Lecture 11a

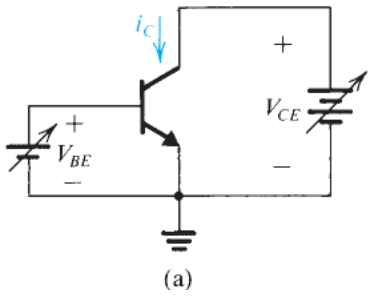
EE-215 Electronic Devices and Circuits

Asst Prof Muhammad Anis Chaudhary

BJT: Current-Voltage Characteristics

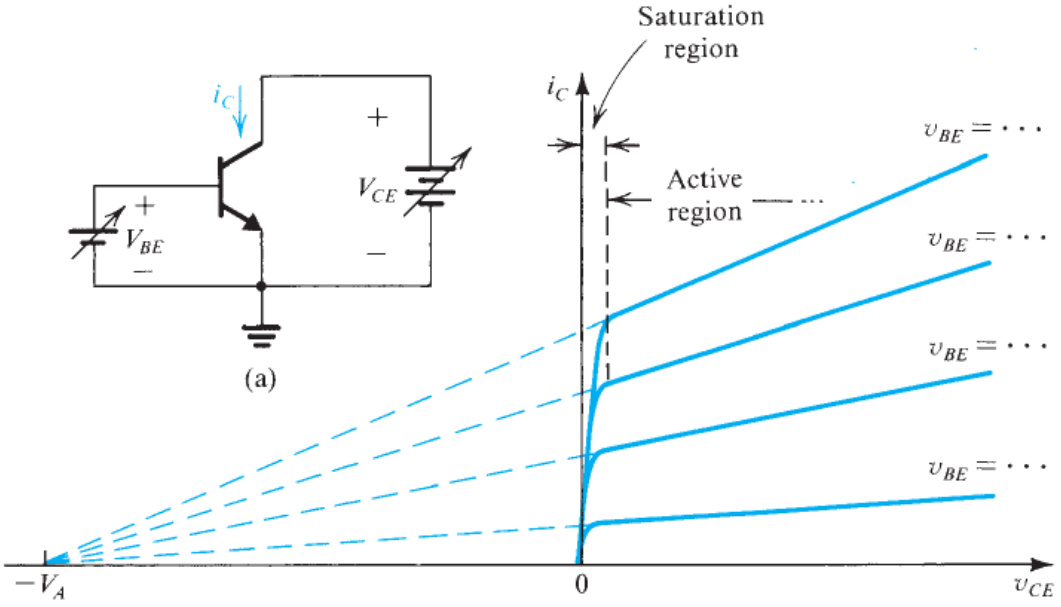
Dependence of i_C on the Collector Voltage - The Early Effect

- Consider the conceptual circuit shown in fig
    - here the transistor is connected in common-emmiter configuration
        - i.e. the emitter acts as a common terminal between the input and output ports
        - the voltage V_{BE} can be set to any desired value



(a)

- for each value of V_{BE}, the corresponding $i_C - v_{CE}$ characteristic curve can be measured point by point
    - by varying the dc voltage V_{CE} and measuring the corresponding i_C
- the resulting family of $i_C - v_{CE}$ characteristic curves are known as “common-emitter characteristics” and are shown in figure below



(b)

- it is clear from fig,

        - practical BJTs show dependence of i_C on the collector voltage, when operated in the active region ($v_{CE} > 0.3V$)
- Recall that, in active region
    - $i_C = I_S e^{v_{BE}/V_T}$ where $I_S = \frac{A_E q D_n n_i^2}{N_A W}$
    - $= \Rightarrow I_S \propto \frac{1}{W}$ or $i_C \propto \frac{1}{W}$
        - where W is the effective base-width
    - thus i_C is inversely proportional to the effective base-width in the active mode
    - At a given value of v_{BE}, increasing v_{CE} increases the reverse-bias voltage v_{CB} on the CBJ
        - and thus increases the width of the depletion region of the CBJ
        - which results in the decrease in the effective base width W

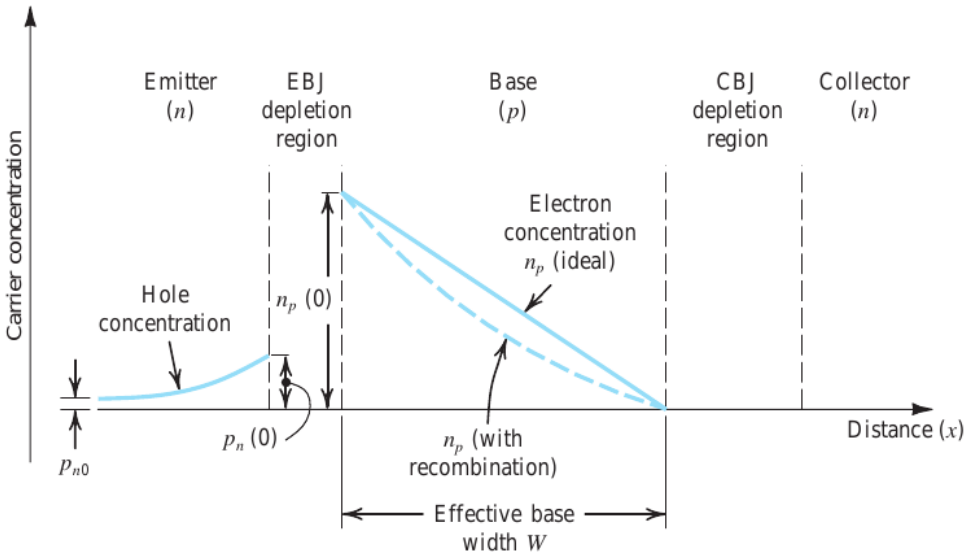
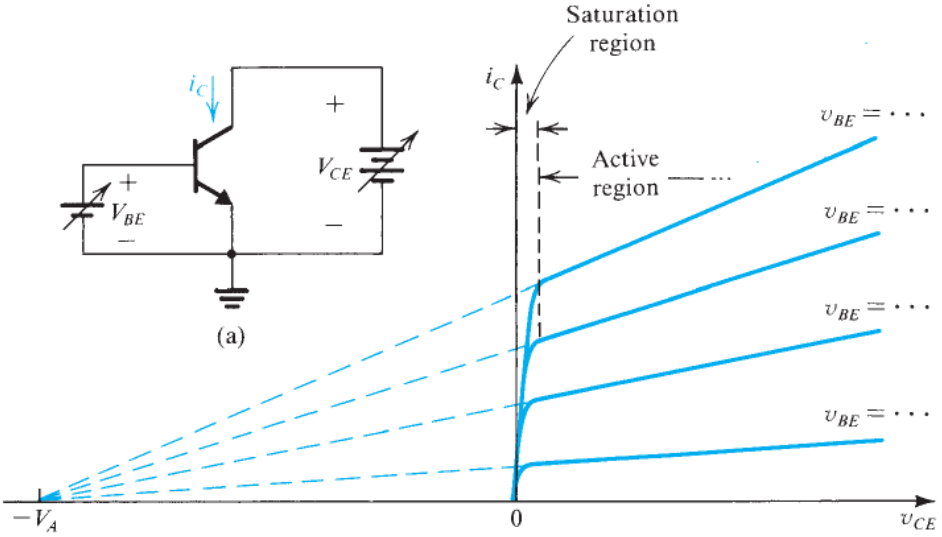
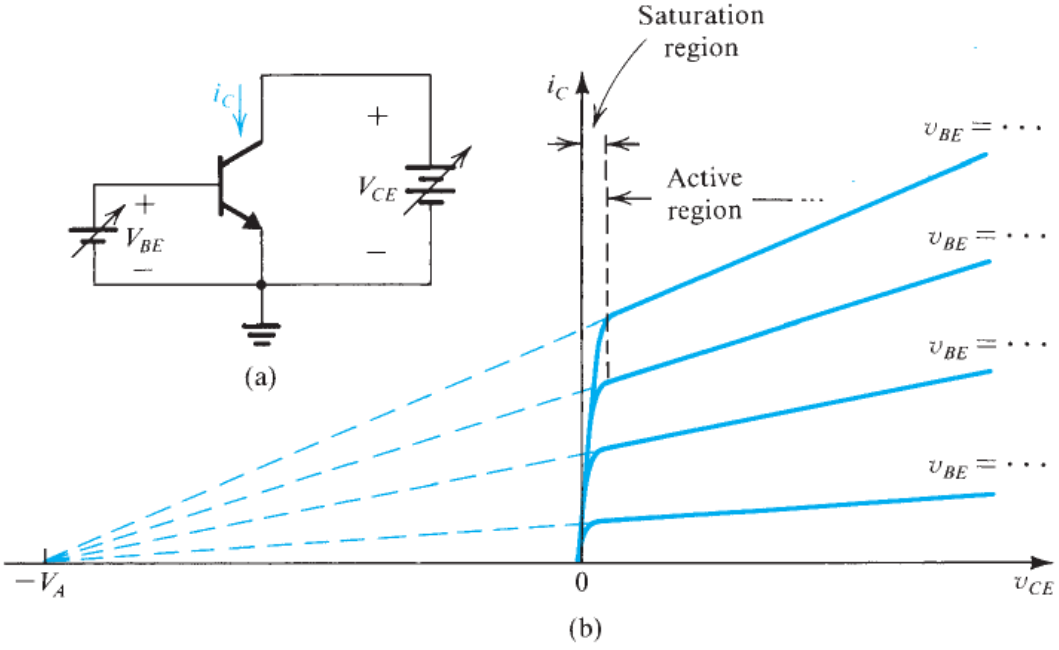


Figure 6.4 Profiles of minority-carrier concentrations in the base and in the emitter of an *npn* transistor operating in the active mode: $v_{BE} > 0$ and $v_{CB} \geq 0$.

    - As $i_C \propto \frac{1}{W}$, this decrease in effective base width results in an increase in i_C
    - This effect is called Early effect or base-width modulation effect
- As a consequency, the $i_C - v_{CE}$ characteristics are not perfectly horizontal straight lines
    - instead they have a finite slope (the chracteristics are straight lines with a finite slope)



- when extrapolated, the characteristic lines meet at a point on the negative v_{CE} axis, at $v_{CE} = -V_A$
- This voltage V_A is a positive number and is called Early voltage



- V_A is a parameter for the particular BJT, and typically lies in the range of 10V to 100V

- Consider the extrapolated lines shown in fig
  - using the straight line equation $y - y_1 = m(x - x_1)$
    - here $y = i_C$, $x = v_{CE}$, $(x_1, y_1)=(-V_A, 0)$, $(x_2, y_2)=(0.3, I_C')$
    - where I_C' is the value of the collector current with the Early effect neglected
- using the straight line equation $y - y_1 = m(x - x_1)$
  - here $y = i_C$, $x = v_{CE}$, $(x_1, y_1)=(-V_A, 0)$, $(x_2, y_2)=(0.3, I_C')$
    - where I_C' is the value of the collector current with the Early effect neglected
    - $m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{I_C' - 0}{0.3 - (-V_A)} = \frac{I_C'}{0.3 + V_A}$

- thus $y - y_1 = m(x - x_1) = \Rightarrow i_C - 0 = \frac{I_C'}{0.3+V_A}\left(v_{CE} - (-V_A)\right)$
- or $i_C = \frac{I_C'}{0.3+V_A}\left(v_{CE} + V_A\right)$
- As $V_A > 0.3 = \Rightarrow 0.3 + V_A \approx V_A$ ($\because$ typically $V_A = 10V \ to \ 100V$)
- $= \Rightarrow i_C \approx \frac{I_C'}{V_A}\left(v_{CE} + V_A\right) = \frac{I_C'}{V_A}v_{CE} + \frac{I_C'}{V_A}V_A = \frac{I_C'}{V_A}v_{CE} + I_C'$
- or $i_C = I_C' + \frac{I_C'}{V_A}v_{CE} = I_C'\left(1 + \frac{v_{CE}}{V_A}\right)$
- $i_C = I_C'\left(1 + \frac{v_{CE}}{V_A}\right) = I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$

- $i_C = I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$
  - the nonzero slope of the $i_C - v_{CE}$ straight lines indicates that
    - the output resistance looking into the collector is not infinite.
  - Rather it is finite and is defined as
    - $r_o = \left[\cdot \frac{\partial i_C}{\partial v_{CE}}\Big|_{v_{BE}=constant}\right]^{-1}$
  - substituting $i_C = I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$ into this relation
  - $r_o^{-1} = \cdot \frac{\partial i_C}{\partial v_{CE}}\Big|_{v_{BE}=constant} = \cdot \frac{\partial}{\partial v_{CE}}\left\{I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)\right\}\Big|_{v_{BE}=constant}$
  - $r_o^{-1} = I_S e^{v_{BE}/V_T}\frac{\partial}{\partial v_{CE}}\left(1 + \frac{v_{CE}}{V_A}\right) = I_C'\frac{\partial}{\partial v_{CE}}\left(1 + \frac{v_{CE}}{V_A}\right)$
- $r_o^{-1} = I_C'\frac{\partial}{\partial v_{CE}}\left(1 + \frac{v_{CE}}{V_A}\right) = I_C'\left(0 + \frac{1}{V_A}\right) = \frac{I_C'}{V_A}$
  - $r_o = \frac{V_A}{I_C'}$
  - where I_C' is the value of the collector current with the Early effect neglected
    - i.e. $I_C' = I_S e^{V_{BE}/V_T}$
  - it is rarely necessary to include the dependence of i_C on v_{CE} in dc bias design and analysis that is performed by hand.
  - The output resistance r_o can be easily included in the circuit model of the transistor
- fig shows the large-signal circuit models of a common-emitter npn transistor operating in the active mode

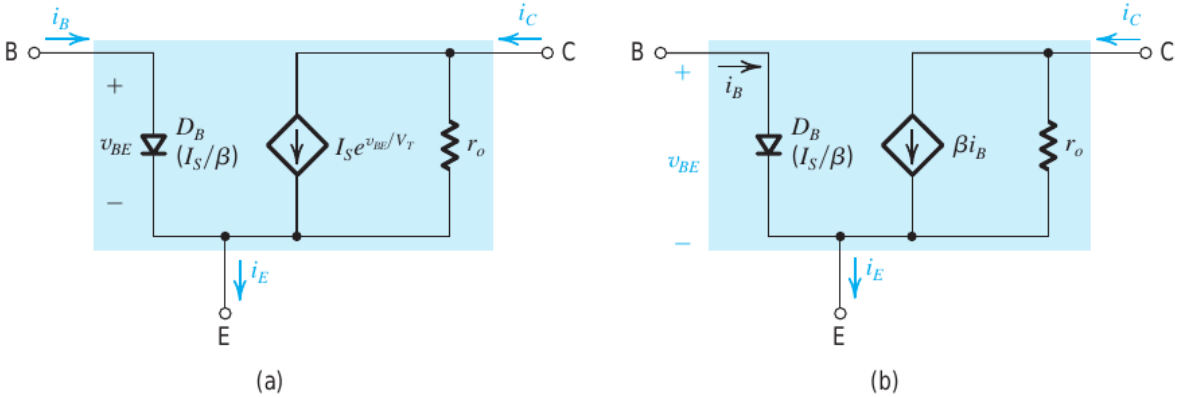


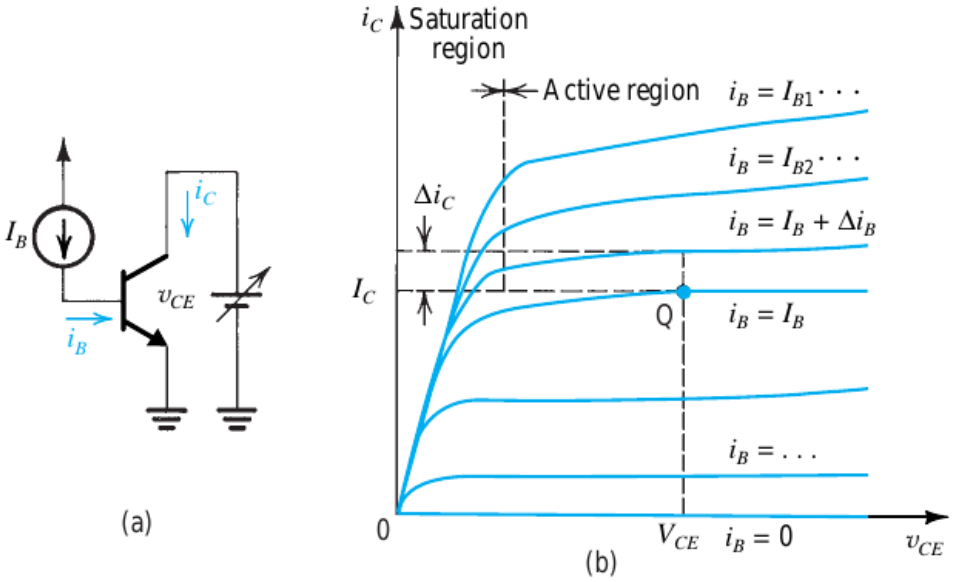
Figure 6.18 Large-signal equivalent-circuit models of an *npn* BJT operating in the active mode in the common-emitter configuration with the output resistance r_o included.

- Note that here the resistance r_o is connected between the collector and the emitter terminals

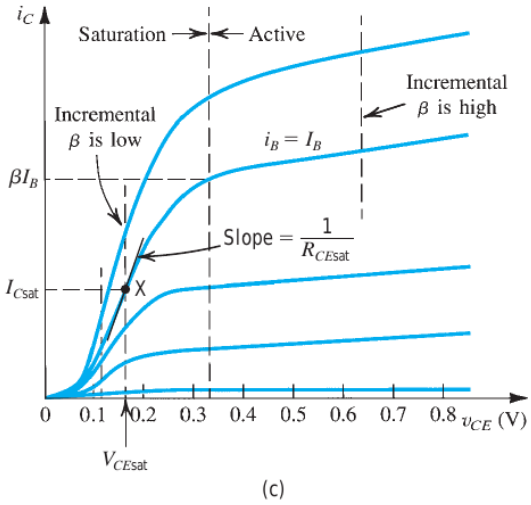
BJT: Current-Voltage Characteristics

An Alternative Form of the Common-Emitter Characteristics

- An alternative way of expressing the transistor common-emitter characteristics is shown in fig



- here the base current i_B rather than v_{BE} is used as a parameter
  - i.e. each $i_C - v_{CE}$ curve is measured with the base fed with a constant current I_B
- the expanded view of the common emitter characteristics in the saturation region is shown in figure
  - Note that the $i_C - v_{CE}$ curves in the saturation region are rather steep,
    - $= \Rightarrow$ the saturated transistor exhibits a low collector-to-emitter resistance R_{CEsat}
      - $R_{CEsat} = . \left. \frac{\partial v_{CE}}{\partial i_C} \right|_{\substack{i_B = I_B \\ i_C = I_{Csat}}}$
      - typically, R_{CEsat} ranges from a few ohms to a few tens of ohms



(c)

- A simple model for the saturated BJT utilizing the constant voltage drop model for EBJ and CBJ can be given as
    - here V_{BE} is assumed constant i.e. $V_{BE} \approx 0.7V$
        - as V_{BE} ranges from 0.6V-0.8V
        - and V_{CE} also is assumed constant, i.e. $V_{CEsat} \approx 0.2V$
            - as V_{CE} ranges from 0.1-0.3V

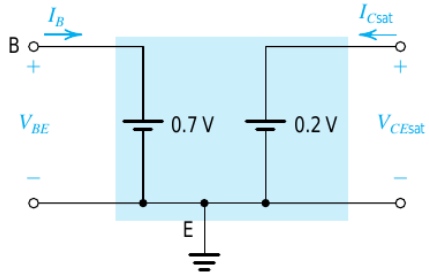


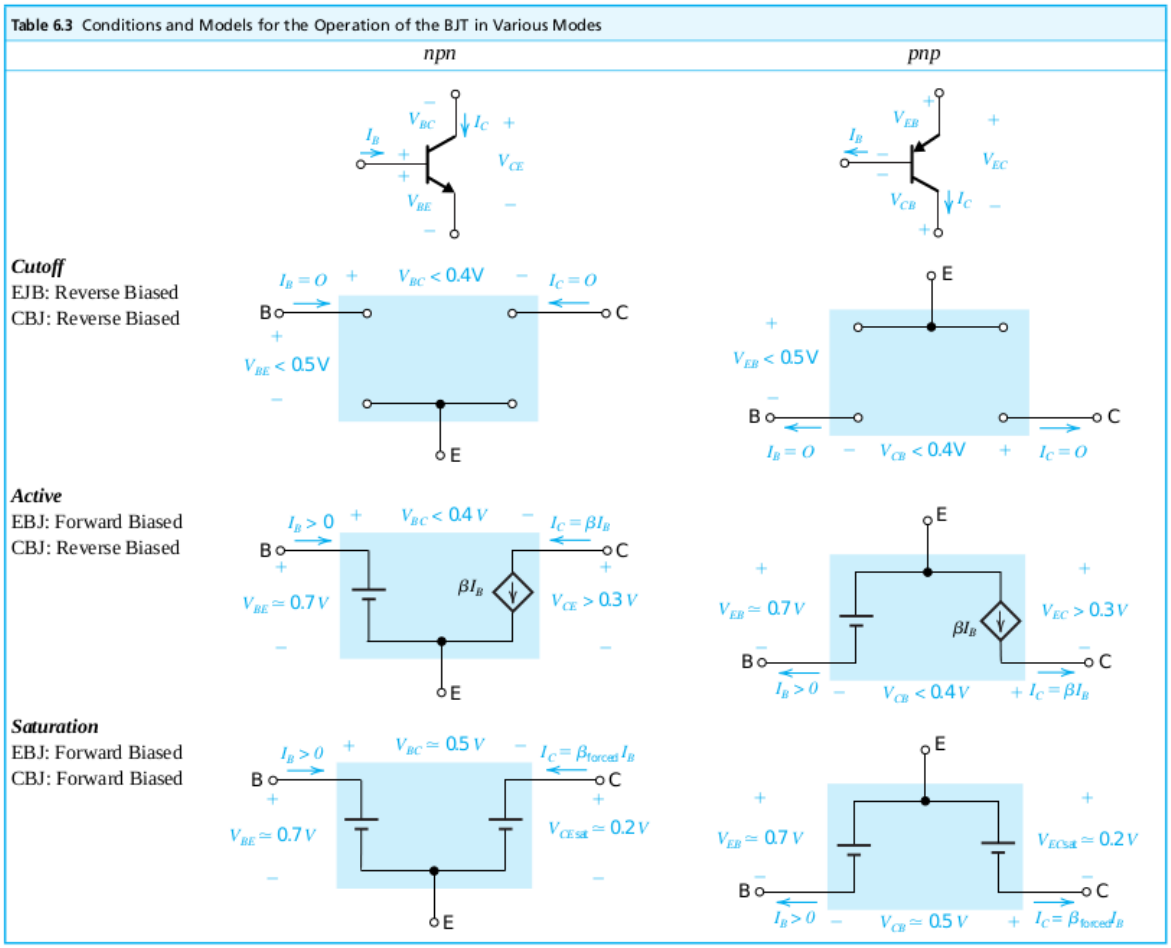
Figure 6.20 A simplified equivalent-circuit model of the saturated transistor.

    - Note that here we have neglected the small saturation resistance R_{CEsat}, to make the model simple for hand calculations

BJT Circuits at DC

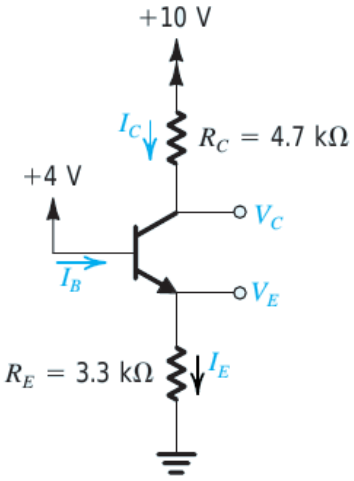
- to analyze the BJT circuits, to which only dc voltages are applied,
    - we will use the simple model in which
        - $|V_{BE}|$ of a conducting transistor is 0.7V
        - and $|V_{CE}|$ of a saturated transistor is 0.2 V
    - we can neglect the Early effect in dc analysis
    - In analyzing a circuit, the first question that one must answer
        - is In which mode is the transistor operating?
    - based upon the terminal voltages, one need to determine whether the BJT is cutoff or conducting
    - if the tranistor is conducting,
        - we need to determine whether it is operating in the active mode or in saturation
- if it is not clear whether the BJT is in active mode or saturation, proceed as follows

- Assume the transistor is in active mode
  - determine the various voltages and currents
  - then check for consistency of the results with the assumption of active-mode operation
  - i.e. $v_{CB} > -0.4$ for an npn and $v_{BC} > -0.4$ for a pnp
  - if the answer is yes, then our task is complete.
  - otherwise assume saturation mode operation and proceed with the analysis
- Note that to test the validity of the assumption of saturation-mode operation,
  - one can compute the ratio I_C/I_B and verify if this ratio is lower than β i.e. $\beta_{forced} < \beta$
  - As β for a given transistor varies over a wide range, use the lowest specified β for this test.



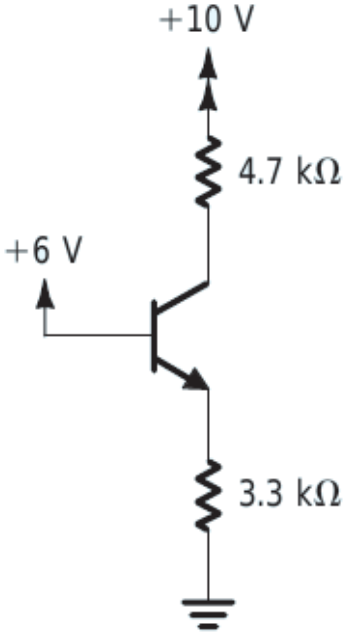
Example 6.4

- Consider the circuit shown in Fig. 6.22(a). We wish to analyze this circuit to determine all node voltages and branch currents. We will assume that β is specified to be 100.



Example 6.5

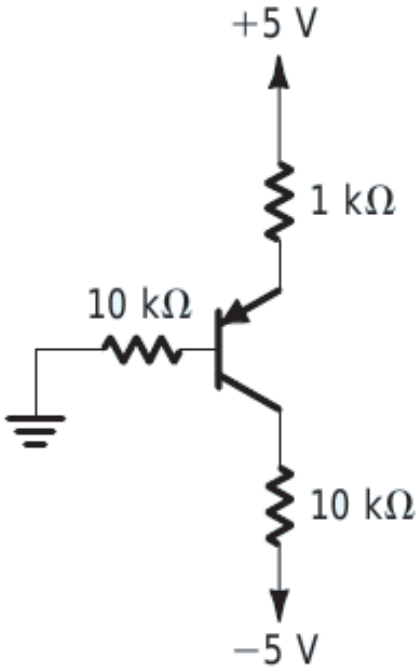
- We wish to analyze the circuit of Fig. 6.23(a) to determine the voltages at all nodes and the currents through all branches. Note that this circuit is identical to that of Fig. 6.22 except that the voltage at the base is now +6 V. Assume that the transistor β is specified to be at least 50.



Example 6.6

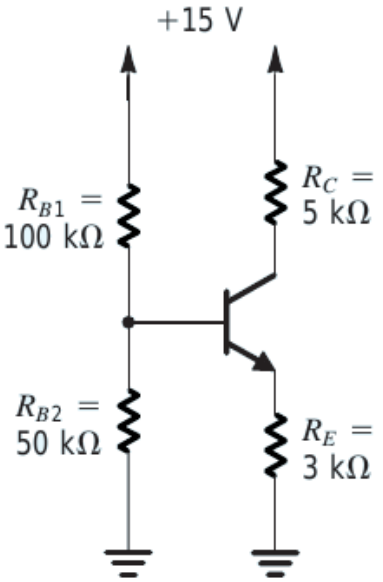
Example 6.9

- We want to analyze the circuit of Fig. 6.27(a) to determine the voltages at all nodes and the currents through all branches. The minimum value of β is specified to be 30.



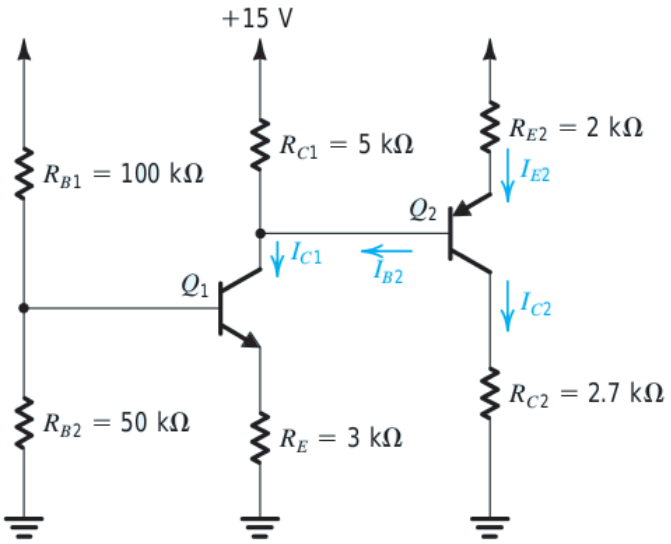
Example 6.10

- We want to analyze the circuit of Fig. 6.28(a) to determine the voltages at all nodes and the currents through all branches. Assume $\beta = 100$.



Example 6.11

- We want to analyze the circuit in Fig. 6.29(a) to determine the voltages at all nodes and the currents through all branches. Assume $\beta = 100$ for both transistors.


+15 V
$R_{B1} = 100\ \text{k}\Omega$
$R_{C1} = 5\ \text{k}\Omega$
$R_{E2} = 2\ \text{k}\Omega$
I_{E2}
Q_2
I_{C1}
I_{B2}
Q_1
I_{C2}
$R_{C2} = 2.7\ \text{k}\Omega$
$R_{B2} = 50\ \text{k}\Omega$
$R_E = 3\ \text{k}\Omega$