UNIVERSITY *of* DELAWARE

Chapter 6

Bipolar Junction Transistors (BJTs)

IN THIS CHAPTER YOU WILL LEARN

1. The physical structure of the bipolar transistor and how it works.
2. How the voltage between two terminals of the transistor controls the current that flows through the third terminal, and the equations that describe these current-voltage characteristics.
3. How to analyze and design circuits that contain bipolar transistors, resistors, and dc sources.

6.1 DEVICE STRUCTURE AND PHYSICAL OPERATION

The *npn* and *pnp* Transistor

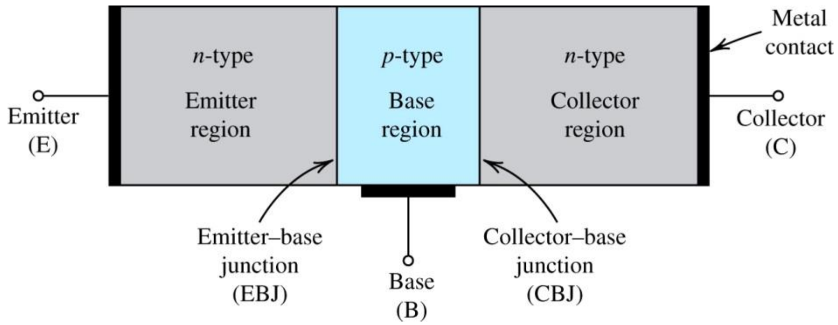


Figure 6.1 A simplified structure of the *npn* transistor.

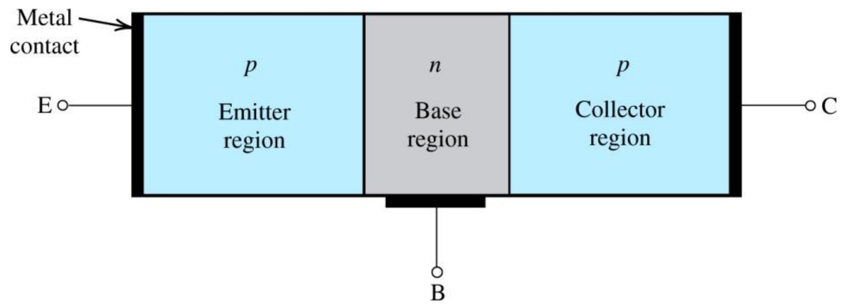
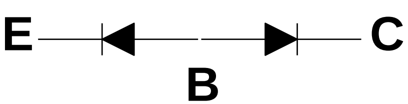
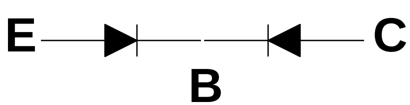


Figure 6.2 A simplified structure of the *pnp* transistor.





The transistor consists of two *pn* junctions, the emitter-base junction (EBJ) and the collector-base junction (CBJ).

Charge carriers of both polarities - that is, electrons and holes - participate in the current-conduction process in a bipolar transistor, which is the reason for the name **bipolar.**

Circuit Symbols for BJTs

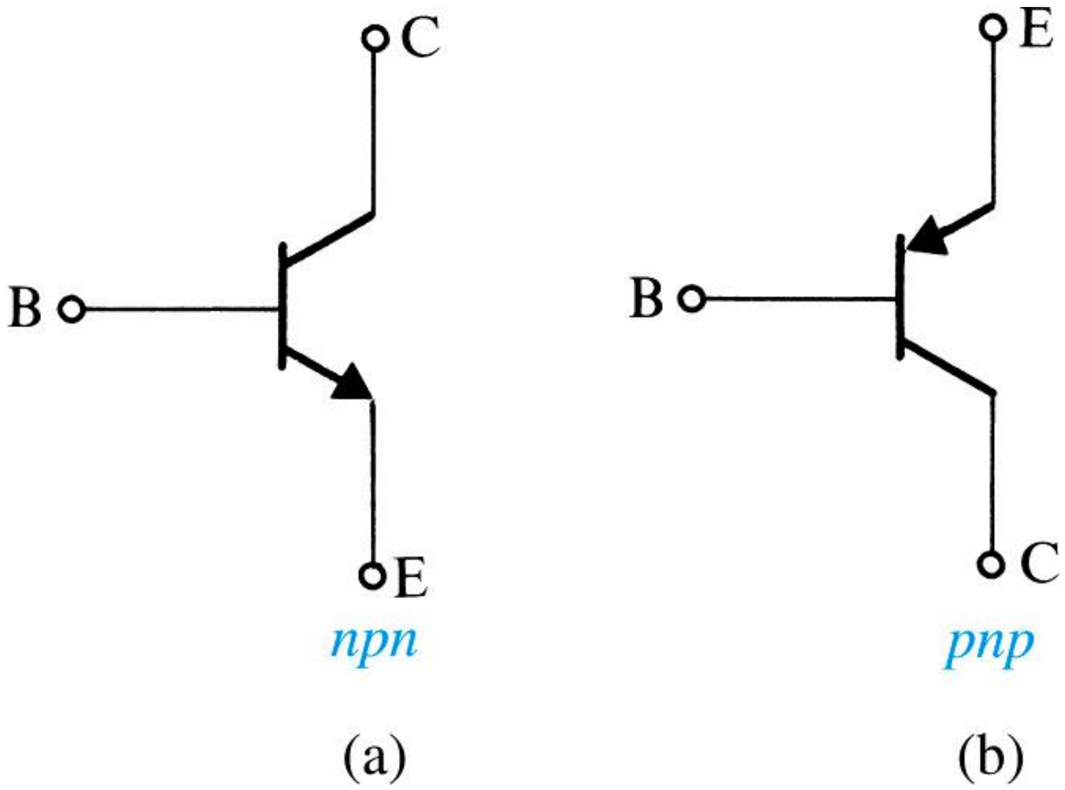


Figure 6.12 Circuit symbols for BJTs.

BJT Modes of Operation

Mode	EBJ	CBJ
Cut-off	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward

Depending on the bias condition (forward or reverse) in each of these junctions, different modes of operation of the BJT are obtained, as shown in the Table above. The active mode is the one used if the transistor is to operate as an amplifier. Switching applications (e.g., logic circuits) utilize both the cutoff mode and the saturation mode. As the name implies, in the cutoff mode no current flows because both junctions are reverse biased.

Operation of the *npn* Transistor in the Active Mode

V_{BE} causes the *p-type* base to be higher in potential than the *n-type* emitter, thus forward-biasing the emitter-base junction. The collector-base voltage V_{CB} causes the *n-type* collector to be at a higher potential than the *p-type* base, thus reverse-biasing the collector-base junction.

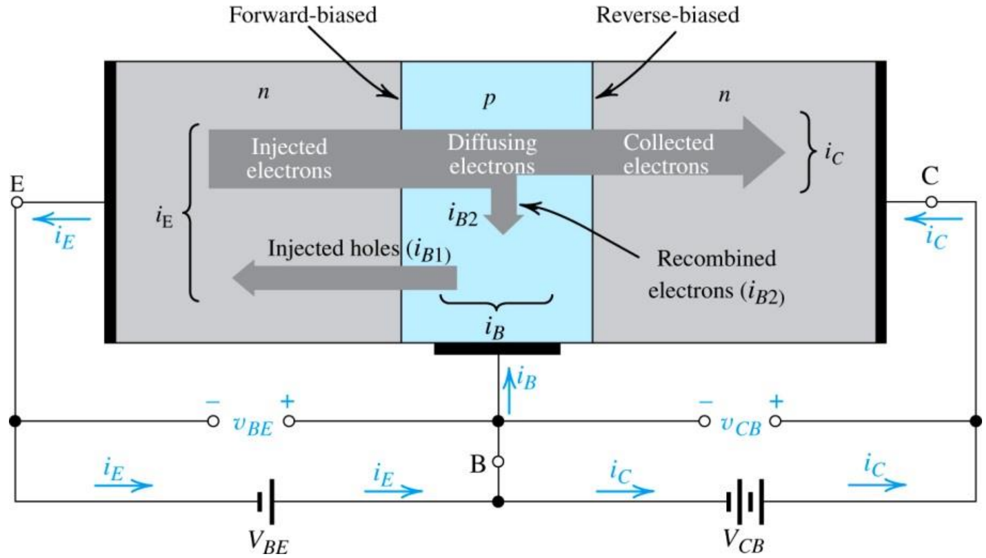


Figure 6.3 Current flow in an *npn* transistor biased to operate in the active mode. (Reverse current components due to drift of thermally generated minority carriers are not shown.)

Minority Carrier Concentrations

$$n_p(0) = n_{p0} e^{v_{BE}/V_T}$$

$$I_n = A_E q D_n \frac{dn_p(x)}{dx} = A_E q D_n \left(-\frac{n_p(0)}{W}\right)$$

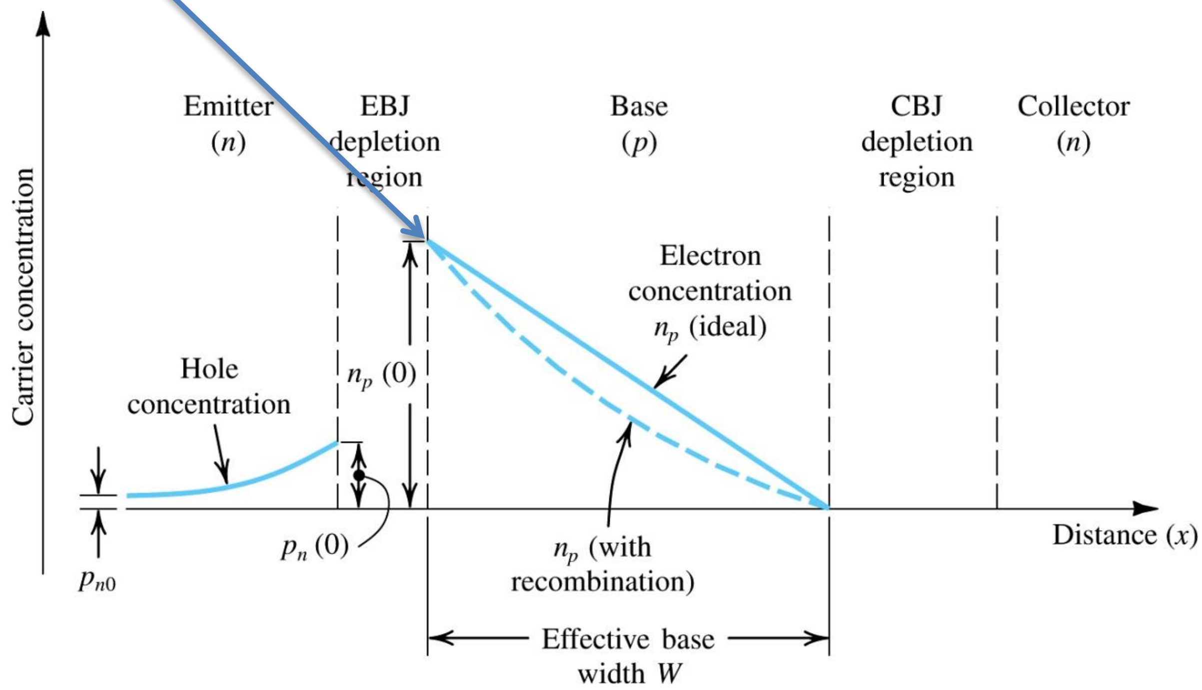


Figure 6.4 Profiles of minority-carrier concentrations in the base and in the emitter of an *npn* transistor operating in the active mode: $v_{BE} > 0$ and $v_{CB} \geq 0$.

The Current-Voltage Relationship of the Junction (Ch 3)

The concentration of holes in the *n* region at the edge of the depletion region will increase considerably. In fact, an important result from device physics shows that the steady-state concentration at the edge of the depletion region will be

$$p_n(x_n) = p_{n0}e^{V/V_T}$$

We describe this situation as follows: The forward-bias voltage *V* results in an excess concentration of minority holes at $x = x_n$, given by

$$\text{Excess concentration at } x = x_n \quad = p_{n0}e^{V/V_T} - p_{n0} = p_{n0}\left(e^{V/V_T} - 1\right)$$

$$p_n(x) = p_{n0} + (\text{excess concentration})e^{-(x-x_n)/L_p}$$

$$p_n(x) = p_{n0} + p_{n0}\left(e^{V/V_T} - 1\right)e^{-(x-x_n)/L_p}$$

L_p is the diffusion length of holes in the *n* material

Active Mode Currents

Emitter current

$$i_E = i_C + i_B$$

$$i_E = \frac{\beta + 1}{\beta} i_C$$

$$i_E = \frac{\beta + 1}{\beta} I_S e^{v_{BE}/V_T}$$

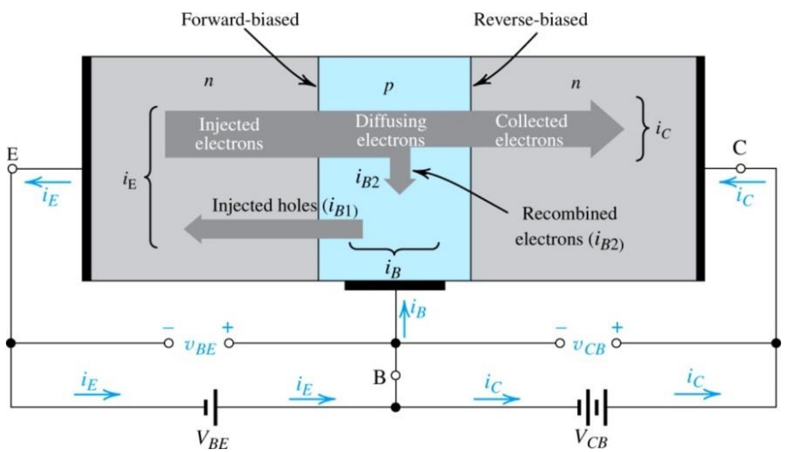


Figure 6.3 Current flow in an *npn* transistor biased to operate in the active mode. (Reverse current components due to drift of thermally generated minority carriers are not shown.)

Collector current

$$i_C = I_n = I_S e^{v_{BE}/V_T}$$

$$I_S = A_E q D_n n_{p0}/W$$

$$I_S = \frac{A_E q D_n {n_i}^2}{N_A W}$$

$$i_C = \alpha i_E$$

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

α is the **common-base current gain**

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

Base current

$$i_B = \frac{i_C}{\beta}$$

$$i_B = \left(\frac{I_S}{\beta}\right) e^{v_{BE}/V_T}$$

β is the **common-emitter current gain**

Large Signal *npn* Equivalent Circuit Models

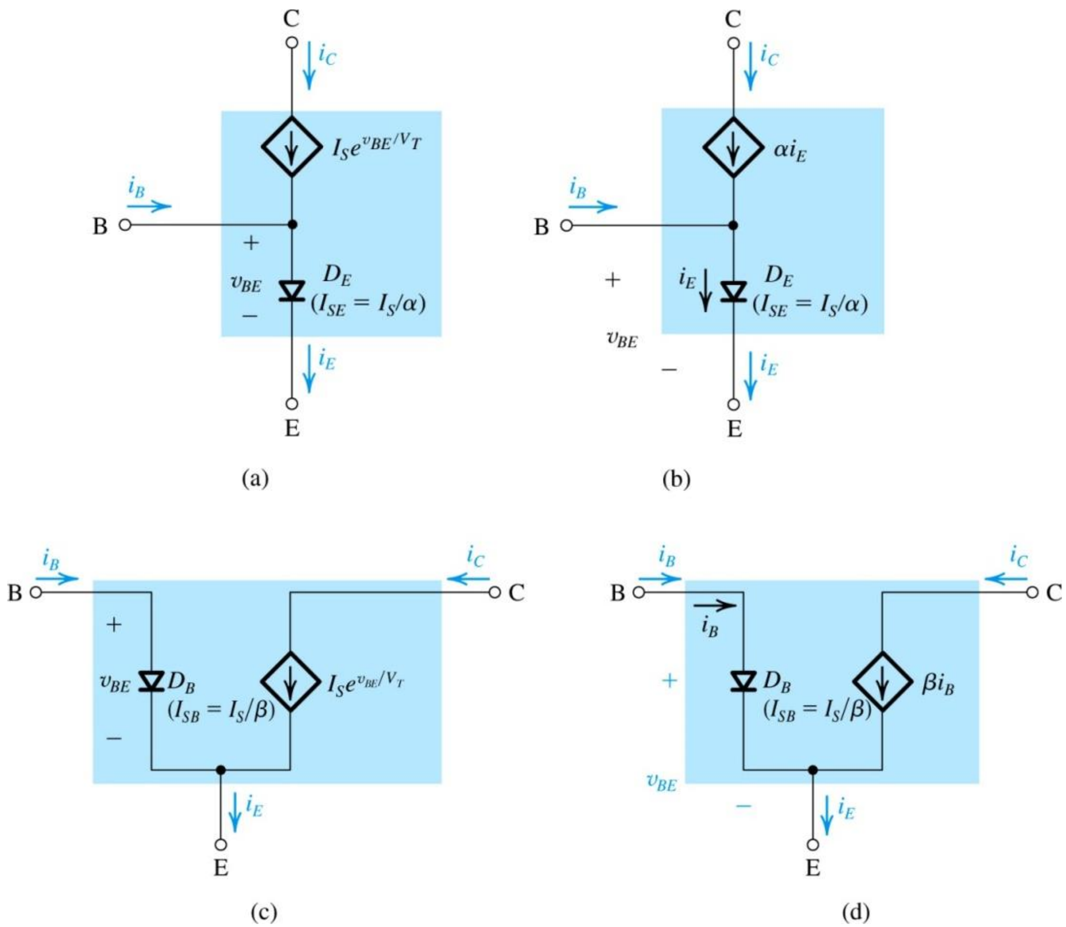


Figure 6.5 Large-signal equivalent-circuit models of the *npn* BJT operating in the forward active mode.

T-Model

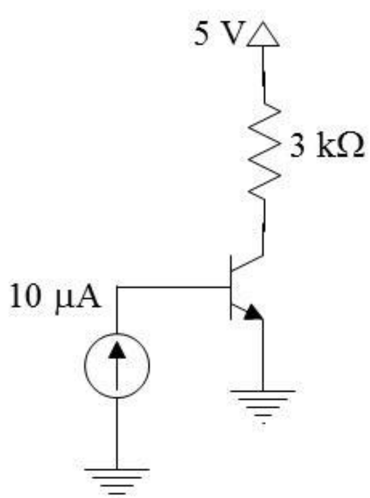
(a) VCCS
(b) CCCS

Hybrid π Model

(a) VCCS
(b) CCCS

Example 6.1

An *npn* transistor having $I_S = 10^{-15}$ A and $\beta = 100$ is connected as follows: The emitter is grounded, the base is fed with a constant-current source supplying a dc current of 10 μA, and the collector is connected to a 5-V dc supply via a resistance R_C of 3 kΩ. Assuming that the transistor is operating in the active mode, find V_{BE} and V_{CE}. Use these values to verify active-mode operation. Replace the current source with a resistance connected from the base to the 5-V dc supply. What resistance value is needed to result in the same operating conditions?

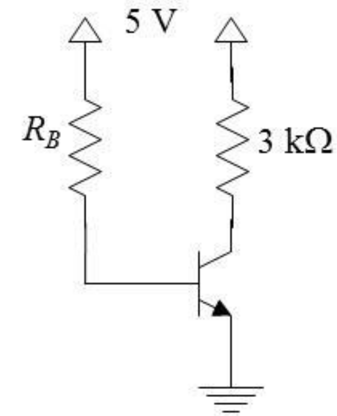


$$i_B = \frac{i_C}{\beta} \qquad I_C = \beta I_B = 1\text{mA} = I_S e^{v_{BE}/V_T}$$

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S}\right) = 0.691\text{ V}$$

$$V_{CE} = V_{CC} - I_C R_C = 5\text{ V} - 3\text{ V} = 2\text{ V}$$

$$R_B = \frac{V_{CC} - V_{BE}}{10\ \mu\text{A}} = \frac{5\text{V} - 0.691\text{V}}{10\ \mu\text{A}} = 431\text{ k}\Omega$$



Structure of Actual Transistors

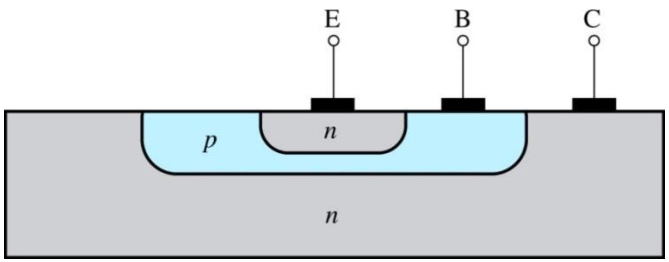
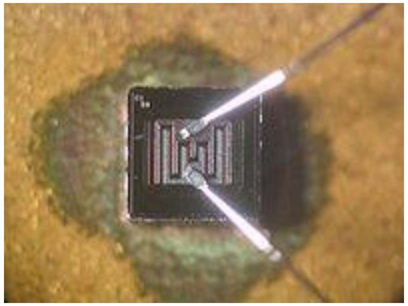


Figure 6.7 Cross-section of an *npn* BJT.

The structure in Fig. 6.7 indicates also that the CBJ has a much larger area than the EBJ. Thus the CB diode D_C has a saturation current I_{SC} that is much larger than the saturation current of the EB diode D_E. Typically, I_{SC} is 10 to 100 times larger than I_{SE} (recall that $I_{SE} = I_S/\alpha \approx I_S$).



Die of a KSY34 high-frequency NPN transistor, base and emitter connected via bonded wires

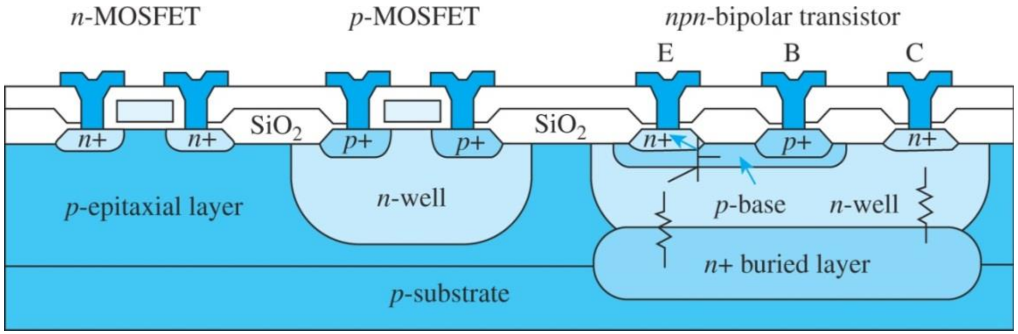


Figure A.10 Cross-sectional diagram of a BiCMOS process.

Operation of the *npn* Transistor in the Saturation Mode

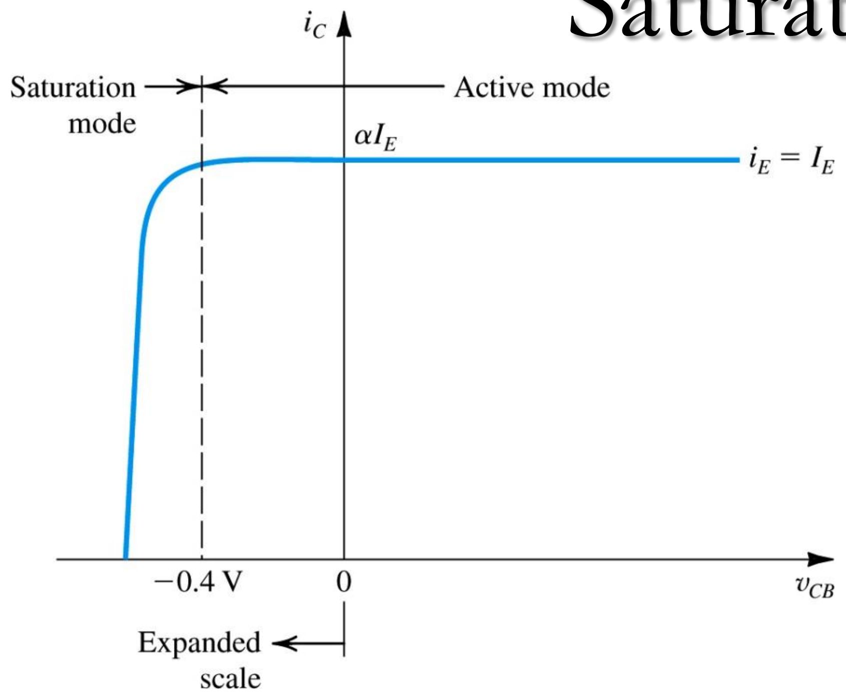


Figure 6.8 The $i_C - v_{CB}$ characteristics of an *npn* transistor fed with a constant emitter current I_E. The transistor enters the saturation mode of operation for v_{CB} < -0.4 V, and the collector current diminishes.

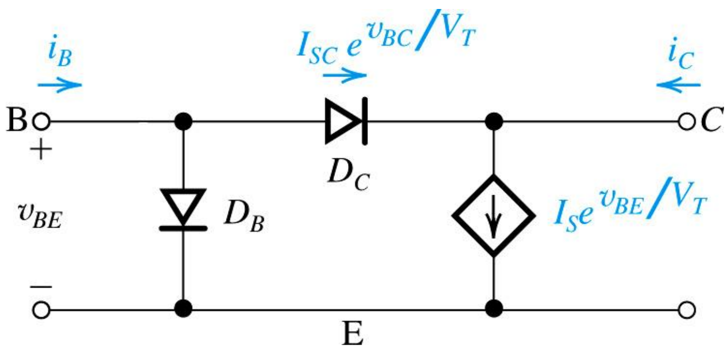


Figure 6.9 Modeling the operation of an *npn* transistor in saturation by augmenting the model of Fig. 6.5(c) with a forward conducting diode D_C. Note that the current through D_C increases i_B and reduces i_C.

$$i_C = I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}$$

$$i_B = \left(\frac{I_S}{\beta}\right) e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}$$

$$\beta = \frac{i_C}{i_B} \qquad \beta|_{\text{forced}} = \frac{i_C}{i_B}|_{\text{saturation}} \leq \beta$$

$$V_{CEsat} = V_{BE} - V_{BC} \approx 0.1 \text{ to } 0.3 \text{ V}$$

Sedra and Smith page 318: Typically we will assume that a transistor at the edge of saturation has V_{CEsat} = 0.3 V, while a transistor deep in saturation has V_{CEsat} = 0.2 V.

Operation of the *pnp* Transistor in the Active Mode

V_{EB} causes the *p-type* emitter to be higher in potential than the *n-type* base, thus forward-biasing the emitter-base junction. The collector-base voltage V_{BC} causes the *p-type* collector to be at a lower potential than the *n-type* base, thus reverse-biasing the collector-base junction.

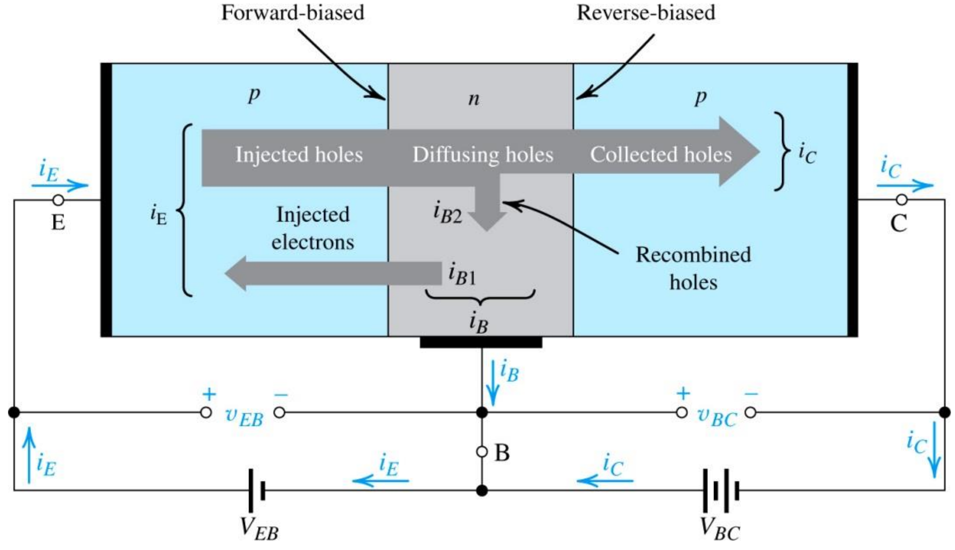


Figure 6.10 Current flow in a *pnp* transistor biased to operate in the active mode.

Large Signal Model for a *pnp* in Active Mode

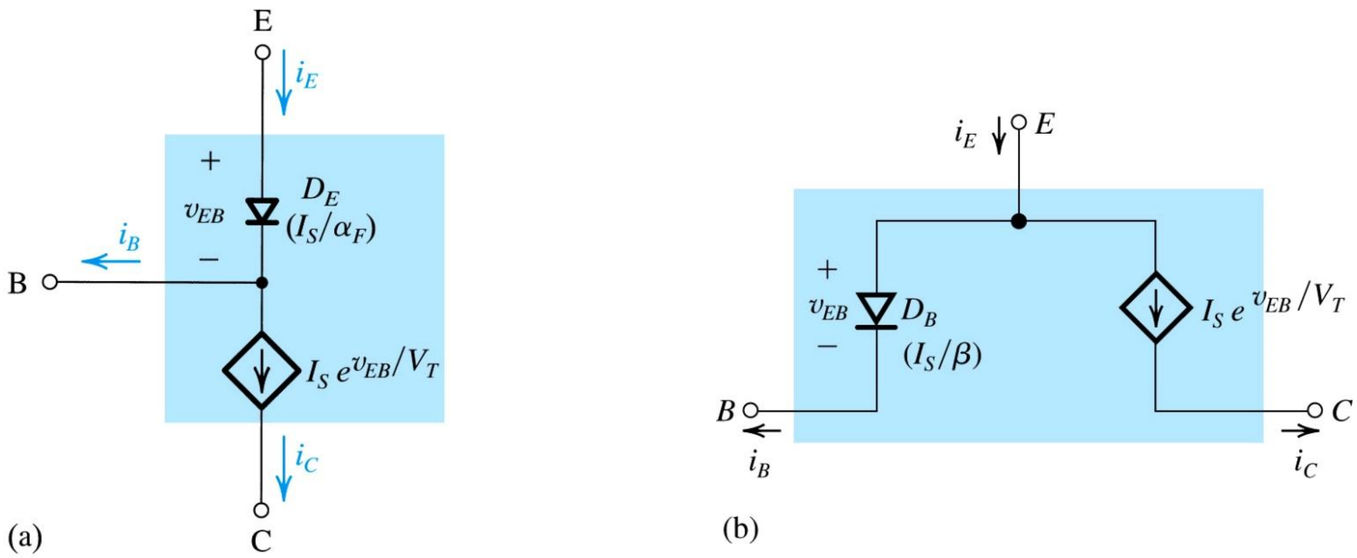


Figure 6.11 Two large-signal models for the *pnp* transistor operating in the active mode.

6.2 CURRENT-VOLTAGE CHARACTERISTICS

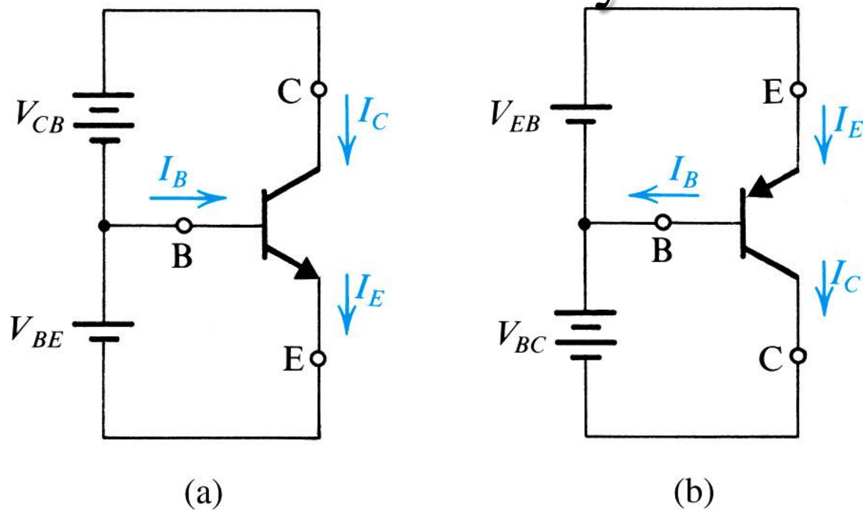
Voltage Polarities and Active Mode Summary

npn transistor

$$I_C = I_S e^{V_{BE}/V_T}$$

$$I_B = \frac{I_C}{\beta} = \left(\frac{I_S}{\beta}\right) e^{V_{BE}/V_T}$$

$$I_E = \frac{I_C}{\alpha} = \left(\frac{I_S}{\alpha}\right) e^{V_{BE}/V_T}$$



pnp transistor

$$I_C = I_S e^{V_{EB}/V_T}$$

$$I_B = \frac{I_C}{\beta} = \left(\frac{I_S}{\beta}\right) e^{V_{EB}/V_T}$$

$$I_E = \frac{I_C}{\alpha} = \left(\frac{I_S}{\alpha}\right) e^{V_{EB}/V_T}$$

an *npn* transistor whose EBJ is forward biased will operate in the active mode as long as the collector voltage does not fall below that of the base by more than approximately 0.4 V. Otherwise, the transistor leaves the active mode and enters the saturation region of operation.

Figure 6.13 Voltage polarities and current flow in transistors biased in the active mode.

$$I_C = \alpha I_E \qquad I_B = (1-\alpha) I_E = \frac{I_E}{\beta+1}$$

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

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

a *pnp* transistor whose EBJ is forward biased will operate in the active mode as long as the collector voltage does not rise above that of the base by more than approximately 0.4 V. Otherwise, the transistor leaves the active mode and enters the saturation region of operation.

Active/Saturation Mode

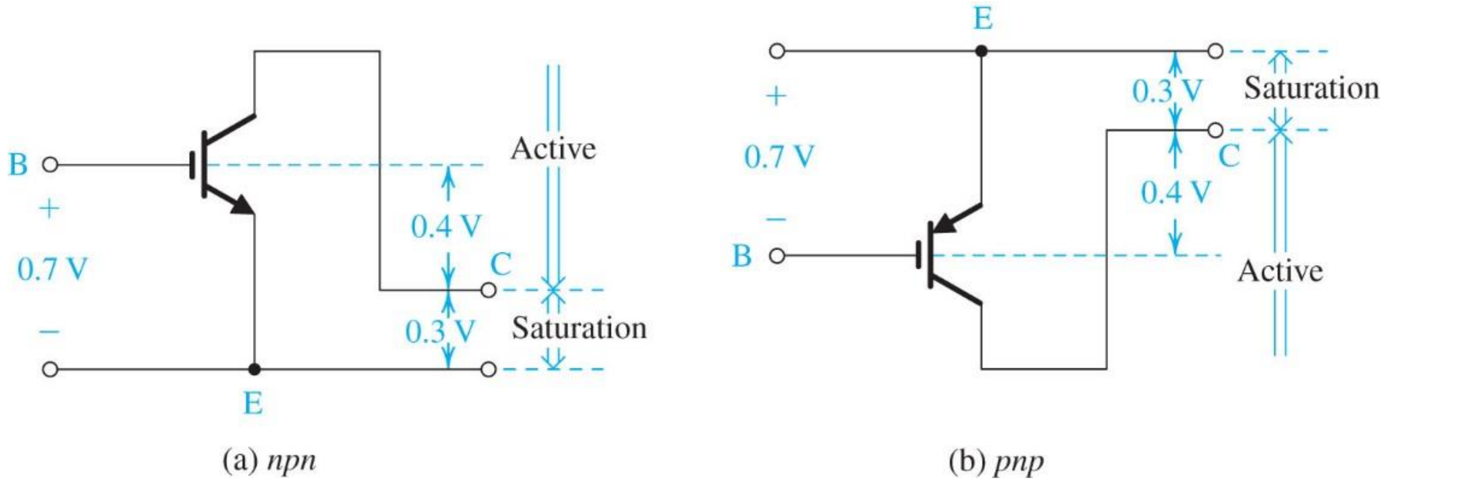


Figure 6.14 Graphical representation of the conditions for operating the BJT in the active mode and in the saturation mode.

Sedra and Smith page 318: Typically we will assume that a transistor at the edge of saturation has V_{CEsat} = 0.3 V, while a transistor deep in saturation has V_{CEsat} = 0.2 V.

Transistor Current Relationships

With respect to $\beta = \frac{\alpha}{1-\alpha}$

	I_C	I_B	I_E
$I_C =$	I_C	βI_B	$\left(\frac{\beta}{\beta+1}\right) I_E$
$I_B =$	$\left(\frac{1}{\beta}\right) I_C$	I_B	$\left(\frac{1}{\beta+1}\right) I_E$
$I_E =$	$\left(\frac{\beta+1}{\beta}\right) I_C$	$(\beta+1)\, I_B$	I_E

With respect to $\alpha = \frac{\beta}{\beta+1}$

	I_C	I_B	I_E
$I_C =$	I_C	$\left(\frac{\alpha}{1-\alpha}\right) I_B$	αI_E
$I_B =$	$\left(\frac{1-\alpha}{\alpha}\right) I_C$	I_B	$(1-\alpha) I_E$
$I_E =$	$\left(\frac{1}{\alpha}\right) I_C$	$\left(\frac{1}{1-\alpha}\right) I_B$	I_E

$$I_E = I_C + I_B$$

Example 6.2

The transistor in the circuit 6.14(a) has $\beta = 100$ and exhibits a v_{BE} of 0.7 V at $I_C = 1$ mA. Design the circuit so that the current of 2 mA flows through the collector and a voltage a +5 V appears at the collector.

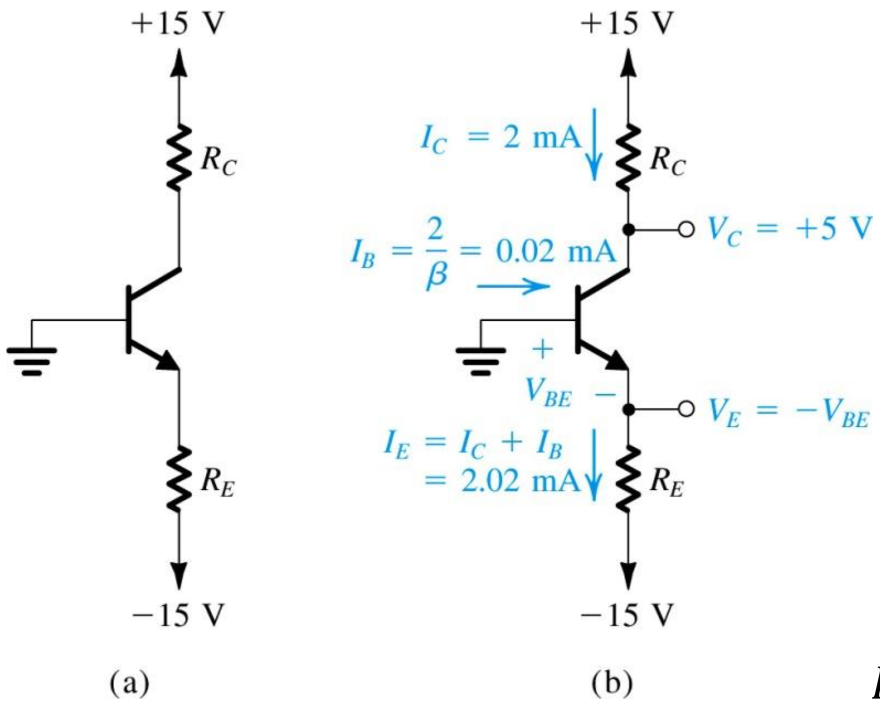


Figure 6.14 Circuit for Example 6.2.

$$R_C = \frac{V_{CC} - V_C}{2\text{ mA}} = \frac{15\text{V} - 5\text{V}}{2\text{ mA}} = 5\text{ k}\Omega$$

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S}\right)$$

$$V_{BE} = 0.7\text{ V} + V_T \ln\left(\frac{2\text{ mA}}{1\text{ mA}}\right) = 0.717\text{ V}$$

$$I_E = \frac{\beta + 1}{\beta} I_C = \frac{101}{100} 2\text{ mA} = 2.02\text{ mA}$$

$$R_E = \frac{V_E - V_{EE}}{I_E} = \frac{15\text{V} - 0.717\text{V}}{2.02\text{ mA}} = 7.071\text{ k}\Omega$$

Exercise 6.13

In the circuit shown in Fig. E6.13, the voltage at the emitter was measured and found to be -0.7 V. If $\beta = 50$, find I_E, I_B, I_C, and V_C.

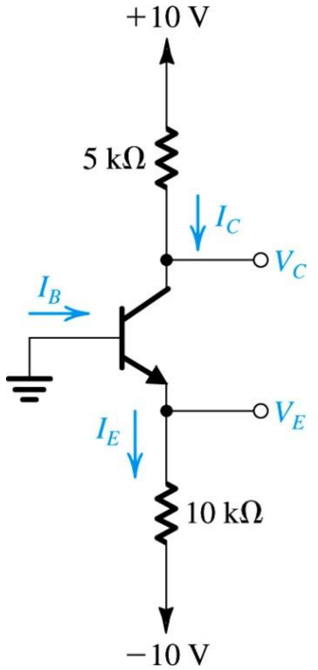


Figure E6.13

$$I_E = \frac{10\text{V} - 0.7\text{V}}{10\text{k}\Omega} = 930\ \mu\text{A}$$

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

$$I_B = \frac{1}{\beta+1} I_E = 18.235\ \mu\text{A}$$

$$I_C = \frac{\beta}{\beta+1} I_E = 911.765\ \mu\text{A}$$

$$V_C = V_{CC} - I_C R_C = 10\text{ V} - 5\text{ V} = 5.441\text{ V}$$

Exercise 6.14

In the circuit shown in Fig. E6.14, measurement indicates V_B to be +1.0 V and V_E to be +1.7 V. What are α and β for this transistor? What voltage V_C do you expect at the collector?

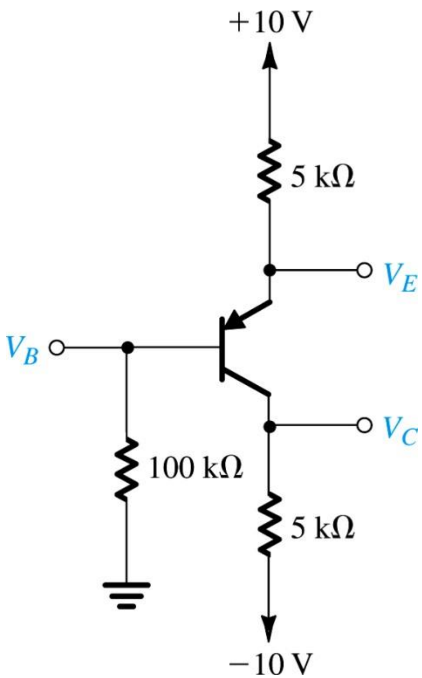


Figure E6.14

$$I_E = \frac{V_{EE} - V_E}{R_E} = \frac{10\text{V} - 1.7\text{V}}{5\text{k}\Omega} = 1.66\text{mA}$$

$$I_B = \frac{V_B}{100\text{k}\Omega} = \frac{1\text{V}}{100\text{k}\Omega} = 0.01\text{mA}$$

$$I_C = I_E - I_B = 1.66\text{mA} - 0.01\text{mA} = 1.65\text{mA}$$

$$\alpha = \frac{I_C}{I_E} = \frac{1.65\text{mA}}{1.66\text{mA}} = 0.99 \qquad \beta = \frac{I_C}{I_B} = \frac{1.65\text{mA}}{0.01\text{mA}} = 165$$

$$V_C = V_{CC} + I_C R_C = -10\text{V} - (1.65\text{mA} \times 5\text{k}\Omega) = -1.75\text{V}$$

The *i-v* Characteristic for an *npn* Transistor.

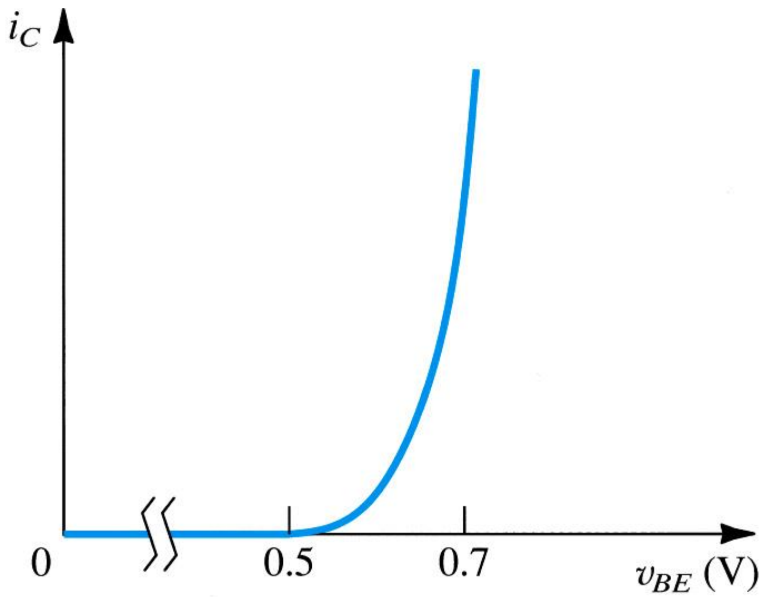


Figure 6.16 The i_C–v_{BE} characteristic for an *npn* transistor.

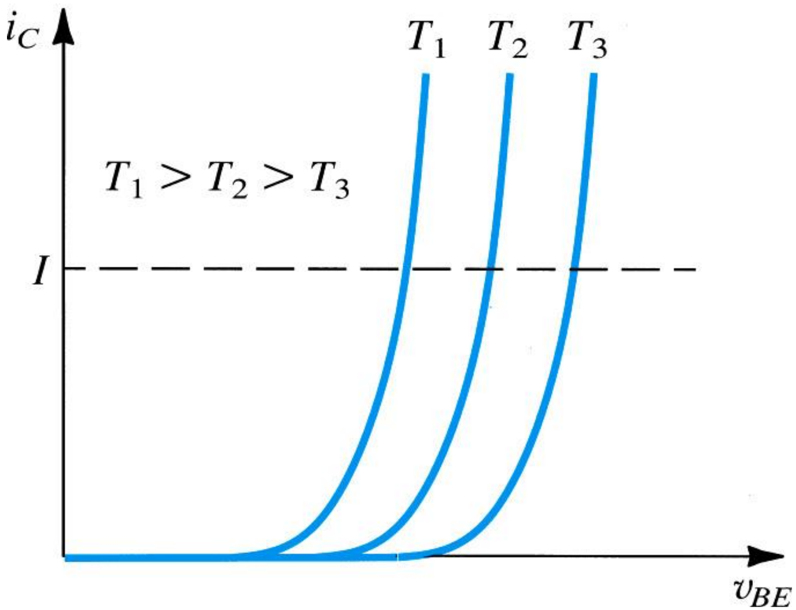


Figure 6.17 Effect of the temperature on the $i_C - v_{BE}$ characteristic. At a constant emitter current (broken line), v_{BE} changes by -2 mV/°C.

Dependence of i_C on the Collector Voltage

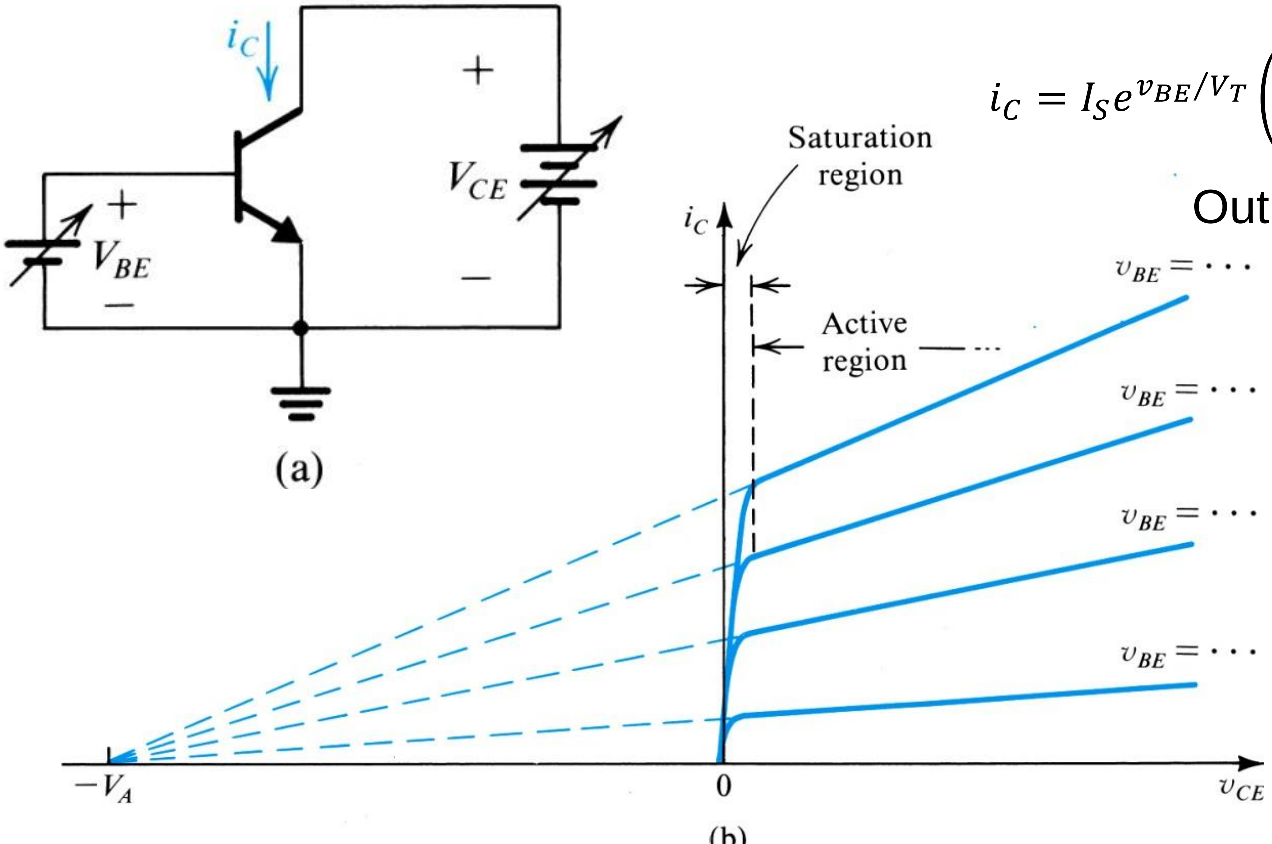


Figure 6.18 (a) Conceptual circuit for measuring the $i_C - v_{CE}$ characteristics of the BJT. (b) the $i_C - v_{CE}$ characteristics of a practical BJT.

$$i_C = I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$$

Output resistance, r_o, is finite

$$r_o \equiv \left[\frac{\partial i_C}{\partial v_{CE}}\Big|_{v_{BE}=constant}\right]^{-1}$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{V_A}{I'_C}$$

Where I'_C is the DC collector current without the Early effect factored in

$$I'_C = I_S e^{V_{BE}/V_T}$$

Large Signal Equivalent Circuit Model of a *npn* BJT in the Active Mode

VCCS version **CCCS version**

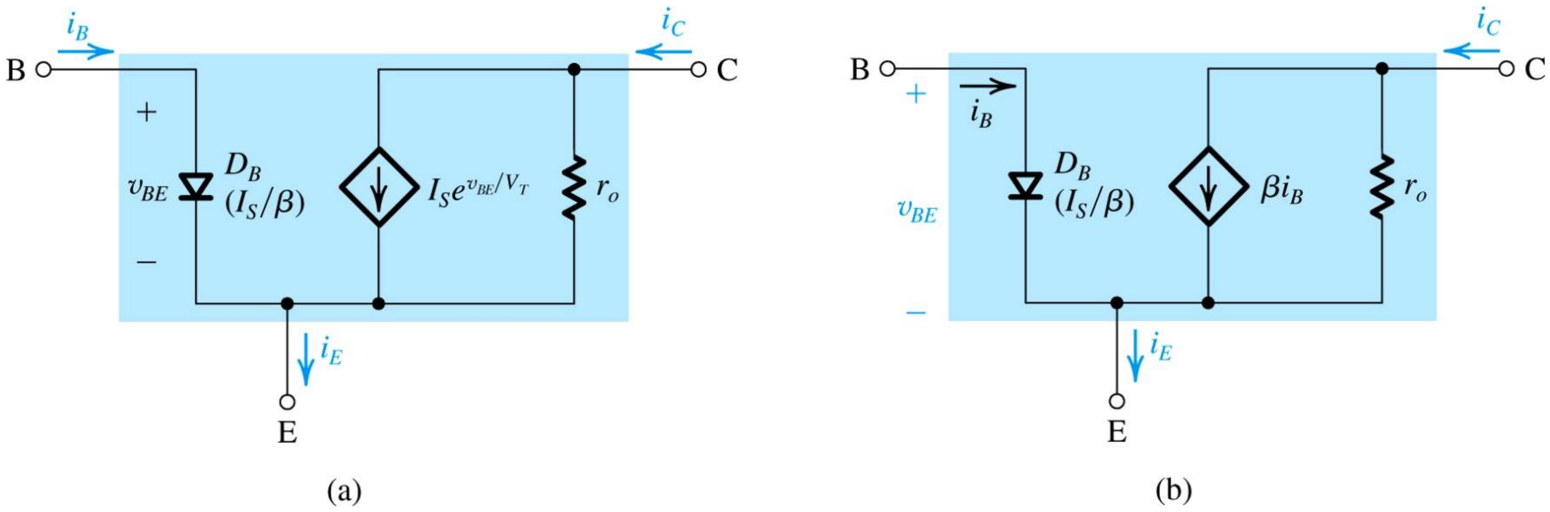


Figure 6.19 Large-signal equivalent-circuit models of an *npn* BJT operating in the active mode in the common-emitter configuration with the output resistance r_o included.

Common Emitter Characteristics

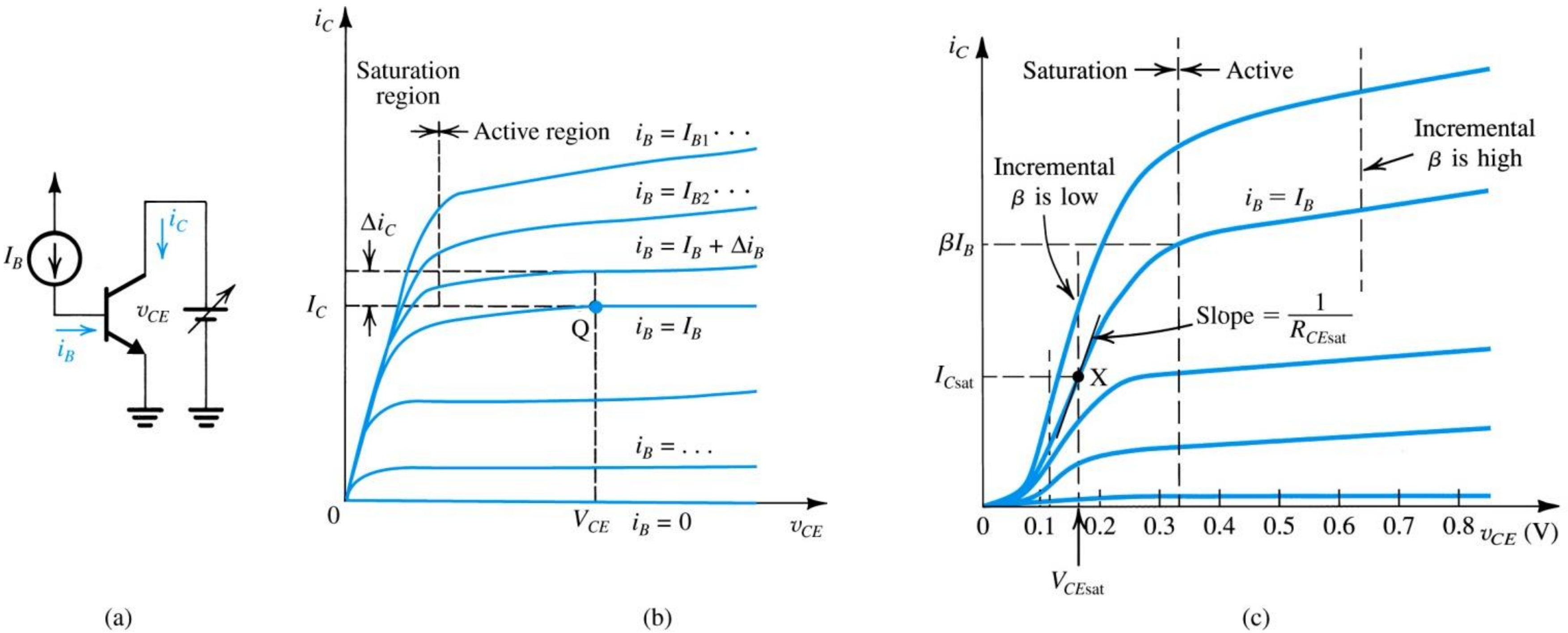


Figure 6.20 Common-emitter characteristics. (**a**) Basic CE circuit; note that in (**b**) the horizontal scale is expanded around the origin to show the saturation region in some detail. A much greater expansion of the saturation region is shown in (**c**).

Simplified Equivalent Circuit for a Transistor in Saturation Mode

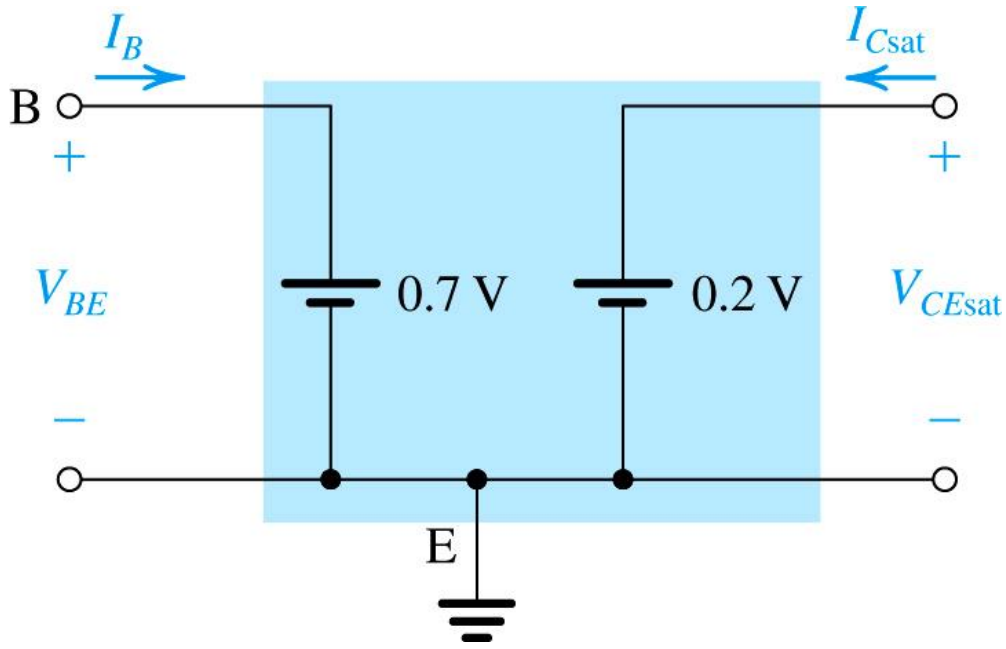


Figure 6.21 A simplified equivalent-circuit model of the saturated transistor.

Example 6.3

For the circuit in Fig. 6.21, it is required to determine the value of the voltage V_{BB} that results in the transistor operating

(a) in the active mode with $V_{CE}= 5$ V

(b) at the edge of saturation

(c) deep in saturation with $\beta_{\text{forced}}= 10$

For simplicity, assume that V_{BE} remains constant at 0.7 V. The transistor β is specified to be 50.

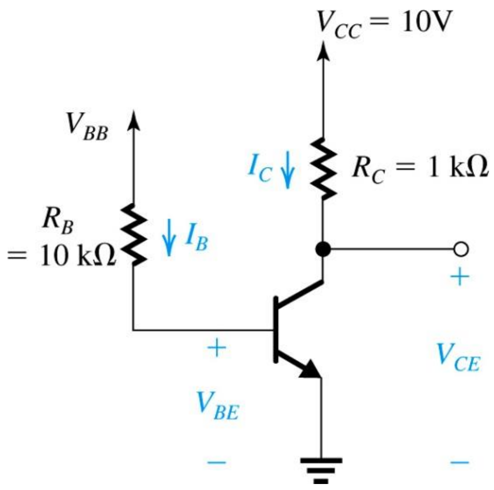


Figure 6.22 Circuit for Example 6.3.

(a) in the active mode with $V_{CE}= 5$ V

$$I_C = \frac{V_{CC} - V_{CE}}{1\text{ k}\Omega} = 5\text{ mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{5\text{ mA}}{50} = 0.1\text{ mA}$$

$$V_{BB} = I_B R_B + V_{BE} = 0.1\text{ mA} \times 10\text{ k}\Omega + 0.7\text{ V} = 1.7\text{ V}$$

Example 6.3b

For the circuit in Fig. 6.21, it is required to determine the value of the voltage V_{BB} that results in the transistor operating
(b) at the edge of saturation
For simplicity, assume that V_{BE} remains constant at 0.7 V. The transistor β is specified to be 50.

Operation at the edge of saturation is obtained with V_{CE} = 0.3 V.

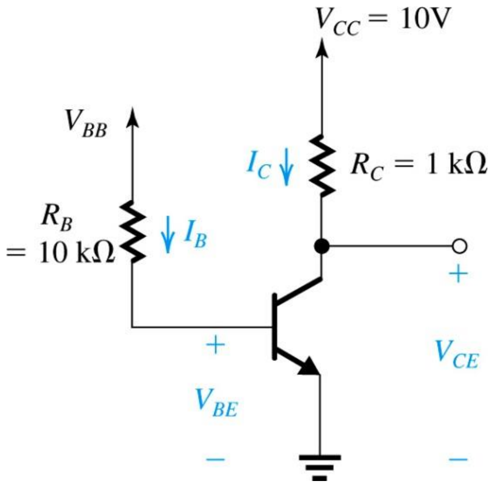


Figure 6.22 Circuit for Example 6.3.

$$I_C = \frac{V_{CC} - V_{CE}}{1\ \mathrm{k\Omega}} = 9.7\ \mathrm{mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{9.7\ \mathrm{mA}}{50} = 0.194\ \mathrm{mA}$$

$$V_{BB} = I_B R_B + V_{BE} = 0.194\ \mathrm{mA} \times 10\ \mathrm{k\Omega} + 0.7\ \mathrm{V} = 2.64\ \mathrm{V}$$

Example 6.3c

For the circuit in Fig. 6.21, it is required to determine the value of the voltage V_{BB} that results in the transistor operating
(c) deep in saturation with $\beta_{\text{forced}} = 10$
For simplicity, assume that V_{BE} remains constant at 0.7 V. The transistor β is specified to be 50.

Operation at the edge of saturation is obtained with $V_{CE} = 0.2$ V.

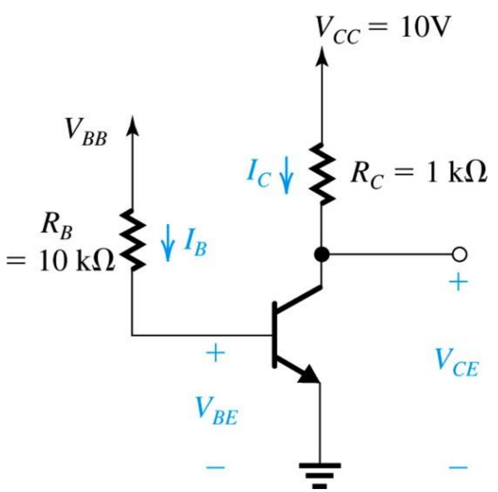


Figure 6.22 Circuit for Example 6.3.

$$I_C = \frac{V_{CC} - V_{CE}}{1\ \text{k}\Omega} = 9.8\ \text{mA}$$

$$I_B = \frac{I_C}{\beta_{\text{forced}}} = \frac{9.8\ \text{mA}}{10} = 0.98\ \text{mA}$$

$$V_{BB} = I_B R_B + V_{BE} = 0.98\ \text{mA} \times 10\ \text{k}\Omega + 0.7\ \text{V} = 10.5\ \text{V}$$

Homework #11

- Read Chapter 6
- Chapter 6 Problems:
  - 6.7
  - 6.8*
  - 6.28*
  - 6.29
  - 6.32*

*** Answers in Appendix L**

6.3 BJT CIRCUITS AT DC

Summary of BJT Conditions and Models

Cutoff
EBJ: Reverse Biased
CBJ: Reverse Biased

Active
EBJ: Forward Biased
CBJ: Reverse Biased

Saturation
EBJ: Forward Biased
CBJ: Forward Biased

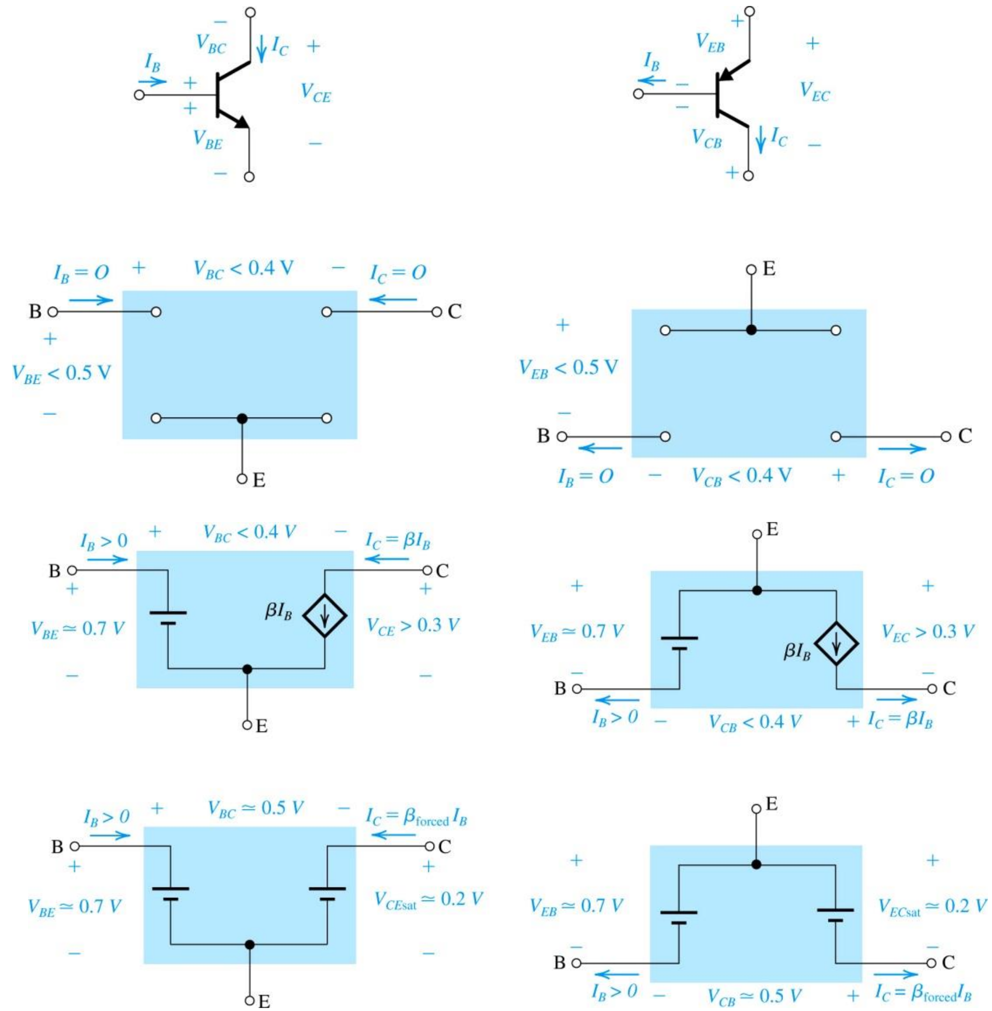


Table 6.3 Conditions and Models for the Operation of the BJT in Various Modes

Example 6.4

Consider the circuit shown in Fig 6.22(a), which is redrawn in Fig 6.22(b) to remind the reader of the convention employed throughout this book for indicating connections to dc sources. We wish to analyze this circuit to determine all the node voltages and branch currents. We will assume that β is specified to be 100.

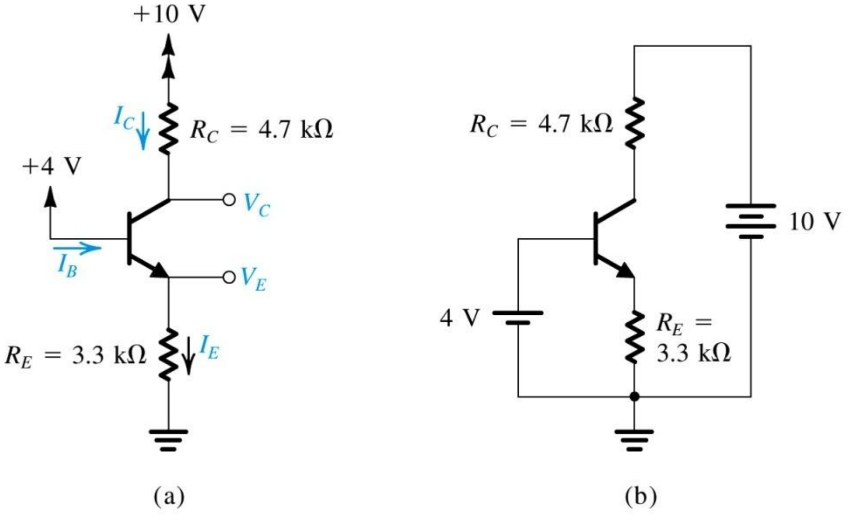


Figure 6.23 Analysis of the circuit for Example 6.4: **(a)** circuit; **(b)** circuit redrawn to remind the reader of the convention used in this book to show connections to the power supply.

Example 6.4

Consider the circuit shown in Fig 6.22(a), which is redrawn in Fig 6.22(b) to remind the reader of the convention employed throughout this book for indicating connections to dc sources. We wish to analyze this circuit to determine all the node voltages and branch currents. We will assume that β is specified to be 100.

$$V_E = V_B - V_{BE} = 4\ V - 0.7\ \text{V} = 3.3\ \text{V}$$

$$I_E = \frac{V_E}{3.3\ \text{k}\Omega} = 1\ \text{mA}$$

$$I_C = \alpha I_E = \frac{\beta}{\beta+1} I_E = 0.99\ \text{mA}$$

$$V_C = 10\ V - I_C R_C = 5.35\ \text{V}$$

$$I_B = \frac{I_E}{\beta+1} = \frac{1\ \text{mA}}{101} = 9.9\ \mu\text{A}$$

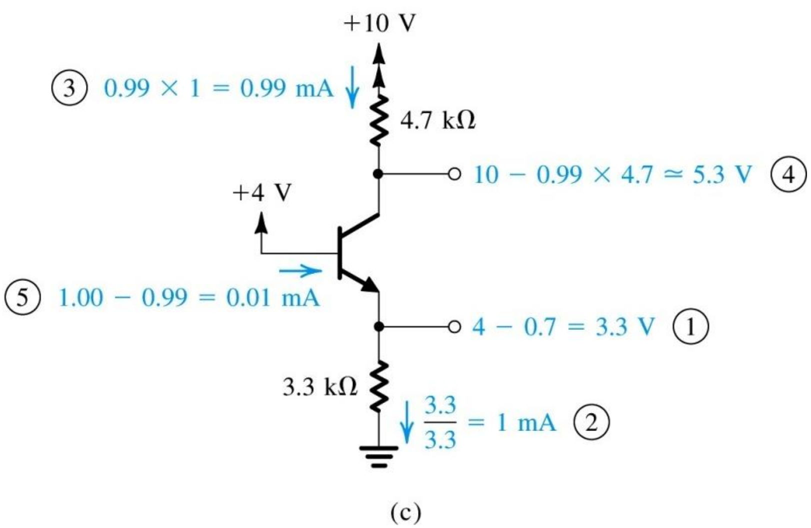


Figure 6.23 (c) analysis with the steps numbered.

Example 6.5

We wish to analyze the circuit of Fig. 6.24(a) to determine the voltages at all nodes and the currents through all branches. Note that this circuit is identical to that of Fig 6.23 except that the voltage at the base is now +6V. Assume that the transistor β is specified to be at least 50.

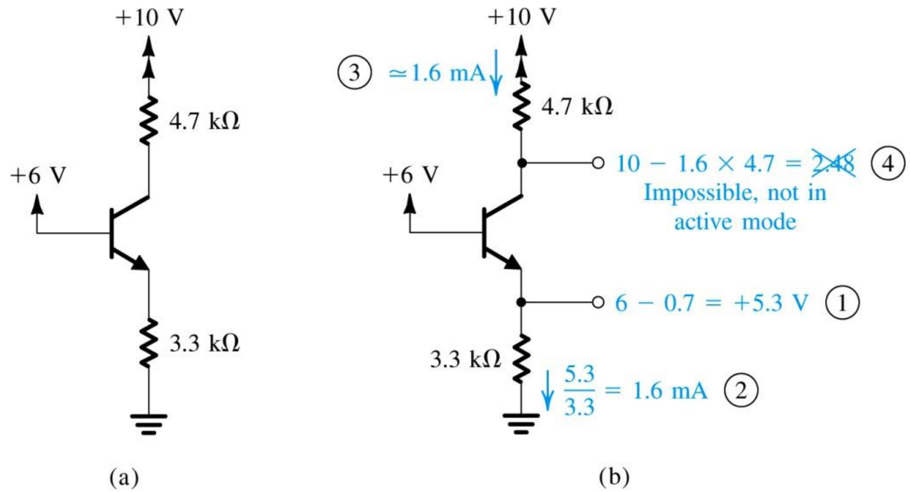


Figure 6.24 Analysis of the circuit for Example 6.5. Note that the circled numbers indicate the order of the analysis steps.

$$V_E = V_B - V_{BE} = 6\,V - 0.7\text{ V} = 5.3\text{ V}$$

$$I_E = \frac{V_E}{3.3\text{ k}\Omega} = 1.6\text{ mA}$$

$$I_C = \alpha I_E = \frac{\beta}{\beta+1} I_E = 1.57\text{ mA}$$

$$V_C = 10\,V - I_C R_C = 2.627\text{ V}$$

Therefore the device is not in active mode but in saturation mode

Example 6.5

We wish to analyze the circuit of Fig. 6.24(a) to determine the voltages at all nodes and the currents through all branches. Note that this circuit is identical to that of Fig 6.23 except that the voltage at the base is now +6V. Assume that the transistor β is specified to be at least 50.

Operation deep in saturation is obtained with $V_{CE} = 0.2$ V.

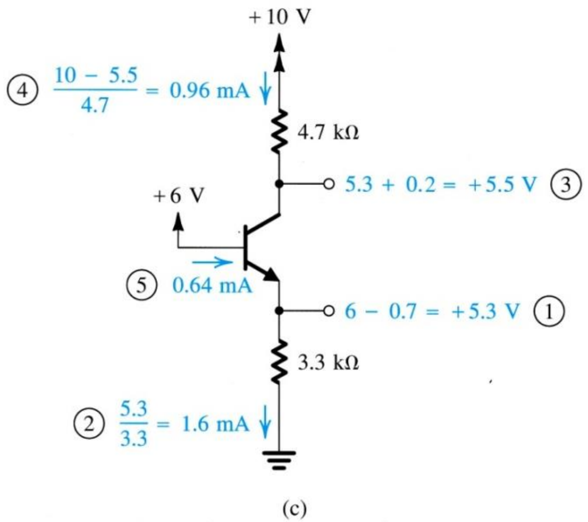


Figure 6.24 Analysis of the circuit for Example 6.5. Note that the circled numbers indicate the order of the analysis steps.

$$V_C = V_E + V_{CEsat} = 5.3\text{ V} + 0.2\text{ V} = 5.5\text{ V}$$

$$I_C = \frac{V_{CC} - V_C}{4.7\text{ k}\Omega} = \frac{10\text{ V} - 5.5\text{ V}}{4.7\text{ k}\Omega} = 0.96\text{ mA}$$

$$I_B = I_E - I_C = 1.6\text{ mA} - 0.96\text{ mA} = 0.64\text{ mA}$$

$$\beta_{\text{forced}} = \frac{I_C}{I_B} = \frac{0.96\text{ mA}}{0.64\text{ mA}} = 1.5$$

Example 6.6

We wish to analyze the circuit of Fig. 6.25(a) to determine the voltages at all nodes and the currents through all branches. Note that this circuit is identical to that considered in Examples 6.4 and 6.5 except that now the base voltage is zero.

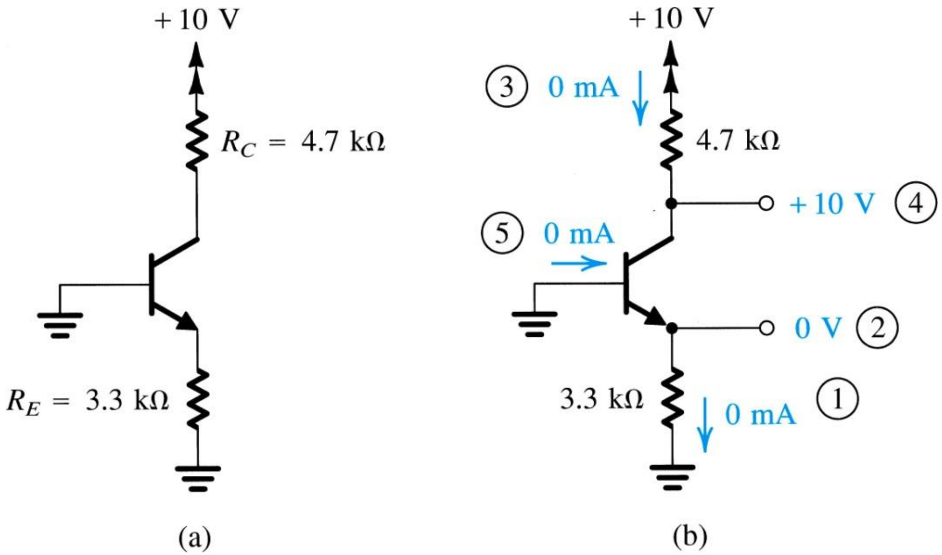


Figure 6.25 Example 6.6: **(a)** circuit; **(b)** analysis, with the order of the analysis steps indicated by circled numbers.

$$V_{BE} = 0\text{ V}$$

$$I_E = 0\text{ mA}$$

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

$$V_C = 10\,V - I_C R_C = 10\text{ V}$$

Example 6.7

We want to analyze the circuit of Fig. 6.26(a) to determine the voltages at all nodes and the currents through all branches.

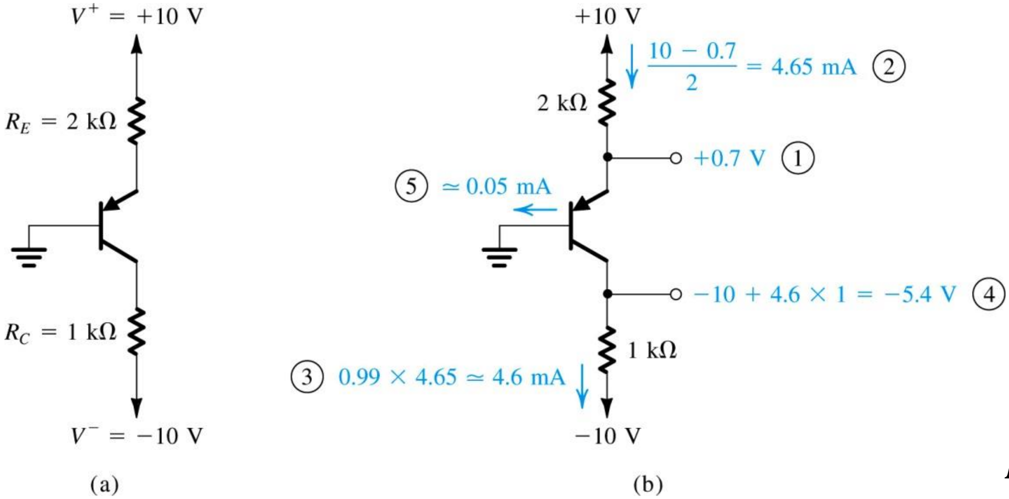


Figure 6.26 Example 6.7: **(a)** circuit; **(b)** analysis, with the steps indicated by circled numbers.

$$V_E = V_B + V_{EB} = +0.7 \text{ V}$$

$$I_E = \frac{10\text{V} - V_E}{2 \text{ k}\Omega} = 4.65 \text{ mA}$$

$$I_C = \alpha I_E = \frac{\beta}{\beta + 1} I_E = 4.6 \text{ mA}$$

$$V_C = -10\ V + I_C R_C = -5.4 \text{ V}$$

$$I_B = \frac{I_E}{\beta + 1} = \frac{4.65 \text{ mA}}{101} = 46\ \mu\text{A}$$

Example 6.8

We want to analyze the circuit in Fig. 6.27(a) to determine the voltages at all nodes and the currents in all branches. Assume $\beta = 100$.

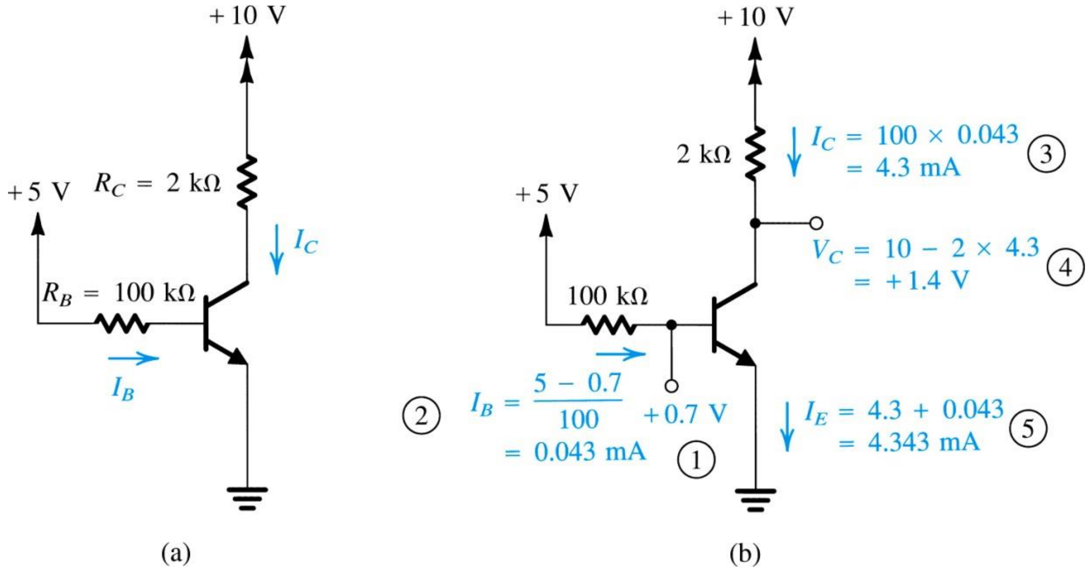


Figure 6.27 Example 6.8: **(a)** circuit; **(b)** analysis, with the steps indicated by the circled numbers.

$$V_B = V_{BE} = 0.7 \text{ V}$$

$$I_B = \frac{5\text{V} - V_B}{100 \text{ k}\Omega} = 0.043 \text{ mA}$$

$$I_C = \beta I_B = 4.3 \text{ mA}$$

$$V_C = 10\,V - I_C R_C = 1.4 \text{ V}$$

$$I_E = (\beta + 1) I_E = 4.343 \text{ mA}$$

Example 6.9

We want to analyze the circuit in Fig.6.28 to determine the voltages at all nodes and the currents through all branches. The minimum value of β is specified to be 30.

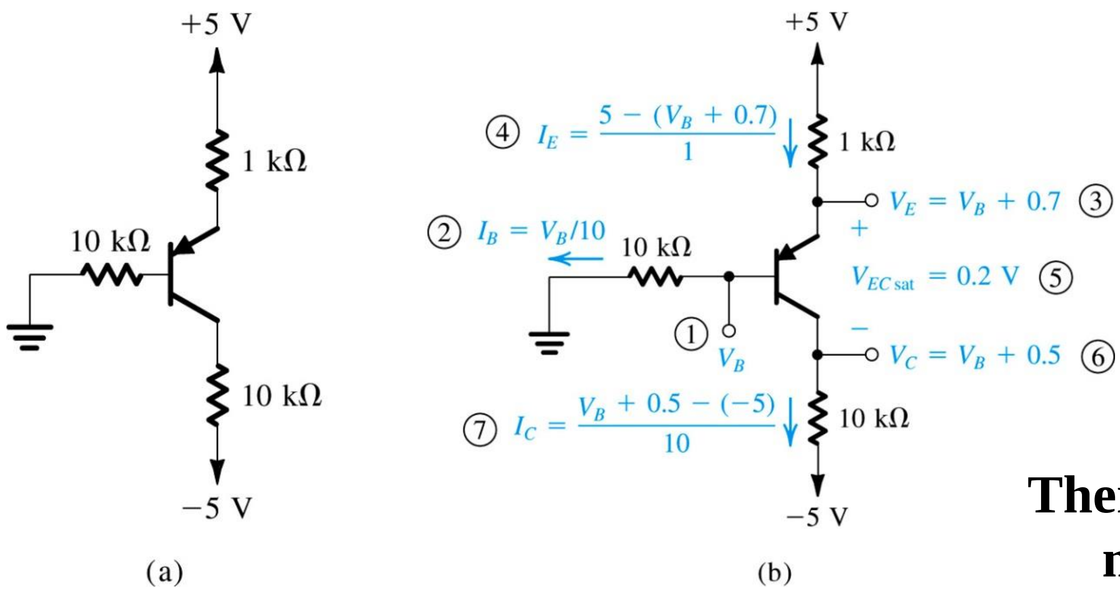


Figure 6.28 Example 6.9: (a) circuit; (b) analysis with steps numbered.

$$V_E = V_B + V_{EB} = +0.7\text{ V}$$

$$I_E = \frac{5\text{V} - V_E}{1\text{ k}\Omega} = 4.3\text{ mA}$$

$$I_C = \alpha I_E = \frac{\beta}{\beta+1} I_E = 4.26\text{ mA}$$

$$V_C = -5\,V + I_C R_C = 37.6\text{ V}$$

Therefore the device is not in active mode but in saturation mode

Example 6.9

We want to analyze the circuit in Fig.6.28 to determine the voltages at all nodes and the currents through all branches. The minimum value of β is specified to be 30.

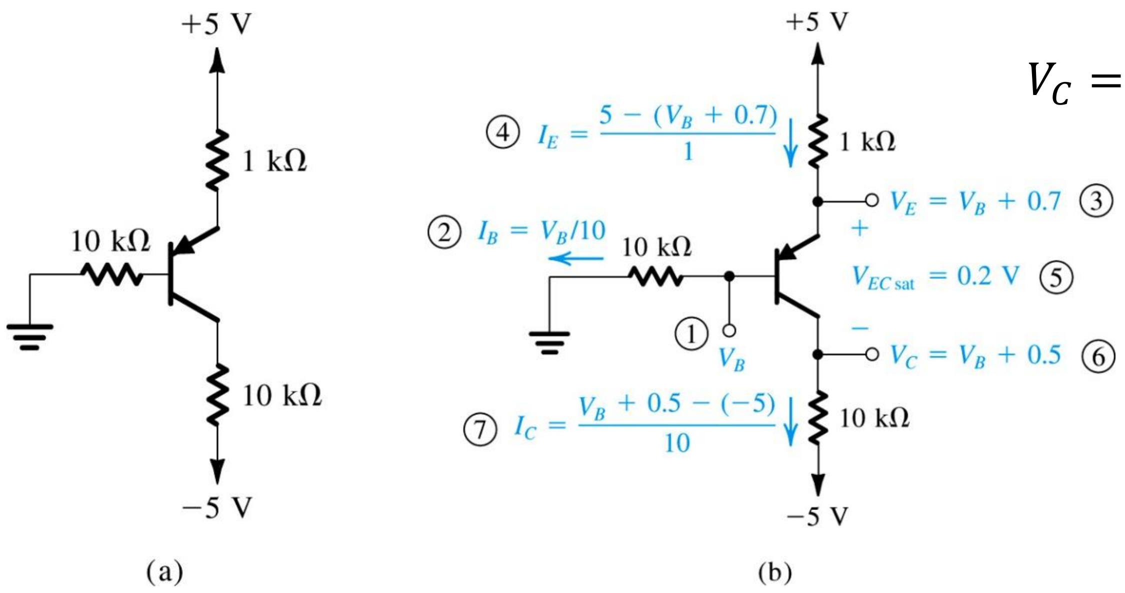


Figure 6.28 Example 6.9: **(a)** circuit; **(b)** analysis with steps numbered.

$$V_E = V_B + V_{EB} = V_B + 0.7\text{ V}$$

$$V_C = V_E - V_{ECsat} = V_B + 0.7\text{ V} - 0.2\text{ V}$$

$$V_C = V_B + 0.5\text{ V}$$

$$I_E = \frac{5\text{V} - V_E}{1\text{ k}\Omega} = \frac{5\text{ V} - V_B - 0.7\text{ V}}{1\text{ k}\Omega}$$

$$I_E = [4.3 - V_B]\text{mA}$$

$$I_B = \frac{V_B}{10\text{ k}\Omega} = [0.1V_B]\text{mA}$$

$$I_C = \frac{V_c - -5\text{V}}{10\text{ k}\Omega} = [0.55 - 0.1V_B]\text{mA}$$

Example 6.9

We want to analyze the circuit in Fig.6.28 to determine the voltages at all nodes and the currents through all branches. The minimum value of β is specified to be 30.

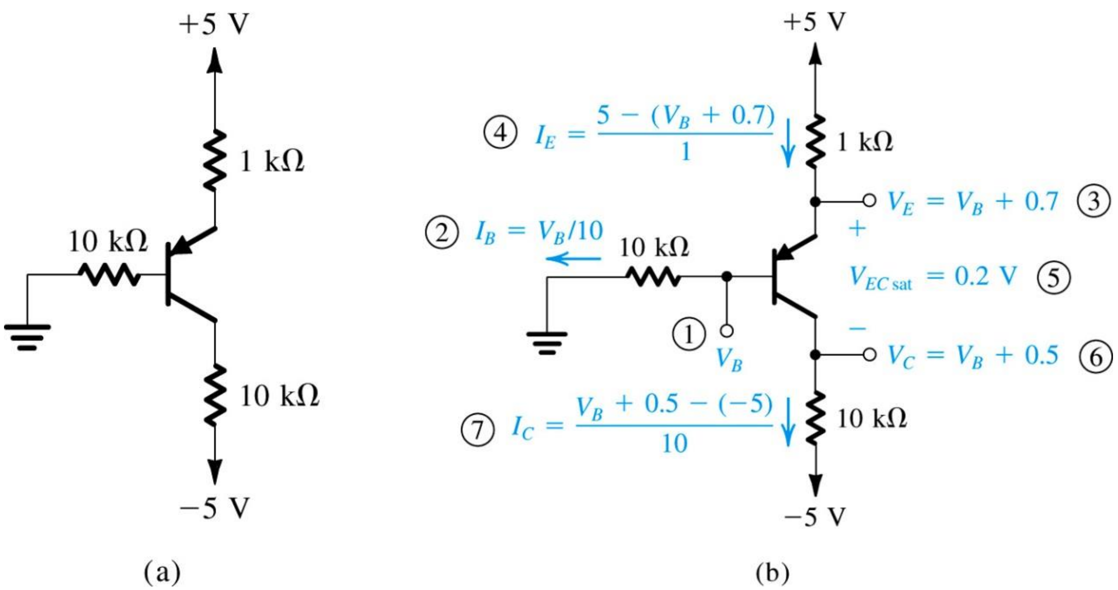


Figure 6.28 Example 6.9: **(a)** circuit; **(b)** analysis with steps numbered.

$$I_E = [4.3 - V_B]\text{mA}$$
$$I_B = [0.1V_B]\text{mA}$$
$$I_C = [5.5 - 0.1V_B]\text{mA}$$

$$I_E = I_B + I_C$$

$$V_B = 3.13\ \text{V} \qquad I_B = 0.31\ \text{mA}$$
$$V_E = 3.83\ \text{V} \qquad I_E = 1.17\ \text{mA}$$
$$V_C = 3.63\ \text{V} \qquad I_C = 0.86\ \text{mA}$$

$$\beta_{\text{forced}} = \frac{I_C}{I_B} = \frac{0.86\ \text{mA}}{0.31\ \text{mA}} = 2.8$$

Example 6.10a

We want to analyze the circuit in Fig. 6.29 to determine the voltages at all nodes and the currents through all branches. Assume $\beta = 100$.

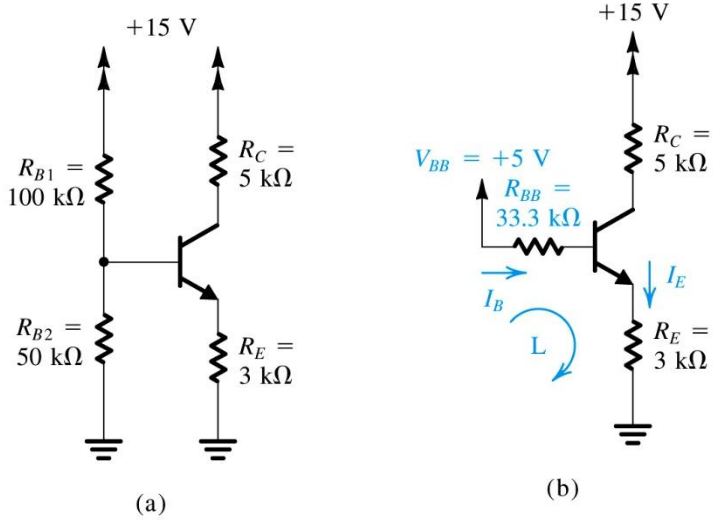


Figure 6.29 Circuits for Example 6.10.

$$V_{BB} = 15\text{V}\frac{50\text{k}\Omega}{100\text{k}\Omega + 50\text{k}\Omega} = 5\text{V}$$

$$R_{BB} = 100\text{k}\Omega \,||\, 50\text{k}\Omega = 33.3\text{k}\Omega$$

$$V_{BB} = I_B R_{BB} + V_{BE} + I_E R_E \qquad I_B = \frac{I_E}{\beta + 1}$$

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + \left[R_{BB}/(\beta+1)\right]}$$

$$= \frac{5\text{V} - 0.7\text{V}}{3\text{k}\Omega + \left[33.3\text{k}\Omega/(100+1)\right]} = 1.29\text{mA}$$

Example 6.10b

We want to analyze the circuit in Fig. 6.29 to determine the voltages at all nodes and the currents through all branches. Assume $\beta = 100$.

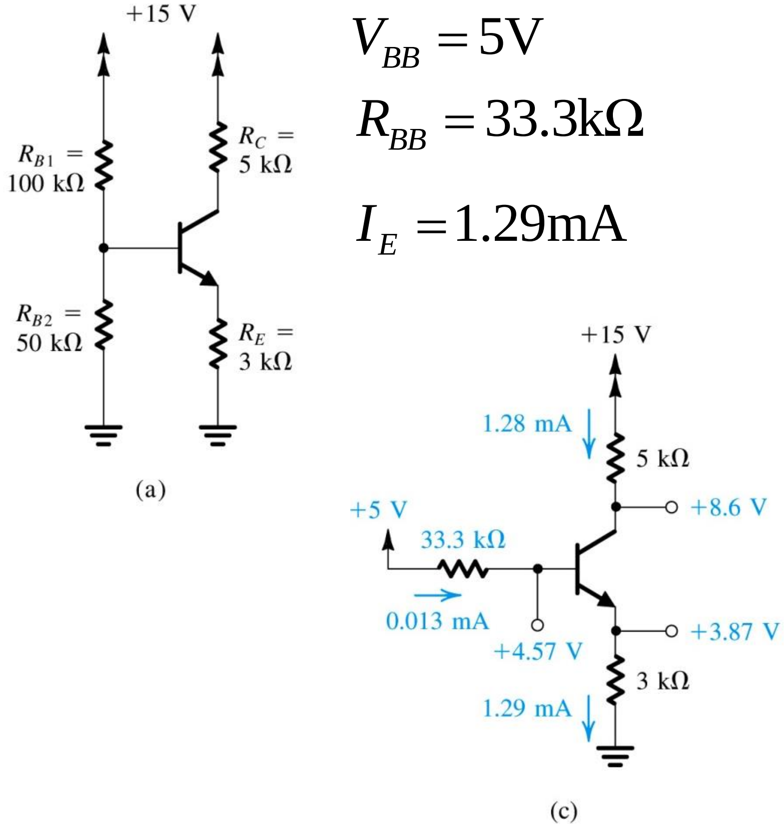


Figure 6.29 Circuits for Example 6.10.

$$V_{BB} = 5\text{V}$$

$$R_{BB} = 33.3\text{k}\Omega$$

$$I_E = 1.29\text{mA}$$

$$I_B = \frac{I_E}{\beta+1} = \frac{1.29\text{mA}}{100+1} = 0.0128\text{mA}$$

$$V_B = V_{BE} + I_E R_E = 0.7\text{V} + 1.29\text{mA} \times 3\text{k}\Omega = 4.57\text{V}$$

$$I_C = \alpha I_E = 0.99 \times 1.29\text{mA} = 1.28\text{mA}$$

$$V_C = V_{CC} - I_C R_C = 15\text{V} - 1.28\text{mA} \times 5\text{k}\Omega = 8.6\text{V}$$

Device is in active mode as initially assumed

Example 6.11a

We want to analyze the circuit in Fig. 6.30(a) to determine the voltages at all nodes and the currents through all branches.

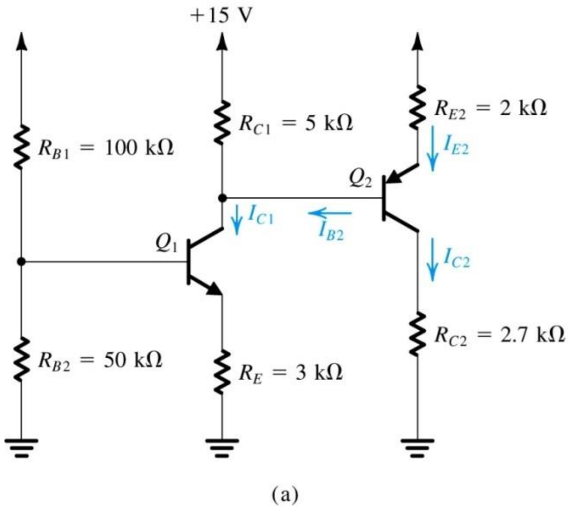


Figure 6.30 Circuits for Example 6.11.

$$V_{B1} = 4.57\text{V}$$

$$I_{E1} = 1.29\text{mA}$$

$$I_{B1} = 0.0128\text{mA}$$

$$I_{C1} = 1.28\text{mA}$$

$$V_{C1} \approx V_{CC} - I_{C1}R_{C1} = 15\text{V} - 1.28\text{mA} \times 5\text{k}\Omega = 8.6\text{V}$$

$$V_{E2} = V_{C1} + V_{EB2} \approx 8.6\text{V} + 0.7\text{V} = 9.3\text{V}$$

$$I_{E2} = \frac{V_{CC} - V_{E2}}{R_{E2}} = \frac{15\text{V} - 9.3\text{V}}{2\text{k}\Omega} = 2.85\text{mA}$$

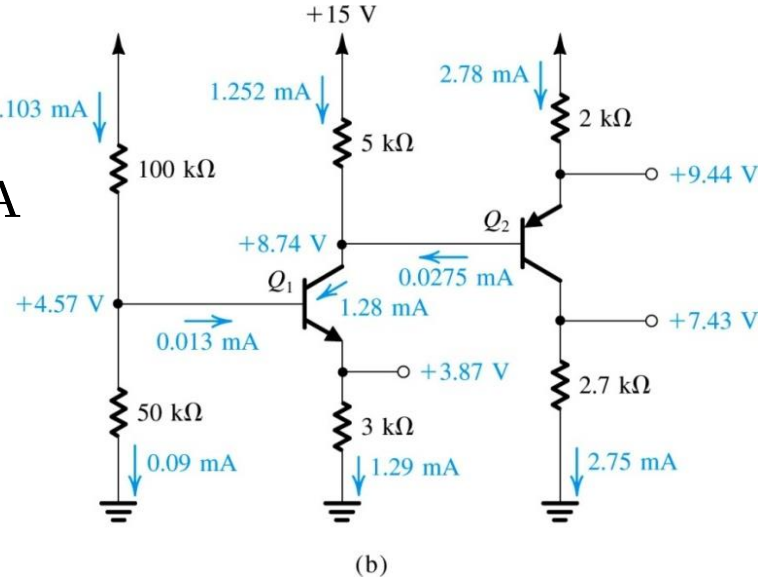
$$I_{C2} = \alpha_2 I_{E2} = 0.99 \times 2.85\text{mA} = 2.82\text{mA}$$

$$V_{C2} = I_{C2}R_{C2} = 2.82\text{mA} \times 2.7\text{k}\Omega = 7.62\text{V}$$

Example 6.11b

We want to analyze the circuit in Fig. 6.30(a) to determine the voltages at all nodes and the currents through all branches.

$$V_{B1} = 4.57\text{V}$$
$$I_{E1} = 1.29\text{mA}$$
$$I_{B1} = 0.0128\text{mA}$$
$$I_{C1} = 1.28\text{mA}$$
$$V_{C1} \approx 8.6\text{V}$$
$$V_{C1} = 8.74\text{V}$$



$$V_{E2} \approx 9.3\text{V} \qquad V_{E2} = 9.44\text{V}$$
$$I_{E2} \approx 2.85\text{mA} \qquad I_{E2} = 2.78\text{mA}$$
$$I_{C2} \approx 2.82\text{mA} \qquad I_{C2} = 2.75\text{mA}$$
$$V_{C2} \approx 7.62\text{V} \qquad V_{C2} = 7.43\text{V}$$

Q_2 is in active mode

$$I_{B2} = \frac{2.78\text{mA}}{100+1} = 0.0275\text{mA}$$

$$I_{B2} = \frac{I_{E2}}{\beta_2+1} = \frac{2.85\text{mA}}{100+1} = 0.028\text{mA}$$

$$\Rightarrow I_{R_{C1}} = I_{C1} - I_{B2} = 1.28\text{mA} - 0.028\text{mA} = 1.252\text{mA}$$

Figure 6.30 Circuits for Example 6.11.

Exercise 6.30

The circuit in Fig. E6.30 is to be connected to the circuit in Fig. 6.30(a) as indicated; specifically, the base of Q_3 is to be connected to the collector of Q_2. If Q_3 has $\beta = 100$, find the new value of V_{C2} and the values of V_{E3} and I_{C3}.

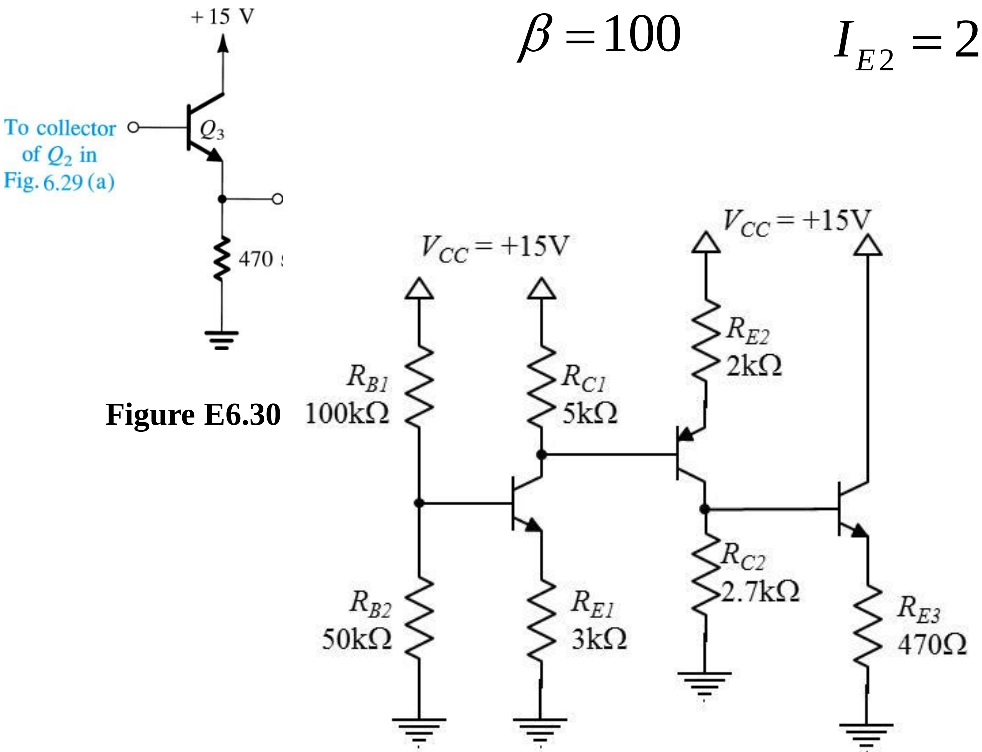


Figure E6.30

$$\beta = 100 \qquad I_{E2} = 2.78\text{mA} \qquad I_{C2} = 2.75\text{mA}$$

$$V_{E3} = V_{C2} - 0.70\text{V}$$

$$I_{E3} = \frac{V_{E3}}{470\Omega} = \frac{V_{C2} - 0.70\text{V}}{470\Omega} = 101 \times I_{B3}$$

$$= 101\left[2.75\text{mA} - \frac{V_{C2}}{2.7\text{k}\Omega}\right]$$

$$\Rightarrow V_{C2} = 7.06\text{V}$$

$$V_{E3} = V_{C2} - 0.7\text{V} = 6.36\text{V}$$

$$I_{C3} = \frac{V_{C2}}{470\Omega} \times \frac{100}{101} = 13.4\text{mA}$$

6.4 TRANSISTOR BREAKDOWN AND TEMPERATURE EFFECTS

BJT Breakdown

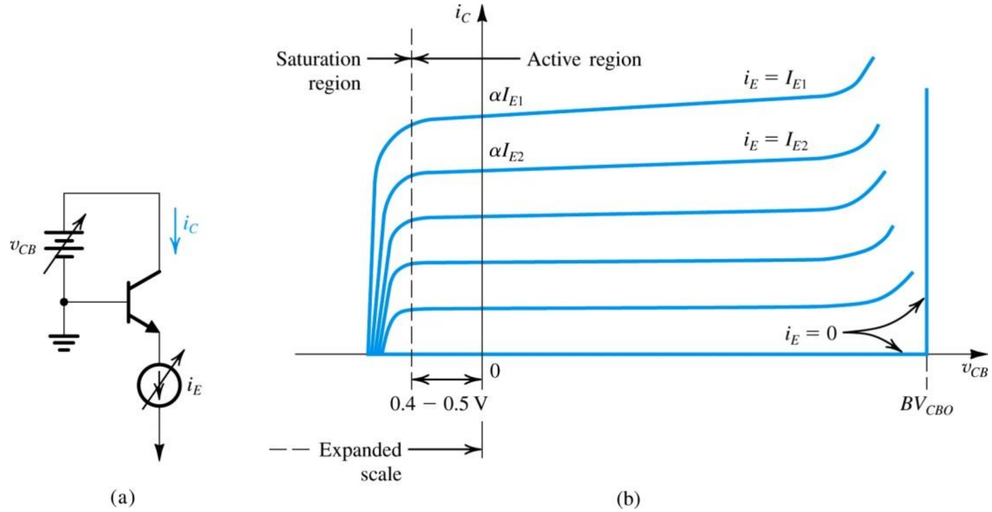


Figure 6.32 The BJT common-base characteristics including the transistor breakdown region.

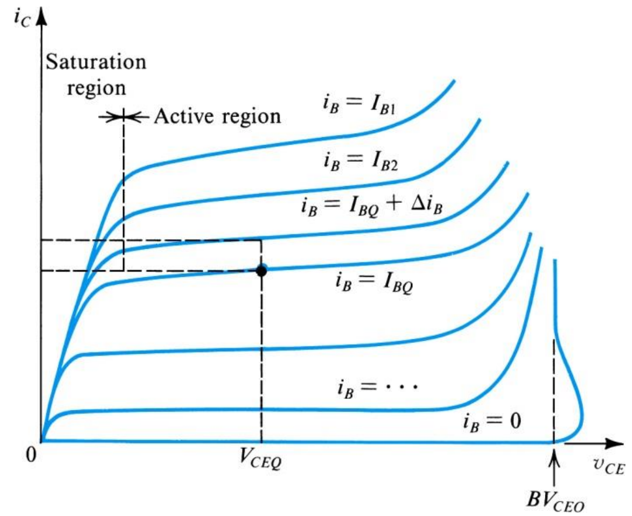


Figure 6.33 The BJT common-emitter characteristics including the breakdown region.

Exercise 6.33

What is the output voltage of the circuit in Fig. E6.33 if the transistor $BV_{BCO} = 70$ V?

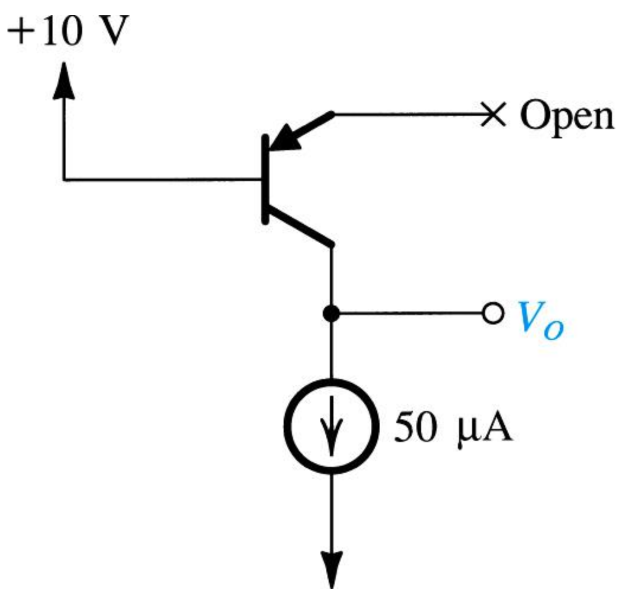


Figure E6.33

$$V_o = V_{BB} - BV_{BCO} = 10\text{V} - 70\text{V} = -60\text{V}$$

Effect of Bias and Temperature on β

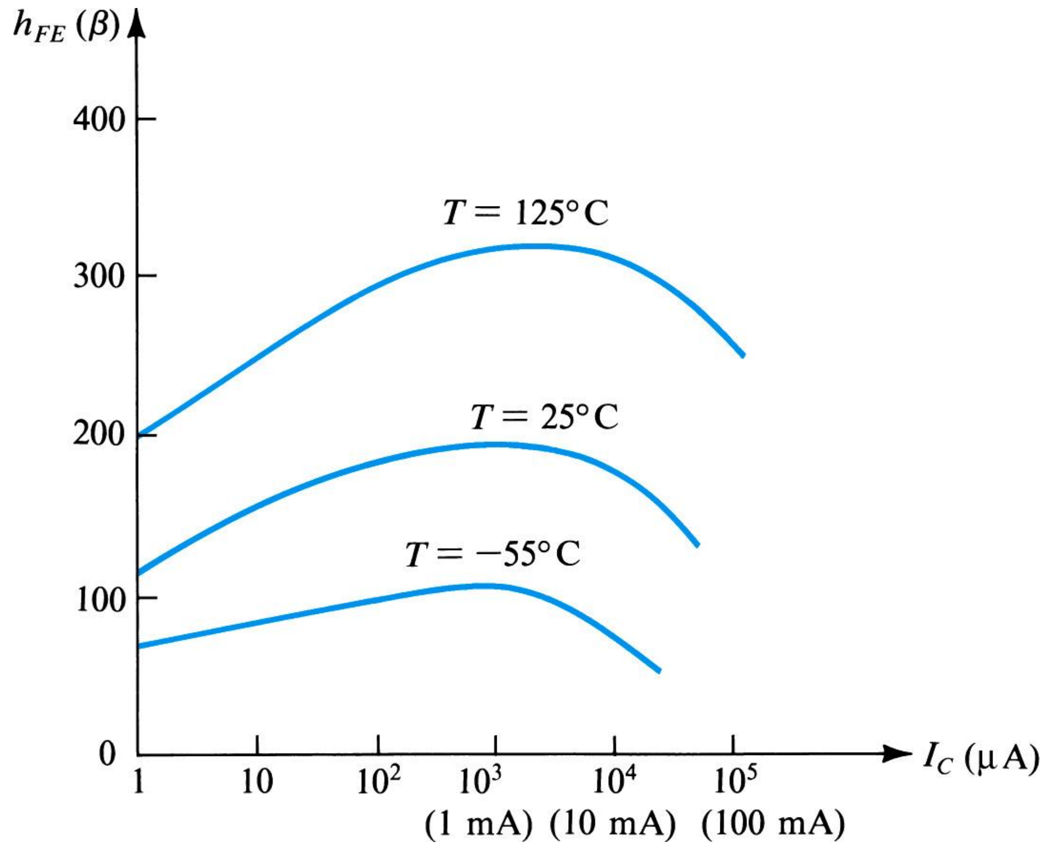


Figure 6.34 Typical dependence of β on I_C and on temperature in an integrated-circuit *npn* silicon transistor intended for operation around 1 mA.

Homework #12

- Read Chapter 6
- Chapter 6 Problems:
  - 6.35
  - 6.51
  - 6.58*
  - 6.61*

*** Answers in Appendix L**

Summary (a)

- Depending on the bias condition on its two junctions, the BJT can operate in one of three possible modes:
  - **cut-off** (both junctions reverse biased)
  - **active** (the EBJ forward-biased and CBJ reversed)
  - **saturation** (both junctions forward biased)
- For amplifier applications, the BJT is operated in the active mode. Switching applications make use of the cutoff and saturation modes.
- A BJT operating in the active mode provides a collector current $i_C = I_S\mathbf{exp}\{v_{BE}/V_T\}$. The base current $i_B = i_C/\beta$, and emitter current $i_E = i_C + i_B$.

Summary (b)

- To ensure operation in the active mode, the collector voltage of an *npn*-transistor must be kept higher than approximately $0.4V$ below the base voltage. For a *pnp*-transistor, the collector voltage must be lower than approximately $0.4V$ above the base voltage. Otherwise, the CBJ becomes forward-biased and the transistor will enter saturation.
- At a constant collector current, the magnitude of the base emitter voltage decreases by about $2mV$ for every 1^{O}C rise in temperature.
- The BJT will be at the edge of saturation when $|v_{CE}|$ is reduced to about 0.3 V. In saturation, $|v_{CE}| \simeq 0.2$ V, and the ratio of i_C to i_B is lower than β (i.e., $\beta_{forced} < \beta$).

Summary (c)

- In the active mode, i_C shows a slight dependence on v_{CE}. This phenomenon, known as the Early Effect, is modeled by ascribing a finite output resistance to the BJT: $r_o = |V_A|/I'_C$ where V_A is the Early Voltage and I'_C is the dc collector current without the Early Effect taken into account. In discrete circuits, r_o plays a minor role and can usually be neglected. This is *not* the case, however, in integrated-circuit design (Chapter 8).
- The dc analysis of transistor circuits is generally simplified by assuming $|V_{BE}| \simeq 0.7$V.

Summary (d)

- If the BJT is conducting, one assumes it is operating in the active mode and, using the active-mode model, proceeds to determine all currents and voltages. The validity of the initial assumption is then checked by determining whether the CBJ is reverse biased. If it is, the analysis is complete; otherwise, we assume the BJT is operating in saturation and redo the analysis, using the saturation-mode model and checking at the end that $I_C < \beta I_B$.