Transistor circuits basics

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Introduction

What is a transistor?

A ***transistor*** is a semiconductor device used to amplify or switch electronic signals and electrical power (WikipediA).

The ***transistor*** is the most important example of an “active” component!

Transistors are used in almost every electric circuit you can imagine. For example, you find transistors in switching circuits, amplifier circuits, oscillator circuits, current source circuits, voltage- regulator circuits, power- supply circuits, digital logic ICs, and almost any circuit that uses small control signals to control larger currents.

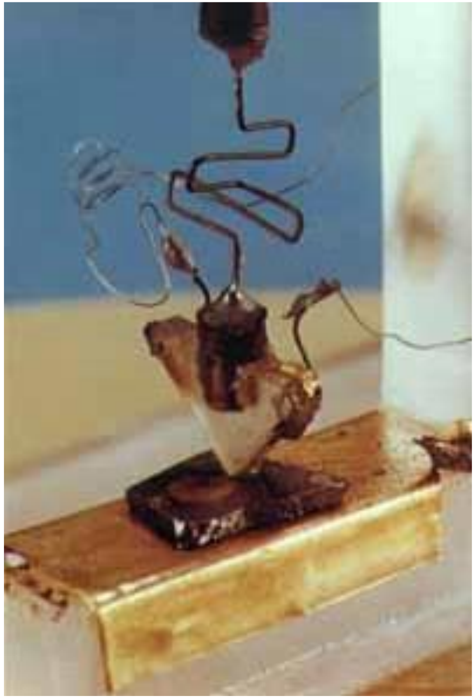
Classification of transistors

Transistors

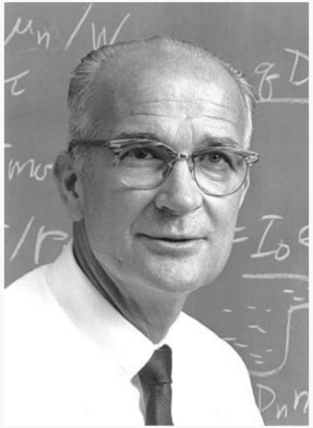
- Bipolar Transistors (BJT)
- Field Effect Transistors FET
- Special type of transistors

Bipolar Transistors

Bipolar Transistors (BJT)



William Shockley



Born	William Bradford Shockley Jr. February 13, 1910 London, England, UK
Died	August 12, 1989 (aged 79) Stanford, California, US
Nationality	American
Alma mater	Caltech (BS, 1932) MIT (PhD, 1936)

Walter Houser Brattain

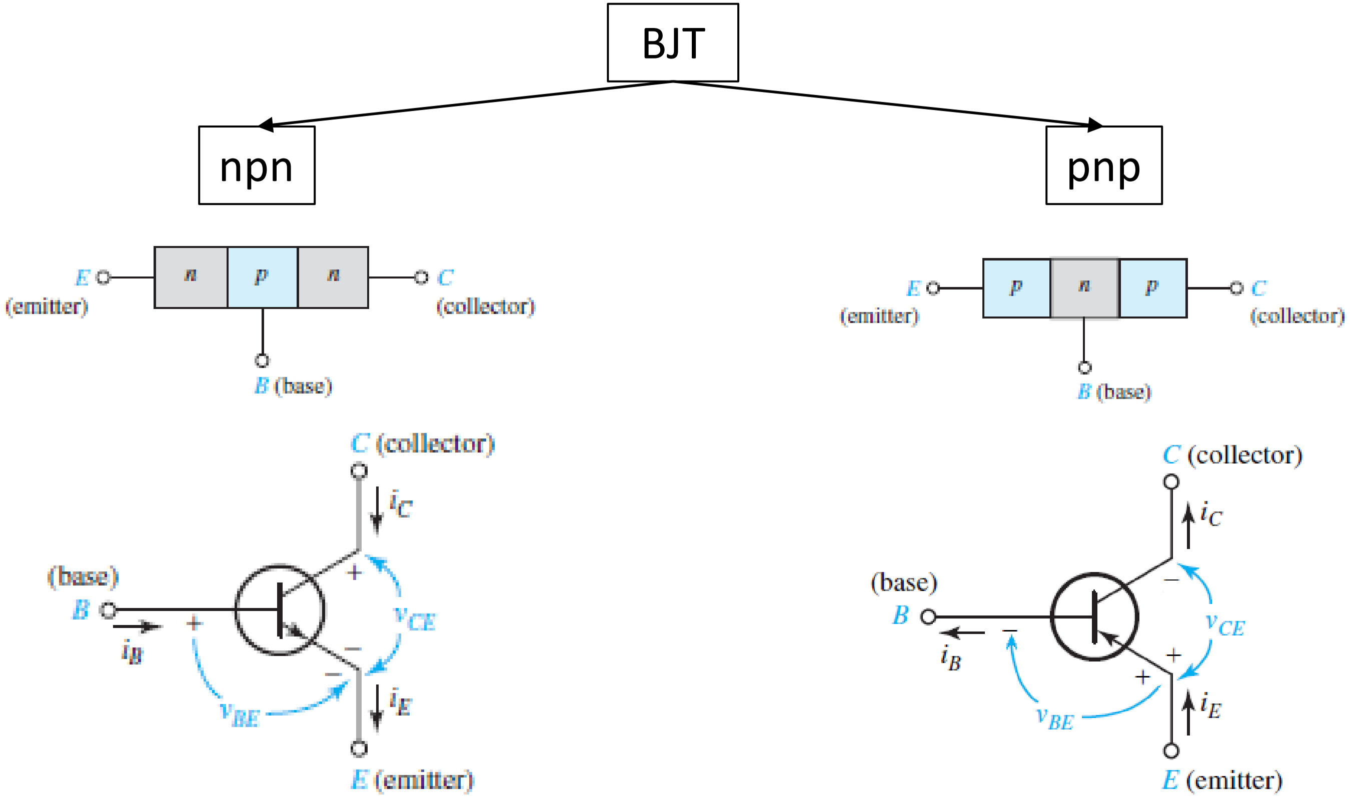
Brattain circa 1950

Born	February 10, 1902 Xiamen, Fujian, China
Died	October 13, 1987 (aged 85) Seattle, Washington, U.S.
Nationality	American
Alma mater	Whitman College University of Oregon University of Minnesota

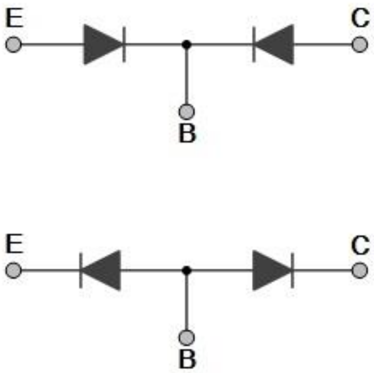
John Bardeen

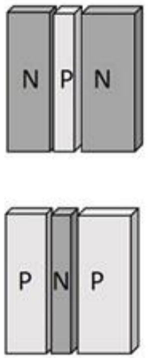
Born	May 23, 1908 Madison, Wisconsin, U.S.
Died	January 30, 1991 (aged 82) Boston, Massachusetts, U.S.
Education	University of Wisconsin (BS, MS) Princeton University (PhD)

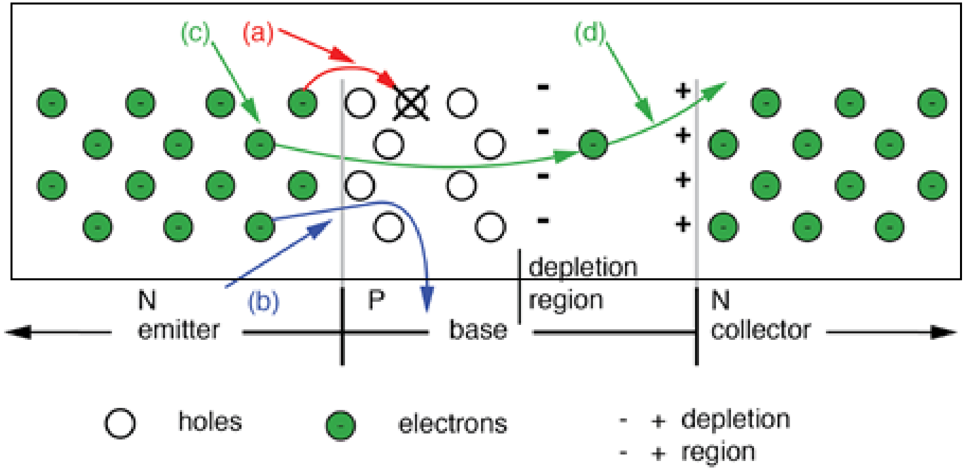
Bipolar Transistors (BJT)



BJT Current Amplification

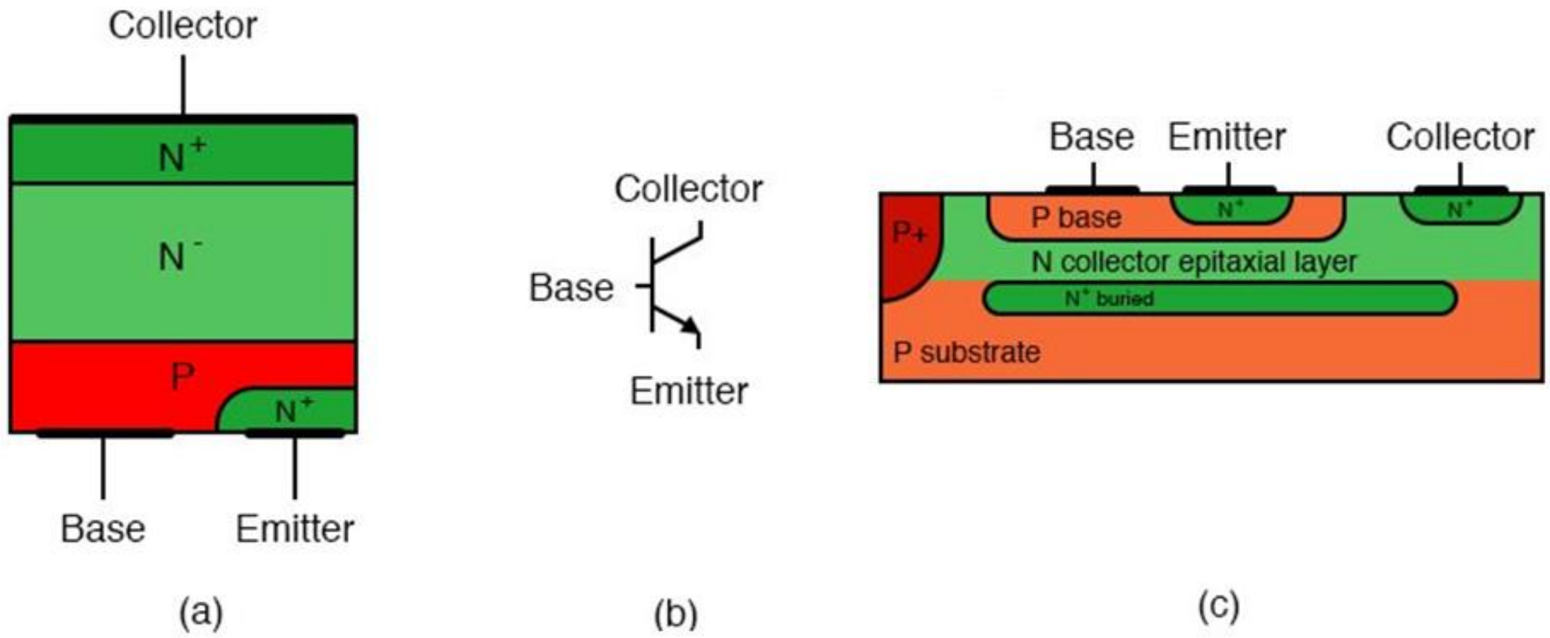




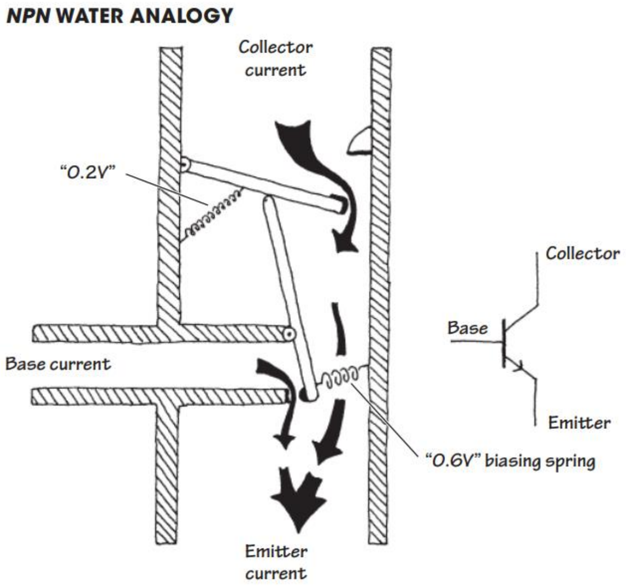


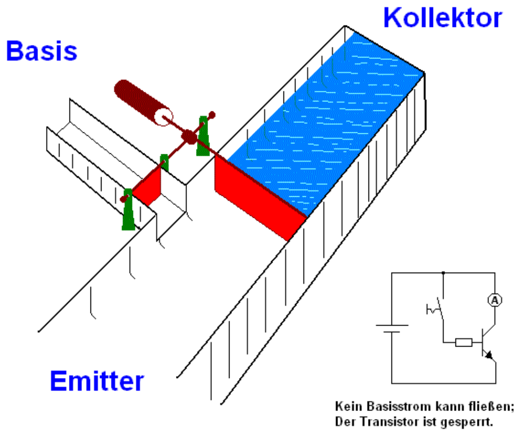
- (a) – recombination of electrons with holes in the p-base
- (b) – emitter current flowing to base
- (c) – the flow of electrons that cross the base
- (d) – the flow of electrons that cross the collector junction

Structure of BT

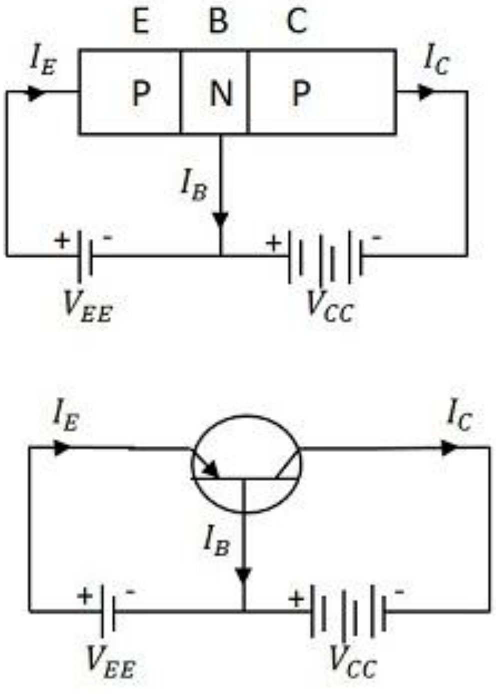


Water analogy bipolar transistors (BJT)

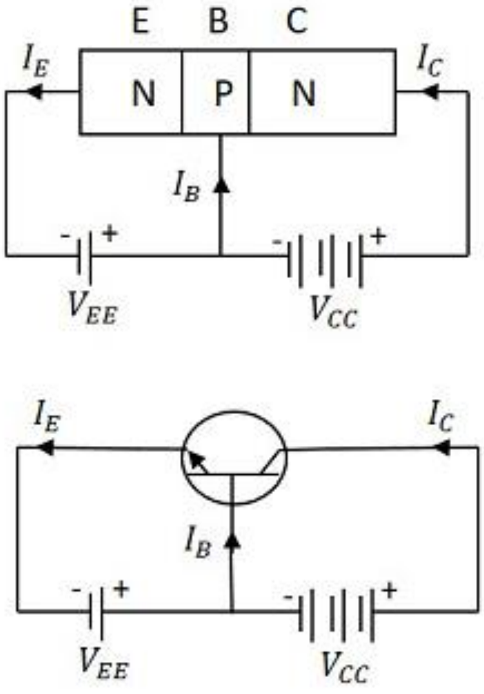




Transistor Biasing

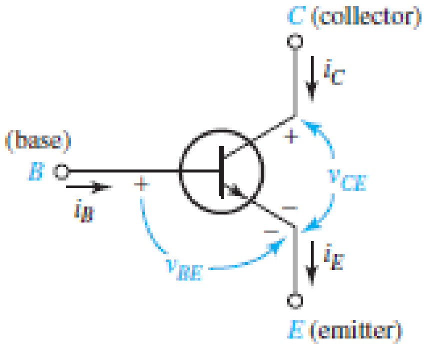


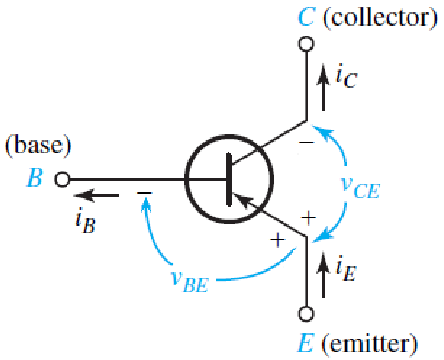
P-N-P Transistor biasing



N-P-N Transistor biasing

Operating modes of BJT

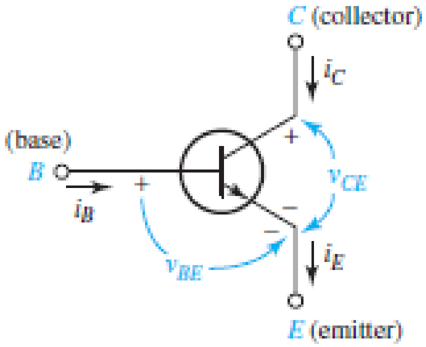




	npn	*pnp*
In the **cutoff mode**		
Emitter junction: *close*	$V_{BE} < 0$	$V_{BE} > 0$
Collector junction: *close*	$V_{BC} < 0$	$V_{BC} > 0$
In the **saturation mode**		
Emitter junction: *open*	$V_{BE} > 0$	$V_{BE} < 0$
Collector junction: *open*	$V_{BC} > 0$	$V_{BC} < 0$
In the **active mode**		
Emitter junction: *open*	$V_{BE} > 0$	$V_{BE} < 0$
Collector junction: *close*	$V_{BC} < 0$	$V_{BC} > 0$

In the **active mode** $i_E = i_B + i_C$

Currents in bipolar transistor



$$i_E = I_{SE} e^{V_{BE}/V_T} = i_C + i_B = \frac{1}{\alpha} i_C + \frac{1}{\alpha} I_{CB0}$$

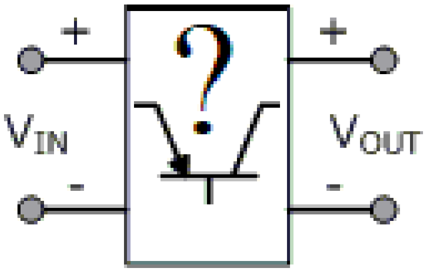
$$i_C = \alpha i_E + I_{CB0}$$

$$i_B = (1-\alpha) i_E - I_{CB0} = \frac{1-\alpha}{\alpha} i_C - \frac{1}{\alpha} I_{CB0}$$

I_{SE} is the reverse saturation current of the emitter junction
I_{CB0} is collector current when emitter is open-circuited or reverse saturation current collector junction
α is the fraction of i_E that contributes to the collector current, ranging from about 0.9 to 0.998.
α is common-base current gain.

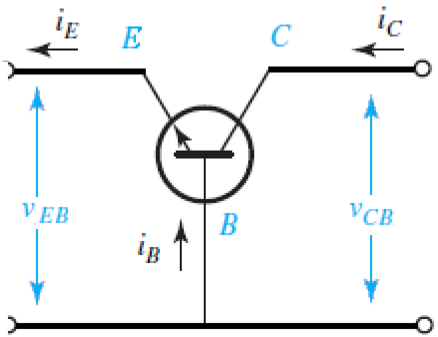
common-emitter current gain: $$\beta = \frac{\alpha}{1-\alpha}$$

Transistor switching circuit



Two-Port Model

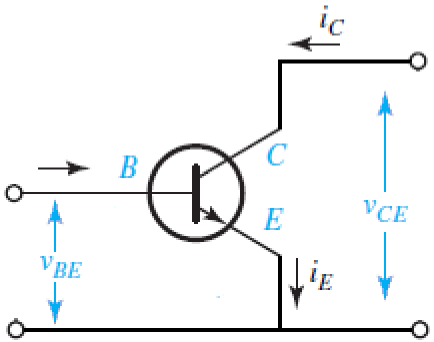
Common Base



Input: i_E, U_{EB}

Output: i_C, U_{CB}

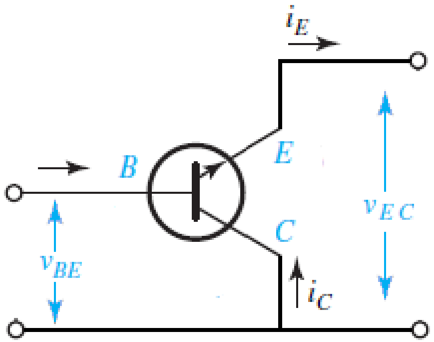
Common Emitter



Input: i_B, U_{BE}

Output: i_C, U_{CE}

Common Collector



Input: i_B, U_{BE}

Output: i_E, U_{EC}

Transistor switching circuit parameters

Characteristic	Common Base	Common Emitter	Common Collector
Input Impedance	Low	Medium	High
Output Impedance	Very High	High	Low
Phase Shift	0º	180º	0º
Voltage Gain	High	Medium	Low (~1)
Current Gain	Low (~1)	High (>>1)	High (>>1)
Power Gain	Low	Very High	Medium
Bandwidth	High	Medium	Medium

$$K_I = {I_{OUT}}/{I_{IN}}$$

$$K_U = {U_{OUT}}/{U_{IN}}$$

$$K_P = K_U * K_I$$

$$R_{IN} = {U_{IN}}/{I_{IN}}$$

$$R_{OUT} = {U_{OUT}}/{I_{OUT}}$$

Models

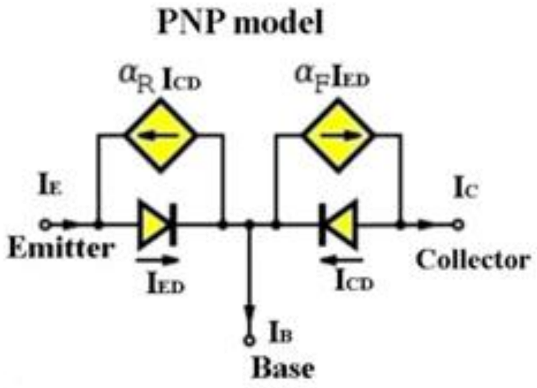
Large-signal models

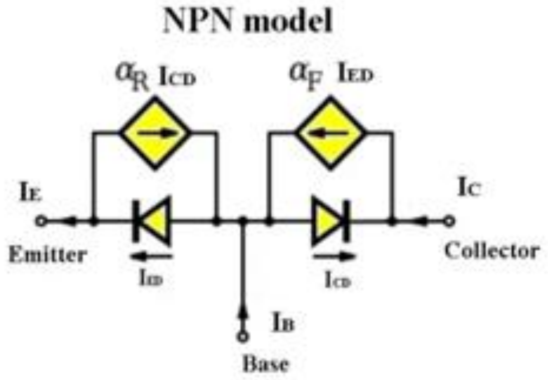
– Ebbers–Moll model: Voltage & current control model
– Gummel–Poon model : charge-control model

Small-signal models

– Hybrid (h) Parameter Model
– Hybrid-pi mode

Ebbers–Moll model

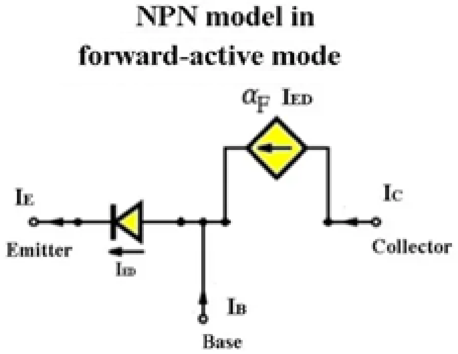




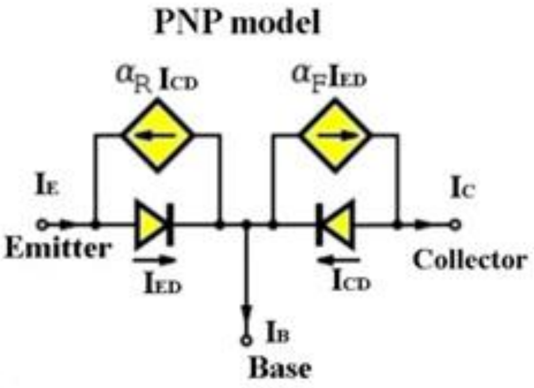
$$I_E = I_{ED} - \alpha_R I_{CD} = I_{E0}\left(e^{U_{EB}/U_T} - 1\right) - \alpha_R I_{C0}\left(e^{U_{CB}/U_T} - 1\right)$$

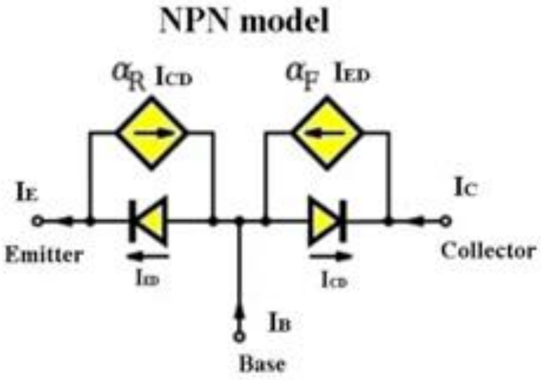
$$I_C = -\alpha_F I_{ED} + I_{CD} = -\alpha_F I_{E0}\left(e^{U_{EB}/U_T} - 1\right) + I_{C0}\left(e^{U_{CB}/U_T} - 1\right)$$

$$I_B = I_E - I_C$$



Ebbers–Moll model





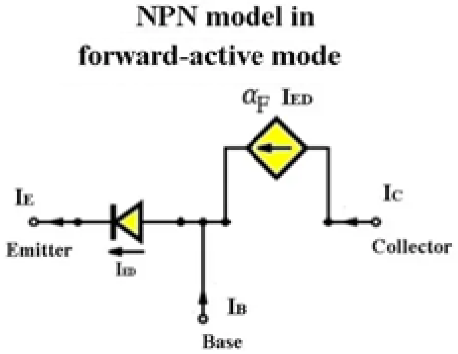
The Ebbers – Moll model is valid:

(a) Only in active mode
(b) Only in active and saturation modes
(c) Only in active and Cut – off modes
(d) In active, saturation and cut – off modes

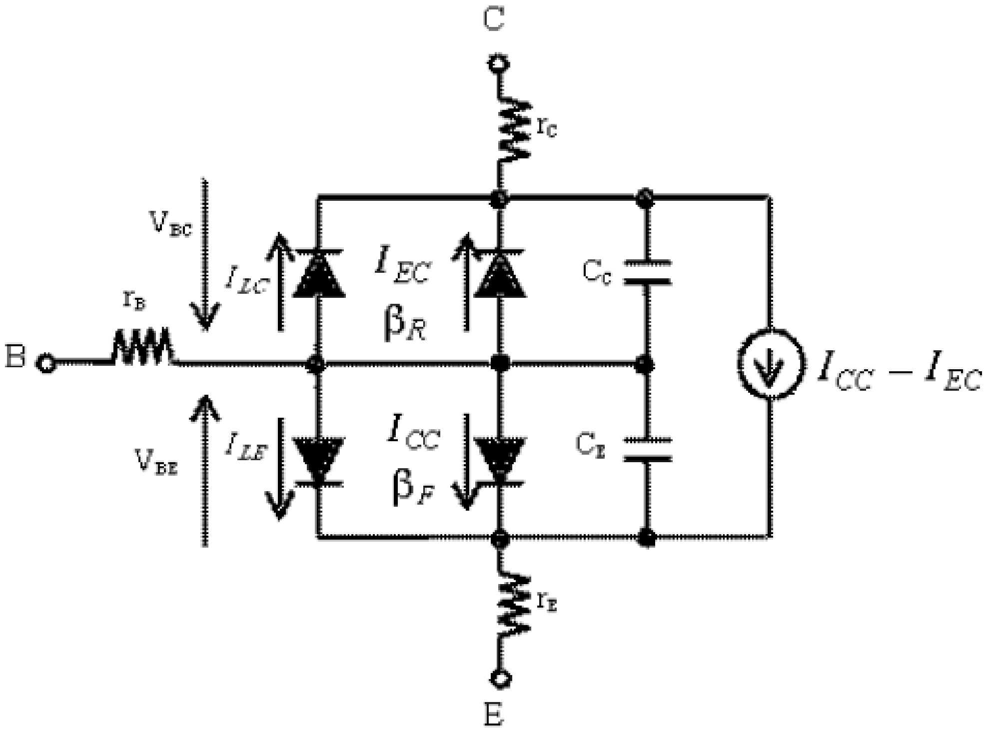
$$I_E = I_{ED} - \alpha_R I_{CD} = I_{E0}\left(e^{U_{EB}/U_T} - 1\right) - \alpha_R I_{C0}\left(e^{U_{CB}/U_T} - 1\right)$$

$$I_C = -\alpha_F I_{ED} + I_{CD} = -\alpha_F I_{E0}\left(e^{U_{EB}/U_T} - 1\right) + I_{C0}\left(e^{U_{CB}/U_T} - 1\right)$$

$$I_B = I_E - I_C$$



Gummel–Poon model



The Gummel-Poon model accounts for the following effects:

(1) Low-current drop in transistor beta or hfe due to recombination of carriers in the BE junction
(2) Complete description of base-width modulation (also known as Early effect)
(3) High-level injection during device saturation
(4) Leakage current in BE and BC junction.

- From F. Kung and H. T. Chuah, "Modeling of Bipolar Junction Transistor in FDTD Simulation of Printed Circuit Board," Progress In Electromagnetics Research, Vol. 36, 179-192, 2002.
- doi:10.2528/PIER02013001

Gummel–Poon model

$$I_{CC} = \frac{I_{ss}}{q_b}\left(\exp\left(\frac{V_{BE}}{V_{TE}}\right)-1\right), \quad V_{TE} = n_F\frac{kT}{q} \tag{1a}$$

$$I_{EC} = \frac{I_{ss}}{q_b}\left(\exp\left(\frac{V_{BC}}{V_{TC}}\right)-1\right), \quad V_{TC} = n_R\frac{kT}{q} \tag{1b}$$

$$I_{LE} = I_{SE}\left(\exp\left(\frac{V_{BE}}{V_{TEL}}\right)-1\right), \quad V_{TEL} = n_E\frac{kT}{q} \tag{1c}$$

$$I_{LC} = I_{SC}\left(\exp\left(\frac{V_{BC}}{V_{TCL}}\right)-1\right), \quad V_{TCL} = n_C\frac{kT}{q} \tag{1d}$$

$$q_b = \frac{q_1}{2} + \sqrt{\left(\frac{q_1}{2}\right)^2 + q_2} \tag{1e}$$

$$q_1 = 1 + \frac{V_{BE}}{V_B} + \frac{V_{BC}}{V_A} \tag{1f}$$

$$q_2 = \frac{I_{SS}}{I_{KF}}\left(\exp\left(\frac{V_{BE}}{V_{TE}}\right)-1\right) + \frac{I_{SS}}{I_{KR}}\left(\exp\left(\frac{V_{BC}}{V_{TC}}\right)-1\right) \tag{1g}$$

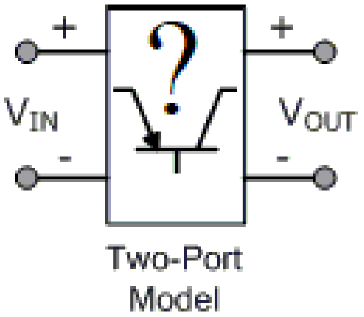
$$C_E(V_{BE}) = \begin{cases} \tau_F\dfrac{\partial I_{CC}}{\partial V_{BE}} + C_{JE}\left(1-\dfrac{V_{BE}}{V_{JE}}\right)^{-m_E}, & V_{BE} < (FC\cdot V_{JE}) \\ \tau_F\dfrac{\partial I_{CC}}{\partial V_{BE}} + \dfrac{C_{JE}}{F_{2E}}\left(F_{3E}+\dfrac{m_E V_{BE}}{V_{JE}}\right), & V_{BE} \geq (FC\cdot V_{JE}) \end{cases} \tag{2a}$$

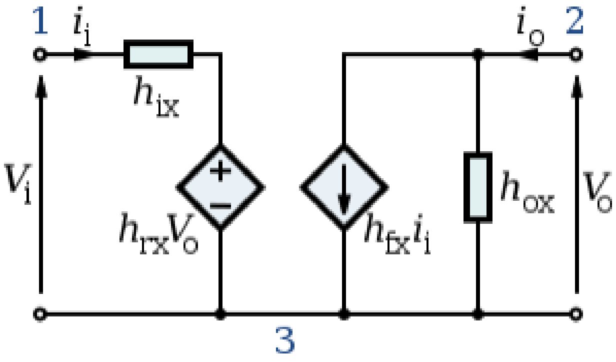
$$F_{2E} = (1-FC)^{1+m_E}, \quad F_{3E} = 1 - FC\cdot(1+m_E) \tag{2b}$$

$$C_C(V_{BC}) = \begin{cases} \tau_R\dfrac{\partial I_{EC}}{\partial V_{BC}} + C_{JC}\left(1-\dfrac{V_{BC}}{V_{JC}}\right)^{-m_C}, & V_{BC} < (FC\cdot V_{JC}) \\ \tau_R\dfrac{\partial I_{EC}}{\partial V_{BC}} + \dfrac{C_{JC}}{F_{2C}}\left(F_{3C}+\dfrac{m_C V_{BC}}{V_{JC}}\right), & V_{BC} \geq (FC\cdot V_{JC}) \end{cases} \tag{2c}$$

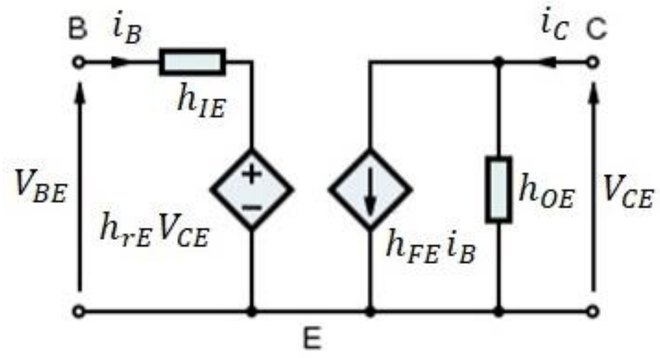
$$F_{2C} = (1-FC)^{1+m_C}, \quad F_{3C} = 1 - FC\cdot(1+m_C) \tag{2d}$$

Hybrid parameter model of BJT





For common emitter topology



$$V_{BE} = h_{IE}i_B + h_{rE}V_{CE}$$
$$i_C = h_{FE}i_B + h_{OE}V_{CE}$$
$$V_{BE} = h_{11}i_B + h_{12}V_{CE}$$
$$i_C = h_{21}i_B + h_{22}V_{CE}$$

$$\begin{bmatrix} V_{BE} \\ i_C \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} i_B \\ V_{CE} \end{bmatrix}$$

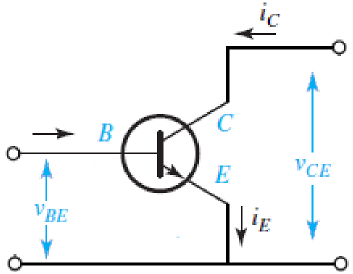
h-parameters can be given by:

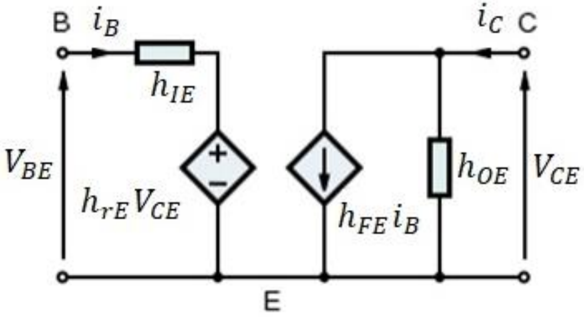
- h_{ie} - The input impedance of transistor (corresponding to the emitter resistance r_e).
- h_{re} - Represents dependence of transistor's I_B-V_{BE} curve on value of V_{CE}. It is very small usually and is often neglected (assumed to be zero).
- h_{fe} - The current-gain of transistor. This parameter is specified as h_{FE} or the DC current-gain (β_{DC}) in datasheets.
- h_{oe} - The output impedance of transistor. This term is usually specified as an admittance and has to be inverted to convert it to the impedance.

h-parameters of Bipolar Junction Transistor

Common Base	Common Emitter	Common Collector	Definitions
$h_{iB} = \frac{V_{EB}}{i_E}$	$h_{iE} = \frac{V_{BE}}{i_B}$	$h_{iC} = \frac{V_{BC}}{i_B}$	Input Impedance with Output Short Circuit
$h_{rB} = \frac{V_{EB}}{V_{CB}}$	$h_{rE} = \frac{V_{BE}}{V_{CE}}$	$h_{RC} = \frac{V_{BC}}{V_{EC}}$	Reverse Voltage Ratio Input Open Circuit
$h_{FB} = \frac{i_C}{i_E}$	$h_{FE} = \frac{i_C}{i_B}$	$h_{FC} = \frac{i_E}{i_B}$	Forward Current Gain Output Short Circuit
$h_{OB} = \frac{i_C}{V_{CB}}$	$h_{OE} = \frac{i_C}{V_{CE}}$	$h_{OC} = \frac{i_C}{V_{EC}}$	Output Admittance Input Open Circuit

For common emitter topology





Input characteristic: $I_B = f(V_{BE})|U_{CE} = const$

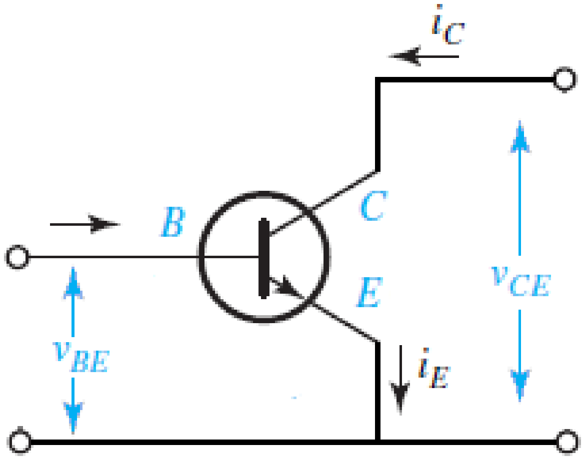
Forward current gain characteristic: $I_C = f(I_B)|U_{CE} = const$

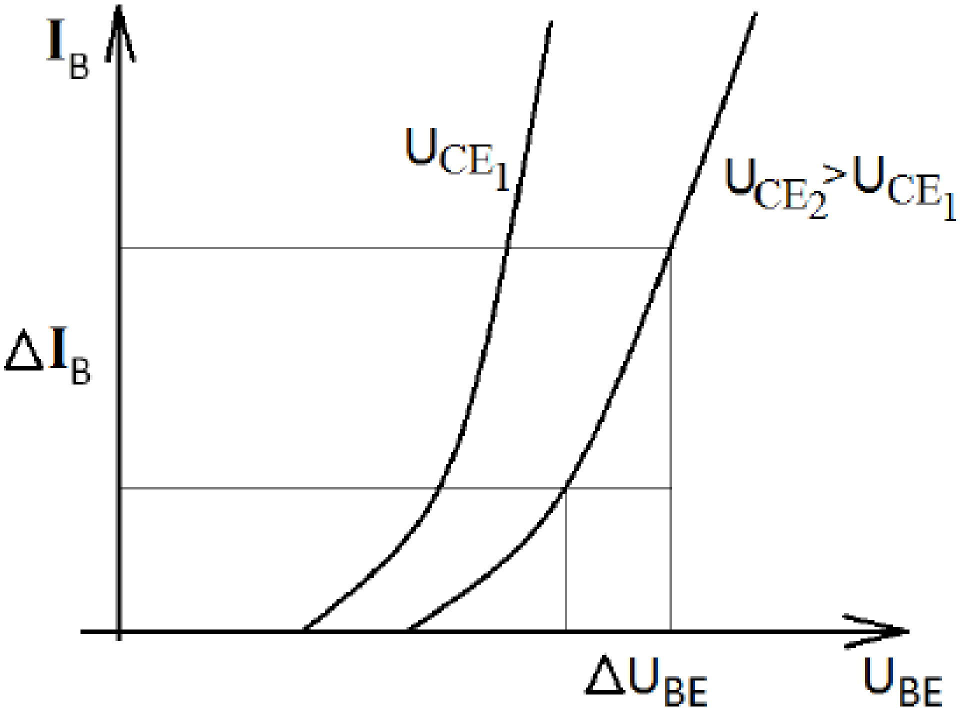
Reverse voltage gain characteristic: $V_{BE} = f(U_{CE})|I_B = const$

Output characteristic: $I_C = f(U_{CE})|I_B = const$

Input characteristic common emitter

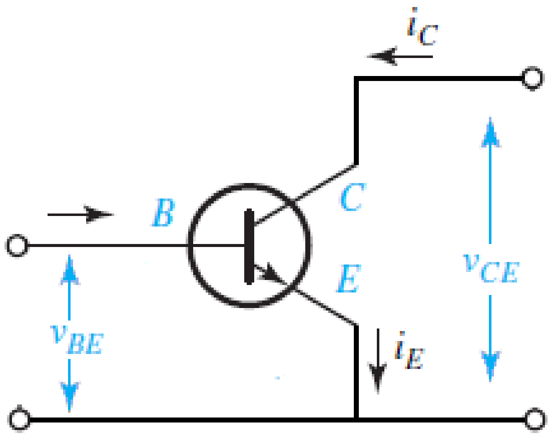
$$I_B = f(V_{BE})|U_{CE} = const$$

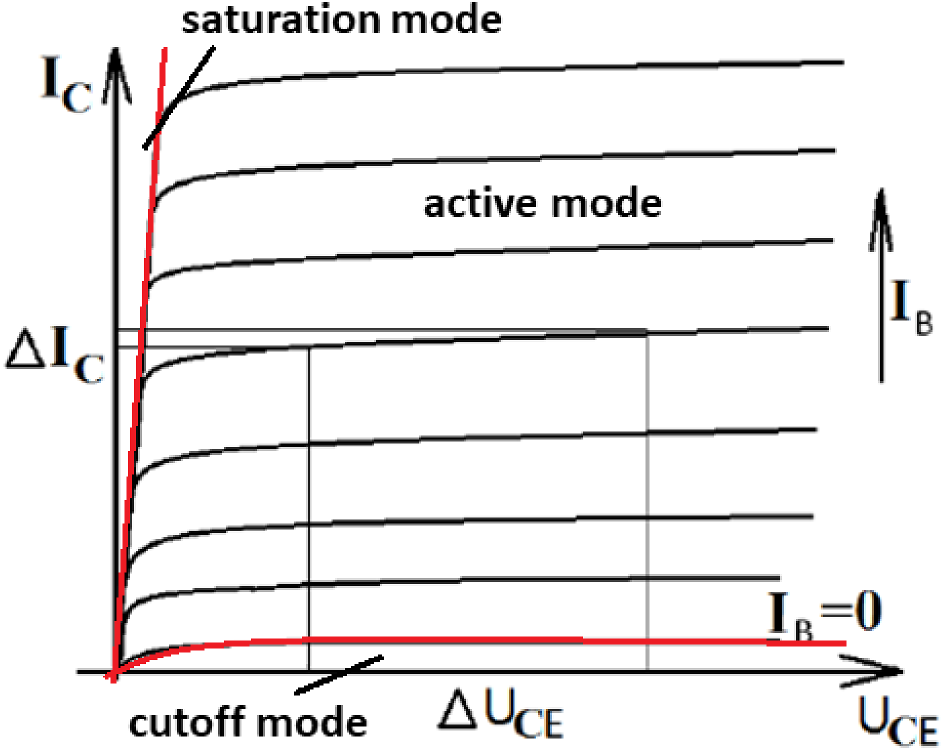




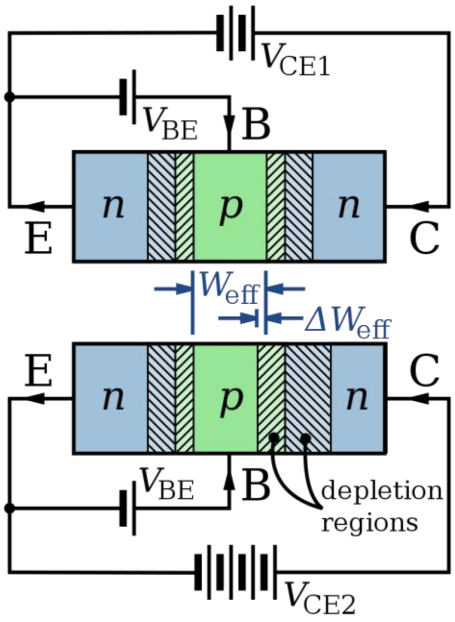
Output characteristic common emitter

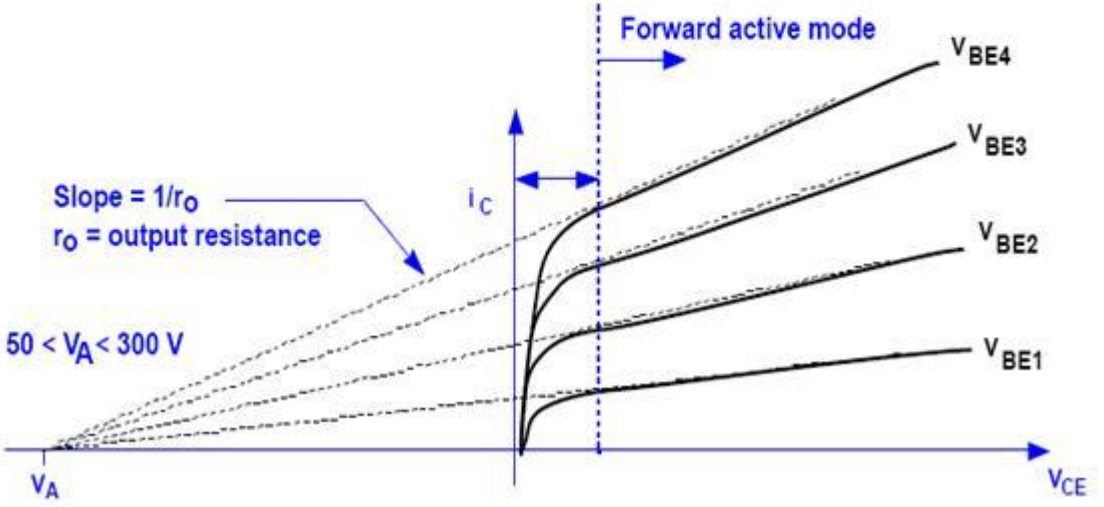
$$I_C = f(U_{CE})|I_B = const$$





"Earley Effect"

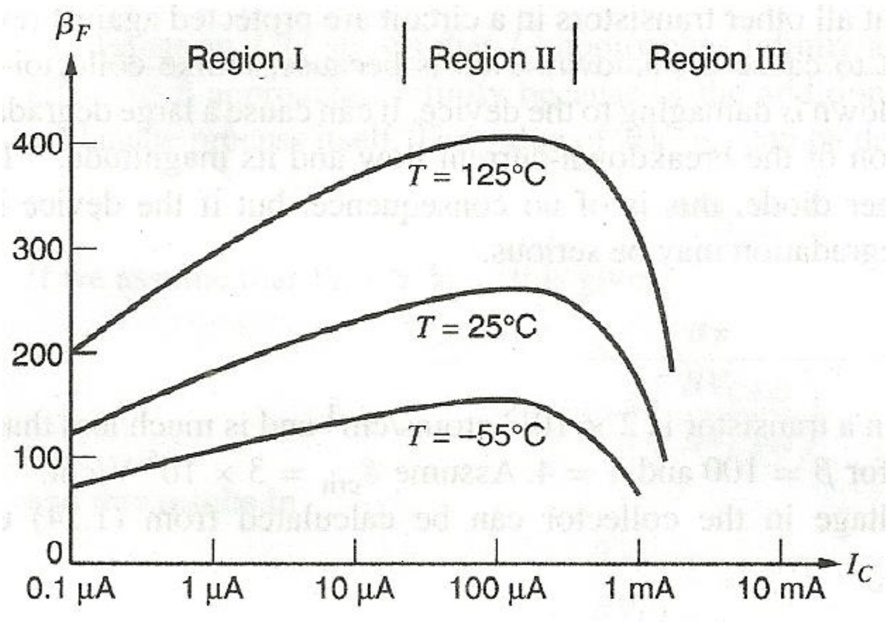




$$r_o \approx \frac{V_A}{I_C}$$

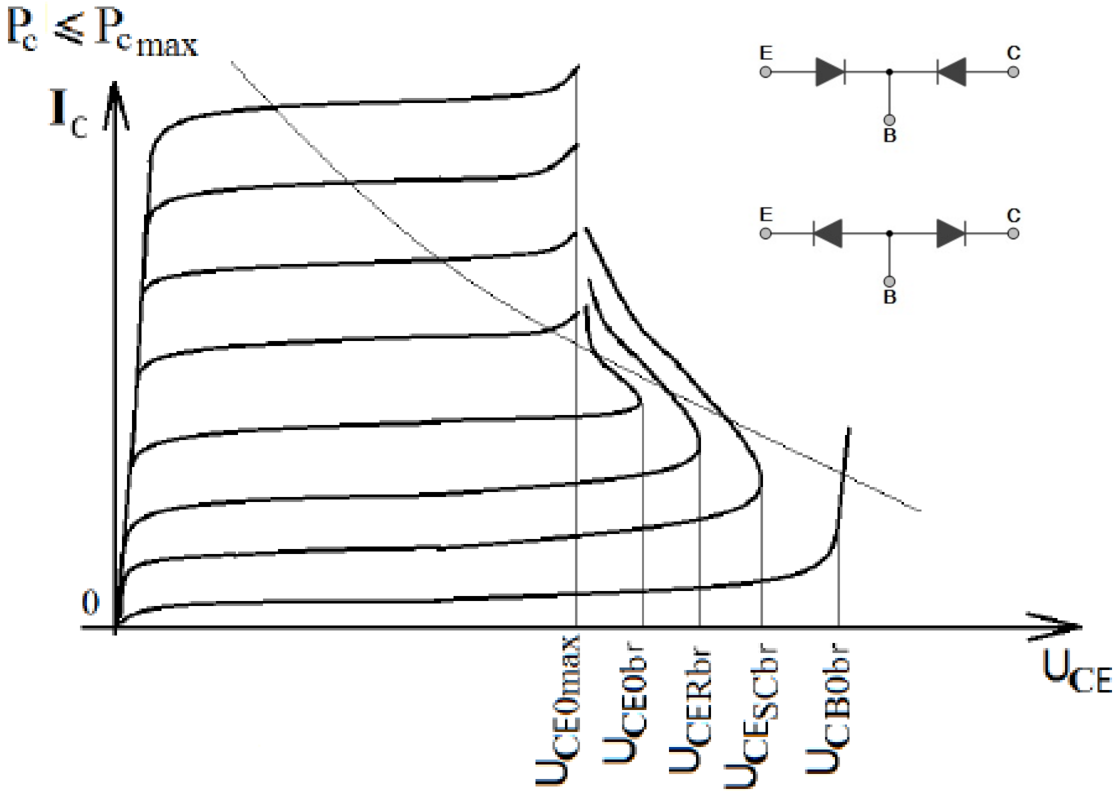
Top: NPN base width for low collector–base reverse bias;
Bottom: narrower NPN base width for large collector–base reverse bias.
Hashed areas are depleted regions.

Current transfer ratio



- Region 1 is the low-current region, where β decreases as Ic decreases,
- Region 2 is the midcurrent region, where β is approximately constant,
- Region 3 is the high-current region, where β decreases as Ic increases.

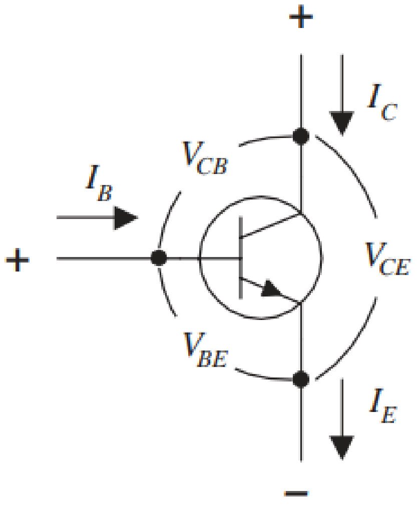
Breakdown of the transistor

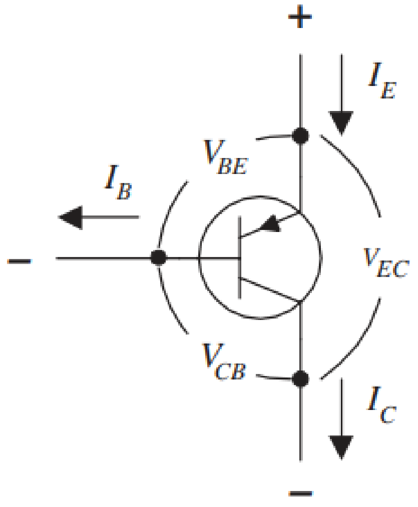


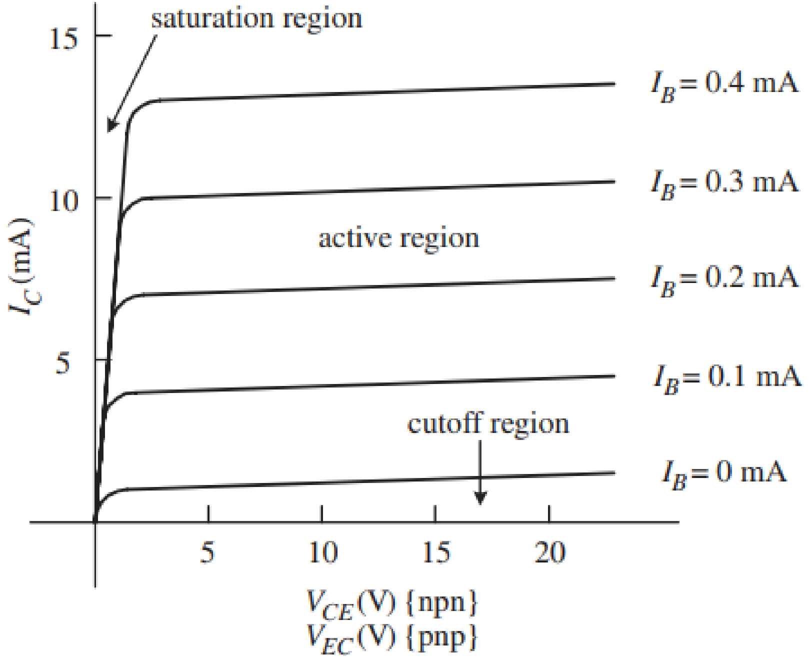
- V_{CBO}, indicates the maximum allowable collector-to-base voltage with the emitter open. The second voltage
- V_{CEO}, is the maximum allowable collector-emitter voltage with the base open.
- The voltage rating, V_{EBO}, is the maximum allowable emitter-base voltage with the collector open.

BJT tasks examples

Main important information for schemes analyze







$$I_C = h_{FE} I_B = \beta I_B$$

IMPORTANT RULES

1. For an *npn* transistor, the voltage at the collector *VC* must be greater than the voltage at the emitter *VE* by at least a few tenths of a volt

2. For an *npn* transistor, there is a voltage drop from the base to the emitter of 0.6 V. For a *pnp* transistor, there is a 0.6- V rise from base to emitter.

BJT tasks examples

Consider the collector current equality

$$I_C = h_{FE} I_B = \beta I_B$$

The h_{FE} of a transistor is often taken to be a constant, typically around 10 to 500, but it may change slightly with temperature and with changes in collector- to-emitter voltage.

For emitter current we have $$I_E = I_C + I_B$$

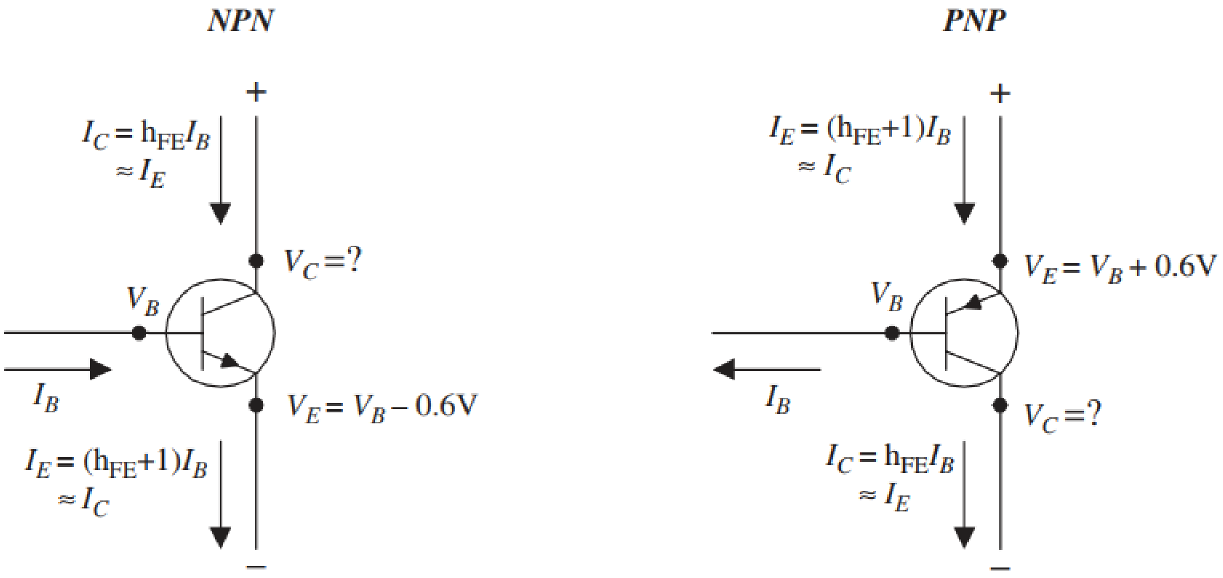
If you combine this equation with the current- gain equation,

$$I_E = (h_{FE} + 1) I_B$$

Such as $h_{FE} \gg 1$ we can use equality

$$I_E \approx I_C$$

All basics equations you can find in this picture



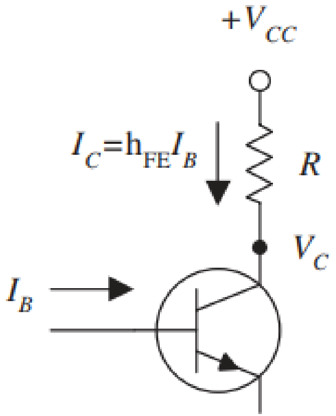
BJT tasks examples

For base-emitter voltage we have

$$V_{BE} = V_B - V_E = +0.6 \text{ V } (npn)$$
$$V_{BE} = V_B - V_E = -0.6 \text{ V } (pnp)$$

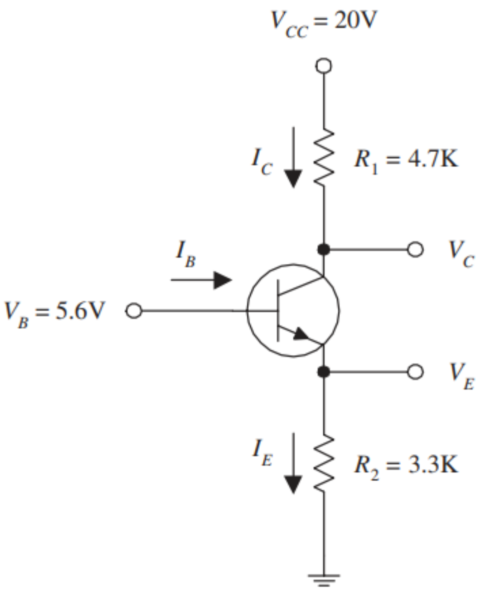
Previous slide shows how all the terminal currents and voltages are related.

The value of collector voltage V_C depends on the network that is connected to it



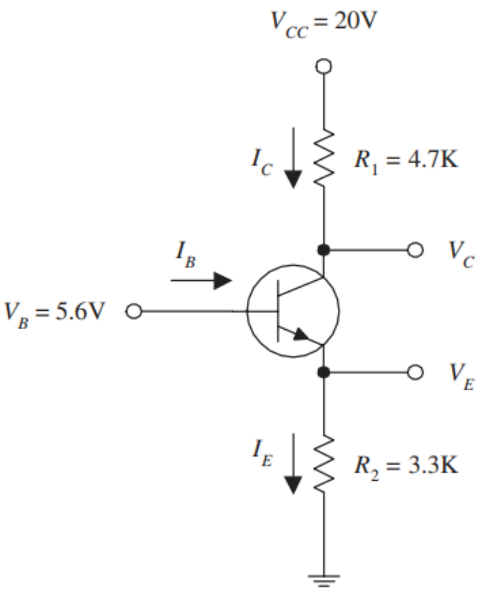
$$V_C = V_{CC} - I_C R$$
$$V_C = V_{CC} - (h_{FE} I_B) R$$

EXAMPLE 1 Given $V_{CC} = +20$ V, $V_B = 5.6$ V, $R_1 = 4.7$ kΩ, $R_2 = 3.3$ kΩ, and $h_{FE} = 100$, find V_E, I_E, I_B, I_C, and V_C.



What should we do?

EXAMPLE 1 Given $V_{CC} = +20$ V, $V_B = 5.6$ V, $R_1 = 4.7$ kΩ, $R_2 = 3.3$ kΩ, and $h_{FE} = 100$, find V_E, I_E, I_B, I_C, and V_C.



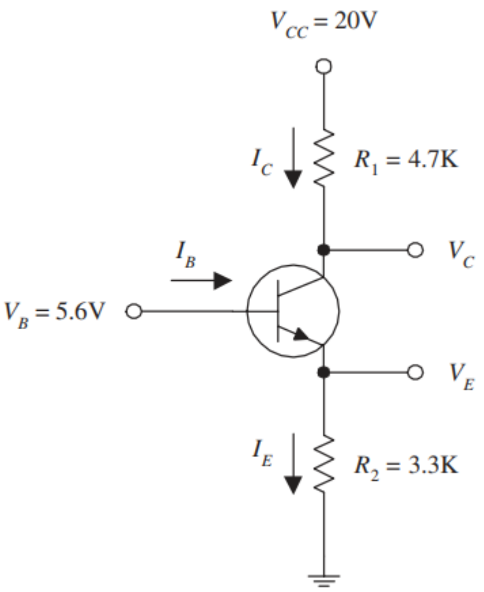
What should we do?

Step 1.

$$V_E = V_B - 0.6\text{ V}$$

$$V_E = 5.6\text{ V} - 0.6\text{ V} = 5.0\text{ V}$$

EXAMPLE 1 Given $V_{CC} = +20$ V, $V_B = 5.6$ V, $R_1 = 4.7$ kΩ, $R_2 = 3.3$ kΩ, and $h_{FE} = 100$, find V_E, I_E, I_B, I_C, and V_C.



What should we do?

Step 1.

$$V_E = V_B - 0.6 \text{ V}$$

$$V_E = 5.6 \text{ V} - 0.6 \text{ V} = 5.0 \text{ V}$$

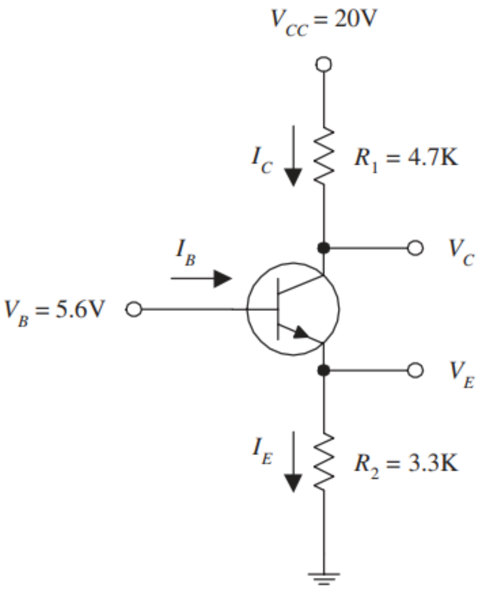
Step 2.

$$I_E = \frac{V_E - 0 \text{ V}}{R_2} = \frac{5.0 \text{ V}}{3300 \ \Omega} = 1.5 \text{ mA}$$

$$I_B = \frac{I_E}{(1 + h_{FE})} = \frac{1.5 \text{ mA}}{(1 + 100)} = 0.015 \text{ mA}$$

$$I_C = I_E - I_B \approx I_E = 1.5 \text{ mA}$$

EXAMPLE 1 Given $V_{CC} = +20$ V, $V_B = 5.6$ V, $R_1 = 4.7$ kΩ, $R_2 = 3.3$ kΩ, and $h_{FE} = 100$, find V_E, I_E, I_B, I_C, and V_C.



What should we do?

Step 1.

$$V_E = V_B - 0.6 \text{ V}$$

$$V_E = 5.6 \text{ V} - 0.6 \text{ V} = 5.0 \text{ V}$$

Step 2.

$$I_E = \frac{V_E - 0 \text{ V}}{R_2} = \frac{5.0 \text{ V}}{3300\ \Omega} = 1.5 \text{ mA}$$

$$I_B = \frac{I_E}{(1 + h_{FE})} = \frac{1.5 \text{ mA}}{(1 + 100)} = 0.015 \text{ mA}$$

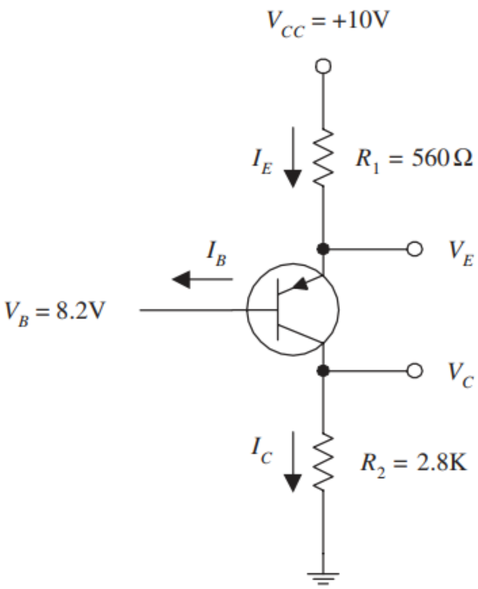
$$I_C = I_E - I_B \approx I_E = 1.5 \text{ mA}$$

Step 3.

$$V_C = V_{CC} - I_C R_1 \qquad V_C = 20 \text{ V} - (1.5 \text{ mA})(4700\ \Omega)$$

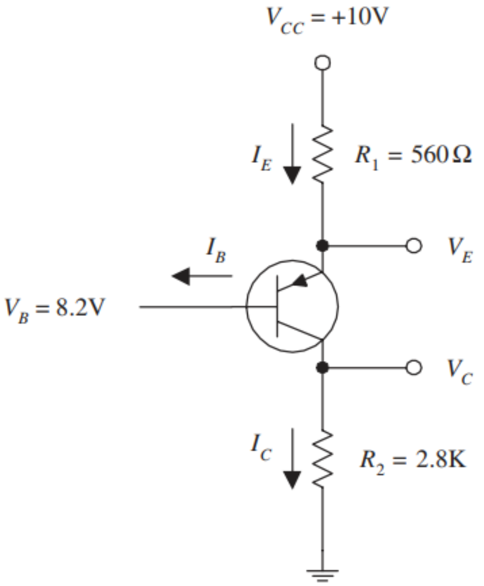
$$V_C = 13 \text{ V}$$

EXAMPLE 2 Given $V_{CC} = +10$ V, $V_B = 8.2$ V, $R_1 = 560\ \Omega$, $R_2 = 2.8\ \text{k}\Omega$, and $h_{FE} = 100$, find V_E, I_E, I_B, I_C, and V_C.



What should we do?

EXAMPLE 2 Given $V_{CC} = +10$ V, $V_B = 8.2$ V, $R_1 = 560\ \Omega$, $R_2 = 2.8\ \text{k}\Omega$, and $h_{FE} = 100$, find V_E, I_E, I_B, I_C, and V_C.



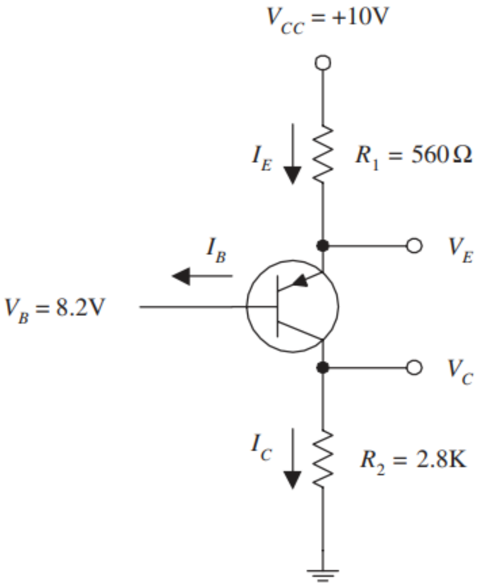
What should we do?

Step 1

$$V_E = V_B + 0.6\ \text{V}$$

$$V_E = 8.2\ \text{V} + 0.6\ \text{V} = 8.8\ \text{V}$$

EXAMPLE 2 Given $V_{CC} = +10$ V, $V_B = 8.2$ V, $R_1 = 560\ \Omega$, $R_2 = 2.8$ kΩ, and $h_{FE} = 100$, find V_E, I_E, I_B, I_C, and V_C.



What should we do?

Step 1

$$V_E = V_B + 0.6\ \text{V}$$

$$V_E = 8.2\ \text{V} + 0.6\ \text{V} = 8.8\ \text{V}$$

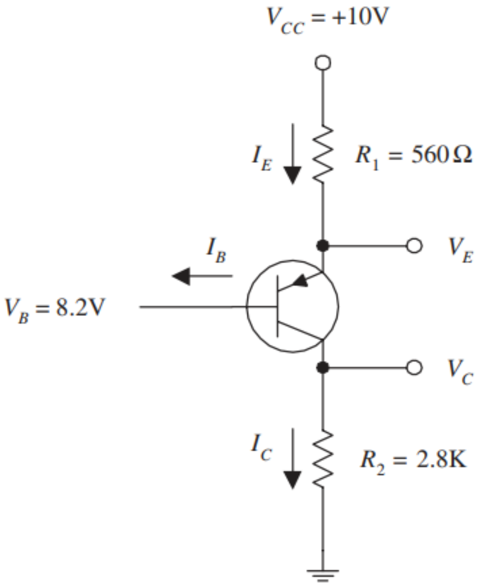
Step 2.

$$I_E = \frac{V_{CC} - V_E}{R_1} = \frac{10\ \text{V} - 8.8\ \text{V}}{560\ \Omega} = 2.1\ \text{mA}$$

$$I_B = \frac{I_E}{(1 + h_{FE})} = \frac{2.1\ \text{mA}}{(1 + 100)} = 0.02\ \text{mA}$$

$$I_C = I_E - I_B \approx I_E = 2.1\ \text{mA}$$

EXAMPLE 2 Given $V_{CC} = +10$ V, $V_B = 8.2$ V, $R_1 = 560\ \Omega$, $R_2 = 2.8$ kΩ, and $h_{FE} = 100$, find V_E, I_E, I_B, I_C, and V_C.



What should we do?

Step 1

$$V_E = V_B + 0.6\text{ V}$$

$$V_E = 8.2\text{ V} + 0.6\text{ V} = 8.8\text{ V}$$

Step 2.

$$I_E = \frac{V_{CC} - V_E}{R_1} = \frac{10\text{ V} - 8.8\text{ V}}{560\ \Omega} = 2.1\text{ mA}$$

$$I_B = \frac{I_E}{(1 + h_{FE})} = \frac{2.1\text{ mA}}{(1 + 100)} = 0.02\text{ mA}$$

$$I_C = I_E - I_B \approx I_E = 2.1\text{ mA}$$

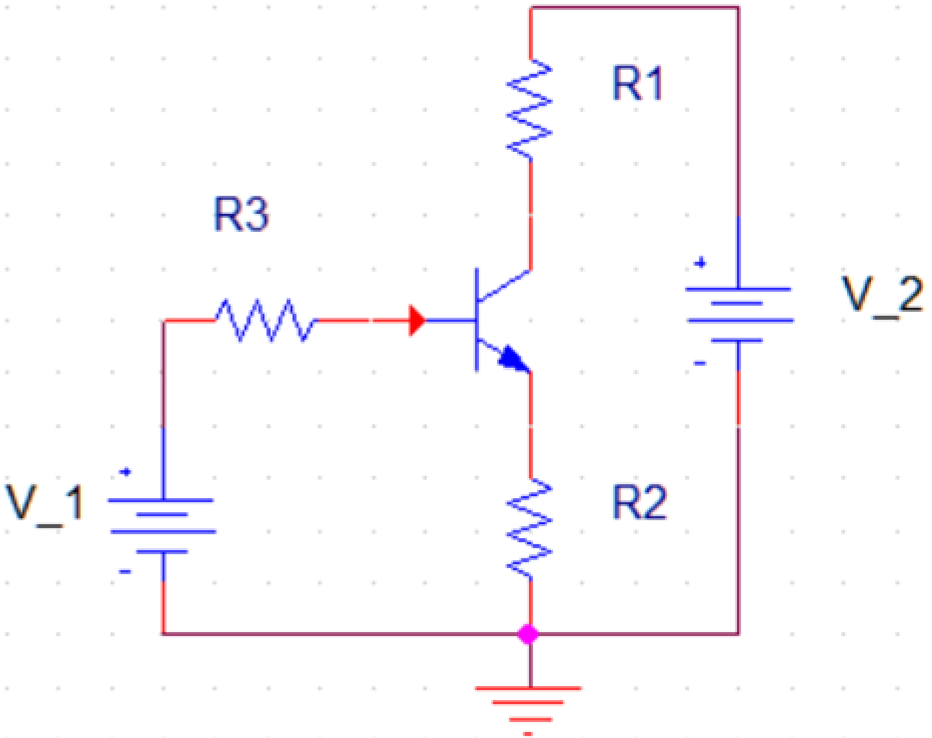
Step 3.

$$V_C = 0\text{ V} + I_C R_2$$

$$V_C = 0\text{ V} + (2.1\text{ mA})(2800\ \Omega)$$

$$V_C = 5.9\text{ V}$$

Task 3: Find voltage drop on R2



Transistor parameters

$$\alpha := 0{,}984$$

$$V_{BE} = 0.7V$$

Element's parameters

$$R1 := 1000\ \Omega$$
$$R2 := 4000\ \Omega$$
$$R3 := 9000\ \Omega$$

DC Sources parameters

$$V\_1 = 7.2V$$

$$V\_2 = 9.1V$$

References

1. Sarma M. S. Introduction to electrical engineering. – New York : Oxford University Press, 2001. – C. 715-716.
2. Paul Scherz, Simon Monk. Practical Electronics for Inventors, Fourth Edition. - McGraw-Hill, Inc., 2016.

Thank you for your attention!