CHAPTER 6

Bipolar Junction Transistors (BJTs)

Outlines

- 6.1 Device structure and physical operation
- 6.2 Current-voltage characteristics
- 6.3 BJT circuits at dc

6.1 Device structure and physical operation

- 6.2.1 Simplified structure and operations
  - NPN and PNP BJT

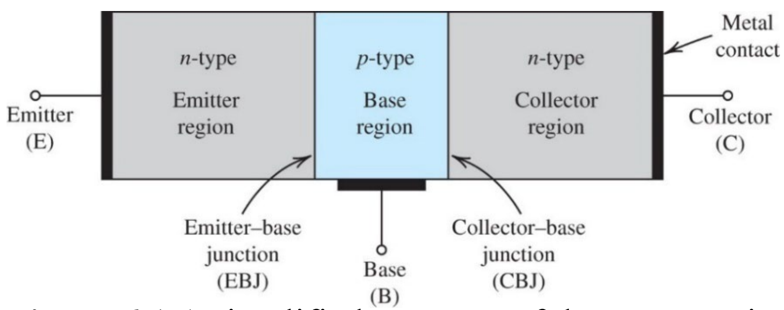


Figure 6.1 A simplified structure of the *npn* transistor.

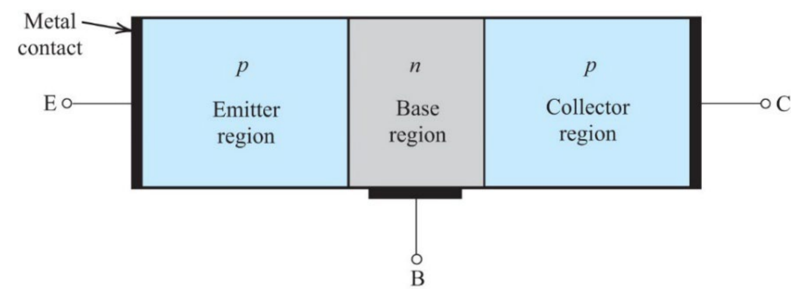
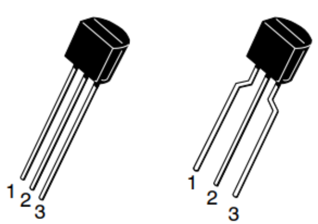
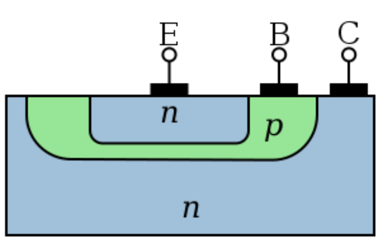
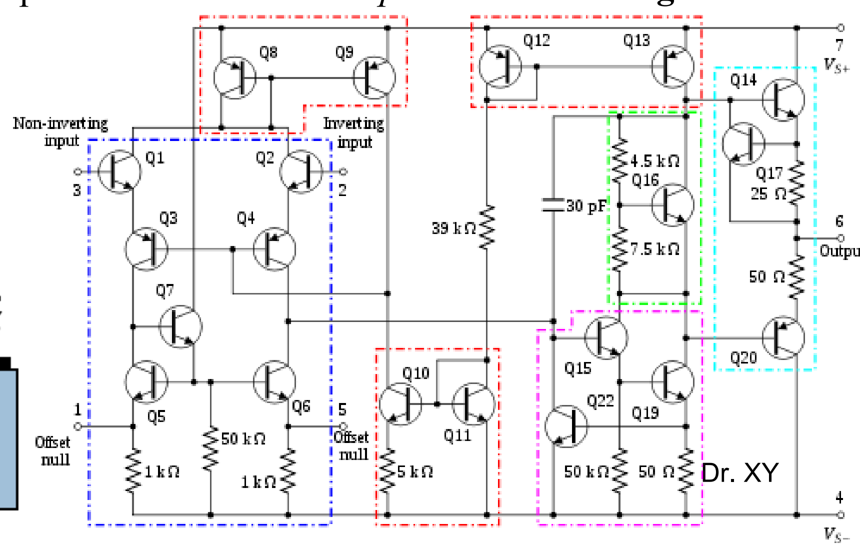
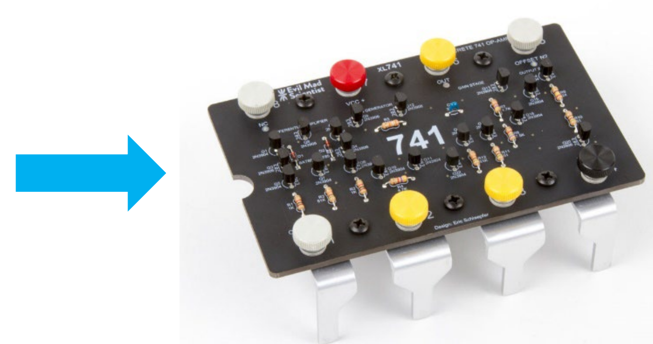


Figure 6.2 A simplified structure of the *pnp* transistor.





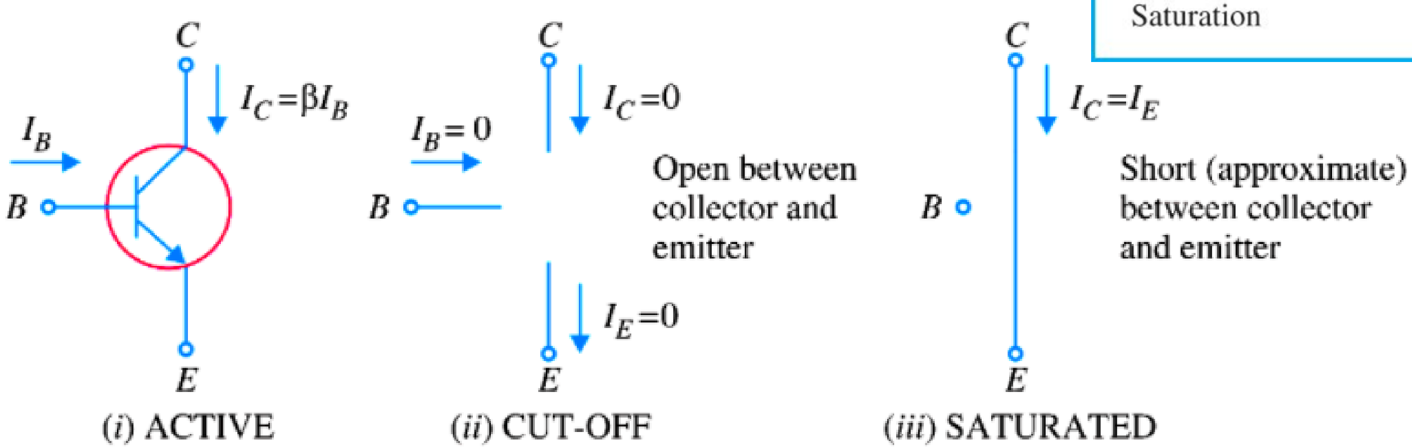




- 6.2.1 Operational modes
  - Cutoff region: There is no base current, so no collector or emitter current.
  - Active region: Collector current is β × base current. BE junction forward bias, or $V_{BE} \approx 0.7V$
  - Saturation region: The collector and emitter are, in effect, shorted together. The transistor behaves a short circuit $V_{BE} \approx 0.7V$

Table 6.1 BJT Modes of Operation

Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward



- 6.1.2 Operational Region of the NPN transistor
  - V_{BE} reverse bias: <u>Cutoff</u>
  - V_{BE} forward bias: <u>Conducts</u>

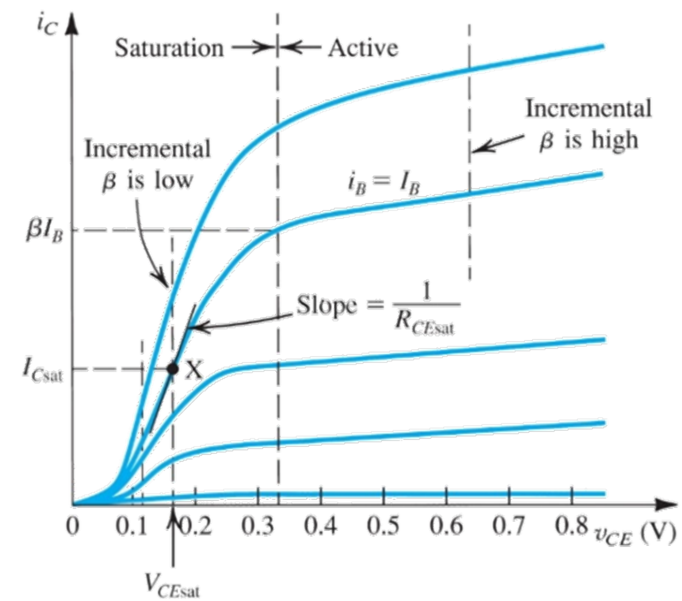
    $I_E = I_C + I_B$; $V_{BE} = 0.7V$

    - Active region: V_{BC} reverse bias ($V_{BC} \leqslant 0.4V$)

      → $V_{CE} \geq 0.3V$: $I_C = \beta I_B$

    - Saturation region: V_{BC} forward bias ($V_{BC} > 0.4V$)

      → $V_{CE} < 0.3V$: $I_C = \beta_{force} I_B$



(c)

- 6.1.2 Operation in the active Region

  $I_C = \beta I_B$ or $I_B = \frac{I_C}{\beta}$,

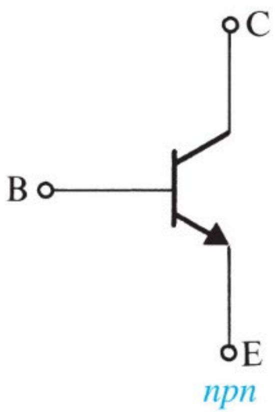
  - β: Common-emitter current gain -- a transistor parameter (50~200)

  $I_E = I_C + I_B$

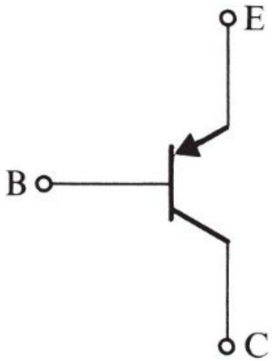
  - $I_E = \beta I_B + I_B = (\beta + 1)I_B$
  - $I_E = I_C + \frac{I_C}{\beta} = \frac{\beta+1}{\beta} I_C$ or $I_C = \frac{\beta}{\beta+1} I_E = \alpha I_E$
    - $\alpha = \frac{\beta}{\beta+1}$ common base current gain

- 6.1.4 Operation in the saturation mode

  $$\beta_{force} = \frac{I_C}{I_B}|_{saturation} \ll \beta$$



- 6.1.5 Operation of the PNP transistor in the active mode
  - V_{EB} makes EB forward bias, V_{CB} makes the CB reverse bias.
  - $I_E = I_C + I_B$, (I_B current is leaving the transistor)
  - Difference: $V_{BE} \Rightarrow V_{EB}$ $V_{CB} \Rightarrow V_{BC}$



pnp

6.2 Current-voltage characteristics

- 6.2.1 Circuit symbols and conventions
  - NPN active:
    - BE junction is forward-bias ($V_{BE} \approx 0.7V$)
    - CB junction is reverse-bias ($V_C - V_B > -0.4V$, or $V_{CE} > 0.3V$)
  - PNP active:
    - EB junction is forward-bias ($V_{EB} \approx 0.7V$)
    - BC junction is reverse-bias ($V_B - V_C > -0.4V$, or $V_{EC} > 0.3V$)

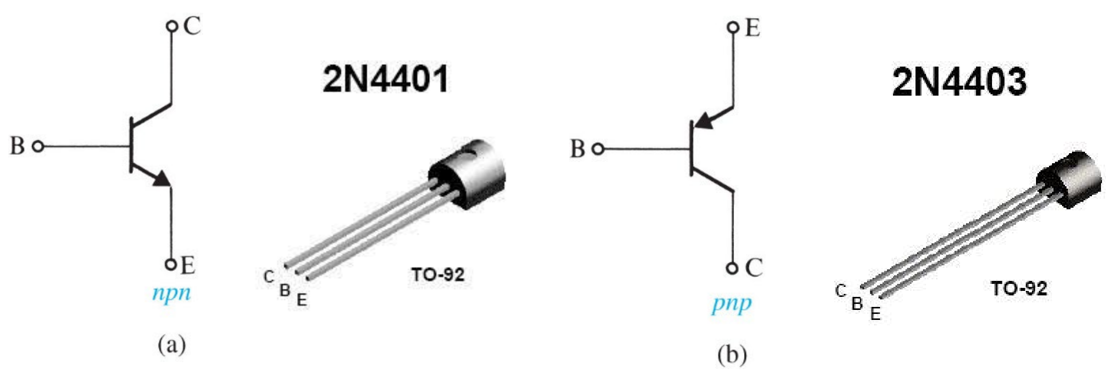


Figure 6.12 Circuit symbols for BJTs.

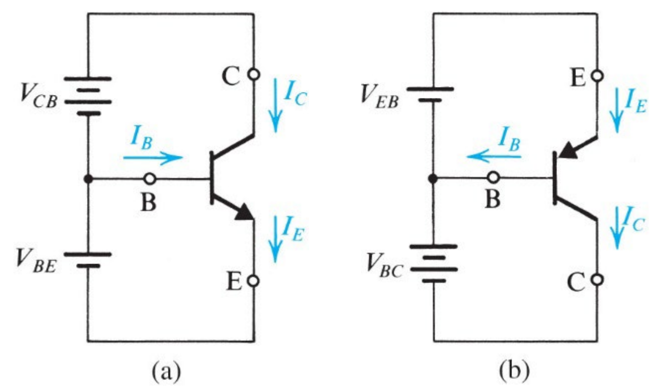


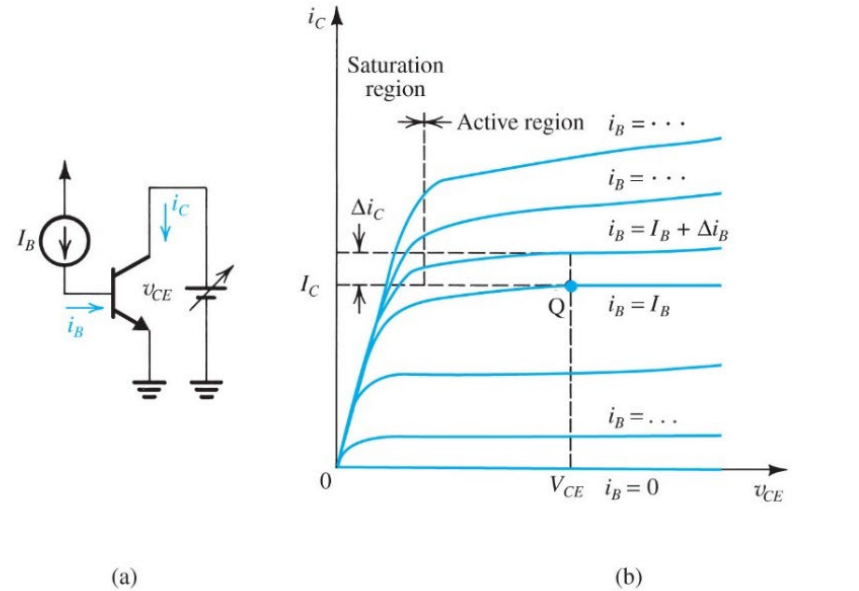
Figure 6.13 Voltage polarities and current flow in transistors operating in the active mode.

- 6.2.4 An alternative form of the common-emitter characteristics
  - Saturation region:
    - $I_{Csat} = \beta_{forced} I_B$

      $\beta_{forced} < \beta$
    - $V_{BE} \approx 0.7V$
    - $V_{CEsat} < 0.3V$

Active-Saturation edge $V_{CE} = 0.3V$

Deep saturation: $V_{CE} = 0.2V$



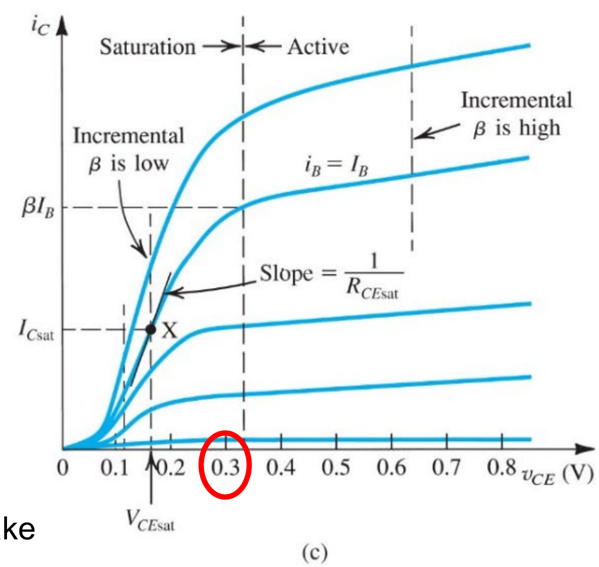


Figure 6.20 Common-emitter characteristics. (**a**) Basic CE circuit; note that in (**b**) the horizontal scale is expanded around the origin to show the saturation region in some detail. A much greater expansion of the saturation region is shown in (**c**).

- Example 6.3

$V_{BE} = 0.7V$ and $\beta = 50$. Find V_{BB} that results in the transistor operating
(a) In the active mode with $V_{CE} = 5V$ (b) At the edge of saturation ($V_{CE} = 0.3V$)
(c) Deep in saturation ($V_{CEsat} = 0.2V$) with $\beta_{forced} = 10$

(a) $I_C = \frac{V_{CC}-V_{CE}}{1} = \frac{10-5}{1} = 5\text{mA}$

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

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

(b) $I_C = \frac{V_{CC}-V_{CE}}{1} = \frac{10-0.3}{1} = 9.7mA$

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

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

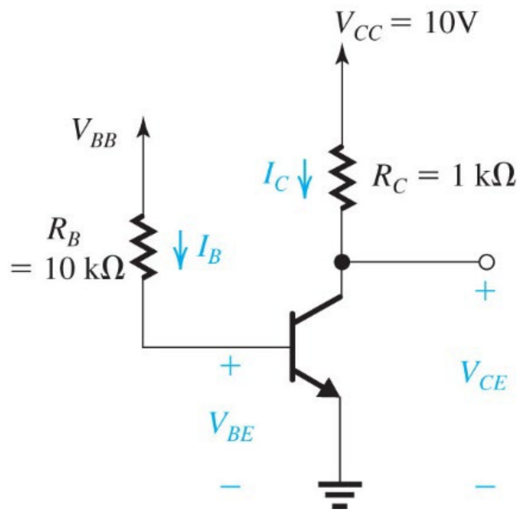


Figure 6.22 Circuit for Example 6.3.

- # Example 6.3

$V_{BE} = 0.7V$ and $\beta = 50$. Find V_{BB} that results in the transistor operating
(a) In the active mode with $V_{CE} = 5V$ (b) At the edge of saturation ($V_{CE} = 0.3V$)
(c) Deep in saturation ($V_{CEsat} = 0.2V$) with $\beta_{forced} = 10$

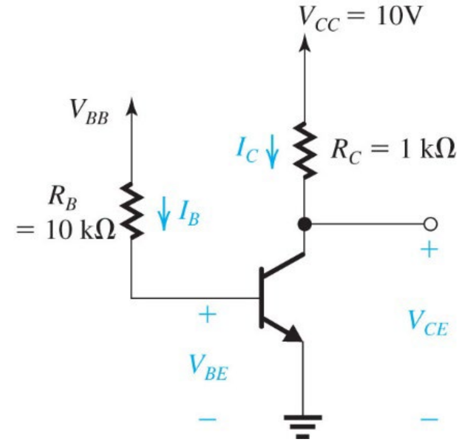


Figure 6.22 Circuit for Example 6.3.

(c) $I_C = \frac{V_{CC}-V_{CEsat}}{1k\Omega} = \frac{10V-0.2V}{1k\Omega} = 9.8mA$

$I_B = \frac{I_C}{\beta_{force}} = \frac{9.8mA}{10} = 0.98mA,$

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

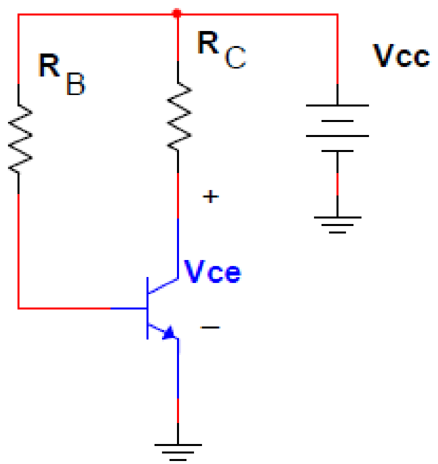
In saturation region, increasing V_{BB} and thus I_B results in negligible change in I_C since V_{CEsat} changes only slightly. Thus I_C is saturated!

• Experiment 8.1

$V_{CC} = 10V$, $R_C = 1k\Omega$.

Find R_B for the following condition for when $V_{CE} = 4V, 5V$, and $8V$.

Measure V_{CE}, V_{BE}, and V_{CB}. In which region does the BJT operate for each corresponding R_B?

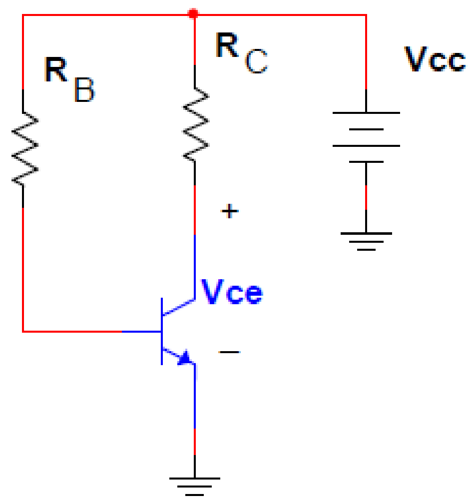


V_{CE} ?	R_B	V_{CE}	V_{BE}	Region
4V				
5V				
8V				

- Experiment 8.2

$V_{CC} = 10V$, $R_C = R_B = 1k\Omega$.

Measure V_{CE}, V_{BE}, and V_{CB}. In which region does the BJT operate for corresponding R_B?



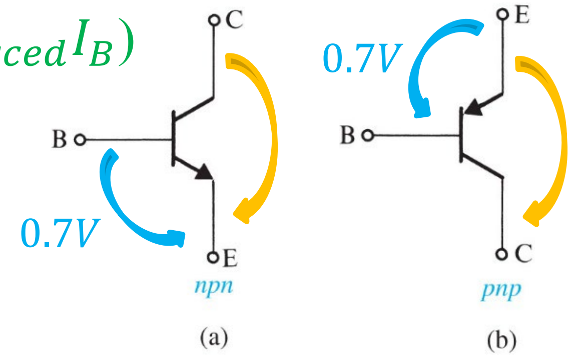
V_{CE}	V_{BE}	Region

6.3 BJT circuits at dc

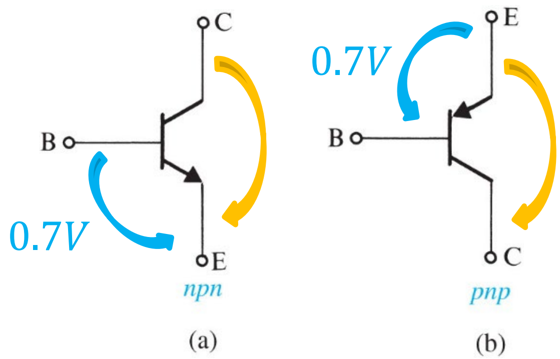
- In which mode is the transistor operating

Top-Bottom (TB) rule: Top greater than bottom!

- First TB (EBJ)?
  - **T>B** ($V_B > V_E$ for NPN and $V_E > V_B$ for PNP) => Conducting ($|V_{BE}| = 0.7V$)
  - **T<B** => **Cutoff**
- Second TB (CBJ)?
  - **T>B** ($V_{CE} > 0.3V$ for NPN and $V_{EC} > 0.3V$ for PNP) => **Active** ($I_C = \beta I_B$)
  - **T<B** => **Saturation** ($|V_{CE}| = 0.2V$, $I_C = \beta_{forced} I_B$)



- Analysis procedure
  - Find conduction (V_B $VS.V_E$: First TB rule)
    - If conducting ($|V_{BE}| = 0.7V$) -> assume in active mode first
    - If not conducting, in cutoff
  - Proceeds all currents and voltages
  - Find active (V_C $VS.V_B$: Second TB rule)
    - In active, $I_C = \beta I_B$
    - If not active, in saturation mode ($|V_{CE}| = 0.2V$) -> redo the analysis



• Example 6.4

Assume $\beta = 100$, analyze this circuit to determine all node voltages and branch currents.

1) Glancing BE is forward bias ($V_{BE} \approx 0.7V$), so the transistor conducts.

KCL1: $4 - 0.7 - I_E R_E = 0$

$$I_E = \frac{3.3}{R_E} = 1mA$$

2) Assume in active mode.

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

$$V_C = 10V - I_C R_c = 10 - 0.99 \times 4.7 = 5.3V$$

So $V_{CE} = 2V > 0.3V$, in active mode.

$$I_B = \frac{I_E}{1+\beta} = \frac{1}{101} \approx 0.01mA$$

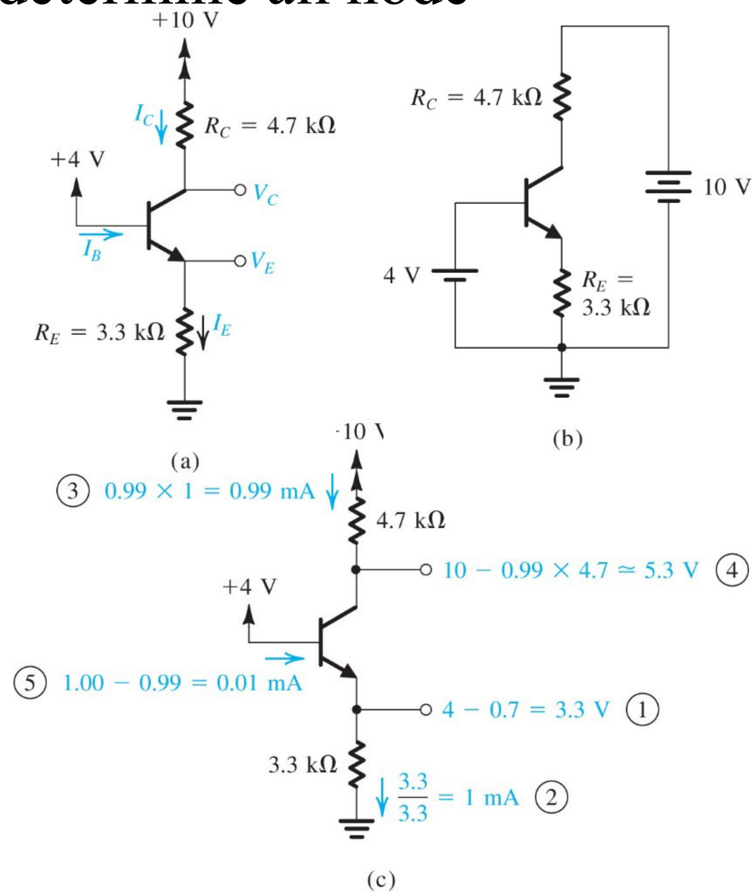


Figure 6.23 Analysis of the circuit for Example 6.4: (**a**) circuit; (**b**) circuit redrawn to remind the reader of the convention used in this book to show connections to the dc sources; (**c**) analysis with the steps numbered.

• Example 6.5

Assume $\beta = 100$, analyze this circuit to determine all node voltages and branch currents. (Hint: if in saturation, $V_{CE} \approx 0.2V$)

1) Glancing BE is forward bias ($V_{BE} \approx 0.7V$),

so the transistor conducts.

KCL1: $6 - 0.7 - I_E R_E = 0$

$$I_E = \frac{5.3}{R_E} = 1.6mA$$

2) Assume in active mode.

$I_C \approx I_E, V_C = 10 - I_C R_c = 10 - 1.6 \times 4.7 = 2.48V$

$V_{CE} = (2.48 - 5.3) < 0.3V$, the assumption is incorrect

3) So reassume in saturation mode ($V_{CE} \approx 0.2V$)

KCL2: $10 - I_C \times 4.7 - 0.2 - I_E \times 3.3 = 0$

Since $I_E = 1.6mA$ (won't change), $I_C = \frac{10-5.5}{4.7} = 0.96mA$

$I_B = I_E - I_C = 1.6 - 0.96 = 0.64mA$

The force β is $\beta_{forced} = \frac{I_C}{I_B} = 1.5$

$V_E = I_E \times 3.3 = 5.3$ V $So\ V_C = V_E + 0.2 = 5.5V$

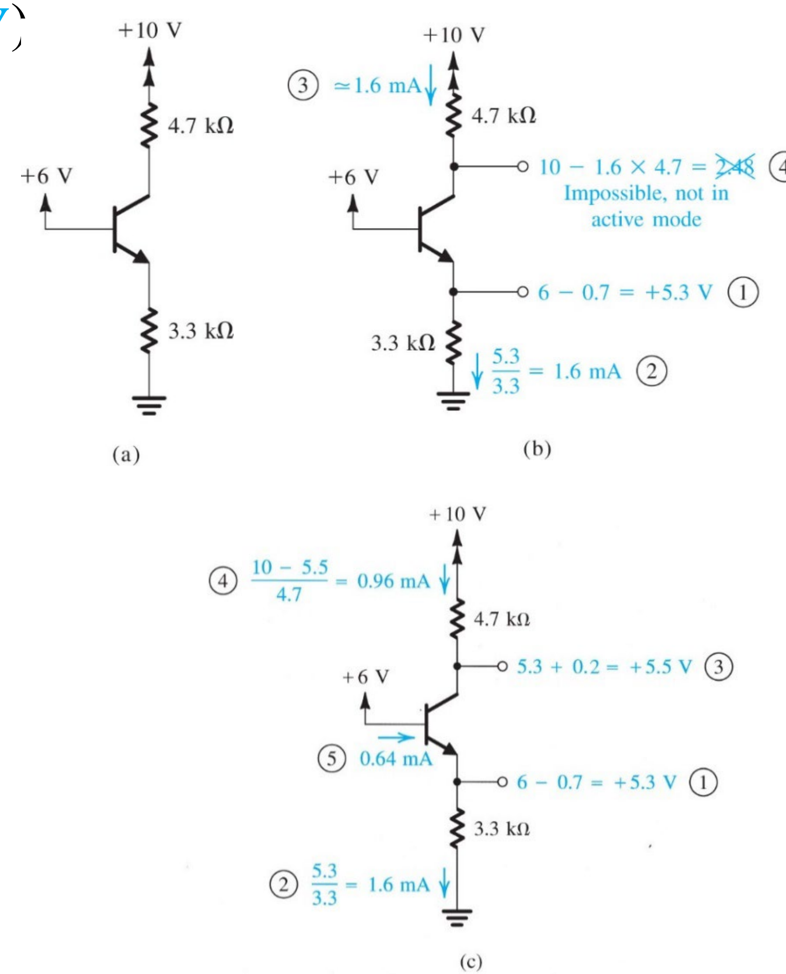


Figure 6.24 Analysis of the circuit for Example 6.5. Note that the circled numbers indicate the order of the analysis steps.

- # Example 6.6

Analyze this circuit to determine all node voltages and branch currents.

Since the base is directly connected to ground and emitter is connected to ground through R_E, the BE cannot conducted and $I_E = 0$

So the transistor is cutoff.

Thus, $I_C = I_B = I_E = 0$

$V_C = 10V, V_B = V_E = 0$

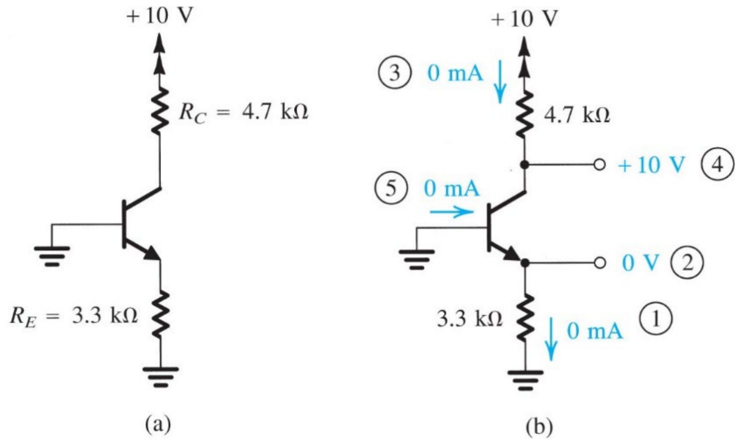
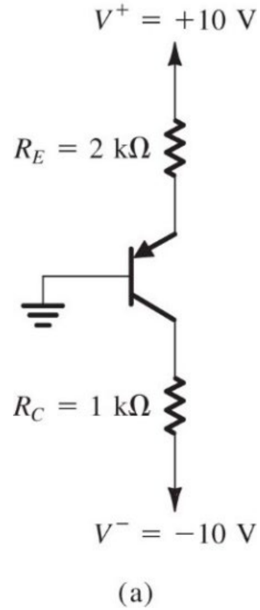


Figure 6.25 Example 6.6: (**a**) circuit; (**b**) analysis, with the order of the analysis steps indicated by circled numbers.

- Example 6.7

Assume $\beta = 100$, analyze this circuit to determine all node voltages and branch currents.



1) Glancing EB is forward bias ($V_{EB} \approx 0.7V$), so the transistor conducts.

KCL1: $10 - I_E R_E - 0.7 = 0$

$$I_E = \frac{9.3}{R_E} = 4.65mA$$

2) Assume in active mode.

$$I_C = \alpha I_E = \frac{\beta}{1+\beta} I_E = 0.99 \times 4.65 = 4.6mA$$

$$V_C = -10 + I_C R_c = -10V + 4.6 \times 1 = -5.4V$$

So $V_{EC} = 6.1V > 0.3V$, in active mode.

$$I_B = \frac{I_c}{\beta} = \frac{4.6}{100} = 0.046mA$$

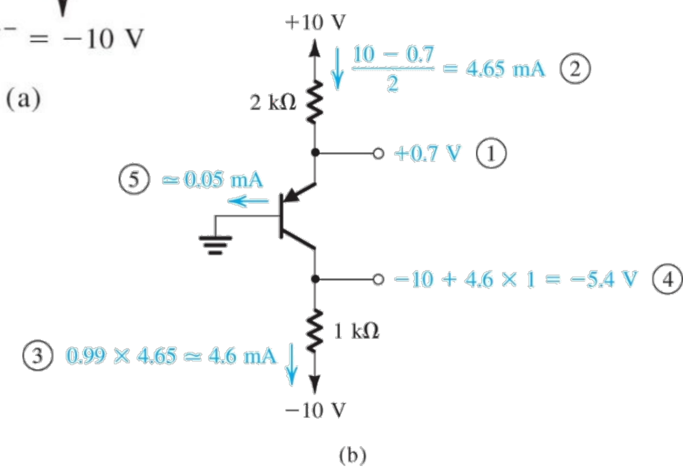


Figure 6.26 Example 6.7: (**a**) circuit; (**b**) analysis, with the steps indicated by circled numbers

• Example 6.8

Assume $\beta = 100$, analyze this circuit to determine all node voltages and branch currents.

1) Glancing BE is forward bias ($V_{BE} \approx 0.7V$),

so the transistor conducts.

KCL1: $5 - I_B R_B - 0.7 = 0$

$$I_B \approx \frac{4.3}{R_B} = 0.043mA$$

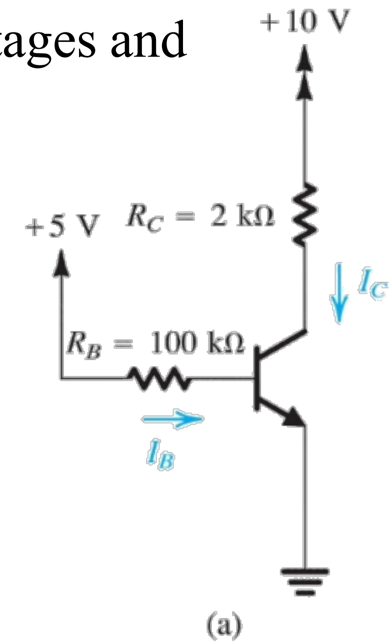
2) Assume in active mode.

$$I_C = \beta I_B = 4.3mA$$

$$V_C = 10V - I_C R_c = 10 - 4.3 \times 2 = 1.4V$$

$V_{CE} = 1.4V > 0.3V$, in active mode.

$$I_E = I_C + I_B = 4.343mA \approx 4.3mA$$



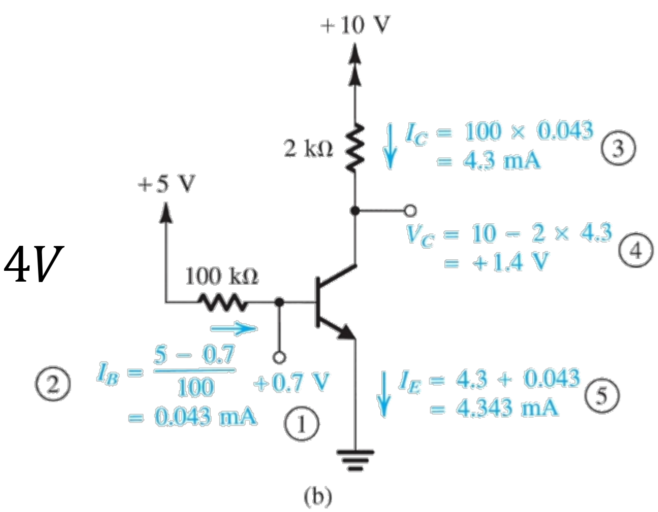


Figure 6.27 Example 6.8: (**a**) circuit; (**b**) analysis, with the steps indicated by the circled numbers.

• Example 6.9

Assume $\beta = 30$, analyze this circuit to determine all node voltages and branch currents. (Hint: if in saturation, $V_{CE} \approx 0.2V$)

1) Glancing EB is forward bias ($V_{EB} \approx 0.7V$), so the transistor conducts.

KCL1: $5 = I_B \times 10 + I_E \times 1 + 0.7$

$I_E = 4.3 - I_B \times 10$

2) Assume in active mode.

$I_E = (\beta + 1)I_B = 31I_B$

Thus $I_B = 0.105mA \quad I_E = 3.255mA$

$I_C = \beta I_B = 30 \times 0.105 = 3.15mA$

$V_B = I_B \times 10 = 1.05V \quad V_E = V_B + 0.7 = 1.75V$

$V_C = -5 + I_C R_c = -5 + 3.15 \times 10 = 26.5V$

Since $V_{EC} < 0.3V$, so must be in saturation mode.

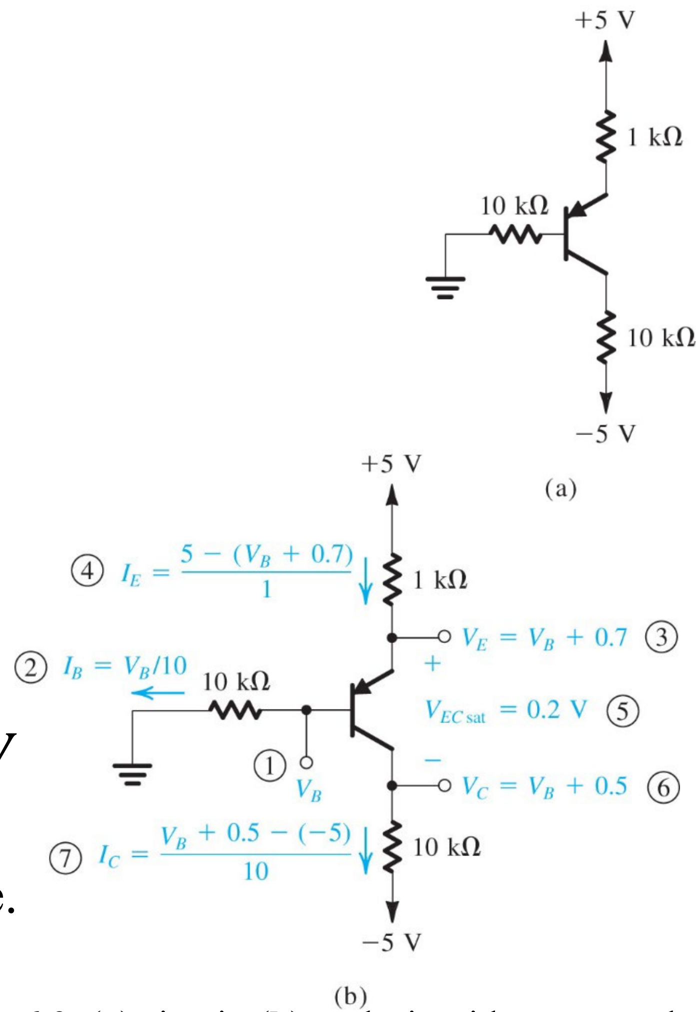


Figure 6.28 Example 6.9: (**a**) circuit; (**b**) analysis with steps numbered.

• Example 6.9 Cont.

Assume $\beta = 30$, analyze this circuit to determine all node voltages and branch currents. (Hint: if in saturation, $V_{CE} \approx 0.2V$)

3) So reassume in saturation mode ($V_{EC} \approx 0.2V$)

KCL1: $5 - I_E \times 1 - 0.7 - I_B \times 10 = 0$ ①

KCL2: $5 - I_E \times 1 - 0.2 - I_C \times 10 - (-5) = 0$ ②

Since $I_E = I_B + I_C$, ③.

$I_B = 0.31mA, I_C =$0.86mA, $I_E = 1.17mA$

$V_E = 5 - I_E \times 1 = 3.83V$,

$V_C = -5 + I_C \times 10 = 3.63V$,

$V_B = I_B \times 10 = 3.13V$

From which we can see the transistor is saturation,

$\beta_{forced} = \frac{I_C}{I_B} = 2.8$ which is much smaller thanβ

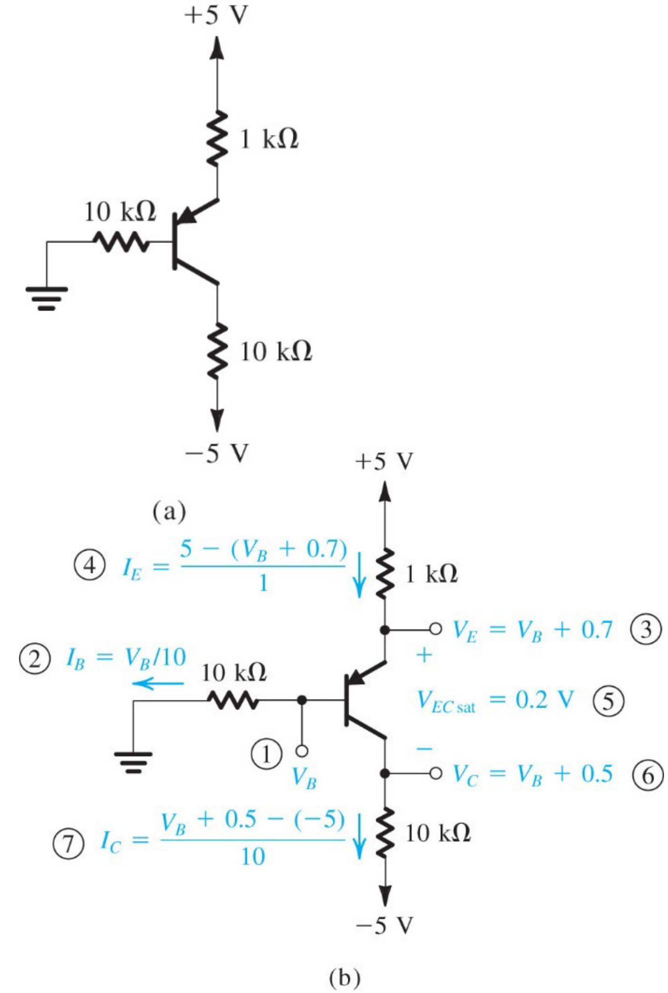


Figure 6.28 Example 6.9: (**a**) circuit; (**b**) analysis with steps numbered.

- # Example 6.10

Assume $\beta = 100$, analyze this circuit to determine all node voltages and branch currents.

Thévenin Equivalent Circuits (a)->(b)

$V_{BB} = 15V \times \frac{R_{B2}}{R_{B2}+R_{B1}} = 5V \quad R_{BB} = R_{B2}||R_{B1} = 33.3k\Omega$

1) Glancing BE is forward bias ($V_{BE} \approx 0.7V$),

so the transistor conducts.

KCL1: $5 - I_B \times 33.3 - 0.7 - I_E \times 3 = 0$

$I_E = \frac{4.3 - I_B \times 33.3}{3}$ ①

2) Assume in active mode. $I_E = (\beta + 1)I_B = 101 I_B$ ②

Thus, $\frac{4.3 - I_B \times 33.3}{3} = 101 I_B \Rightarrow I_B = 0.0128mA$,

$I_E = 101 \times I_B = 1.29mA$,

$I_C = I_E = I_B = 1.28mA$

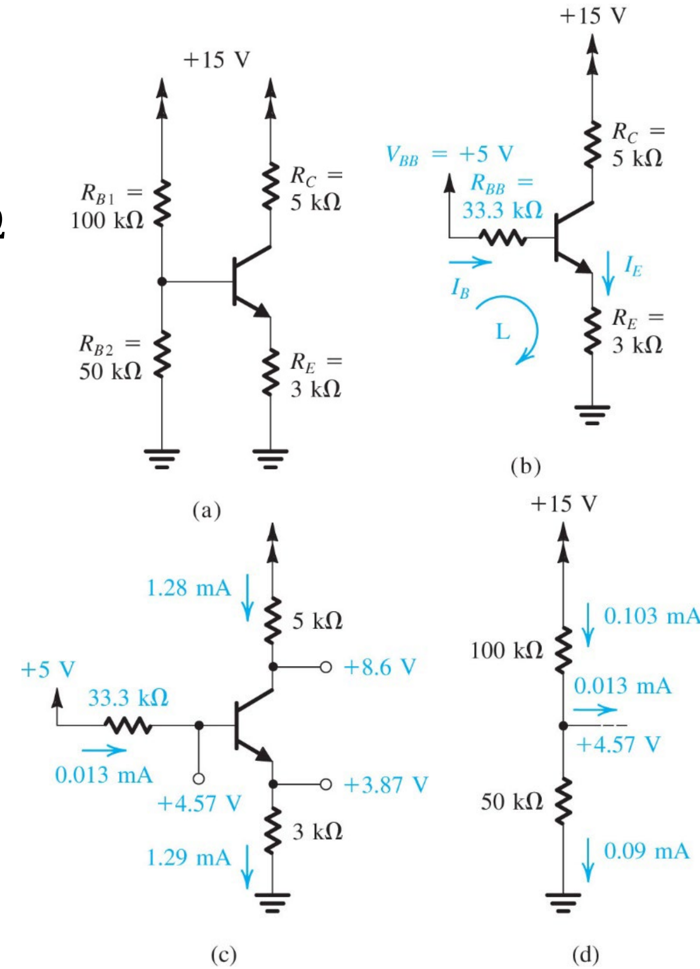


Figure 6.29 Circuits for Example 6.10.

• Example 6.10

Assume $\beta = 100$, analyze this circuit to determine all node voltages and branch currents.

$V_B = 5 - I_C \times 33.33 = 4.57V,$

$V_E = V_B - 0.7 = 3.87V,$

$V_C = 15V - I_C \times 5 = 8.6V$

$V_{CE} = 4.73V > 0.3V$, in active region.

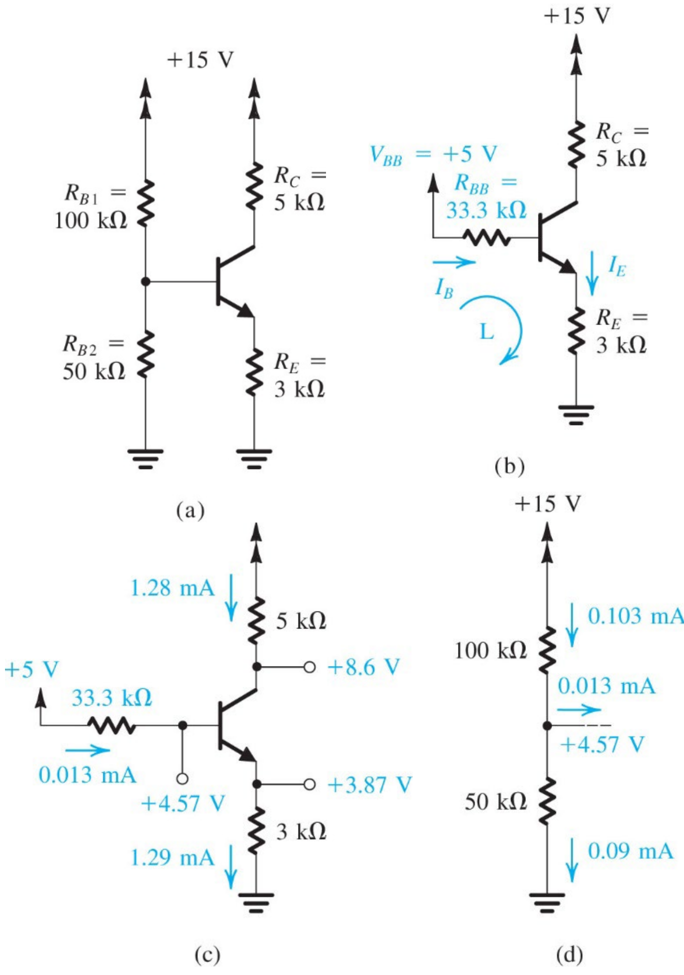


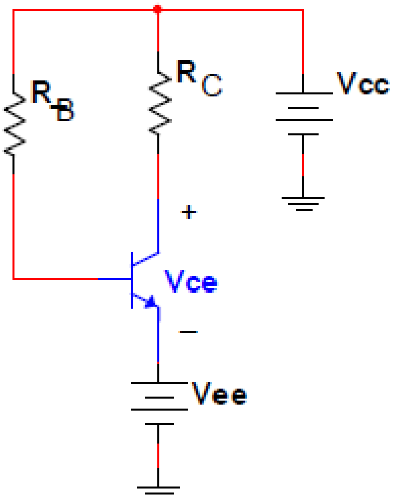
Figure 6.29 Circuits for Example 6.10.

- Experiment 9.1

Set up the following circuit with NPN BJT (**2N3904/2N4401**).

$V_{cc} = 5V, V_{ee} = 8V$.

Measure V_{CE}, V_{BE}, and V_{CB}. In which region does the BJT operate for each corresponding R_C and R_B? Briefly explain and comment your results.

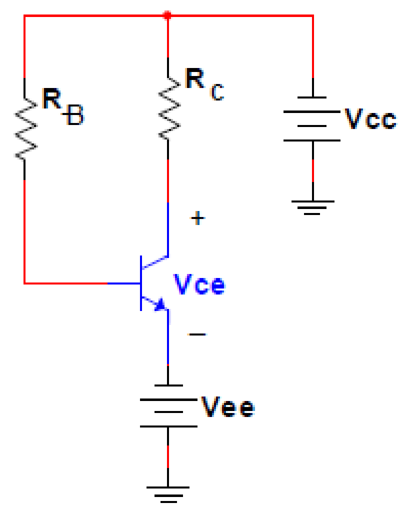


R_C	R_B	V_{CE}	V_{BE}	Region
$1k\Omega$	$1k\Omega$			
$1k\Omega$	$1M\Omega$			

- # Experiment 9.2

$V_{cc} = -5V, V_{ee} = -8V.$

Measure V_{CE}, V_{BE}, and V_{CB}. In which region does the BJT operate for each corresponding R_C and R_B? Briefly explain and comment your results.

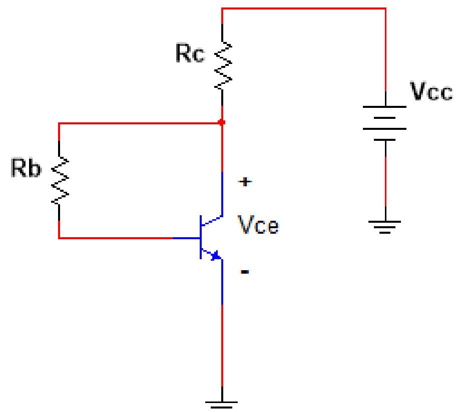


R_C	R_B	V_{CE}	V_{BE}	Region
$1k\Omega$	$1k\Omega$			
$1k\Omega$	$1M\Omega$			

- Experiment 9.3

$V_{cc} = 5V.$

Measure V_{CE}, V_{BE}, and V_{CB}. In which region does the BJT operate for each corresponding R_C and R_B? Briefly explain and comment your results.



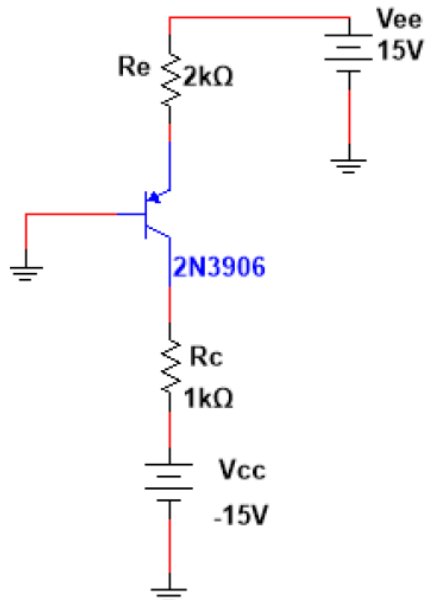
R_C	R_B	V_{CE}	V_{BE}	Region
$1k\Omega$	$1k\Omega$			
$1k\Omega$	$1M\Omega$			

- Experiment 9.4

Set up the following circuit with PNP BJT (**2N3906/4403**).

$V_{ee} = 15V$ and $V_{cc} = -15V$.

Measure V_{EC}, V_{EB}, and V_{BC}. In which region does the BJT operate for each corresponding R_E and R_B? Briefly explain and comment your results.



R_E	R_C	V_{EC}	V_{EB}	Region
$2k\Omega$	$1k\Omega$			

HW6

- Problems
  - PP.360, 6.48 – Current-voltage characteristics
  - PP.339, Exercice 6.22 – BJT circuits at DC #1
  - PP.339, Exercice 6.23 – BJT circuits at DC #2
  - PP.340, Exercice 6.24 – BJT circuits at DC #3
- Submission requirement:
  - Add the cover page!!!
  - Print the HW6.pdf out and answer all the questions
- Due: TBA (Late assignments: 40% deduction.)