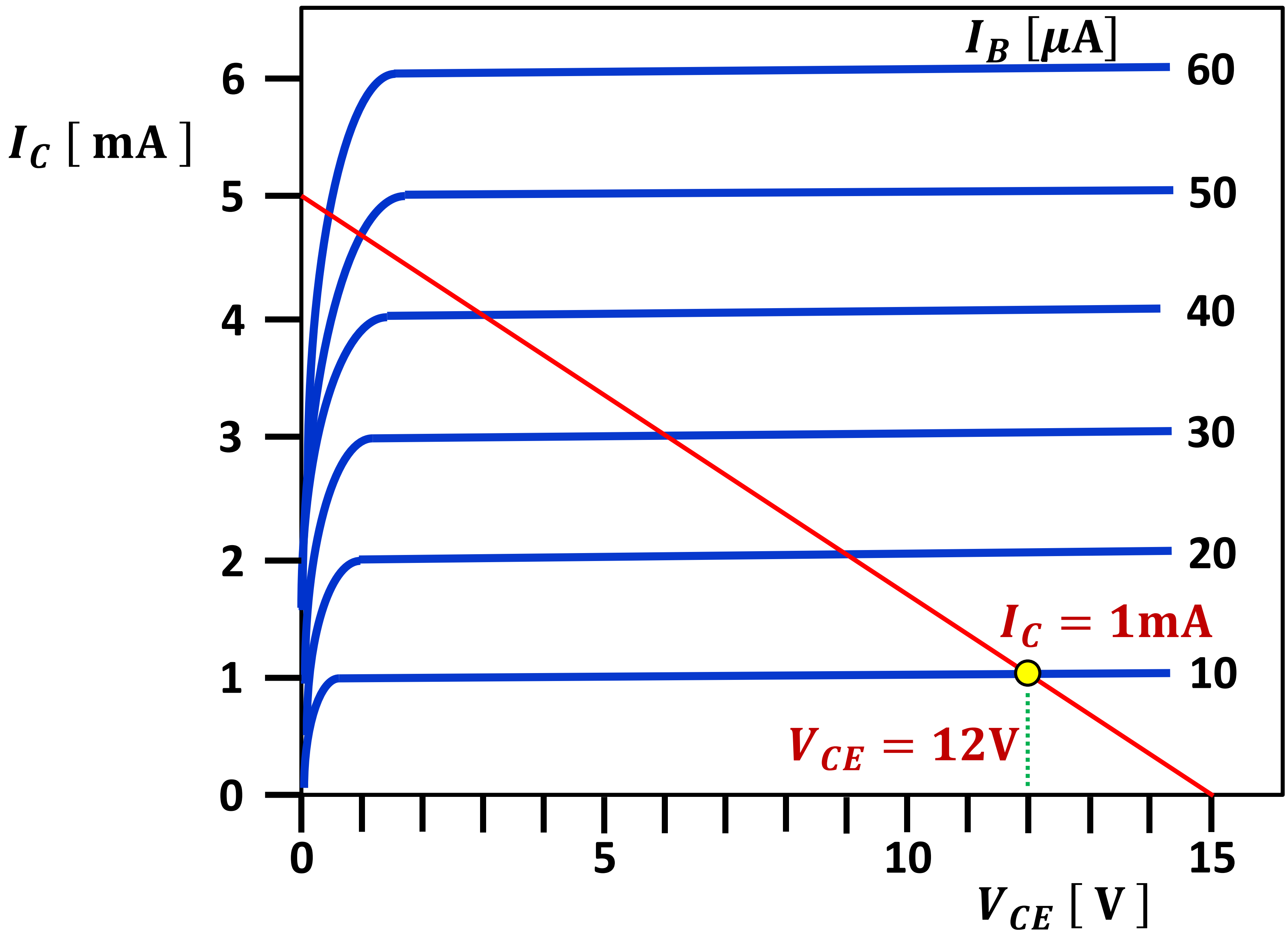


From the curves

$$I_C = 1\text{mA}$$

$$V_{CE} = 12\text{V}$$

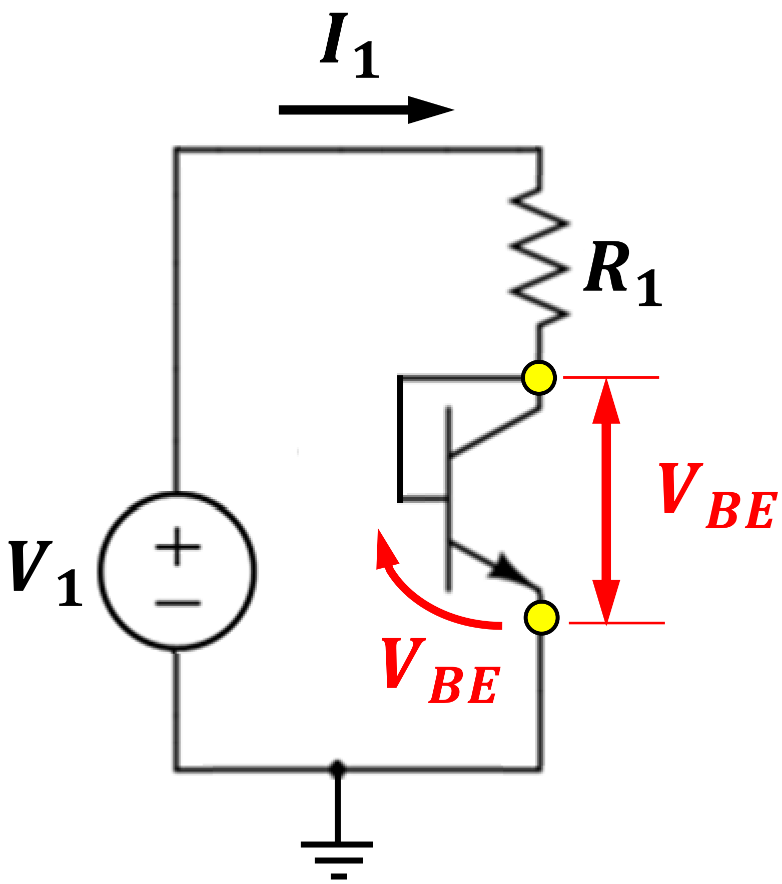
Example of graphical use of BJT I-V curves



BJT wired as a diode

$$-V_1 + R_1 I_1 + V_{BE} = 0$$

$$I_1 = \frac{V_1 - V_{BE}}{R_1}$$



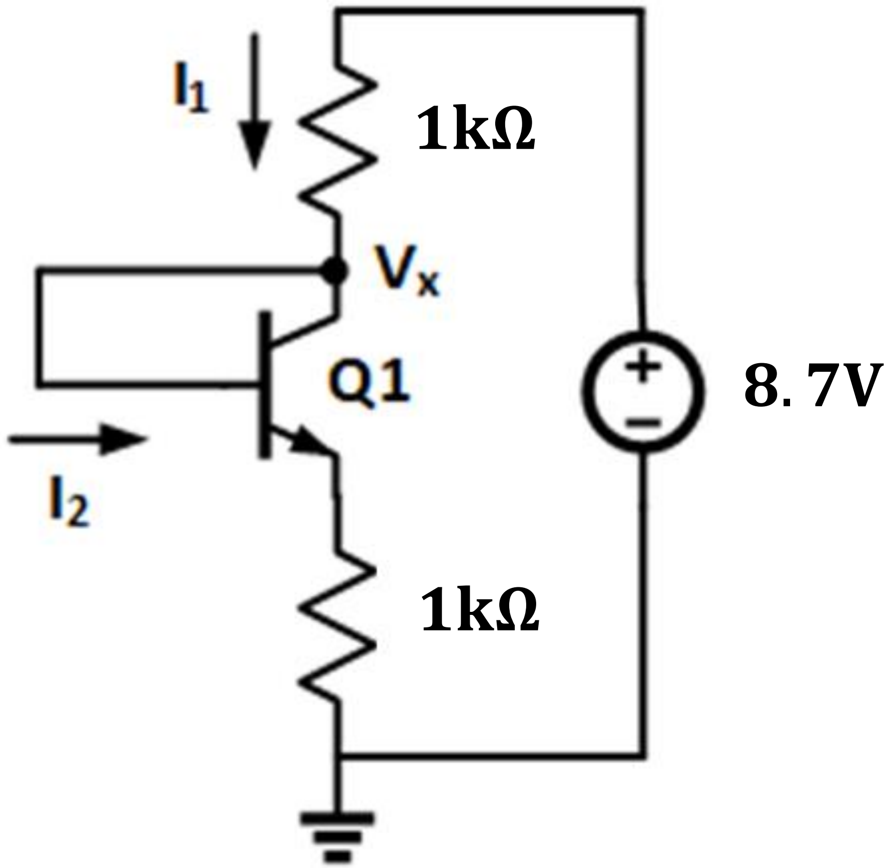
As long as $V_1 > V_{BE}(\text{on})$, the BJT is in Forward-Active mode.

BJT's wired as in the diagram, are often adopted in integrated circuits, to obtain ultra-low leakage diodes and for design of circuits which are temperature compensating.

$$\beta = 100$$

$$V_{BE}(on) = 0.7\text{V}$$

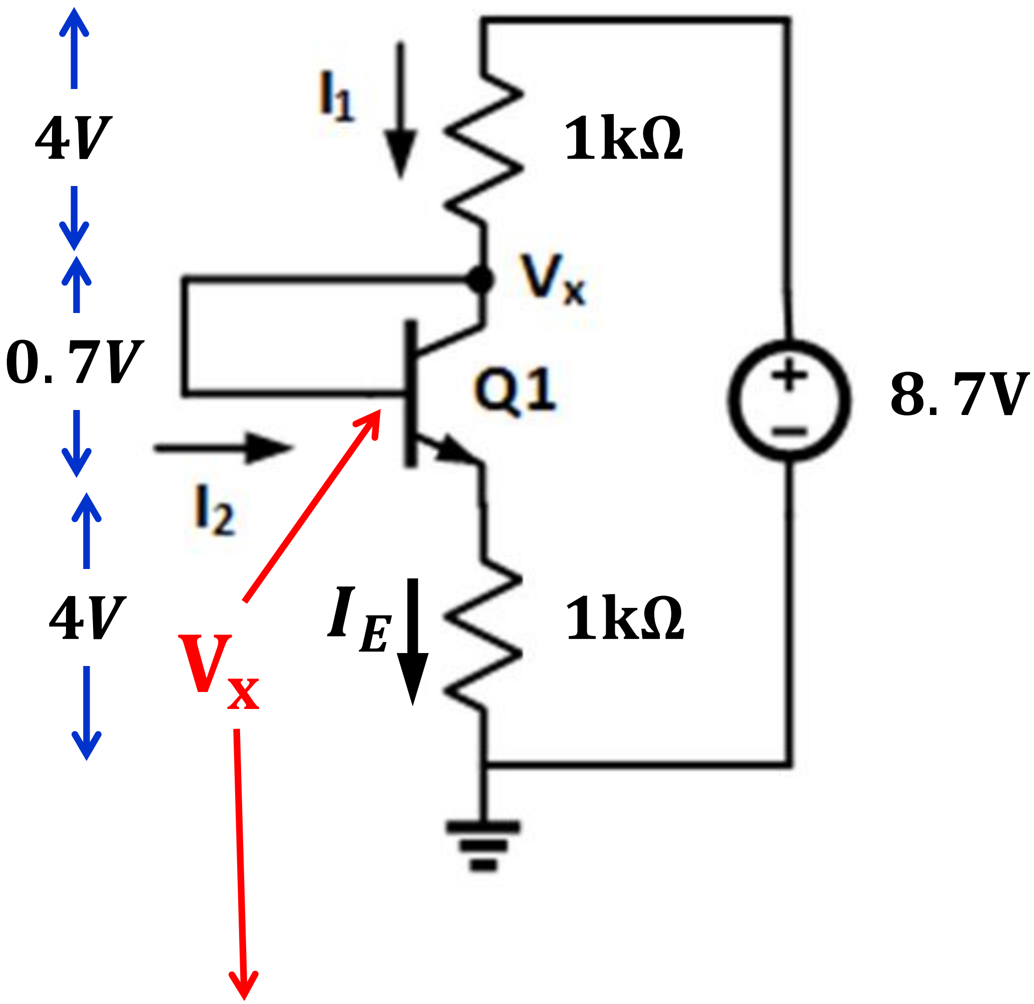
$$V_{CE}(sat) = 0.2\text{V}$$



$\beta = 100$

$V_{BE}(on) = 0.7V$

$V_{CE}(sat) = 0.2V$



Assume: BJT ON

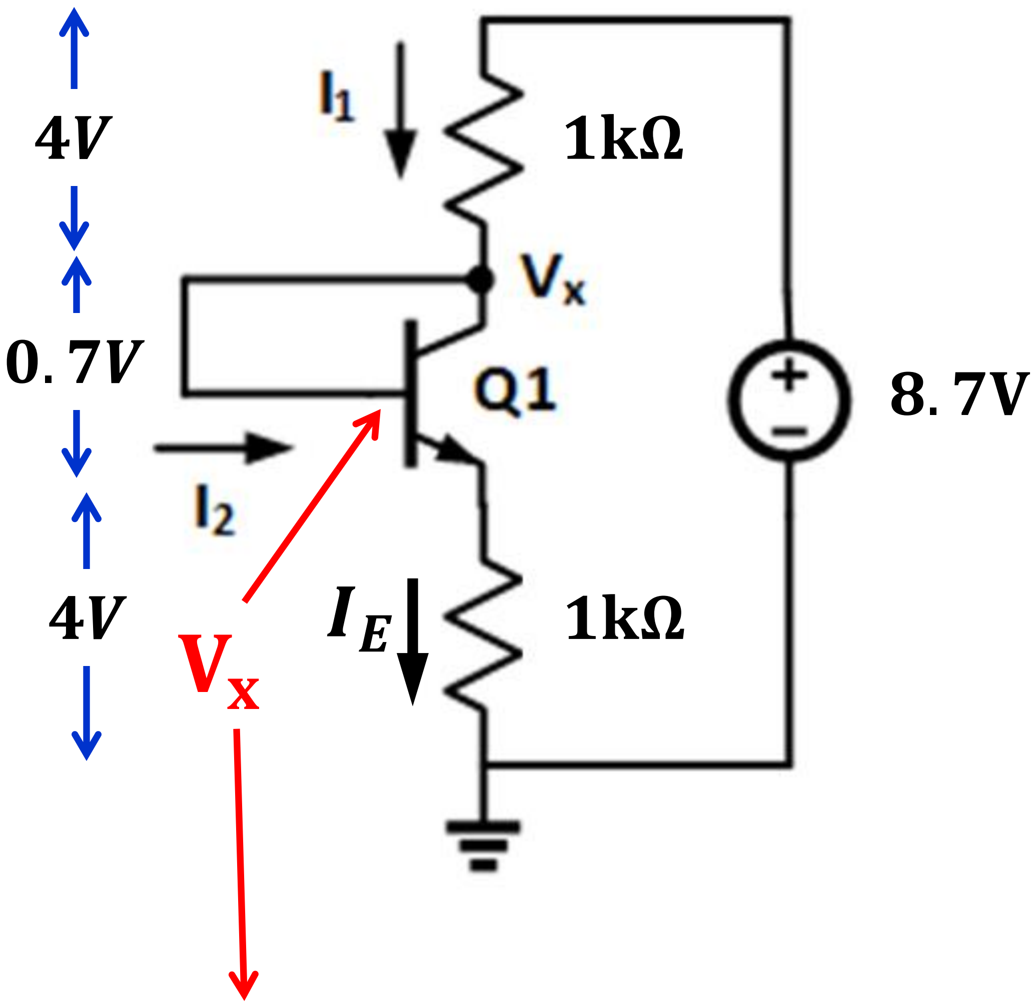
$$V_{BE} = V_{CE} = 0.7V$$

$$V_x = V_{CE} + 4V = 4.7V$$

$$\beta = 100$$

$$V_{BE}(on) = 0.7\text{V}$$

$$V_{CE}(sat) = 0.2\text{V}$$



Assume: BJT ON

$$I_1 = I_C + I_2$$

$$= I_C + I_B$$

$$I_1 = I_E$$

$$I_1 = 1k\Omega \times 4\text{V}$$
$$= 4\text{mA}$$

$$I_E = 1k\Omega \times 4\text{V}$$
$$= 4\text{mA}$$

$$V_{BE} = V_{CE} = 0.7V$$

$$\text{V}_\text{x} = V_{CE} + 4V = 4.7V$$