ECE 205 “Electrical and Electronics Circuits”

Spring 2024 – LECTURE 24

MWF – 12:00pm

Prof. Umberto Ravaioli

2062 ECE Building

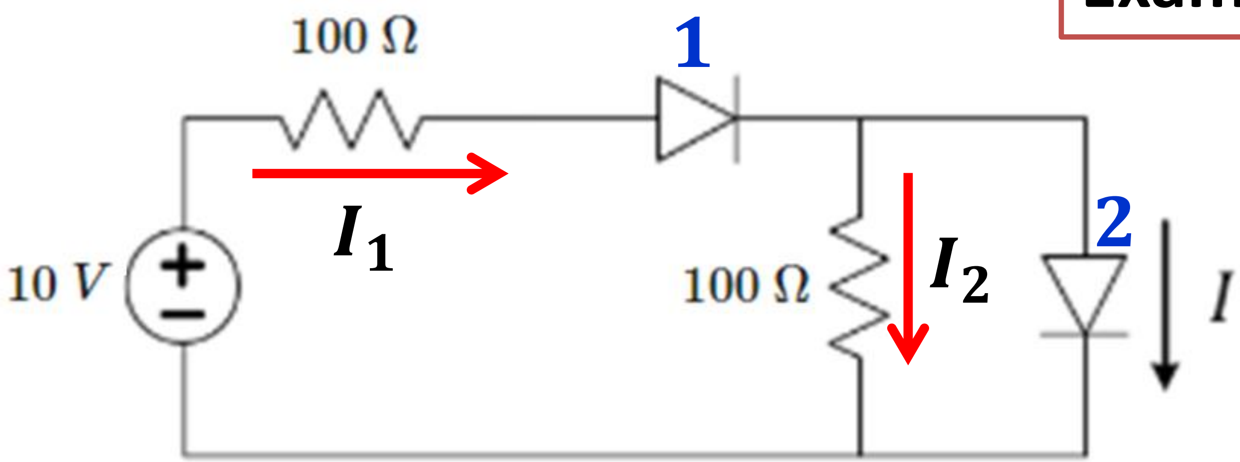
Lecture 24 – Summary

Learning Objectives

1. More problems on diodes
2. Introduction to the bipolar junction transistor (BJT)
3. Modes of operations of a BJT
4. Amplification
5. Solution approaches for BJT circuits

We solved this problem last time

Example 4A: Solve for I



$V_F = 4\text{V}$

Assume both diodes conduct

$$I_1 = I_2 + I$$

KVL $-10 + 100I_1 + 4 + 4 = 0$

$$I_1 = \frac{2}{100} = 20\text{mA} \qquad I_2 = \frac{4}{100} = 40mA$$

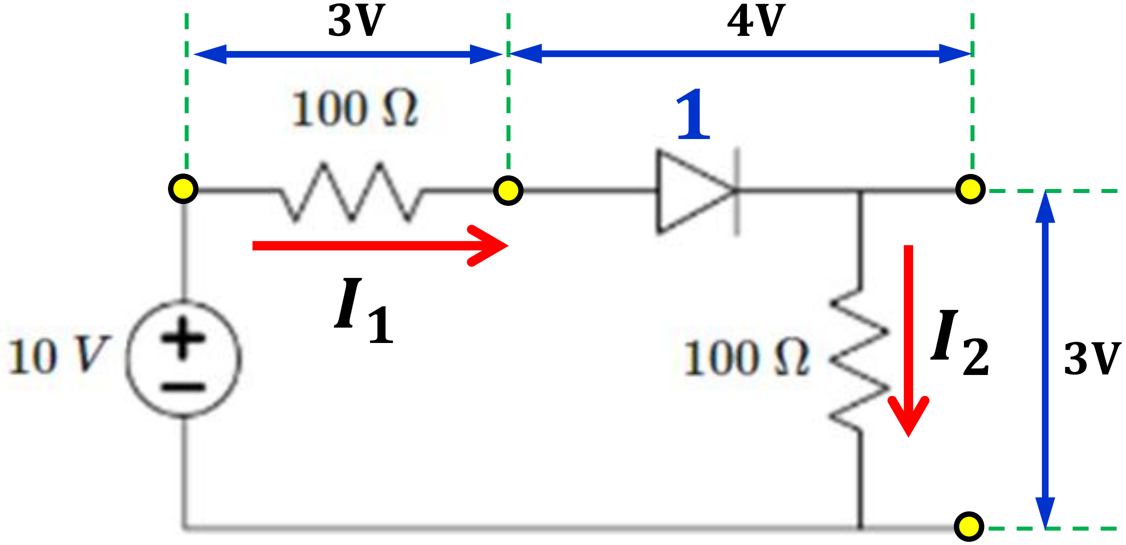
But $I_2 > I_1 \longrightarrow$ diode **2** cannot conduct

$I = 0$

new KVL with diode 2 open circuit

$$-10 + 100I_1 + 4 + 100I_1 = 0$$

$$I_1 = \frac{6}{200} = 30\text{mA}$$

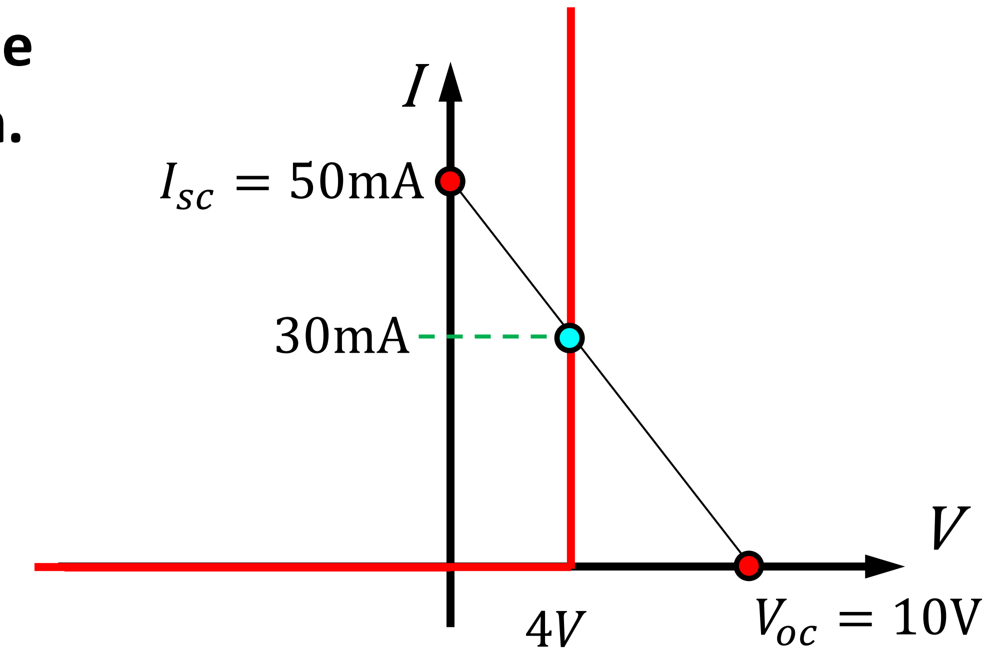


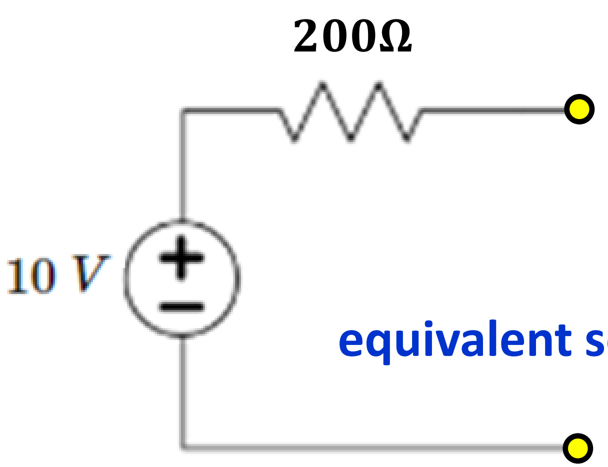
$I = 0$

$V_F = 4V$

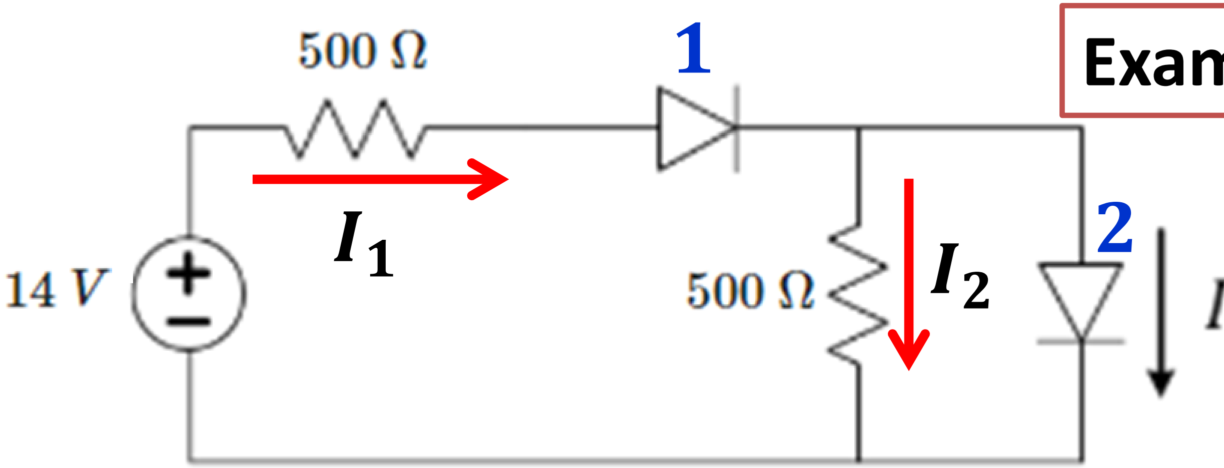
$I_1 = I_2 = 30mA$

Only diode 1 conducts. The two resistors drop 3V each.





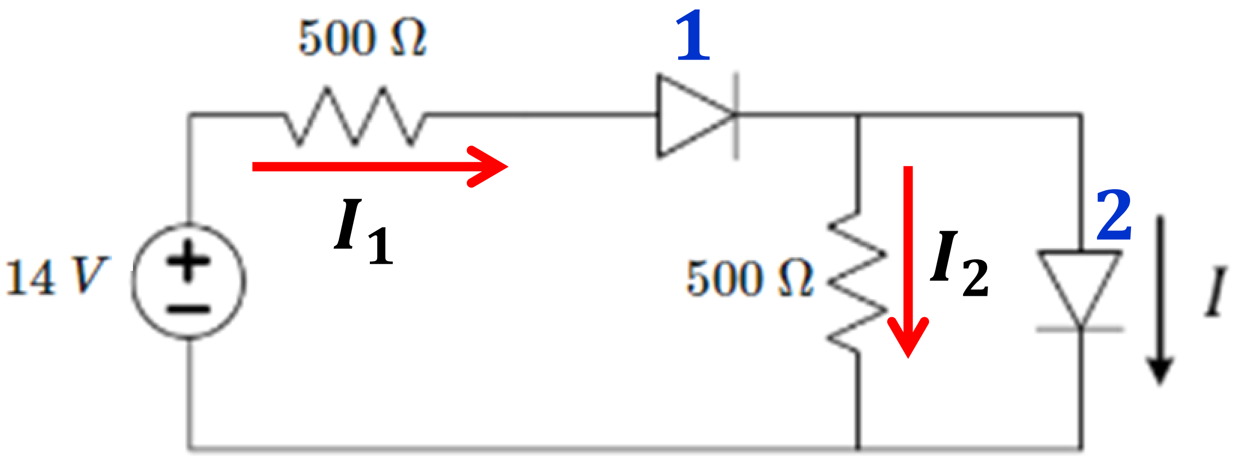
equivalent source



Example 4B: Solve for I

$V_F = 4\text{V}$

The source voltage has been increased



$V_F = 4\text{V}$

Assume both diodes conduct

$$I_1 = I_2 + I$$

KVL

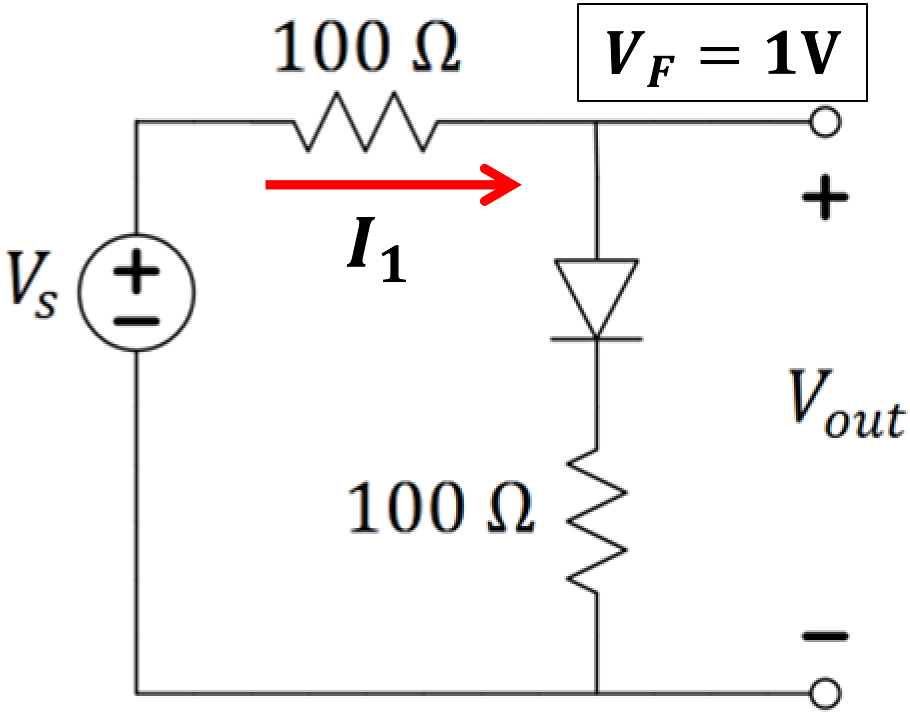
$$-14 + 500 I_1 + 4 + 4 = 0$$

$$I_1 = \frac{6}{500} = 12\text{mA}$$

$$I_2 = \frac{4}{500} = 8\text{mA} < I_1$$

$$I = I_1 - I_2 = 4\text{ mA}$$

Assumption is valid – No contradiction

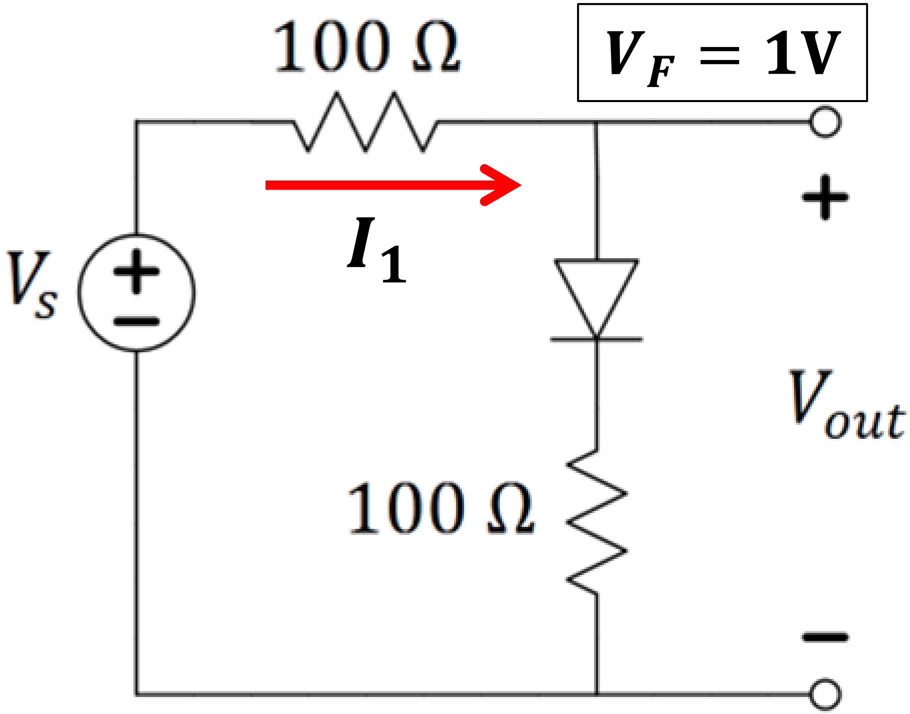


Example 5: Solve for V_{out}

Find V_{out} when

a) $V_S = 5\text{V}$

b) $V_S = -12\text{V}$



Example 5: Solve for V_{out}

Find V_{out} when

a) $V_S = 5\text{V}$

b) $V_S = -12\text{V}$

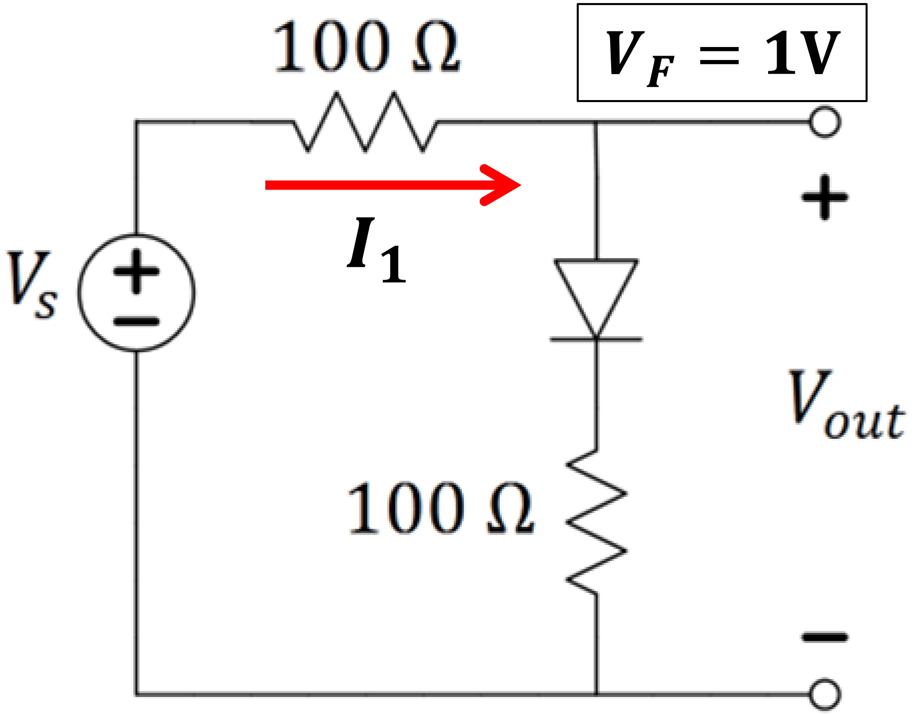
a)

$$-5 + 100I_1 + 1 + 100\,I_1 = 0$$

$$200I_1 = 4 \quad \rightarrow \quad I_1 = 20\text{mA}$$

$$V_{out} = 100 \times 20\text{m} + 1 = 3\text{V}$$

Example 5: Solve for V_{out}



Find V_{out} when

a) $V_S = 5\text{V}$

b) $V_S = -12\text{V}$

a)

$$-5 + 100I_1 + 1 + 100\,I_1 = 0$$

$$200I_1 = 4 \quad \rightarrow \quad I_1 = 20\text{mA}$$

$$V_{out} = 100 \times 20\text{m} + 1 = 3\text{V}$$

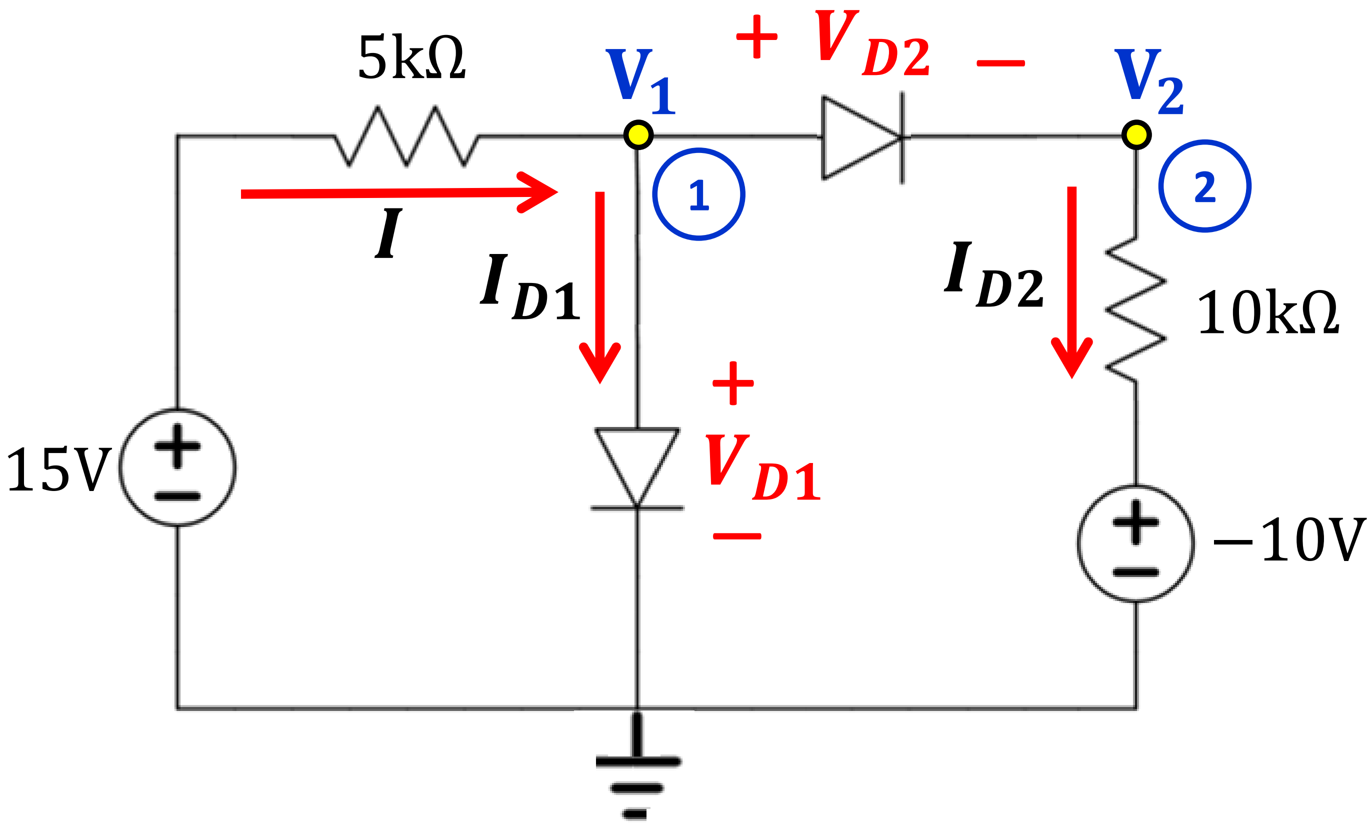
b)

$$I_1 = 0\text{ A}$$ **Diode does not conduct (reverse bias)**

$$V_{out} = -12\text{V}$$

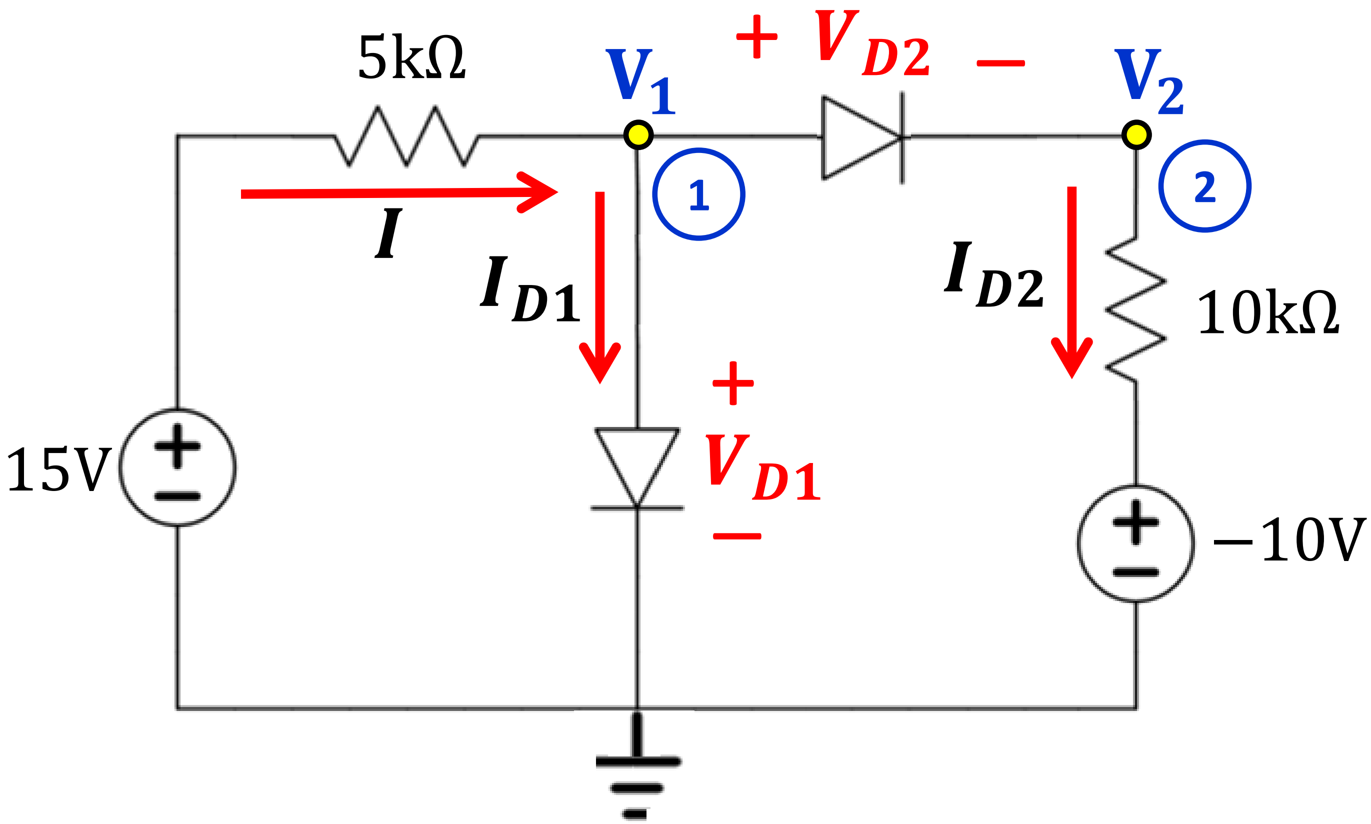
Example 6: Solve for I_{D1} and I_{D2}

$V_{D1} = V_{D2} = 0.7\text{V}$



Example 6: Solve for I_{D1} and I_{D2}

$V_{D1} = V_{D2} = 0.7\text{V}$

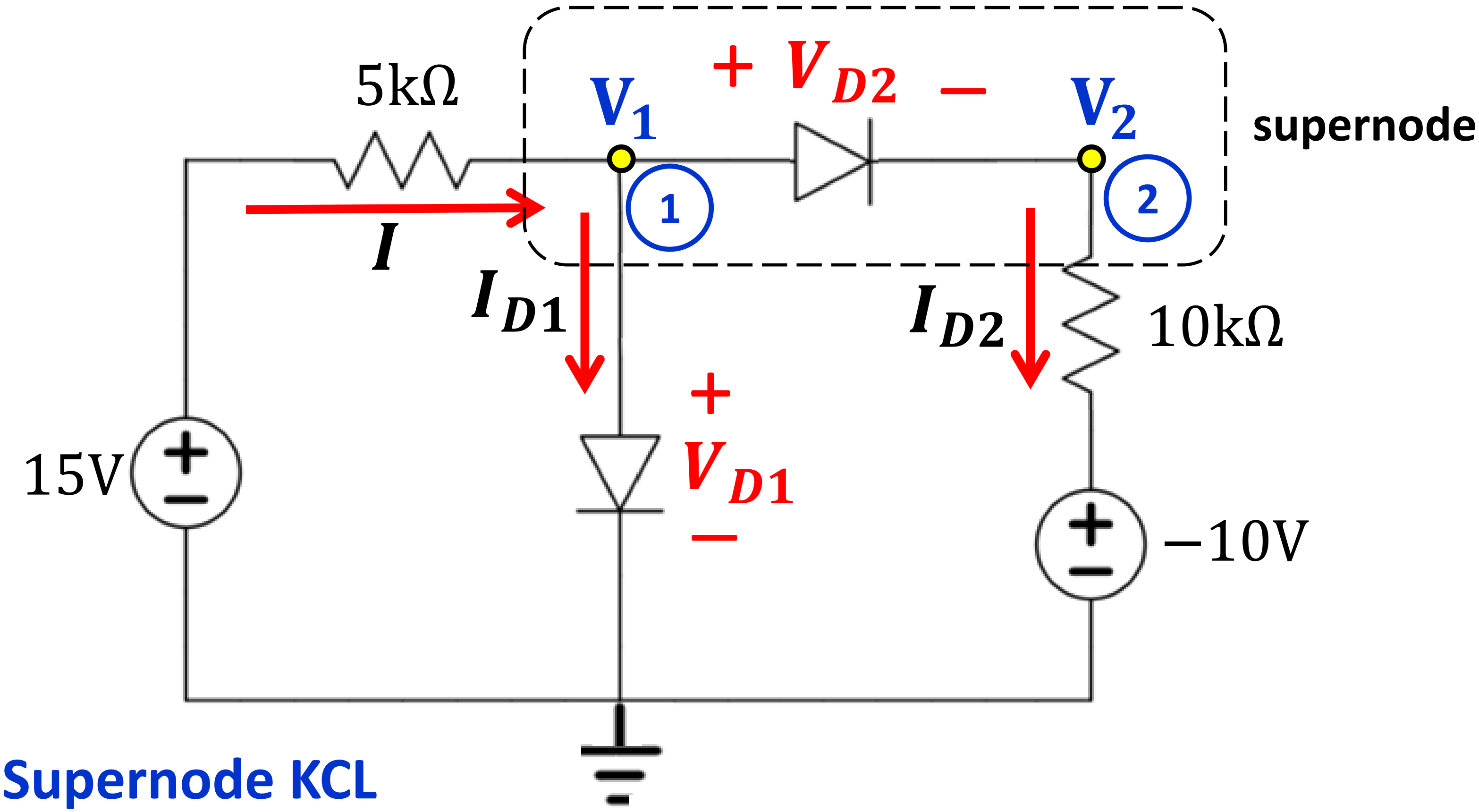


- **Assume both diodes are ON**
- **By inspection:**

$$\mathbf{V_1 = V_{D1} = 0.7V}$$

$$\mathbf{V_1 - V_2 = 0.7V}$$

$$\mathbf{V_2 = V_1 - V_{D2} = 0.7 - 0.7 = 0V}$$

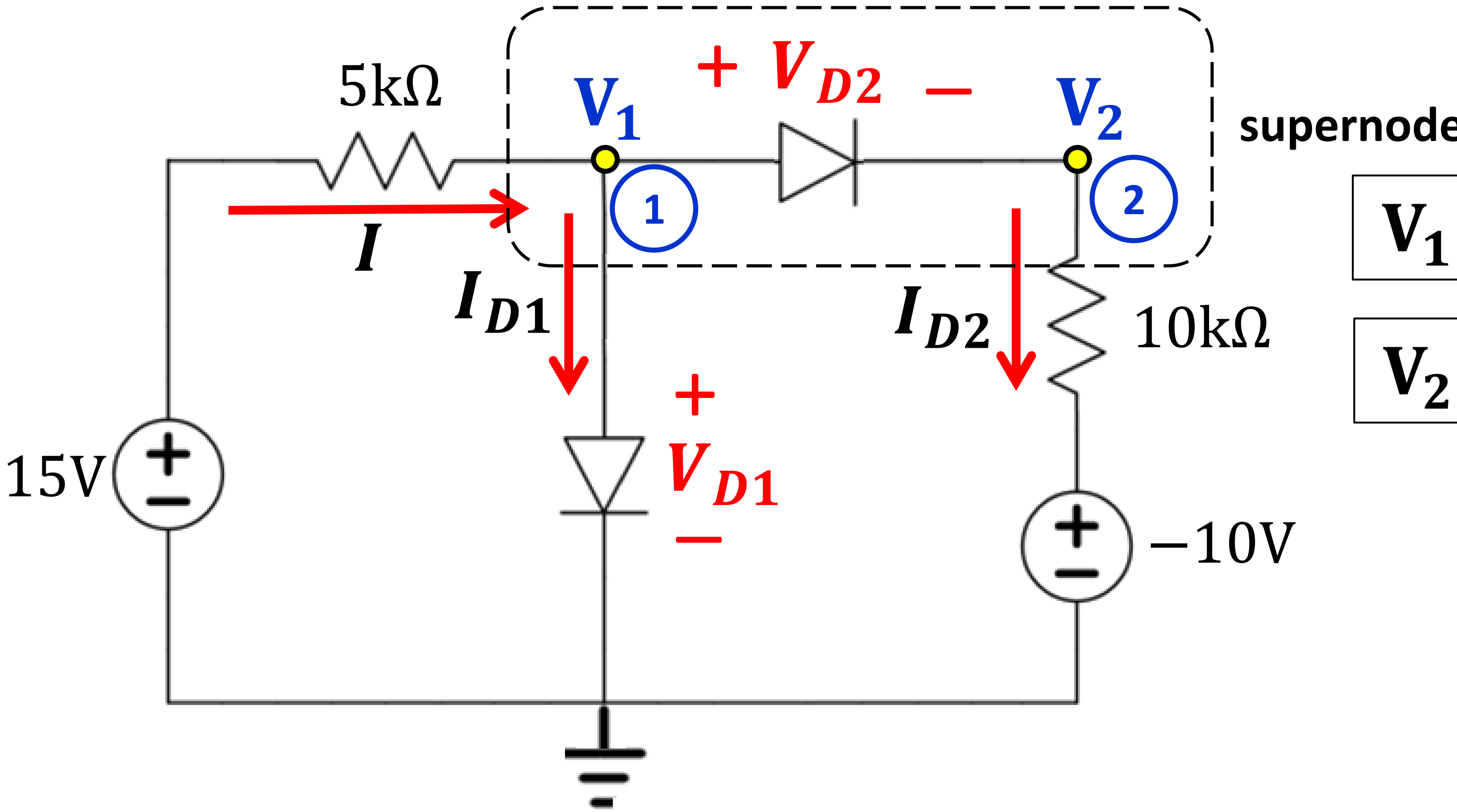


Supernode KCL

$$\frac{V_1 - 15}{5k} + I_{D1} + \frac{V_2 - (-10)}{10k} = 0$$

$$\frac{0.7 - 15}{5k} + I_{D1} + \frac{0 + 10}{10k} = 0$$

$$I_{D1} = \frac{9.3}{5k} = 1.86\text{mA}$$



$$\mathbf{V_1 = 0.7V}$$

$$\mathbf{V_2 = 0V}$$

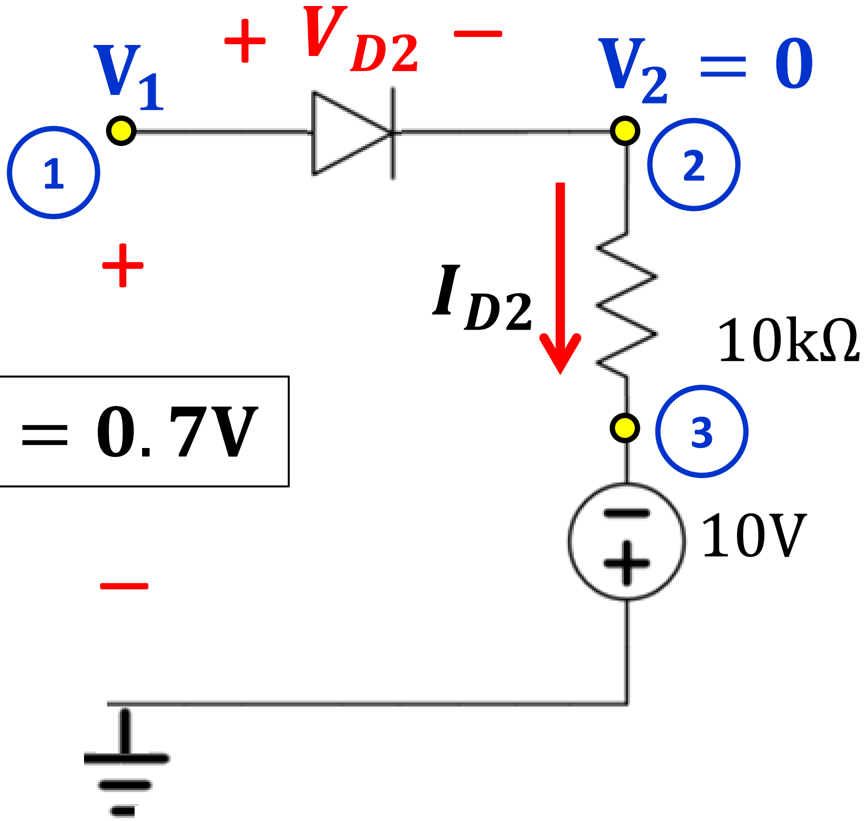
$$I_{D1} = \frac{9.3}{5k} = 1.86\text{mA}$$

$$I_{D2} = \frac{V_2 + 10}{10k} = 1\text{mA}$$

$$I = \frac{15 - 0.7}{5k} = 2.86\text{mA} = I_{D1} + I_{D2}$$

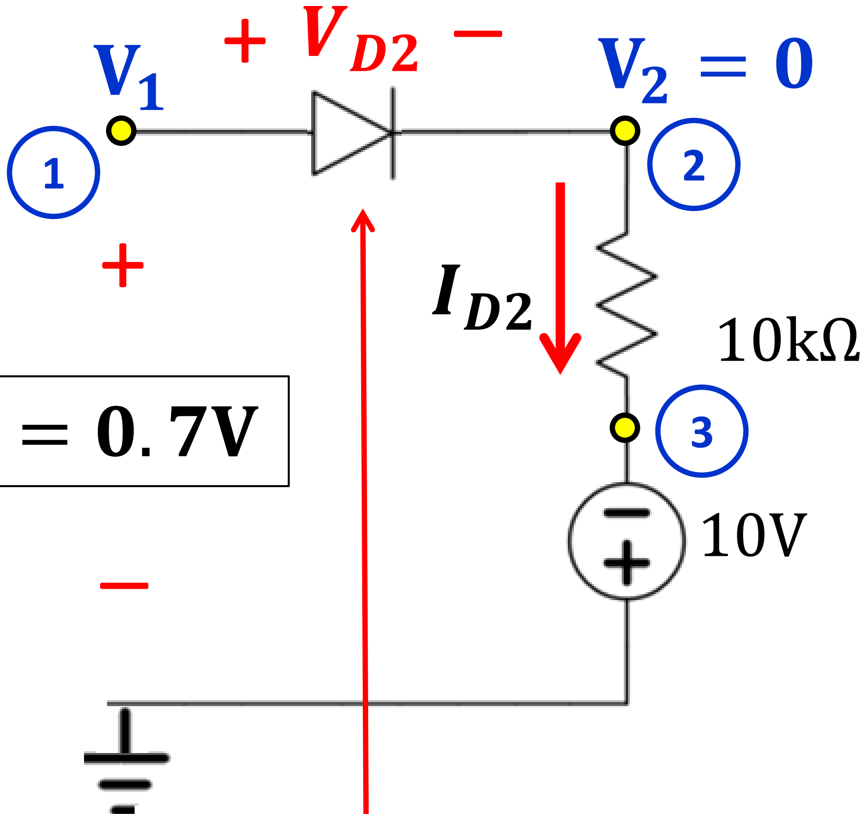
Results present no contradiction, both diodes are ON

Right side of the circuit

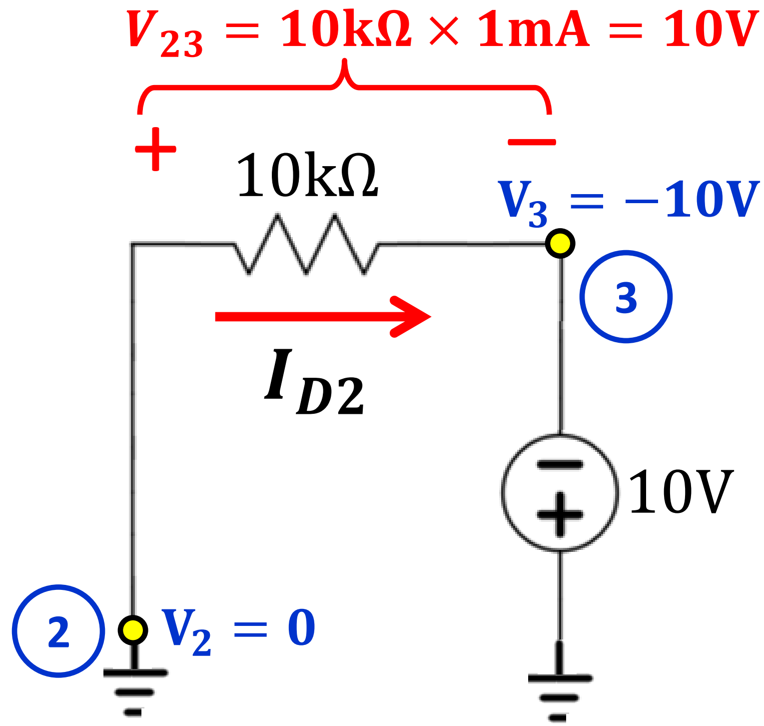


$$V_1 = 0.7V$$

Right side of the circuit



$$V_1 = 0.7V$$



This is the effective circuit seen by the 10V source

$$-V_2 + 10k\, I_{D2} - 10 = 0$$

$V_2 = 0$

Because of continuity (KCL) at node 2, this is the current which flows also through the diode

$$I_{D2} = \frac{10}{10k} = 1mA$$

More diode problems

in the extra video posted on Canvas at

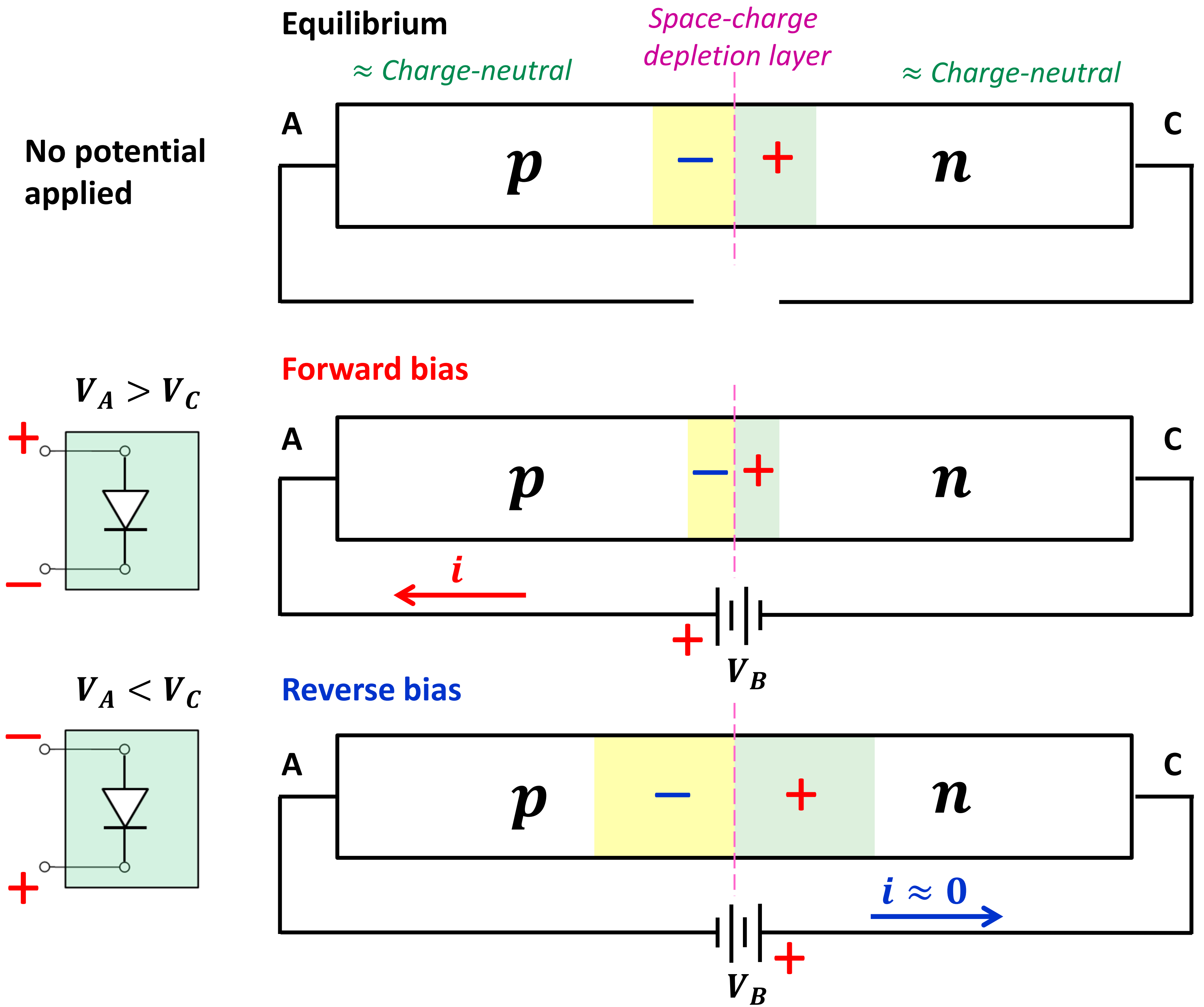
Module Week 10

Mon 3/25

(it includes solution of Worksheet 8)

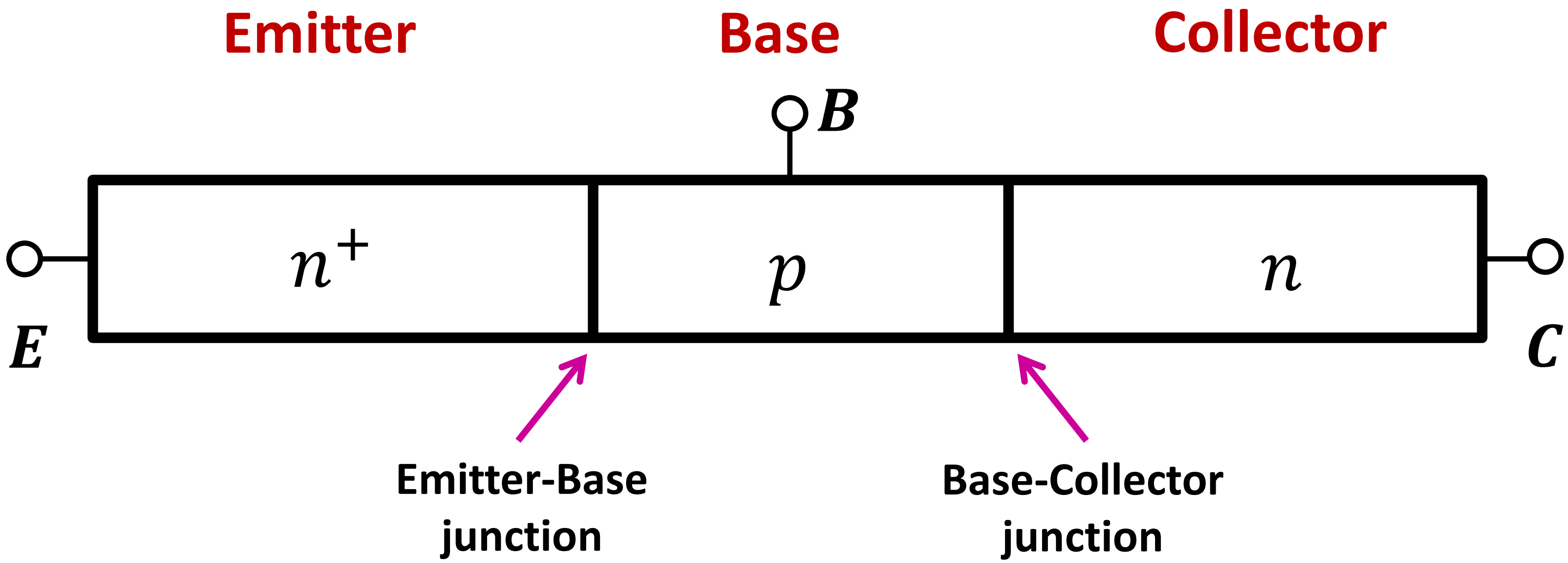
Bipolar Junction Transistor

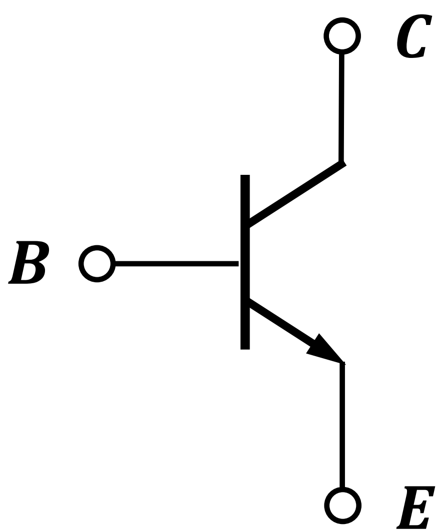
- We start from the *p-n* junction
- What happens if we create a structure with two *p-n* junctions?



Equilibrium
Space-charge depletion layer
≈ Charge-neutral
≈ Charge-neutral
No potential applied
A
C
p
n
−
+
Forward bias
$V_A > V_C$
+
−
i
V_B
Reverse bias
$V_A < V_C$
$i \approx 0$

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

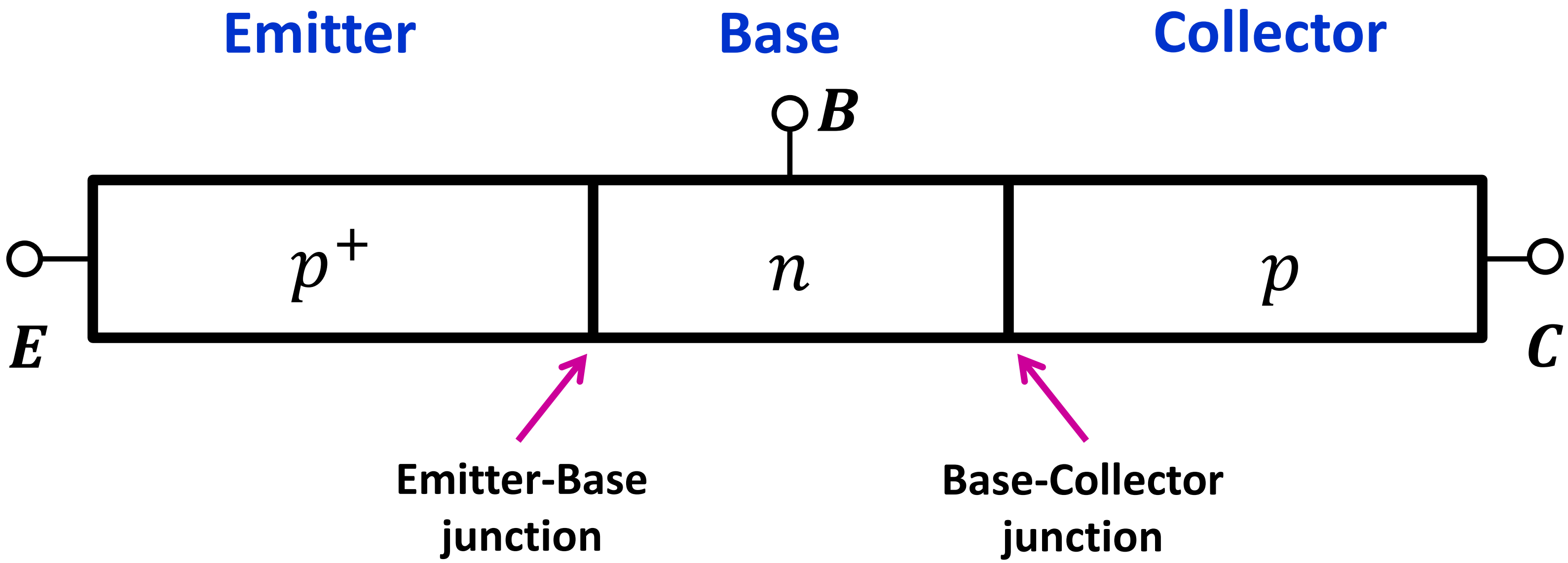


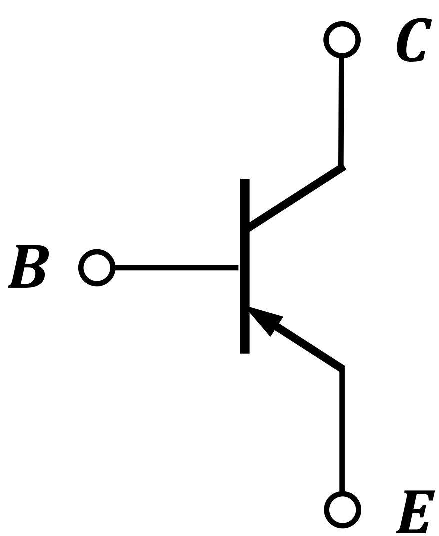


Circuit Symbol

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

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

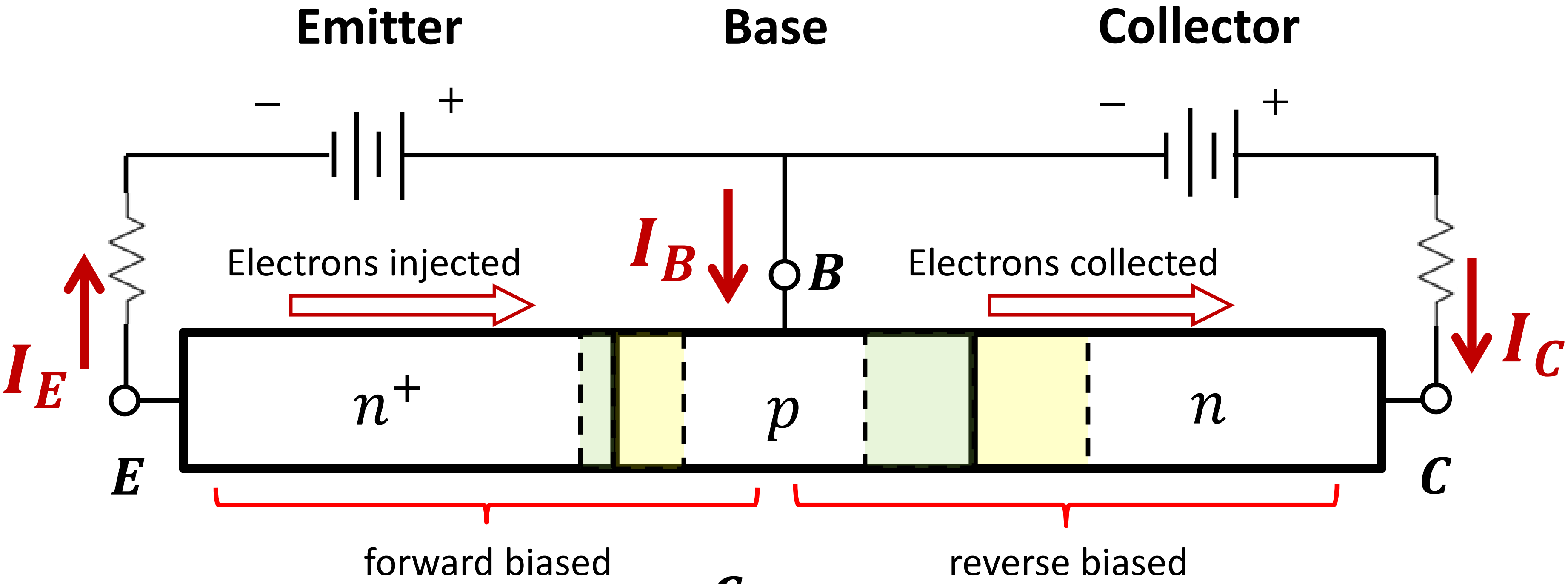


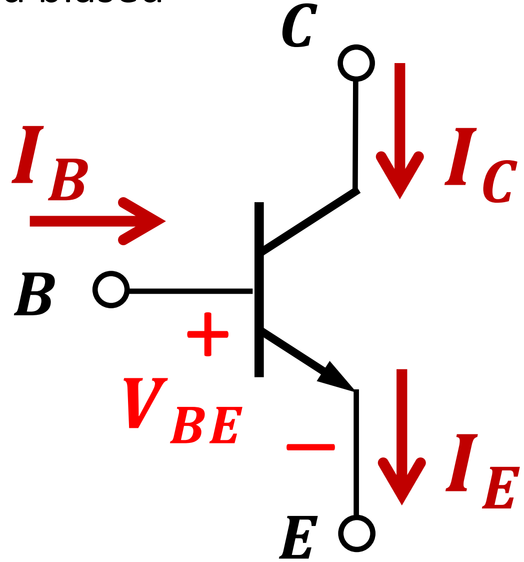


Circuit Symbol

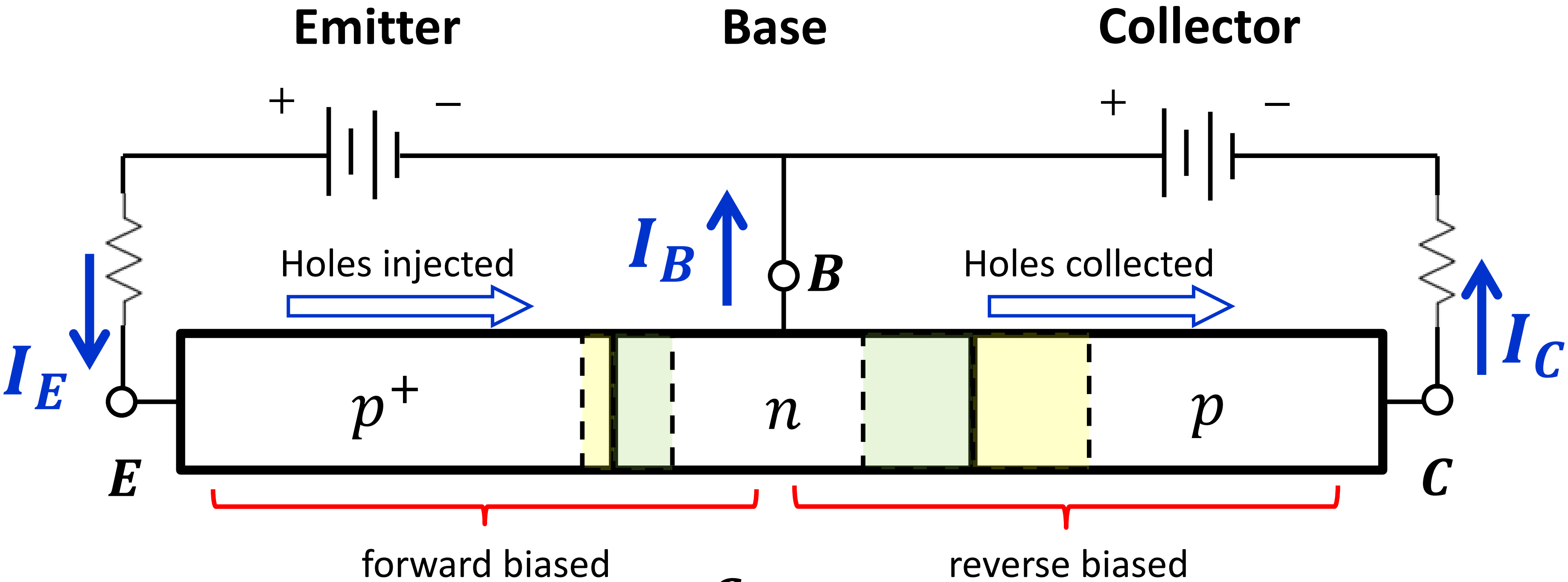
p-n-p BJT

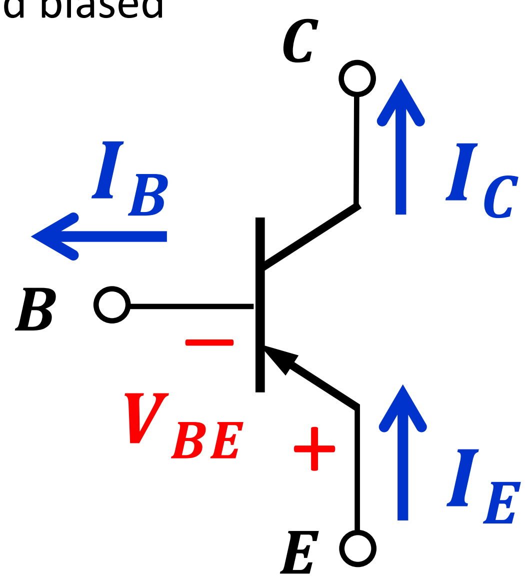
Bipolar Junction Transistor (BJT) *n-p-n*



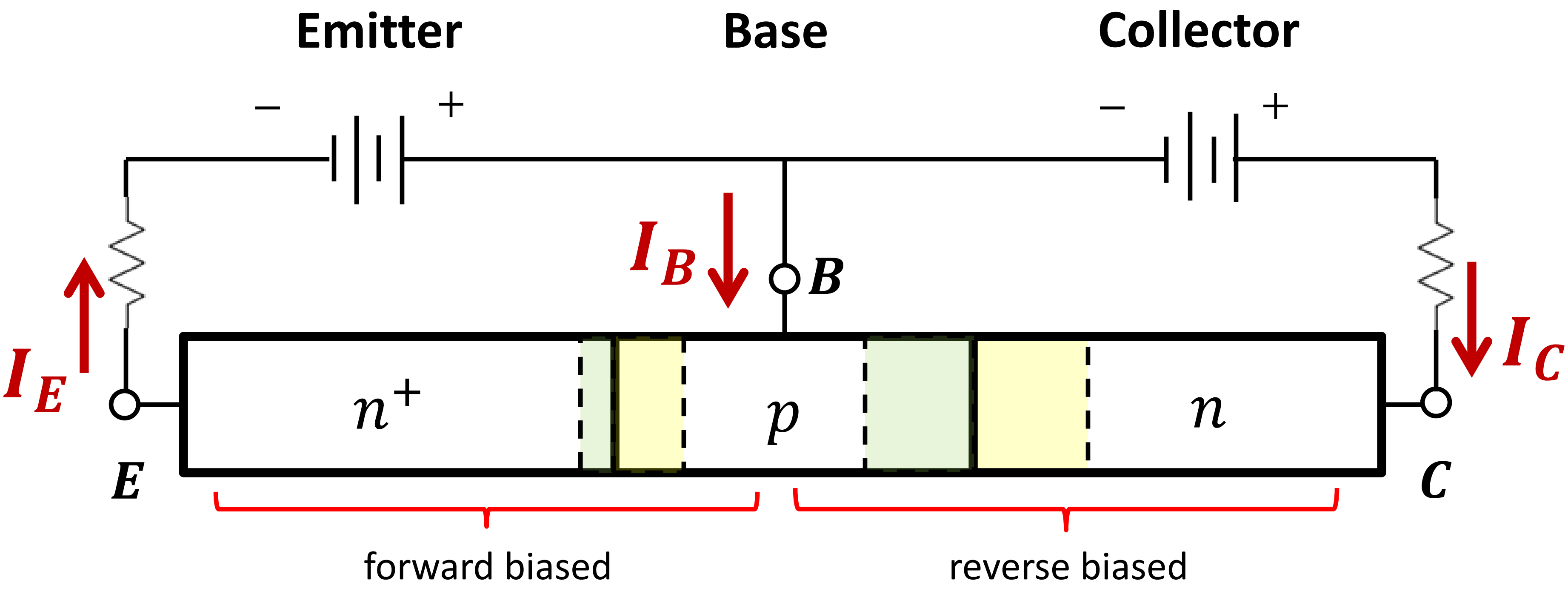


Bipolar Junction Transistor (BJT) *p-n-p*





Simple physics explanation – Forward active mode

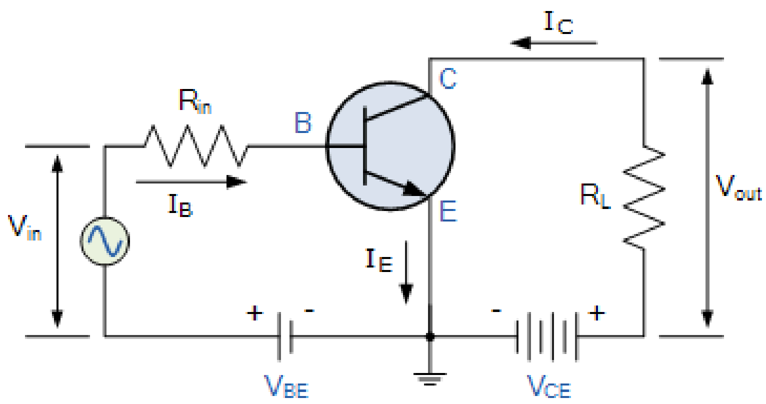


Electrons are injected from the emitter into the base through a forward biased emitter-base diode

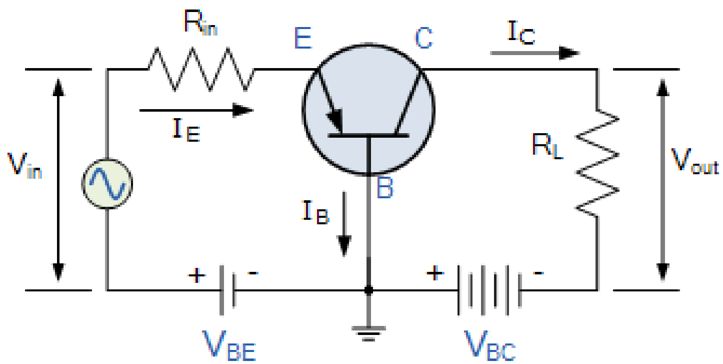
Most electrons traverse the base. The base current injects holes which recombine with some electrons, controlling the current flow from emitter to collector.

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

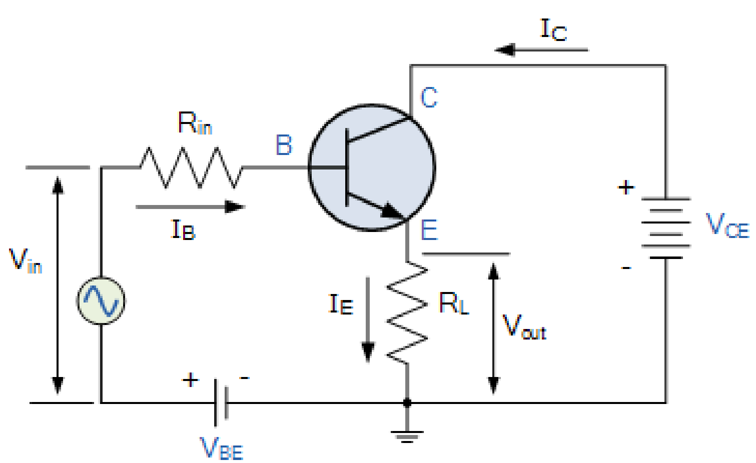
Transistor circuit configurations



Common Emitter
- **Current gain**
- **Voltage gain**

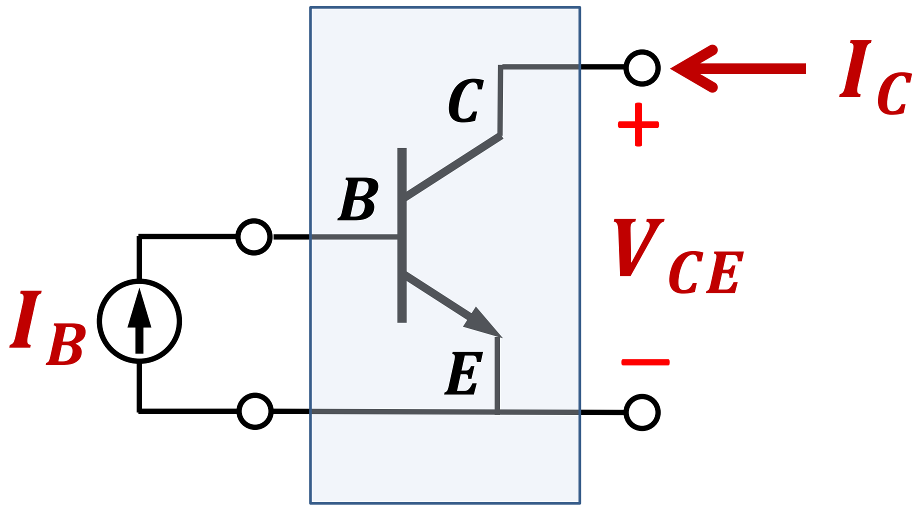


Common Base
- **Voltage gain**

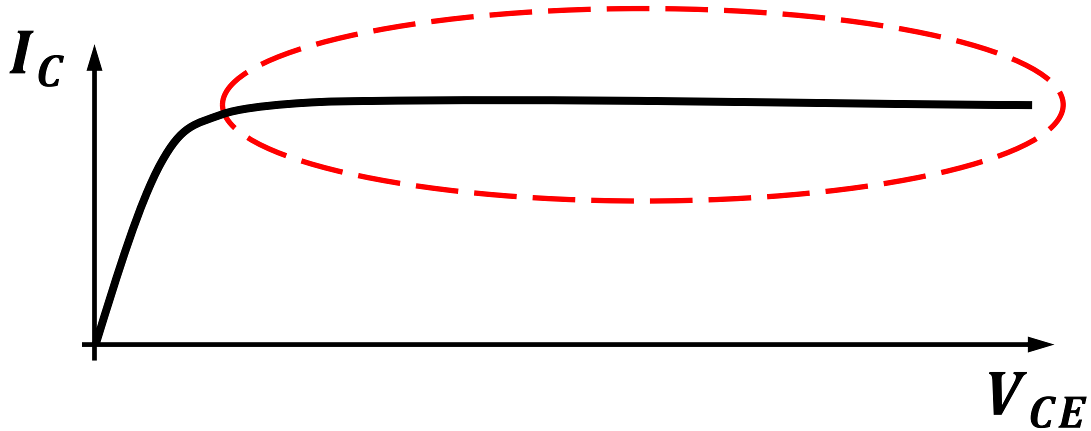


Common Collector
- **Current gain**

Common Emitter is the most important configuration

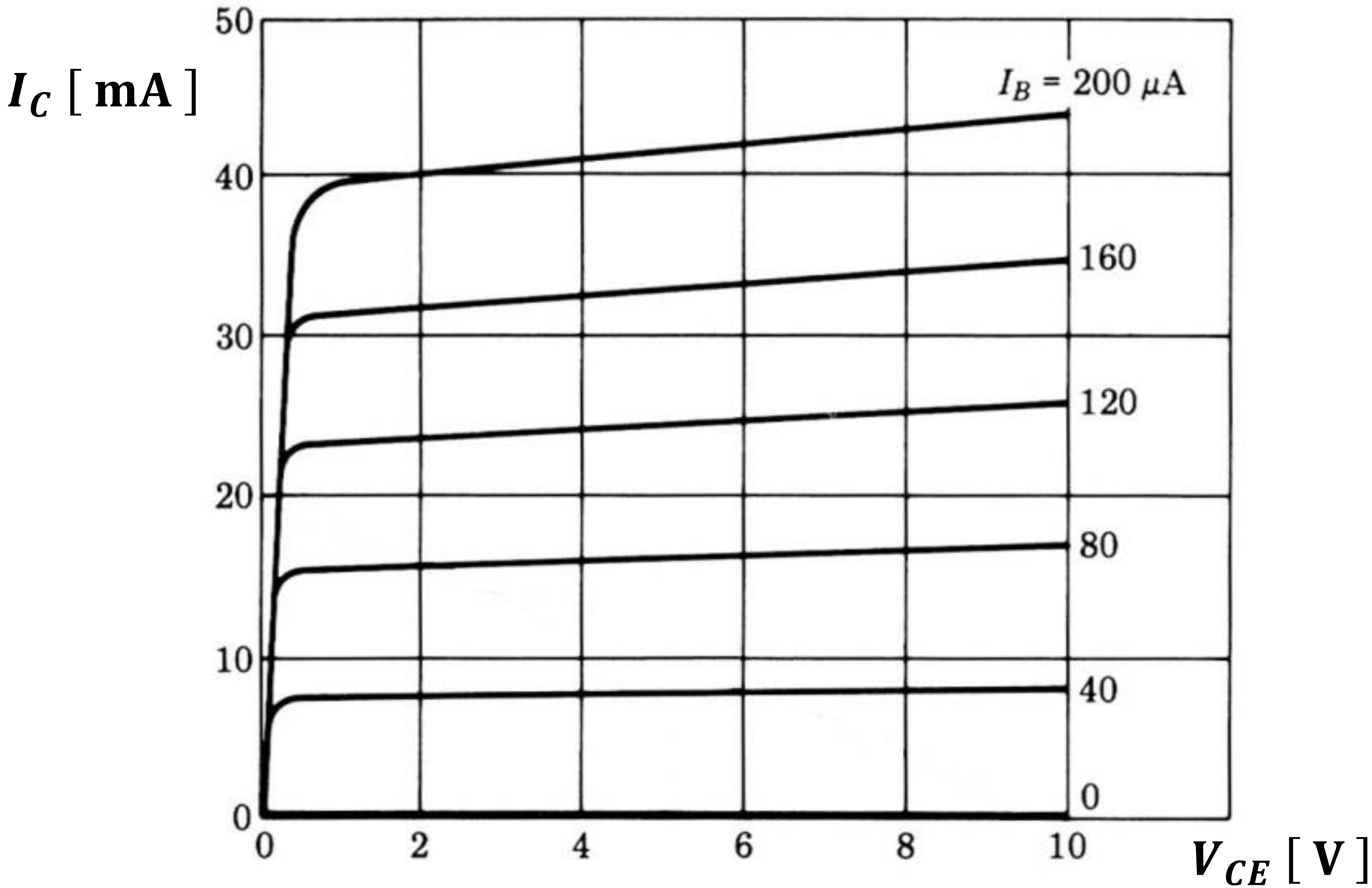


For a given I_B(input) we can measure the resulting I_C and V_{CE} (output)

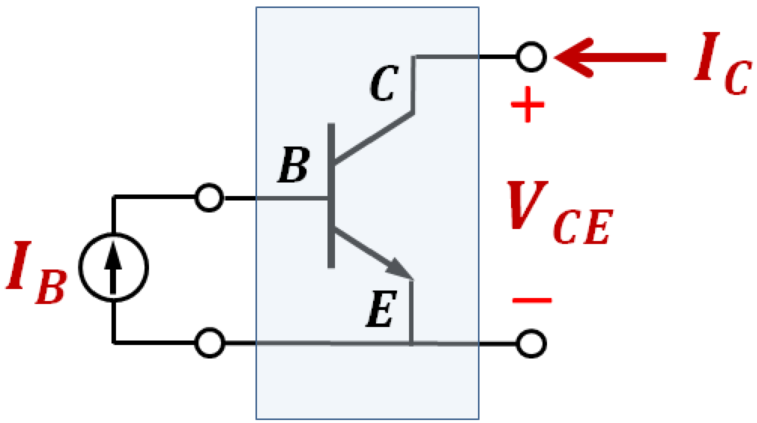


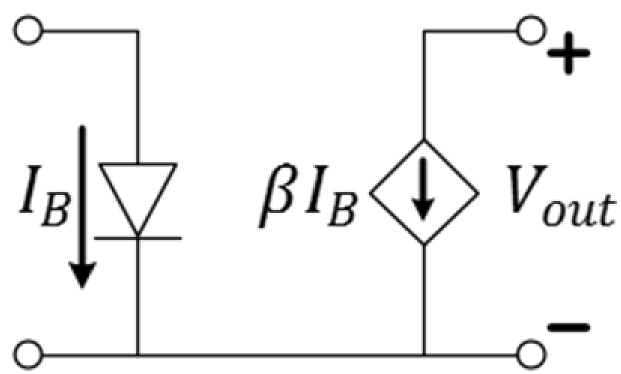
Flat – like current source

Example of complete I-V curves



BJT common emitter n-p-n circuit model





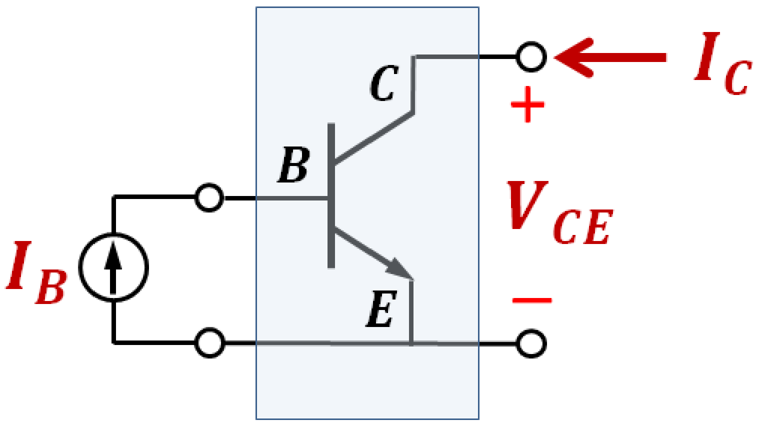
β is the common emitter current gain factor (typically, between 5 and 100)

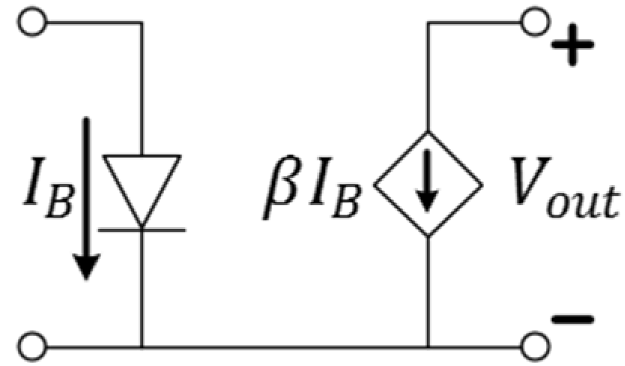
NOTE: The transistor has a small DC current in input and a much larger DC current in output.

However, it DOES NOT produce power. The power is provided by the DC sources which bias the device.

An AC input signal is amplified and a much larger AC signal is obtained at the output (at the cost of DC power).

States of BJT operation: 1) Cut-off mode



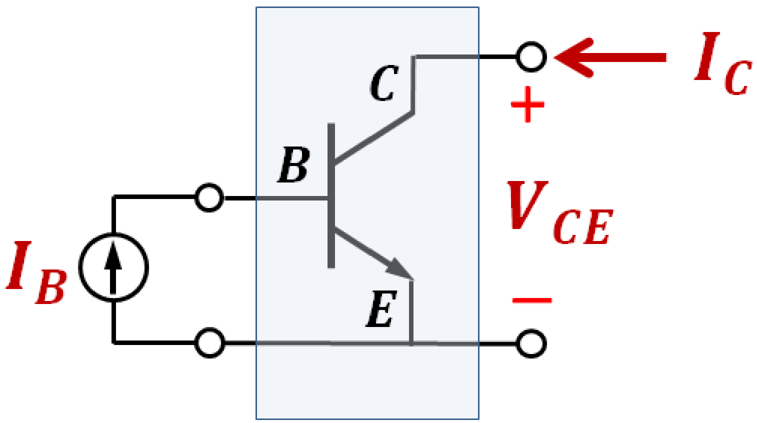


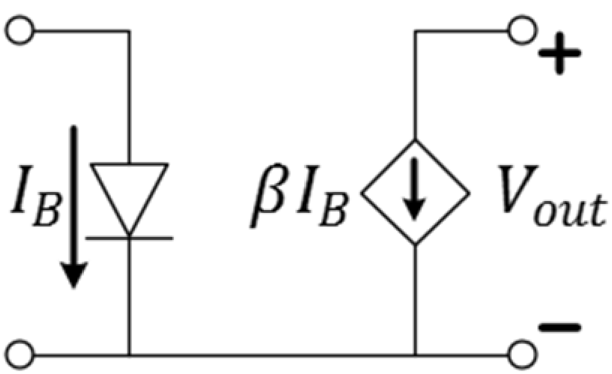
OFF: $V_{BE} < V_{BE}(\mathrm{ON})$

The base-emitter junction is like a *p-n* diode junction. If it is biased below threshold, the base current is negligible and there is no collector current in output. The output voltage V_{CE} is maximum (equal to the DC voltage applied to the collector).

For silicon transistors, typically $V_{BE}(\mathrm{ON}) \approx 0.6\mathrm{V}$ to $0.7\mathrm{V}$

States of BJT operation: 2) Forward Active mode





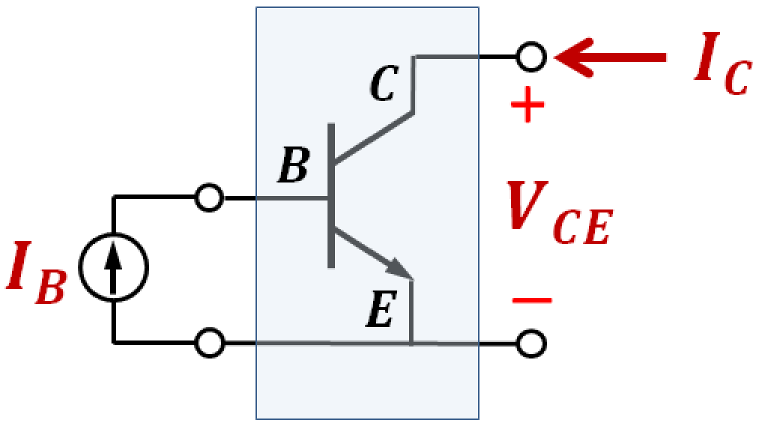
ON: $V_{BE} = V_{BE}(\mathrm{ON})$ & $V_{CE} > V_{CE}(\mathrm{sat})$

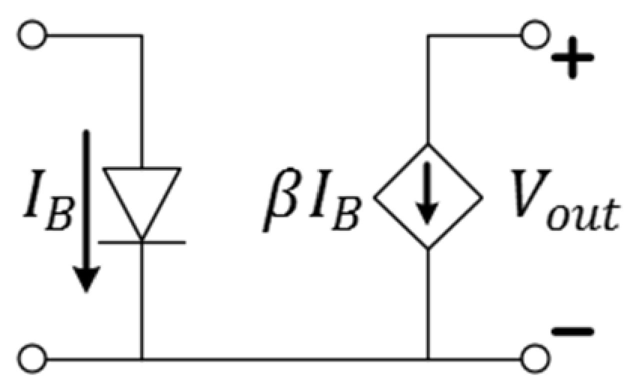
The base-emitter junction conducts, with input current I_B. The output voltage V_{CE} is less than the DC bias voltage on the collector.

As long as V_{CE} is larger than a minimum "saturation" value $V_{CE}(\mathrm{sat})$, the transistor is in forward active mode, with collector current βI_B proportional to the base current.

For silicon transistors, typically $V_{CE}(\mathrm{sat}) \approx 0.2\mathrm{V}$

States of BJT operation: 3) Saturation mode



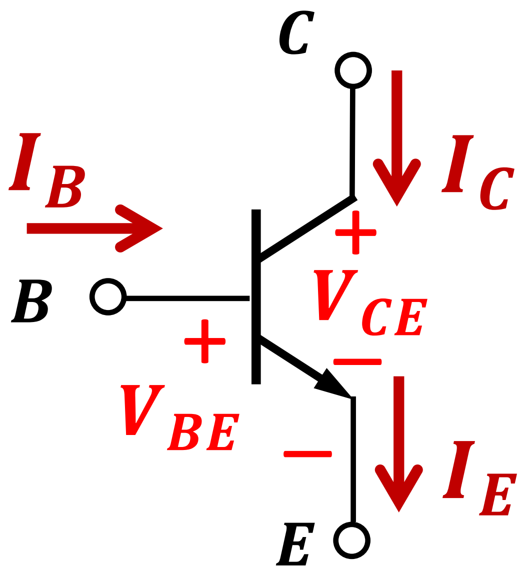


ON: $V_{BE} = V_{BE}(\mathrm{ON})$ **&** $V_{CE} = V_{CE}(\mathrm{sat})$

When the base current I_B exceeds a certain value, the voltage V_{CE} reaches the minimum saturation value $V_{CE}(\mathrm{sat})$.

The collector current saturates and can no longer follow the base current.

When the transistor is ON



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

$I_B > 0$ $\quad I_C > 0$ $\quad I_E > 0$

$$I_E = I_B + I_C$$

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

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

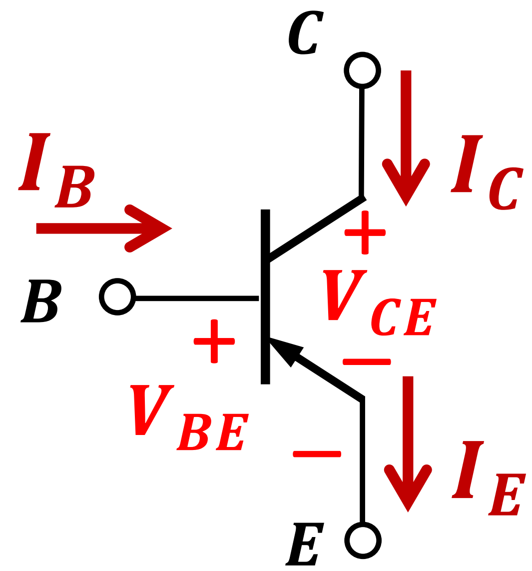
When the transistor is ON

In Forward Active mode

$$I_C = \beta\, I_B$$

KCL $$I_E = I_B + I_C$$

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



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

$$\alpha = \frac{\beta}{\beta + 1}$$

$$I_C = \alpha I_E$$

$$\beta = \frac{\alpha}{1 - \alpha}$$

Current transfer ratio

Quantifies the % of electrons originating from the emitter which are able to reach the collector

BJT solution strategy (Summary)

STEP 1 – Check if the BJT is ON

The voltage applied in input must turn on the *p-n* junction (diode) between base and emitter so that $V_{BE} = V_{BE}(\text{on})$ $I_B \neq 0$

If BJT is OFF $\rightarrow$ STOP here. If BJT is ON $\rightarrow$ PROCEED to STEP 2

STEP 2 – Assume that the BJT is in Forward Active state

$V_{BE} = V_{BE}(\text{on})$ $I_C = \beta\, I_B$

If circuit analysis shows that $V_{CE} > V_{CE}(\text{sat})$ the assumption is verified.

If assumption is verified $\rightarrow$ STOP here. If not $\rightarrow$ PROCEED to STEP 3

STEP 3 – Select Saturation state

If the result from circuit analysis at STEP 2 is that $V_{CE} < V_{CE}(\text{sat})$ then the calculated collector current is excessive.

Set $V_{CE} = V_{CE}(\text{sat})$ **and calculate the corresponding** $I_C = I_C(\text{sat})$

BJT solution strategy

STEP 1 – Check if the BJT is ON

The voltage applied in input must turn on the *p-n* junction (diode) between base and emitter so that

$$\boxed{V_{BE} = V_{BE}(\text{on})} \qquad \boxed{I_B \neq 0}$$

If BJT is OFF $\rightarrow$ STOP here. If BJT is ON $\rightarrow$ PROCEED to STEP 2

BJT solution strategy

STEP 2 – Assume BJT is in Forward Active state

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

$$I_C = \beta\, I_B$$

If circuit analysis shows that $V_{CE} > V_{CE}(\text{sat})$ the assumption is verified.

If assumption is verified→ STOP here. If not → PROCEED to STEP 3

BJT solution strategy

STEP 3 – Select Saturation state

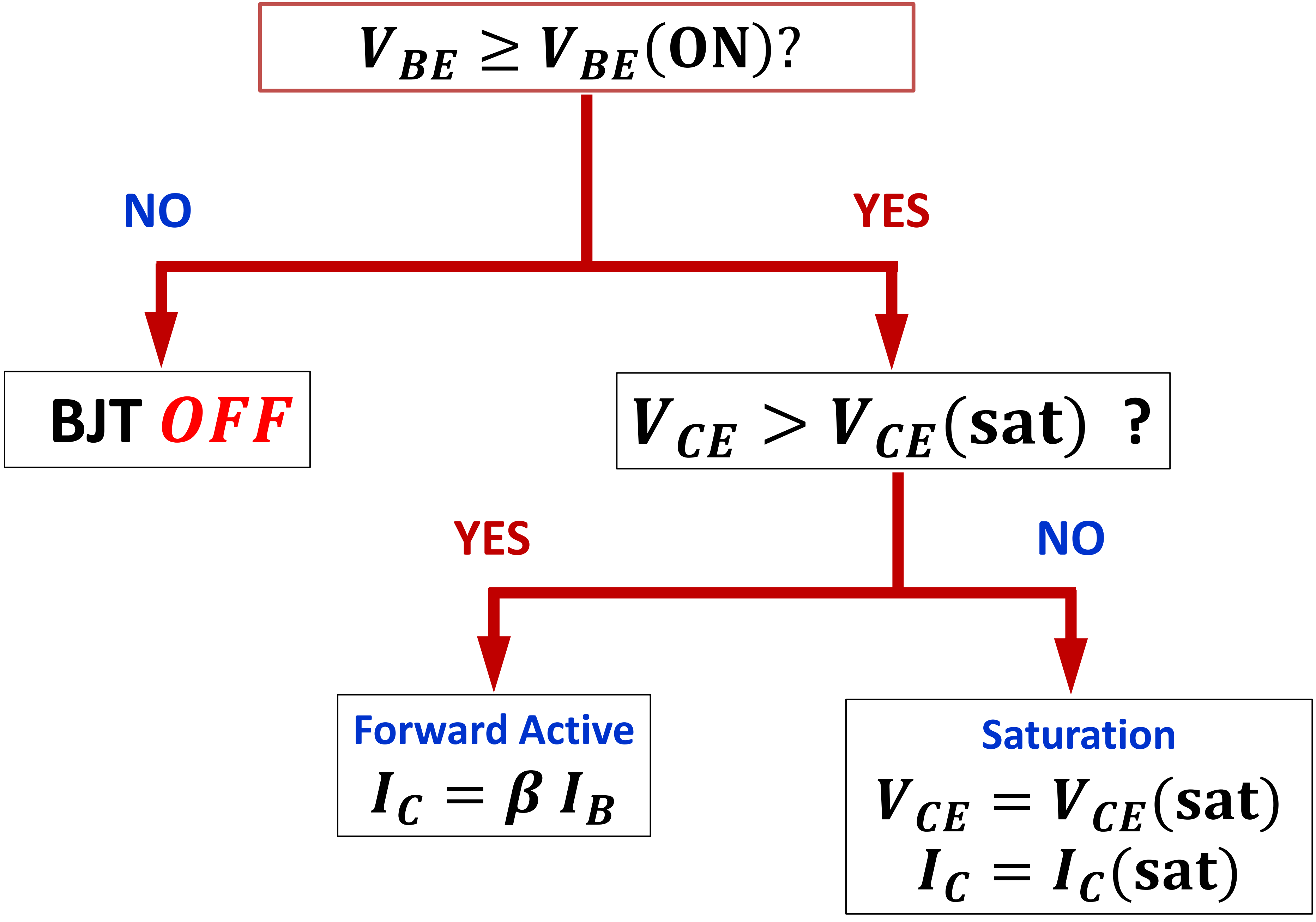
If the result from circuit analysis at STEP 2 is that

$$V_{CE} < V_{CE}(\mathrm{sat})$$

then the calculated collector current is excessive.

Set $$V_{CE} = V_{CE}(\mathrm{sat})$$

and calculate the corresponding $$I_C = I_C(\mathrm{sat})$$


$V_{BE} \geq V_{BE}(\mathrm{ON})?$
NO
YES
BJT OFF
$V_{CE} > V_{CE}(\mathrm{sat})$?
YES
NO
Forward Active
$I_C = \beta\, I_B$
Saturation
$V_{CE} = V_{CE}(\mathrm{sat})$
$I_C = I_C(\mathrm{sat})$