ECE 205 “Electrical and Electronics Circuits”

Spring 2024 – LECTURE 28

MWF – 12:00pm

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2062 ECE Building

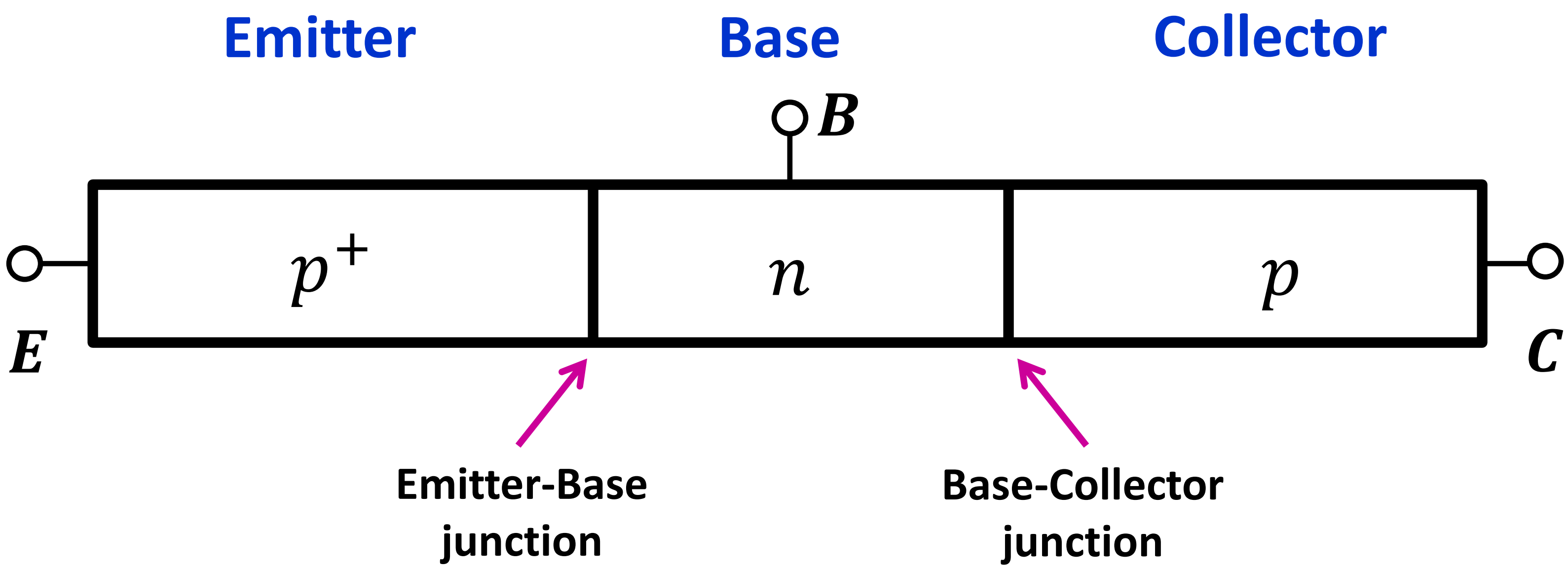
Lecture 28 – Summary

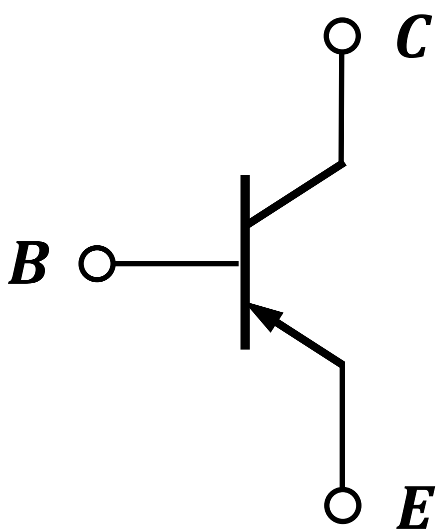
Learning Objectives

1. *p-n-p* transistor
2. Power consumption of BJT

p-n-p Transistors

Bipolar Junction Transistor (BJT) *p-n-p*

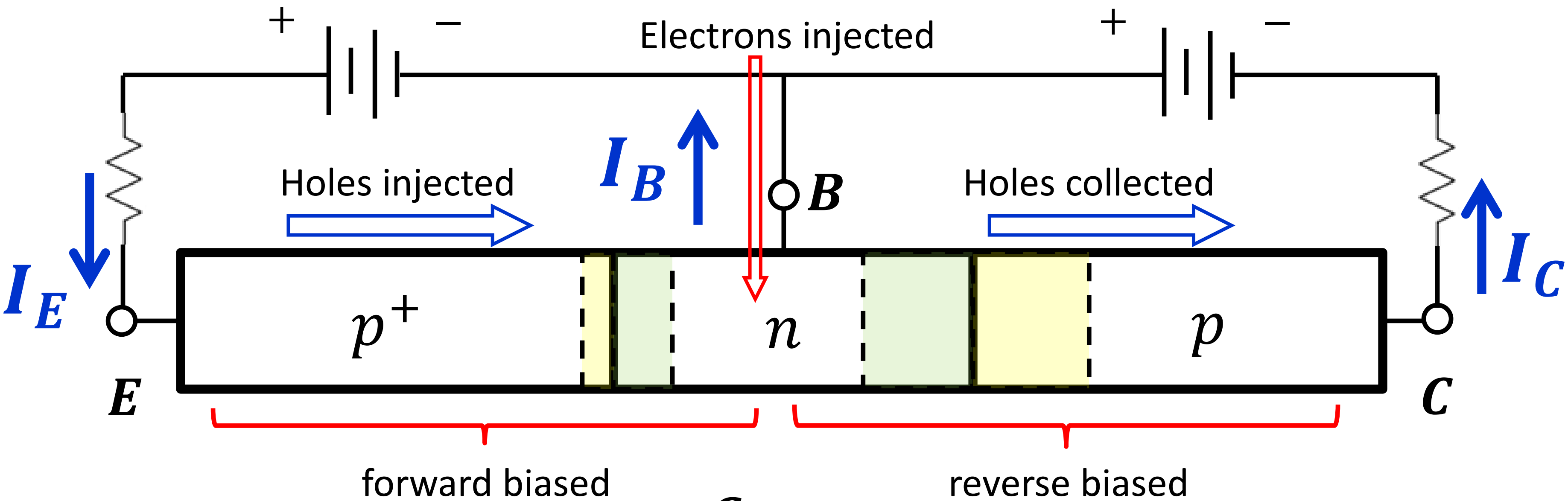


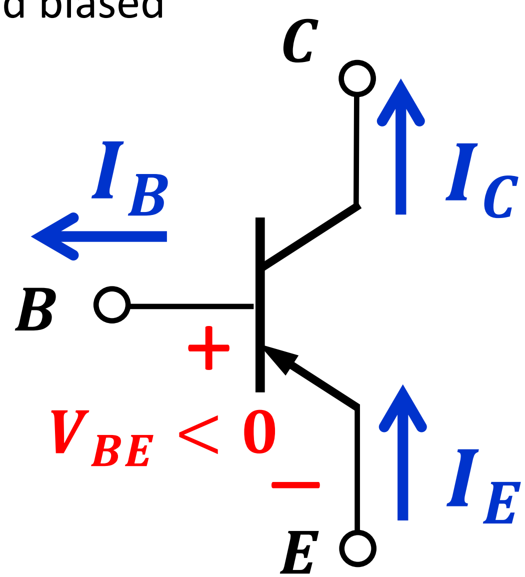


Circuit Symbol

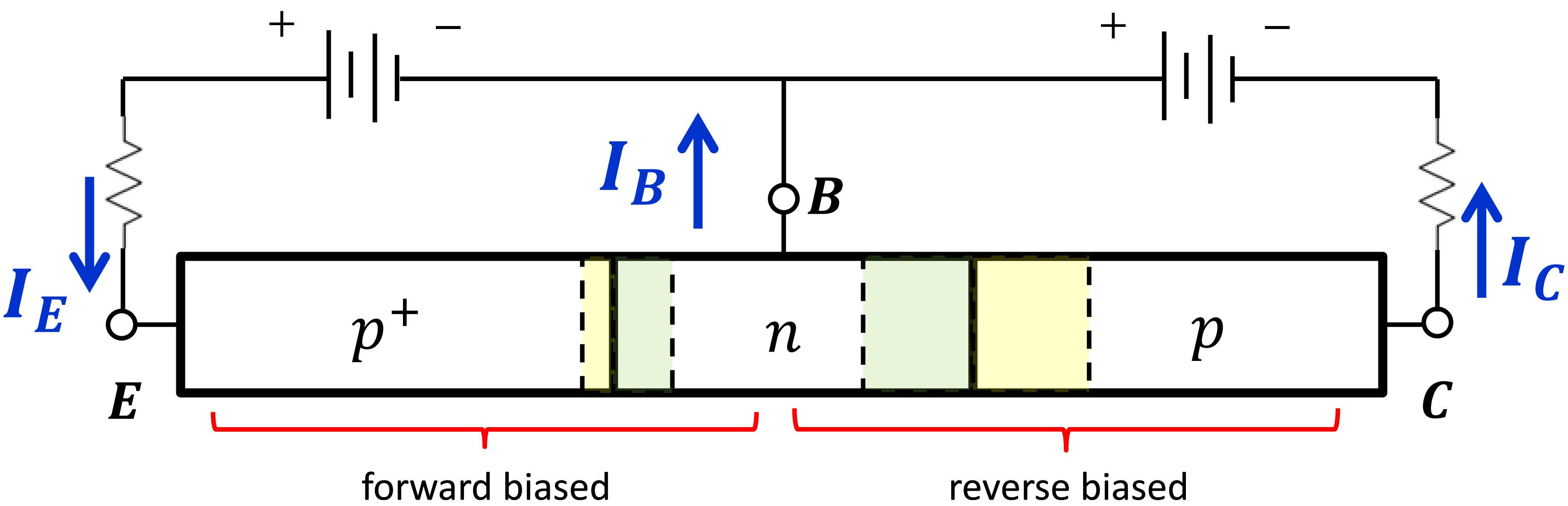
p-n-p **BJT**

Bipolar Junction Transistor (BJT) *p-n-p*





Simple physics explanation – Forward active mode

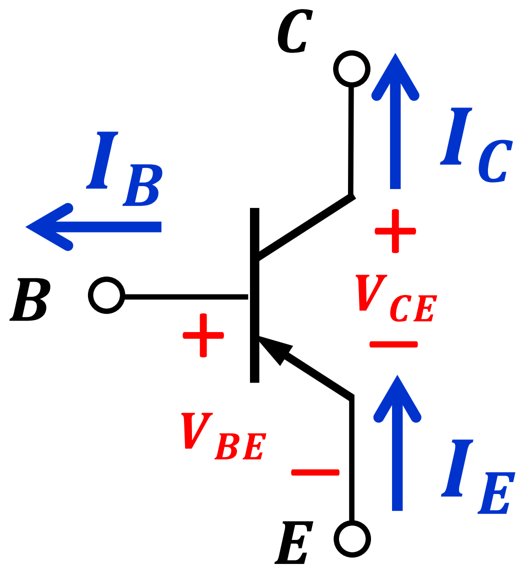


Holes are injected from the emitter into the base through a forward biased emitter-base diode

Most holes traverse the base. The base current injects electrons which recombine with some holes, controlling the electric current flow from emitter to collector.

Holes reaching the reverse biased junction are swept into the collector by high electric field in the depletion region.

p-n-p **transistors operate similarly to** ***n-p-n*** **transistors, except that polarities are reversed**



p-n-p **BJT**

$$V_{BE} = V_{BE}(\text{ON}) \approx -0.6 \ \ \text{to} \ \ -0.7\text{V}$$

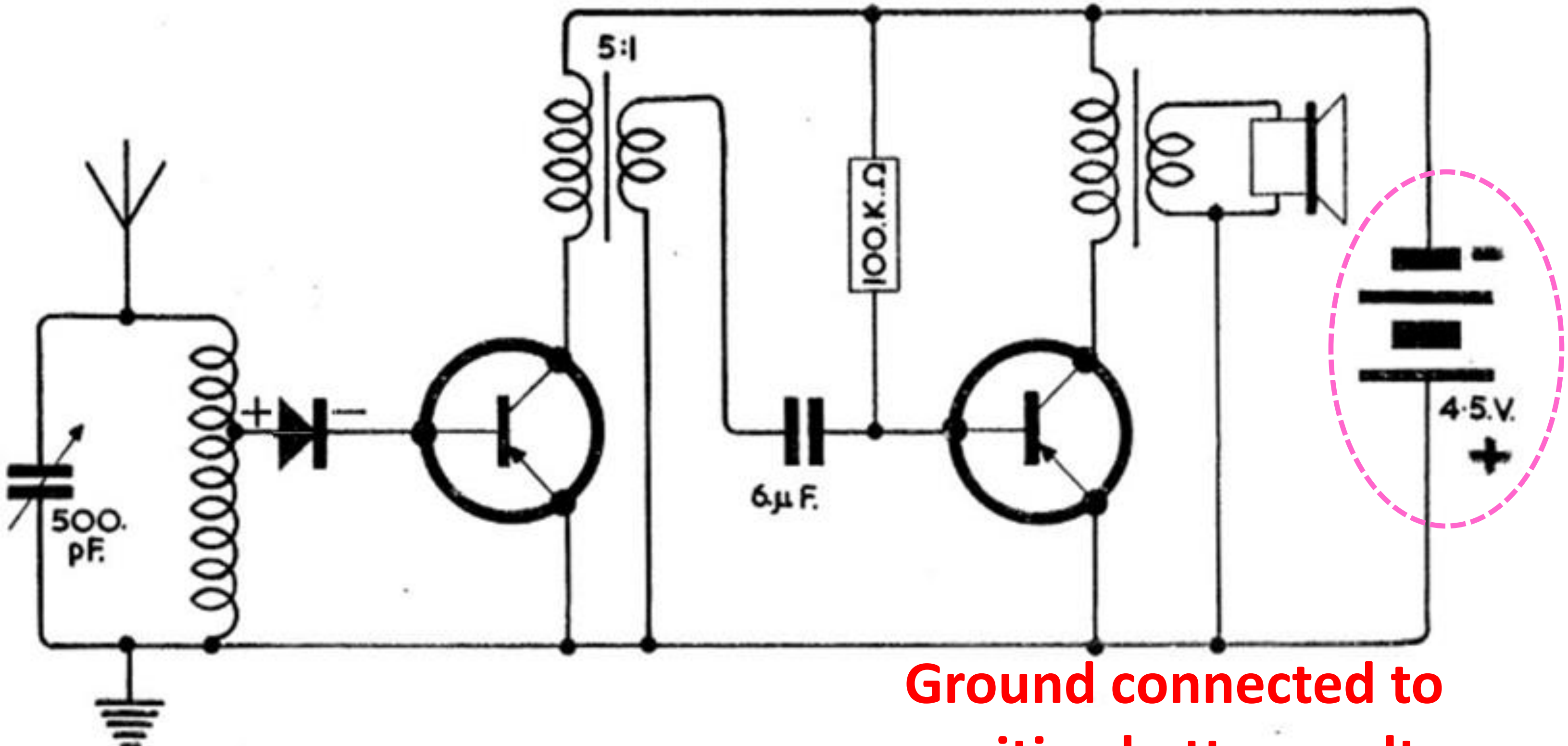
$$V_{CE}(\text{sat}) \approx -0.2$$

$$I_E = I_B + I_C$$

$$I_C = \beta\, I_B$$ **Forward Active mode**

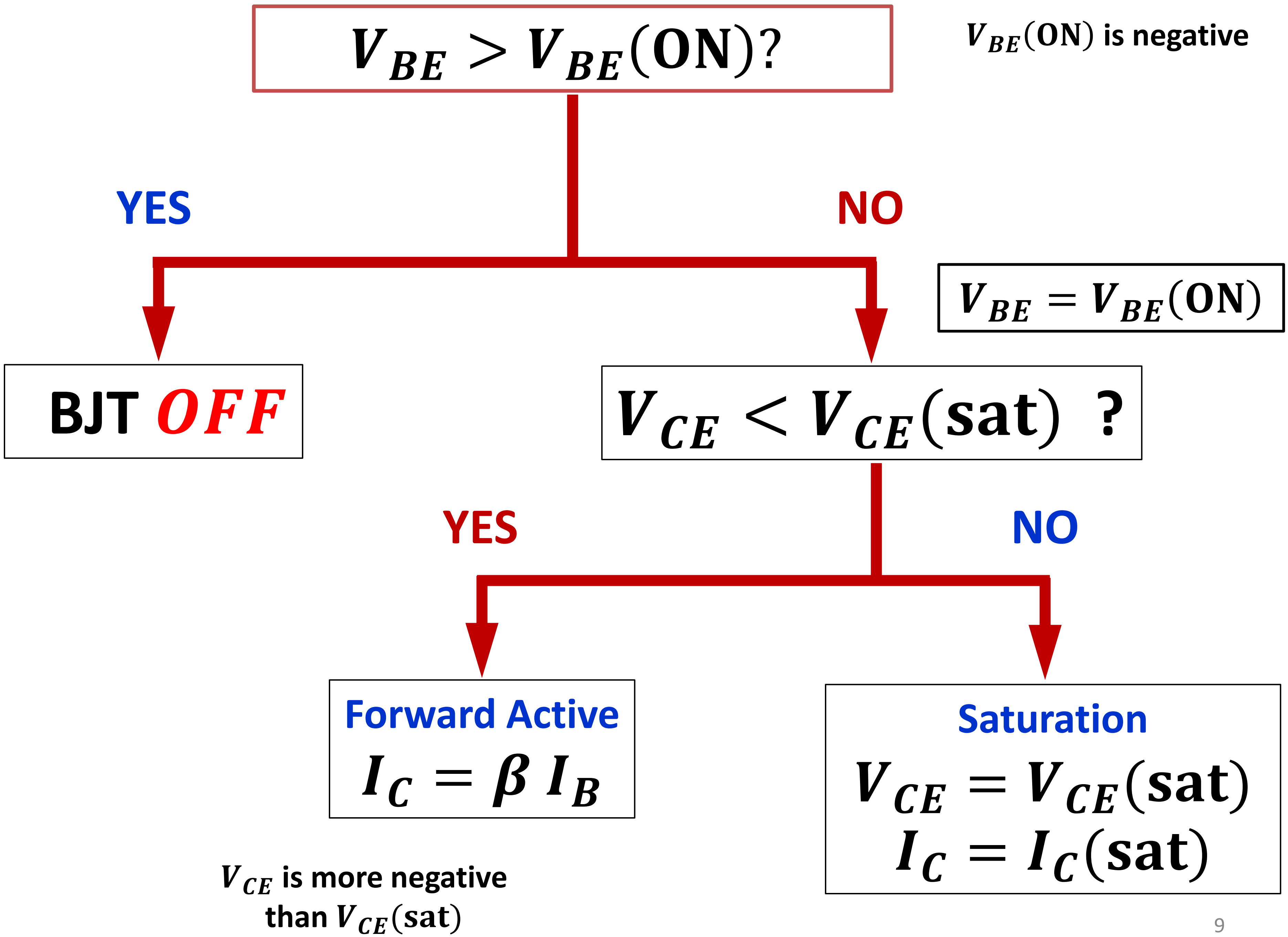
***p-n-p* transistors** **were widely used in the beginning of solid-state electronics, because easier to manufacture with older technologies. Here is a simple radio diagram from a 1959 booklet for enthusiasts.**

Collector connected to negative battery voltage

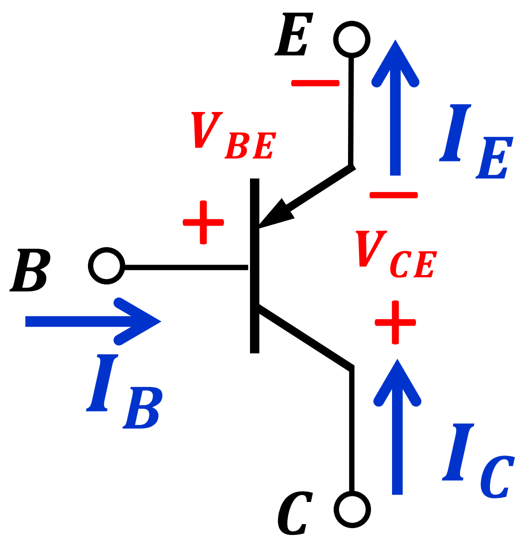


Ground connected to positive battery voltage

Adapted from: C. Sinclair – Practical Transistor Receivers - Book I, p. 15, Bernards Pubs. (1959)

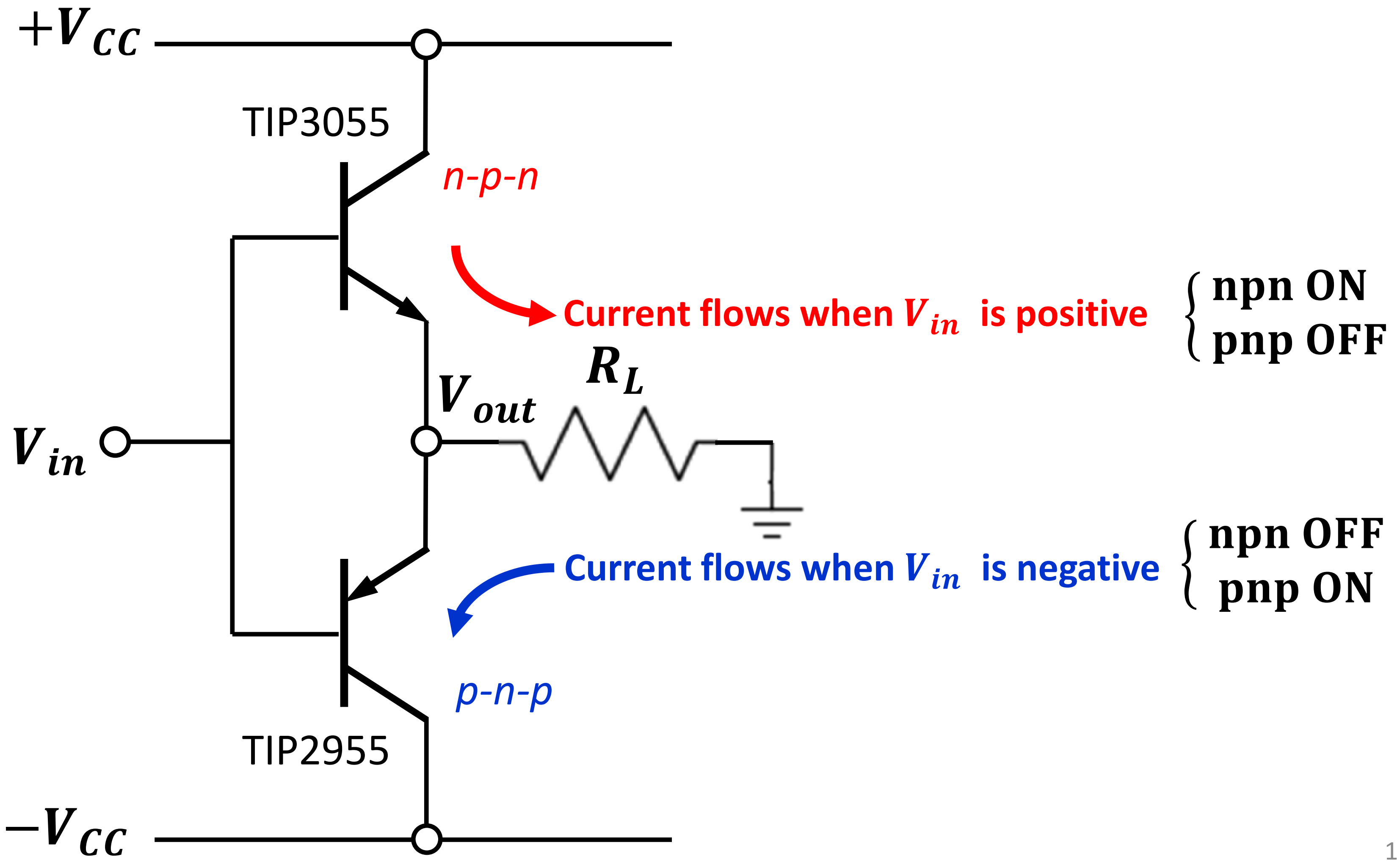

$V_{BE} > V_{BE}(\mathrm{ON})?$
$V_{BE}(\mathrm{ON})$ is negative
YES
NO
$V_{BE} = V_{BE}(\mathrm{ON})$
BJT *OFF*
$V_{CE} < V_{CE}(\mathrm{sat})$?
YES
NO
Forward Active
$I_C = \beta\, I_B$
Saturation
$V_{CE} = V_{CE}(\mathrm{sat})$
$I_C = I_C(\mathrm{sat})$
V_{CE} is more negative
than $V_{CE}(\mathrm{sat})$

In some cases it is convenient to draw *p-n-p* transistors with the emitter up, particularly in circuits where they are paired with *n-p-n* transistors



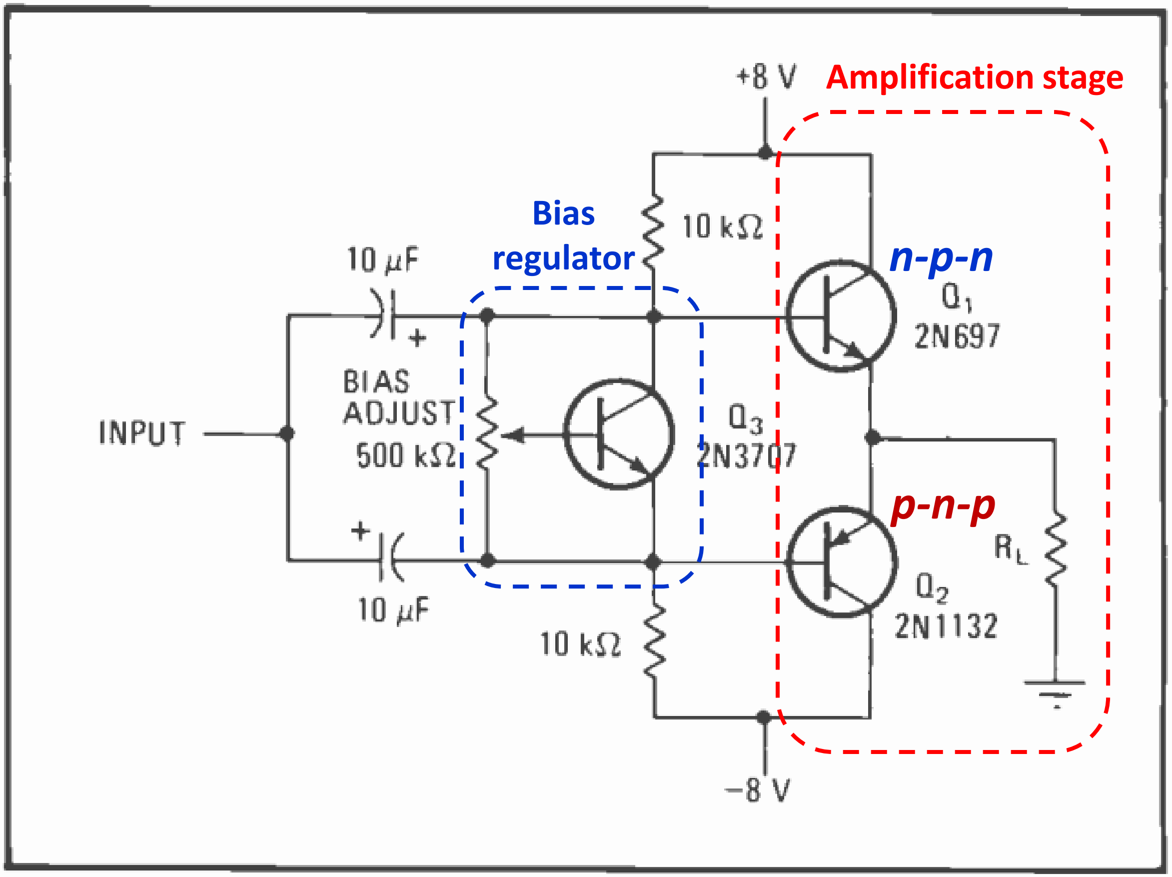
***p-n-p* BJT**

As an example, a matched pair of power complementary transistors (rated up to 15A), used to regulate electric motors as in robotic applications, for even control in both forward and reverse motion. A similar design is used in B-class amplifiers (next slide).



Design example (Electronics Designer's Casebook, (1976) p. 68)

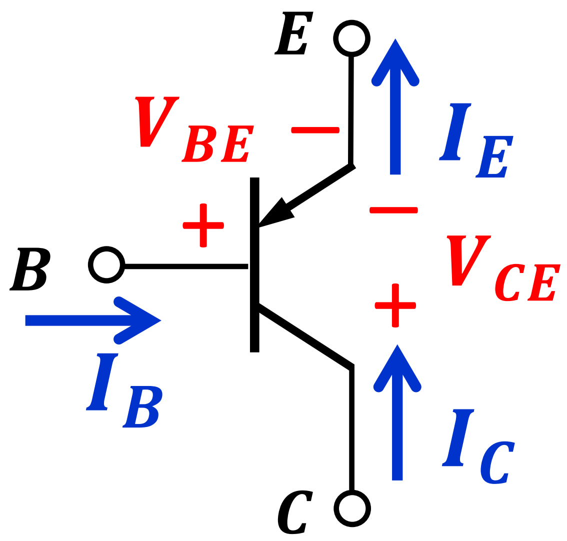
https://worldradiohistory.com/Archive-Electronics/Electronics-Designer's-Cookbook.pdf



Crossover-distortion regulator. Complementary transistors Q_1 and Q_2 form a power amplifier stage in which the bias point is controlled closely through transistor Q_3 acting as a voltage regulator. The bias-adjusting potentiometer permits exact setting of the stage's bias point so that crossover distortion is held to a minimum. The transistor regulator also automatically compensates for varying temperature.

We will solve a problem with the *p-n-p* transistor configuration below, without using negative bias.

Collector is connected toward ground and the emitter is connected to a positive bias.



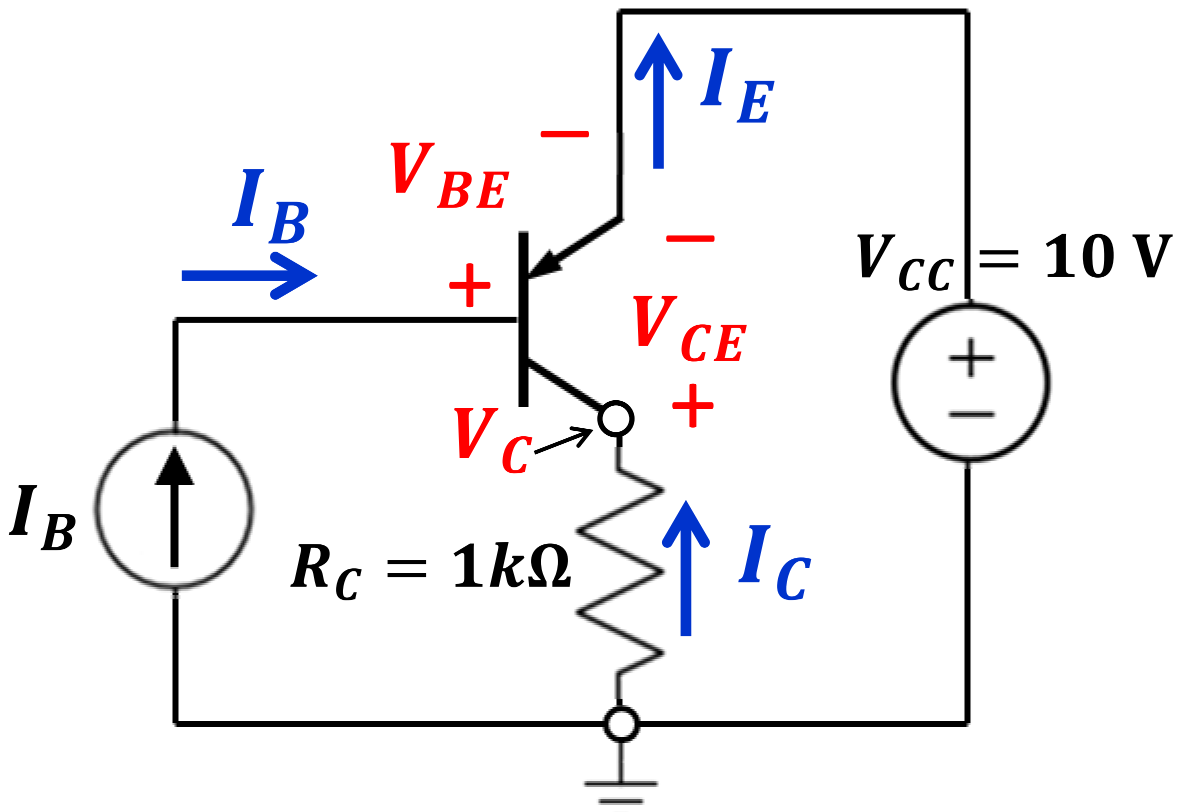
***p-n-p* BJT**

p-n-p Circuit Example 1: Find: I_C, V_{CE}, V_C

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

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

$\beta = 5$



(a) $I_B = 0\ \text{A}$

(b) $I_B = -1\ \text{mA}$

(c) $I_B = -5\ \text{mA}$

p-n-p Circuit Example 1: Find: I_C, V_{CE}, V_C

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

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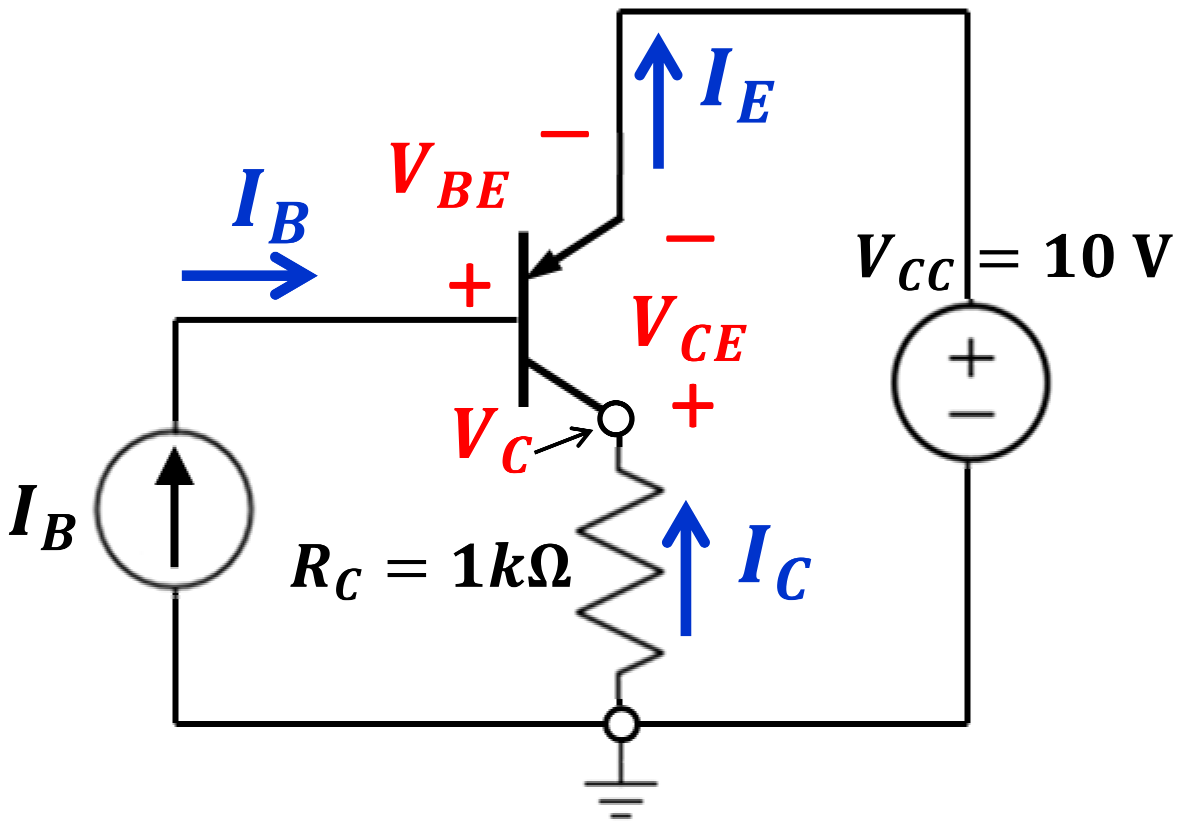


(a) $I_B = 0\text{ A}$

Transistor is OFF

$$I_C = 0\text{ A}$$

$$V_{CE} = -10\text{V}$$

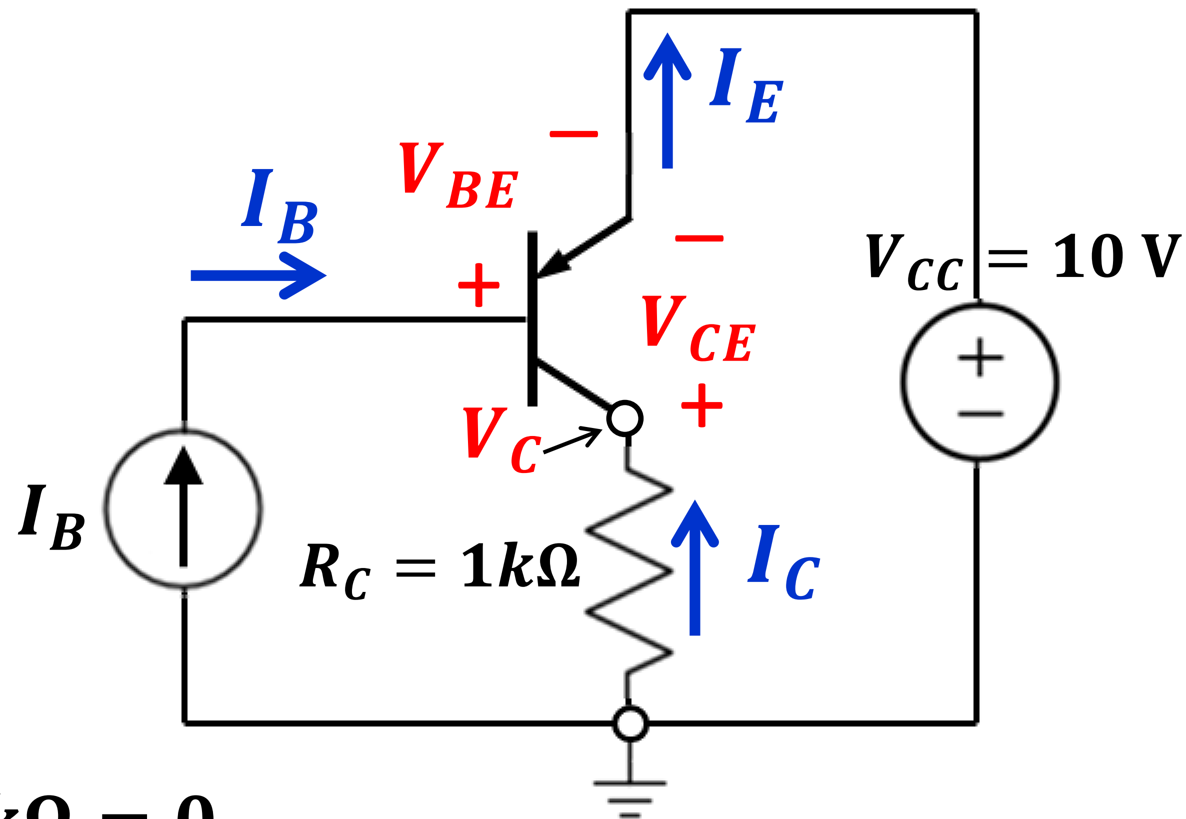
$$V_C = 0\text{ V}$$

Find: I_C, V_{CE}, V_C

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

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

$\beta = 5$



(b) $I_B = -1$ mA

Assume Forward Active Mode

$$I_C = \beta I_B = -5 \text{ mA}$$

$$V_{CE} + 10 + I_C \times 1k\Omega = 0$$

$$V_{CE} = -10 - (-5\text{mA}) \times 1k\Omega = -5 \text{ V} < V_{CE}(\text{sat})$$ OK

$$V_C = -I_C \times 1\text{k}\Omega = -(-5\text{mA}) \times 1\text{k}\Omega = 5 \text{ V}$$

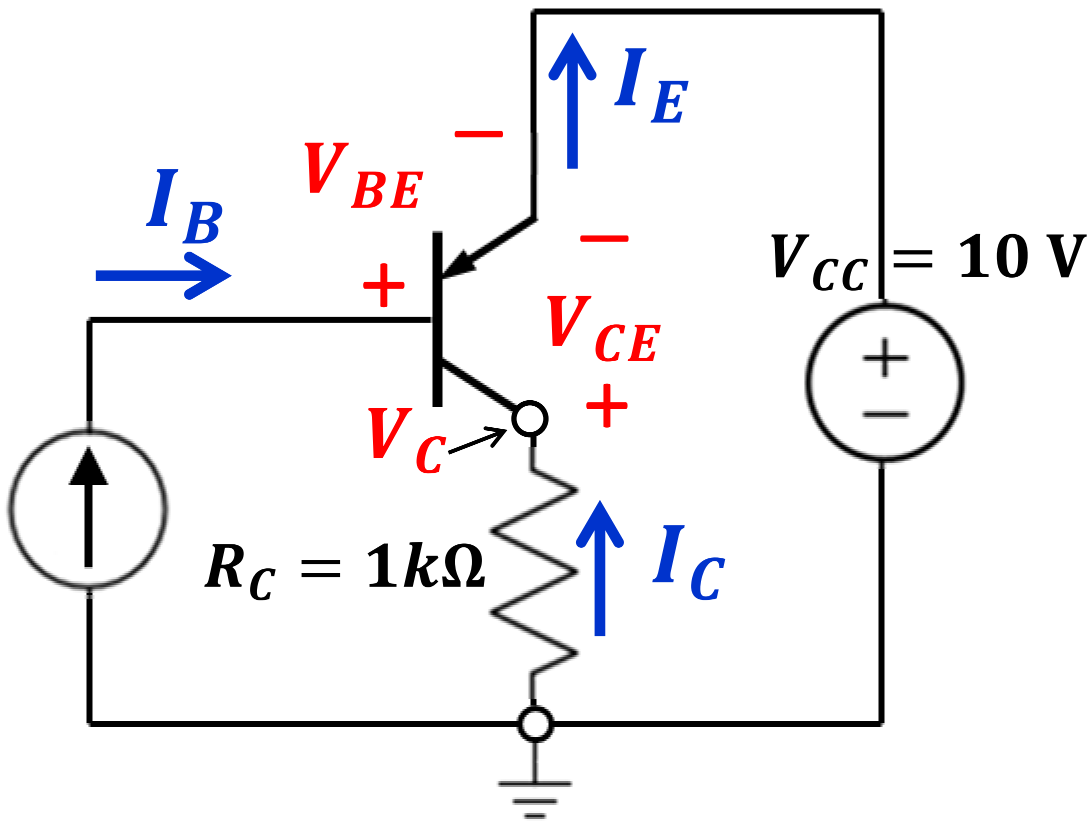
Also: $V_C = V_{CC} + V_{CE} = 10 - 5 = 5$ V

Find: I_C, V_{CE}, V_C

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

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

$\beta = 5$



(c) $I_B = -5$ mA

Assume Forward Active Mode

$$I_C = \beta I_B = -25 \text{ mA}$$

$$V_{CE} + 10 + I_C \times 1\text{k}\Omega = 0$$

$$V_{CE} = -10 - (-25\text{mA}) \times 1\text{k}\Omega = 15 \text{ V } > V_{CE}(\text{sat})$$

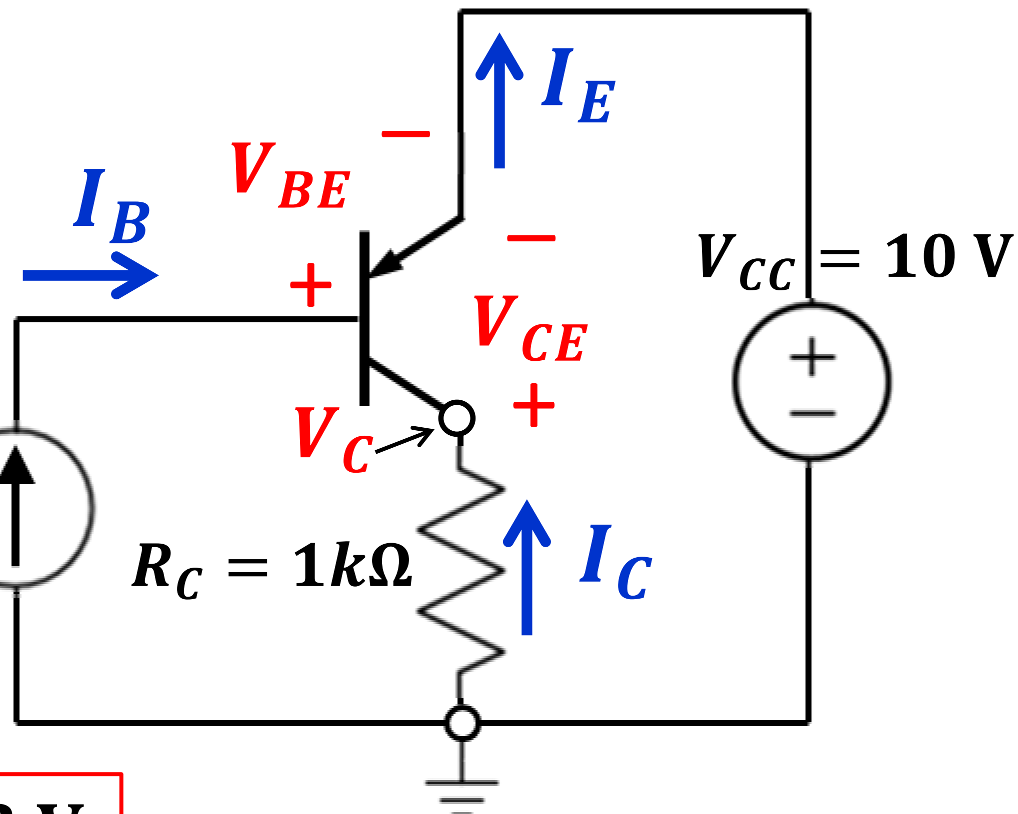
Not OK

Find: I_C, V_{CE}, V_C

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

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

$\beta = 5$



(c) $I_B = -5$ mA

BJT is in saturation

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

$$I_C(\text{sat}) \times 10\text{k}\Omega - 0.2 + 10 = 0$$

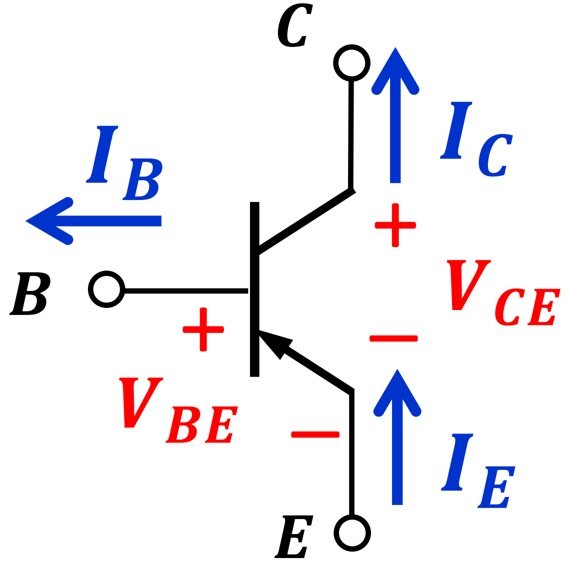
$$I_C(\text{sat}) = \frac{-10 + 0.2}{1\text{k}\Omega} = -9.8\text{mA}$$

$$V_C = -I_C \times 1\text{k}\Omega$$

$$V_C = 9.8\text{ V}$$

Now we solve the same problem but with the *p-n-p* transistor configuration below, where we shift the ground reference. THERE IS COMPLETE EQUIVALENCE WITH THE PREVIOUS CIRCUIT.

Collector is connected to a negative bias, emitter is connected toward ground (all voltages shifted by -10V).



***p-n-p* BJT**

This is to give you a template in case of future need…

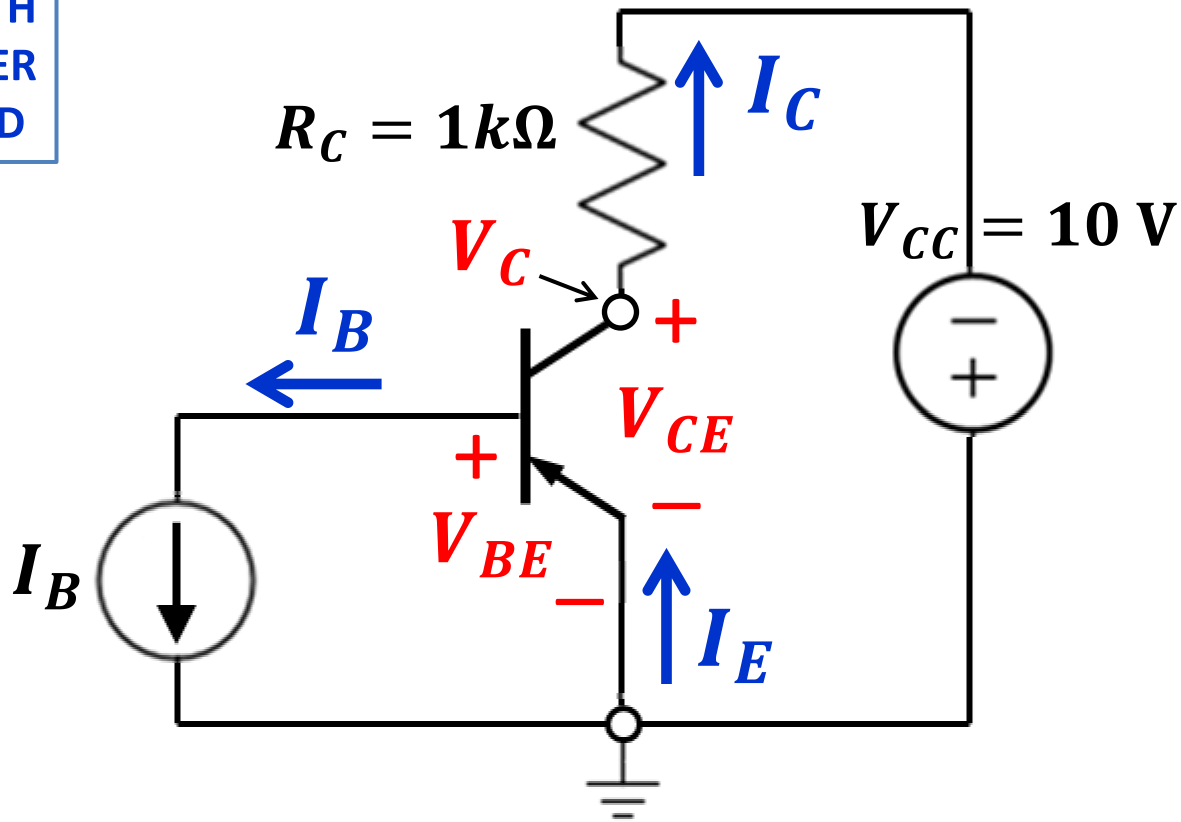
p-n-p Circuit Example 1: Find: I_C, V_{CE}, V_C

SAME PROBLEM BUT WITH NEGATIVE BIAS AND EMITTER CONNECTED TOWARD GROUND

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

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

$\beta = 5$



(a) $I_B = 0\text{ A}$

Transistor is OFF

$$I_C = 0\text{ A}$$

$$V_{CE} = -10\text{V}$$

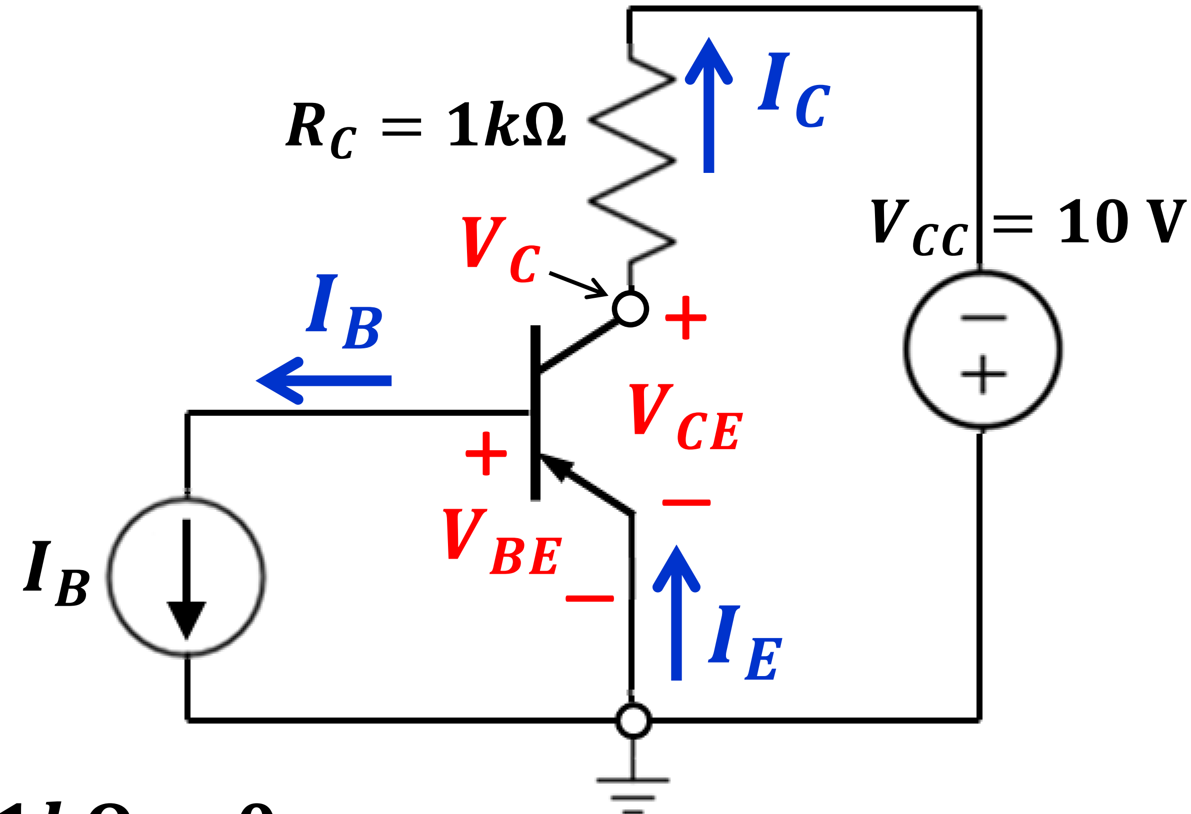
$$V_C = -10\text{ V}$$

Find: I_C, V_{CE}, V_C

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

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

$\beta = 5$



(b) $I_B = 1$ mA

Assume Forward Active Mode

$$I_C = \beta I_B = 5\ \mathrm{mA}$$

$$-V_{CE} - 10 + I_C \times 1k\Omega = 0$$

$$V_{CE} = -10 + 5\mathrm{mA} \times 1k\Omega = -5\ \mathrm{V} < V_{CE}(\mathrm{sat})$$ **OK**

$$V_C = -10 + I_C \times 1\mathrm{k}\Omega = -10 + 5\mathrm{mA} \times 1\mathrm{k}\Omega = -5\ \mathrm{V}$$

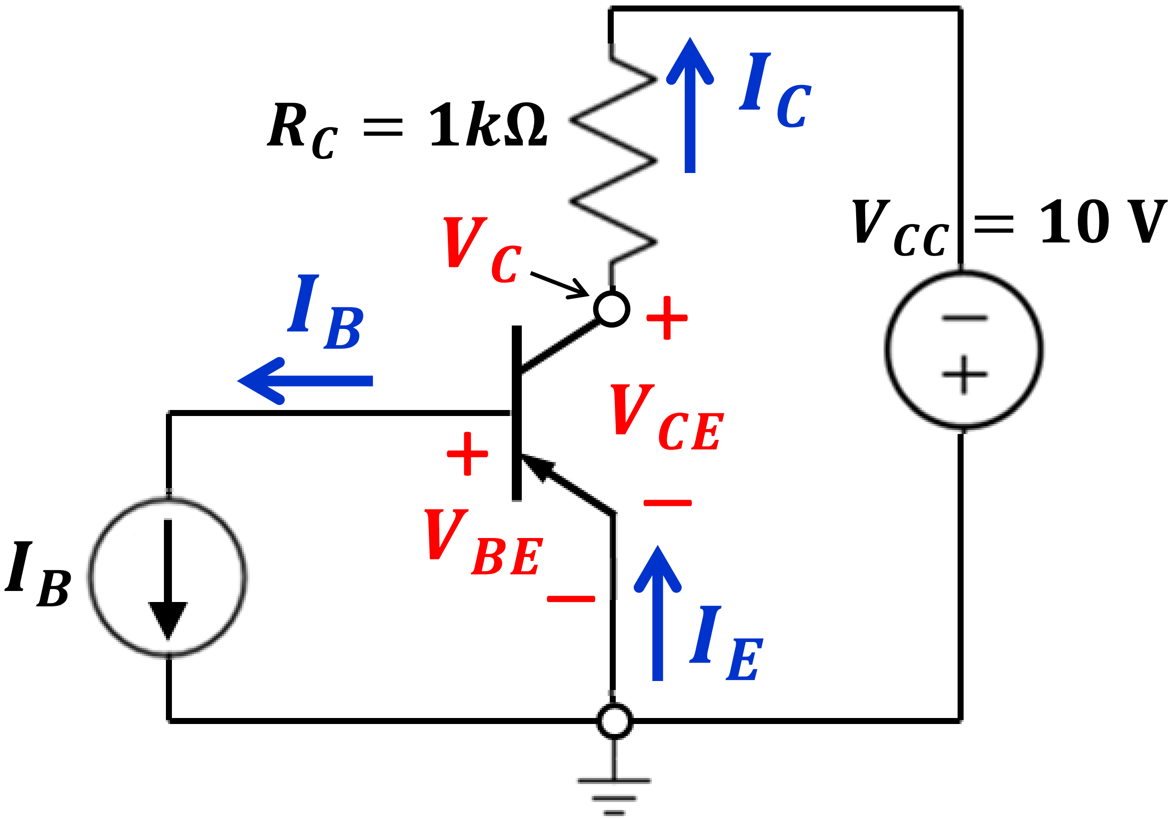
Also: $V_C = V_{CE} = -5\ \mathrm{V}$

Find: I_C, V_{CE}, V_C

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

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

$\beta = 5$



(c) $I_B = 5$ mA

Assume Forward Active Mode

$$I_C = \beta I_B = 25 \text{ mA}$$

$$-V_{CE} - 10 + I_C \times 1\text{k}\Omega = 0$$

$$V_{CE} = -10 + 25\text{mA} \times 1\text{k}\Omega = 15 \text{ V} > V_{CE}(\text{sat})$$

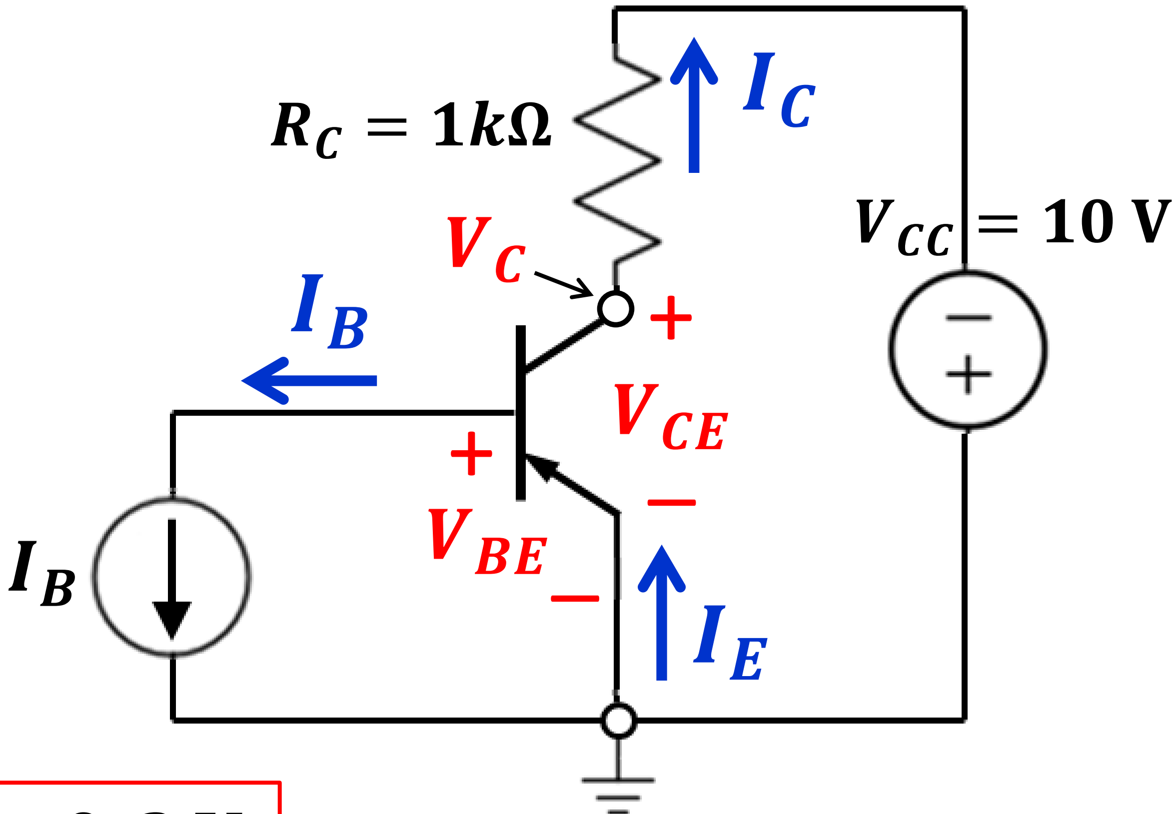
Not OK

Find: I_C, V_{CE}, V_C

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

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

$\beta = 5$



(c) $I_B = 5$ mA

BJT is in saturation

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

$$I_C(\text{sat}) \times 10\text{k}\Omega - (-0.2) - 10 = 0$$

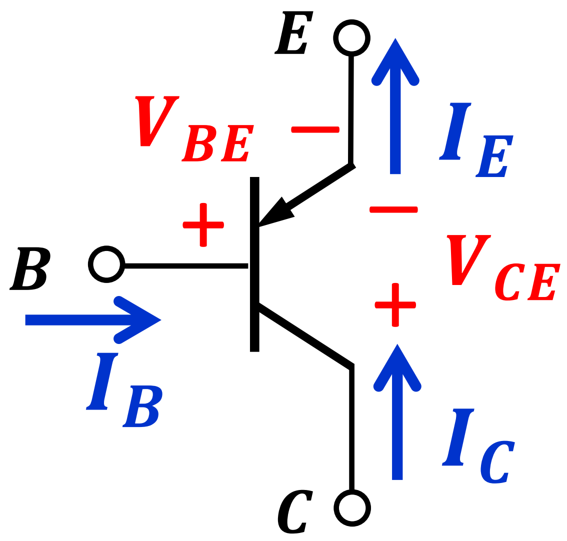
$$I_C(\text{sat}) = \frac{10 - 0.2}{1\text{k}\Omega} = 9.8\text{mA}$$

$$V_C = V_{CE}$$

$$V_C = -0.2\text{ V}$$

We solve again a problem with the *p-n-p* transistor configuration below, without using negative bias.

Collector is connected toward ground and the emitter is connected to a positive bias.



p-n-p BJT

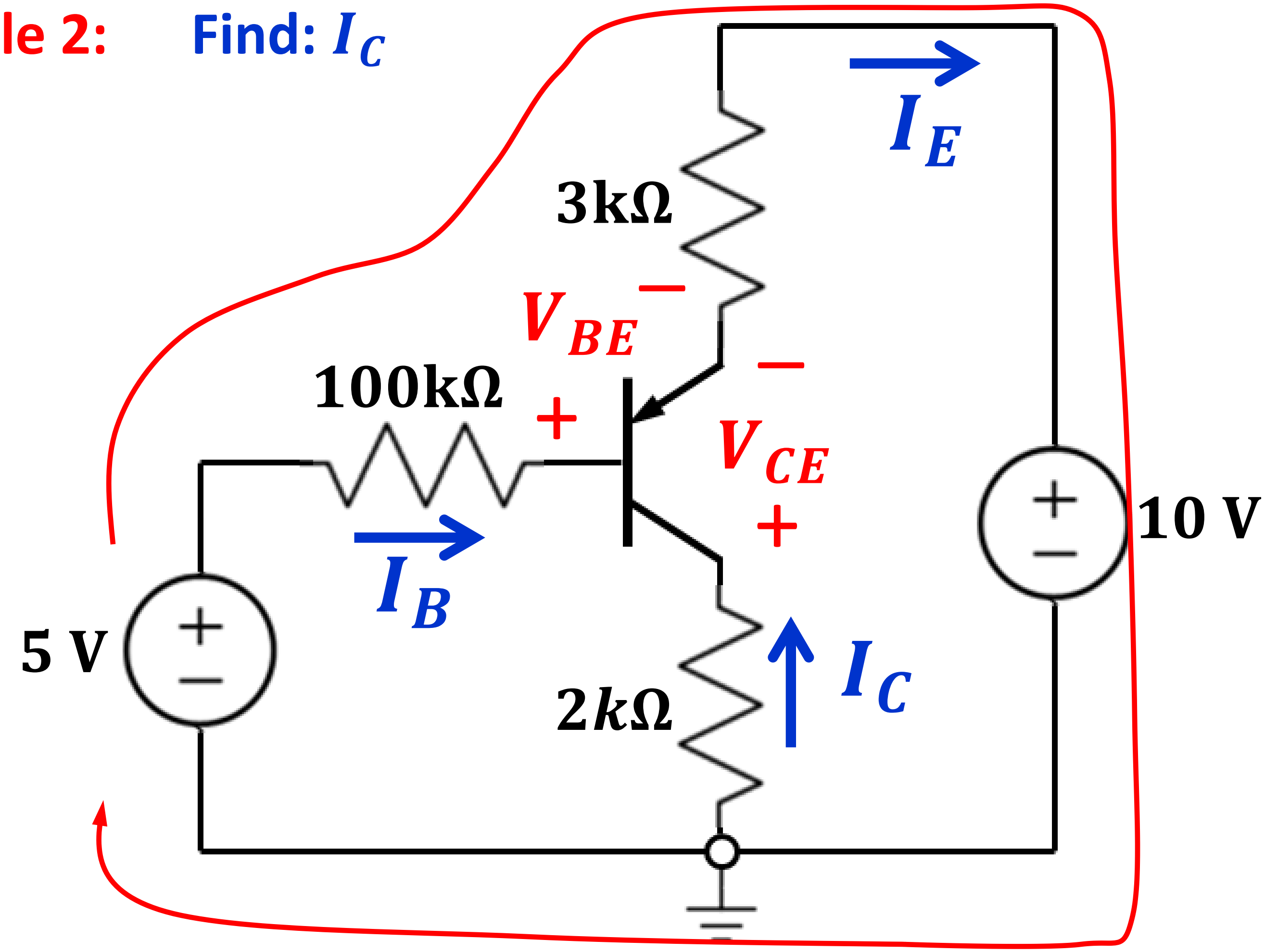
p-n-p Circuit Example 2: Find: I_C

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

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

$$\beta = 10$$

Assume Forward-Active mode



$$-5 + I_B R_B + V_{BE} + 3\text{k}\, I_E + 10 = 0$$

$$100\text{k}\, I_B - 0.7 + 3\text{k}(\beta + 1) I_B + 5 = 0$$

$$100\text{k}\, I_B + 3\text{k}(10 + 1) I_B = -4.3$$

$$I_B = -4.3/133\text{k}$$

$$\boxed{I_B = -0.0323\text{mA}}$$

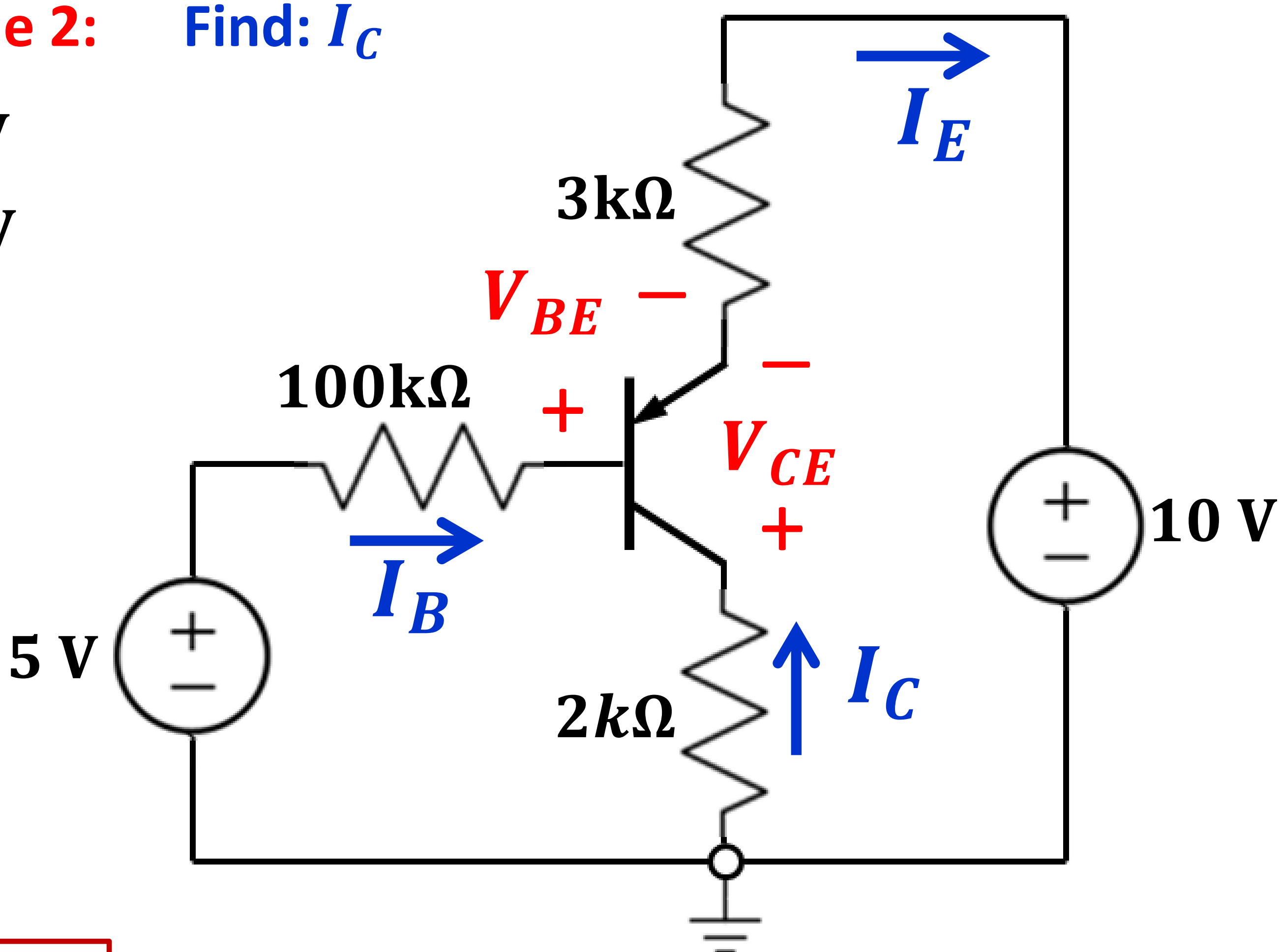
p-n-p Circuit Example 2: Find: I_C

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

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

$\beta = 10$

Assume Forward-Active mode



$I_B = -0.0323\text{mA}$

$I_C = \beta I_B = -0.323\text{mA}$

$I_E = (\beta + 1) I_B = -0.355\text{mA}$

$$10 + 3\text{k}\, I_E + V_{CE} + 2\text{k}\, I_C = 0$$

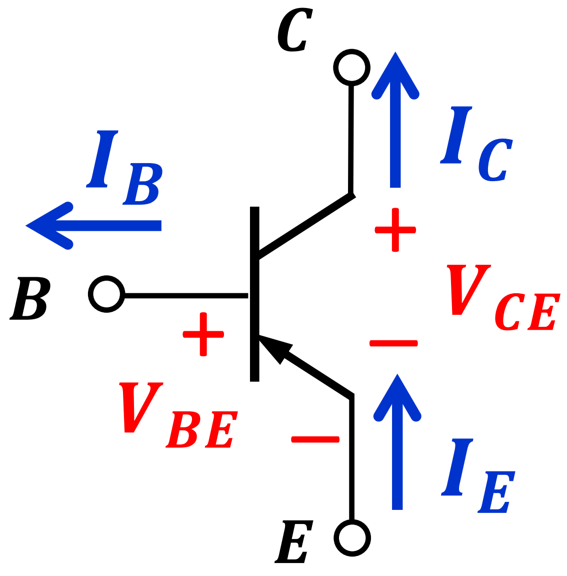
$$V_{CE} = -8.289\ \text{V}$$

MORE NEGATIVE THAN $V_{CE}(\text{sat})$

OK

Now we solve the same problem but with the *p-n-p* transistor configuration below, where we shift the ground reference. THERE IS COMPLETE EQUIVALENCE WITH THE PREVIOUS CIRCUIT.

Collector is connected to a negative bias, emitter is connected toward ground.



p-n-p **BJT**

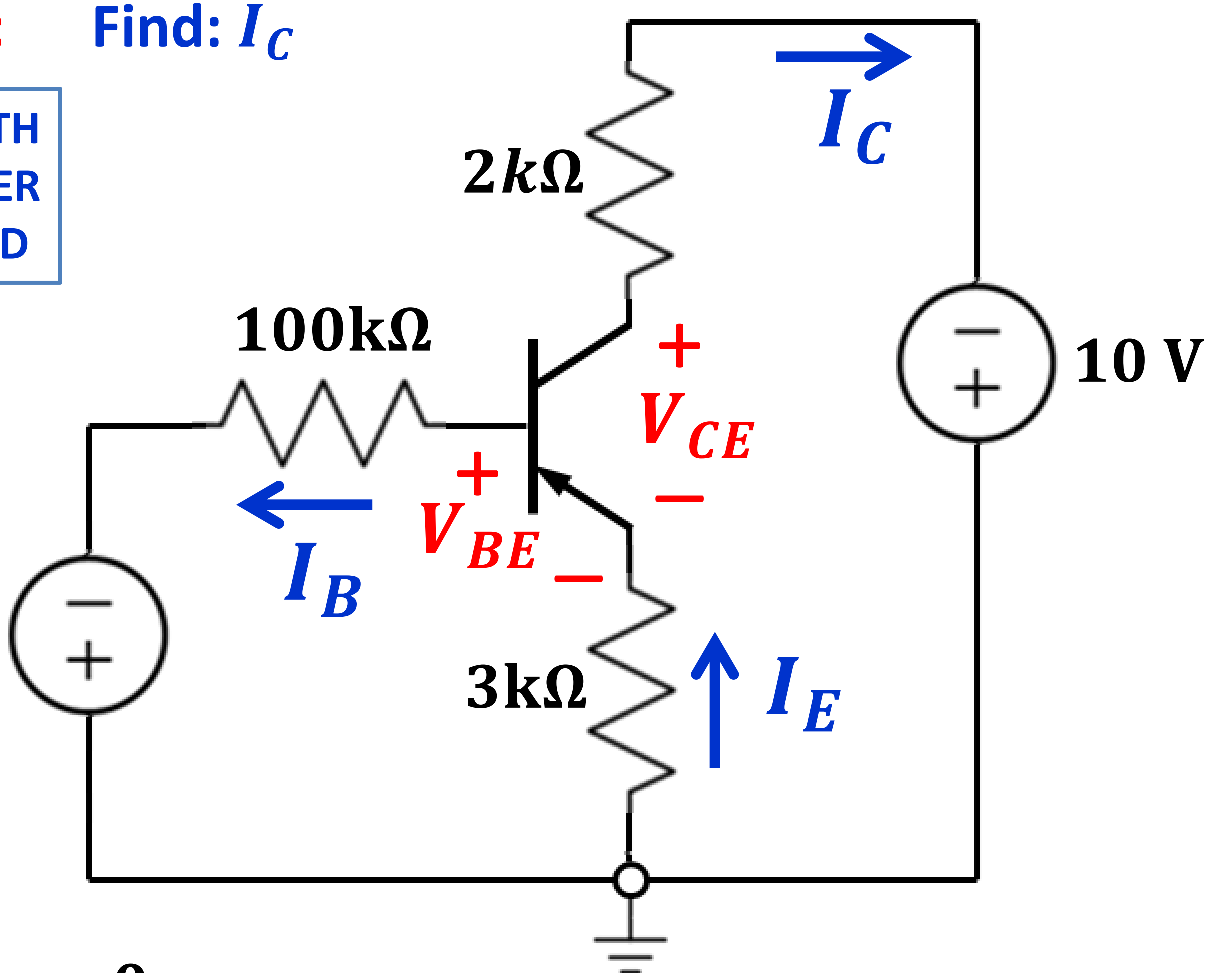
p-n-p Circuit Example 2: Find: I_C

SAME PROBLEM BUT WITH NEGATIVE BIAS AND EMITTER CONNECTED TOWARD GROUND

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

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

$\beta = 10$



Assume Forward-Active mode

$$5 - I_B R_B + V_{BE} - 3\text{k}\, I_E = 0$$

$$5 - 100\text{k}\, I_B - 0.7 - 3\text{k}(\beta + 1) I_B = 0$$

$$4.3 = 100\text{k}\, I_B + 3\text{k}(10 + 1) I_B$$

$$I_B = 4.3/133\text{k}$$

$$I_B = 0.0323\text{mA}$$

p-n-p Circuit Example 2: Find: I_C

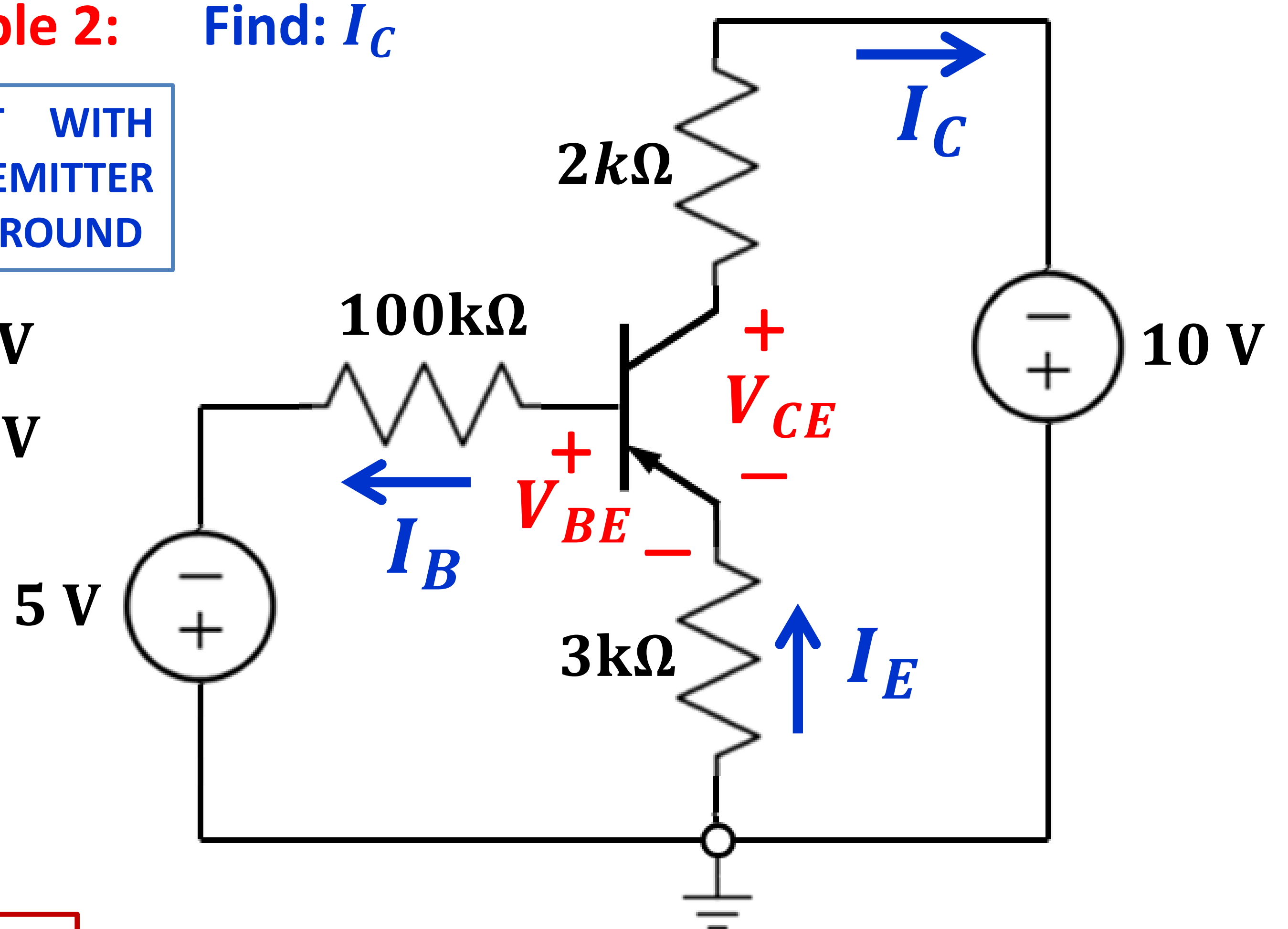
SAME PROBLEM BUT WITH NEGATIVE BIAS AND EMITTER CONNECTED TOWARD GROUND

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

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

$$\beta = 10$$

Assume Forward-Active mode



$$-10 + 3\text{k}\, I_E - V_{CE} + 2\text{k}\, I_C = 0$$

$$V_{CE} = -8.289\text{ V}$$

$$I_B = 0.0323\text{mA}$$

$$I_C = \beta I_B = 0.323\text{mA}$$

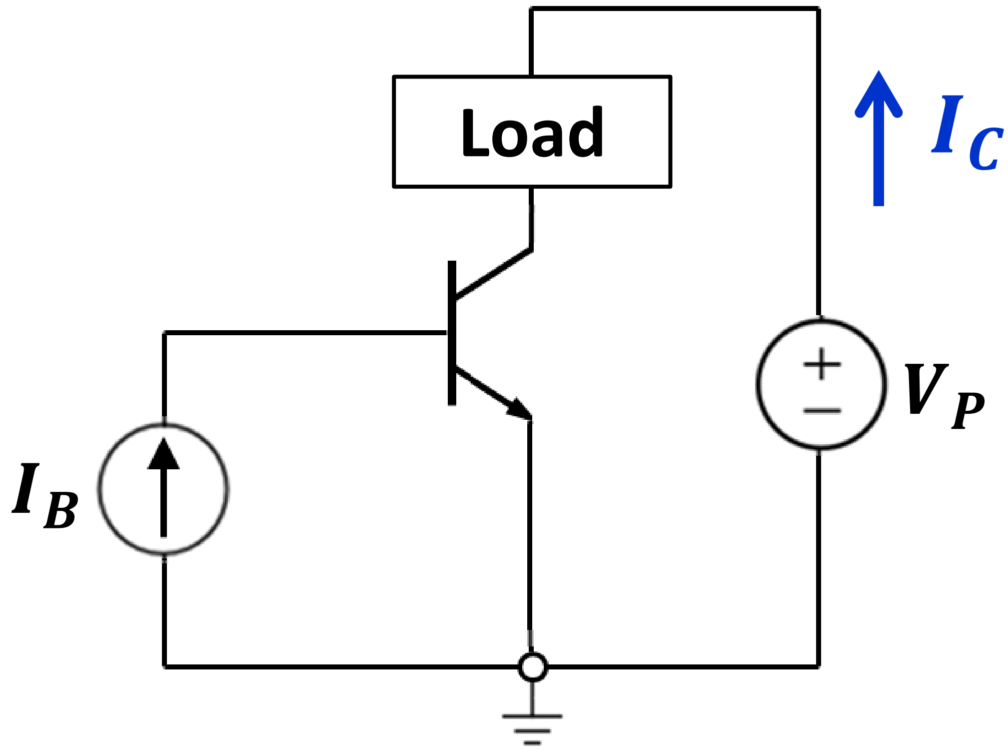
$$I_E = (\beta + 1) I_B = 0.355\text{mA}$$

MORE NEGATIVE THAN $V_{CE}(\text{sat})$
OK

Power in Transistor

BJT as a switch

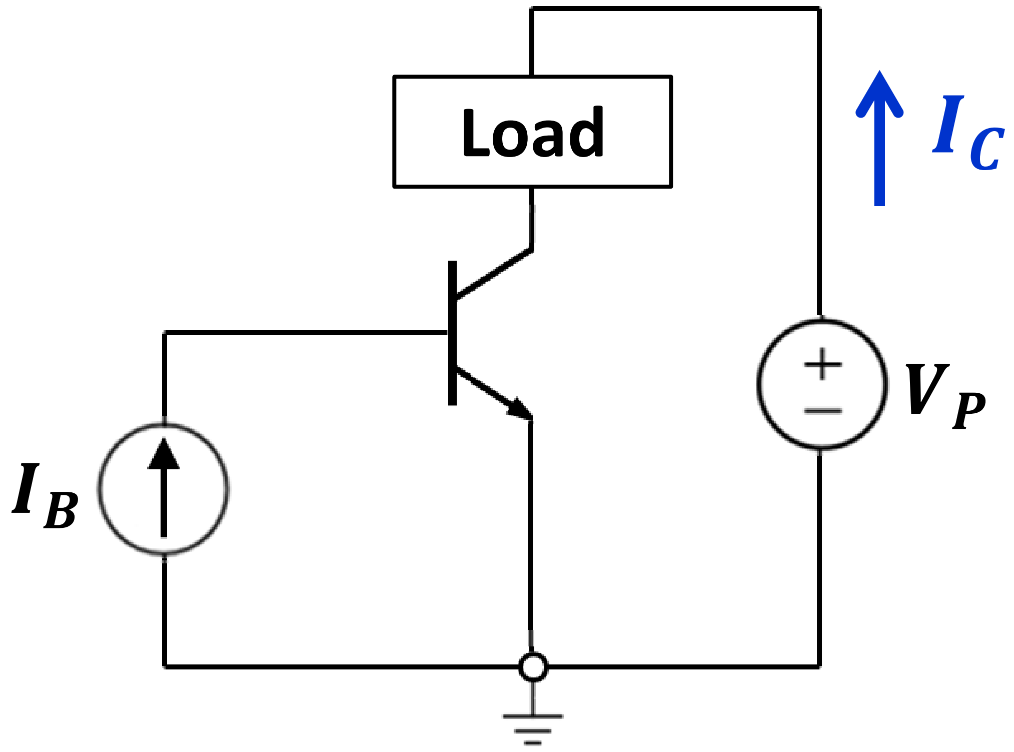
The BJT has important applications as a current controlled "valve" or as a "logic" element



We wish to switch ON and OFF power consumption by the load using a BJT instead of a mechanical switch.

BJT as a switch

Power consumed by the transistor is lost (it is part of operation costs)



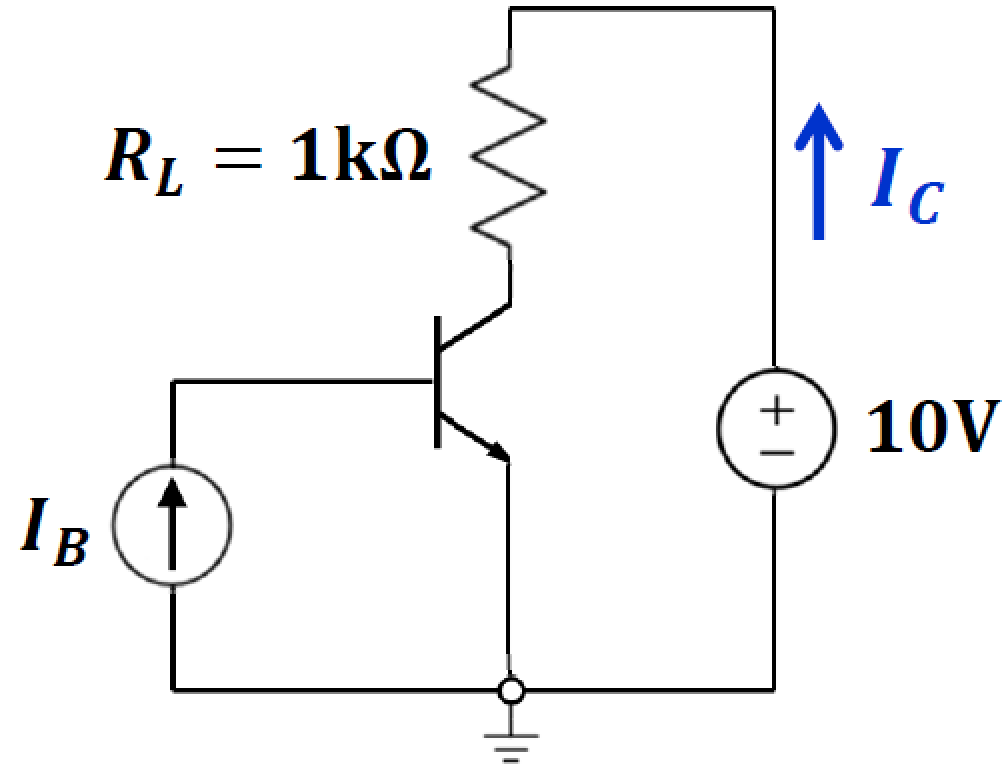
$$P_{BJT} = V_{BE} \times I_B + V_{CE} \times I_C$$

Example: Find P_{BJT} and P_{Load}

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

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

$\beta = 50$



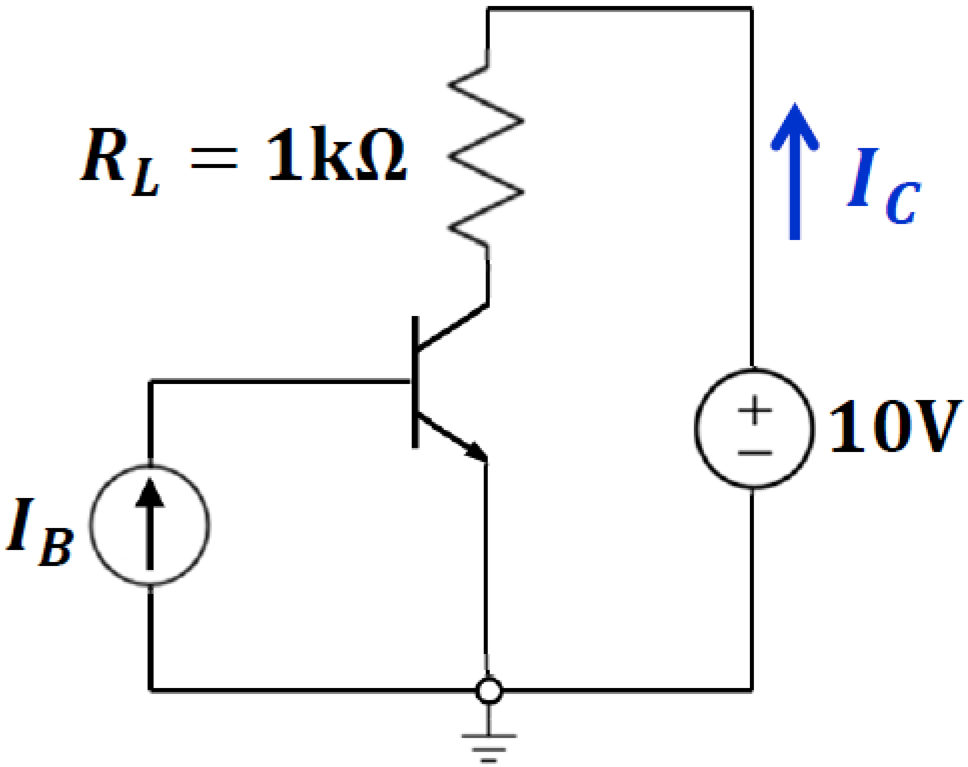
1. $I_B = 0\text{ mA}$
2. $I_B = 0.1\text{ mA}$
3. $I_B = 0.5\text{ mA}$

Example: Find P_{BJT} and P_{Load}

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

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

$\beta = 50$



1. $I_B = 0 \text{ mA}$

BJT is OFF

$$P_{BJT} = 0 \text{ W}$$

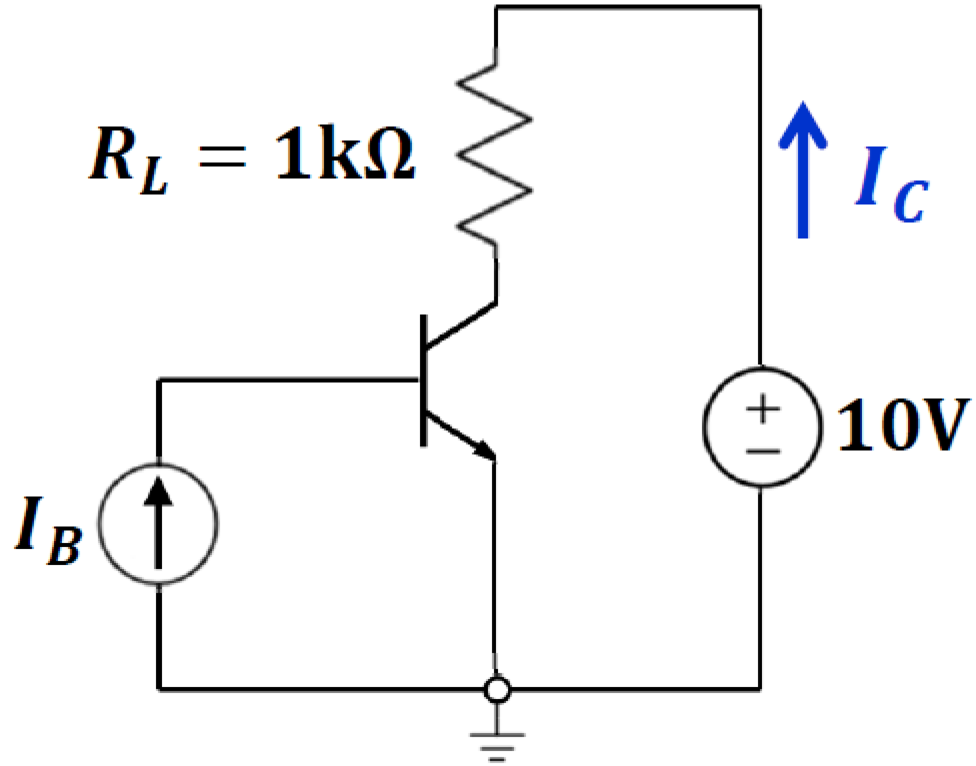
$$P_{Load} = 0 \text{ W}$$

Example: Find P_{BJT} and P_{Load}

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

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

$\beta = 50$



2. $I_B = 0.1\ \text{mA}$

Assume Forward Active mode

$I_C = \beta I_B = 5\text{mA}$

$V_{CE} = 10 - I_C R_L = 5\text{V}$

$$P_{BJT} = V_{BE} \times I_B + V_{CE} \times I_C = 0.7 \times 0.1\,\text{m} + 5 \times 5\,\text{m}$$

$$P_{BJT} = 25.07\text{mW}$$

$$P_{Load} = I_C^2 R_L = (5\text{mA})^2 \times 1\text{k}\Omega = 25\text{mW}$$

Example: Find P_{BJT} and P_{Load}

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

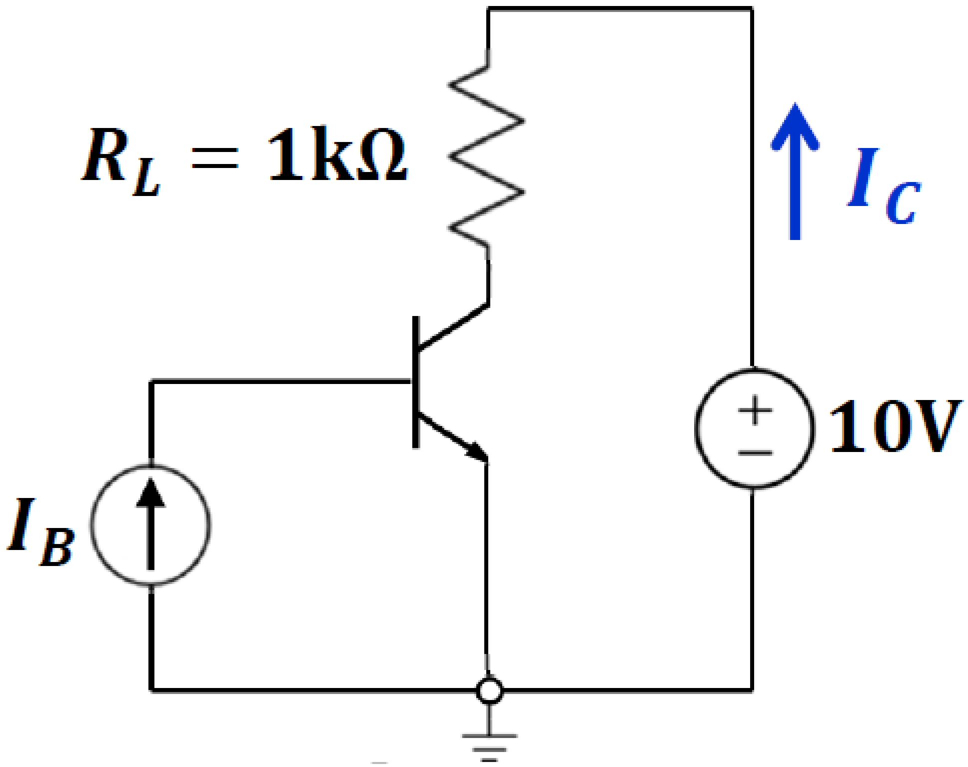
$V_{CE}(\text{sat}) = 0.2\text{V}$

$\beta = 50$

3. $I_B = 0.5 \text{ mA}$

BJT is in Saturation

$I_C(\text{sat}) = 9.8\text{mA}$



$$P_{BJT} = 0.7 \times 0.5\text{m} + 0.2 \times 9.8\text{m} = 2.31 \text{ mW}$$

$$P_{Load} = I_C^2 R_L = (9.8\text{mA})^2 \times 1\text{k}\Omega = 96.04\text{mW}$$

BJT is most efficient as a switch in Saturation