BENHA UNIVERSITY
FACULTY OF ENGINEERING AT SHOUBRA

ECE-312
Electronic Circuits (A)

Lecture #3
BJT Biasing Circuits

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Agenda

- Operating Point
- Transistor DC Bias Configurations
- Design Operations
- Various BJT Circuits
- Troubleshooting Techniques & Bias Stabilization
- Practical Applications

Introduction

- Any increase in ac voltage, current, or power is the result of a transfer of energy from the applied dc supplies.
- The analysis or design of any electronic amplifier therefore has two components: a dc and an ac portion.

- Basic Relationships/formulas for a transistor:

$$V_{BE} \cong 0.7\text{ V}$$

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

$$I_C = \beta I_B$$

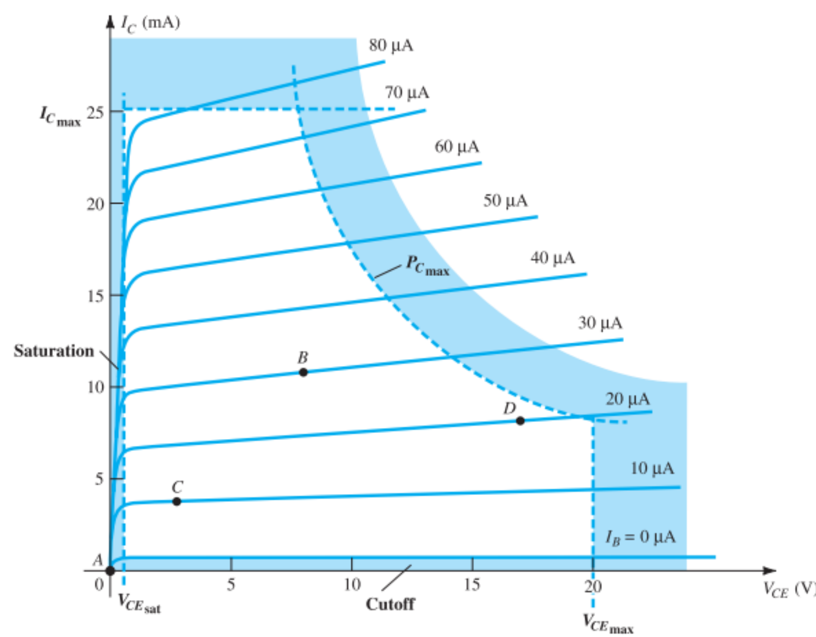
- ***Biasing*** means applying of dc voltages to establish a fixed level of current and voltage. >>> Q-Point

Operating Point

- For transistor amplifiers the resulting dc current and voltage establish an operating point on the characteristics that define the region that will be employed for amplification of the applied signal.
- Because the operating point is a fixed point on the characteristics, it is also called the quiescent point (abbreviated Q-point).

Transistor Regions Operation:

1. Linear-region operation:
   - Base–emitter junction forward-biased
   - Base–collector junction reverse-biased
2. Cutoff-region operation:
   - Base–emitter junction reverse-biased
   - Base–collector junction reverse-biased
3. Saturation-region operation:
   - Base–emitter junction forward-biased
   - Base–collector junction forward-biased

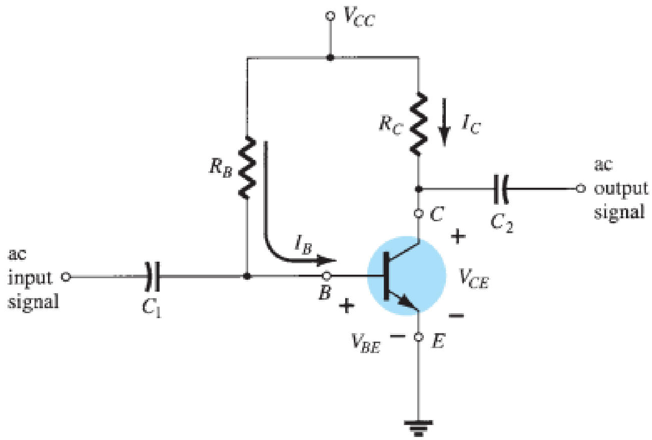


- Fixed-Bias Configuration
- Emitter-Bias Configuration
- Voltage-Divider Bias Configuration
- Collector Feedback Configuration
- Emitter-Follower Configuration
- Common-Base Configuration
- Miscellaneous Bias Configurations

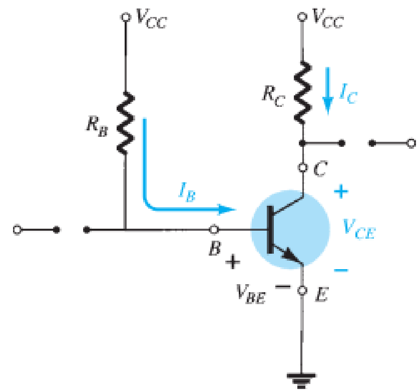
TRANSISTOR DC BIAS CONFIGURATIONS

Fixed-Bias Configuration

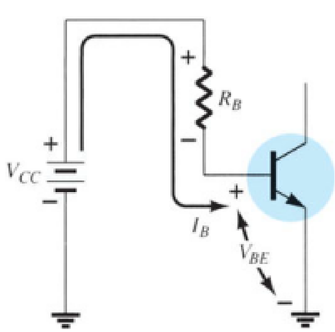
- Fixed-bias circuit.



- DC equivalent ct.



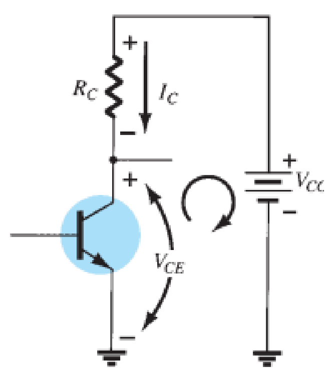
- Base–emitter loop.



$$+V_{CC} - I_B R_B - V_{BE} = 0$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

- Collector–emitter loop.



$$I_C = \beta I_B$$

$$V_{CE} + I_C R_C - V_{CC} = 0$$

$$V_{CE} = V_{CC} - I_C R_C$$

$$V_{CE} = V_C - V_E$$

$$V_{CE} = V_C$$

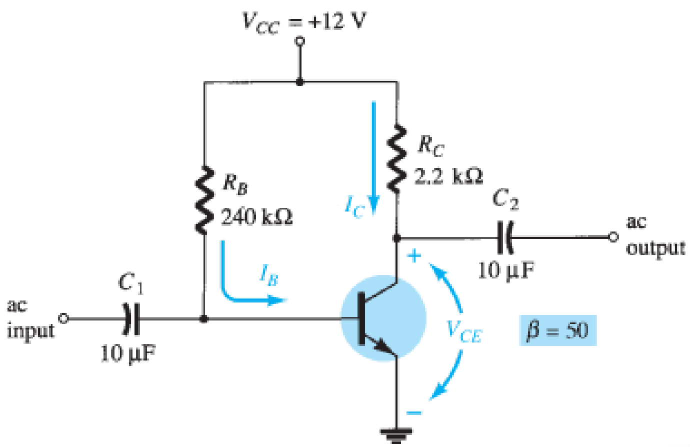
$$V_{BE} = V_B - V_E$$

$$V_{BE} = V_B$$

Fixed-Bias Configuration Example

EXAMPLE 4.1 Determine the following for the fixed-bias configuration

a. I_{B_Q} and I_{C_Q}.
b. V_{CE_Q}.
c. V_B and V_C.
d. V_{BC}.



Solution:

a. Eq. (4.4): $$I_{B_Q} = \frac{V_{CC} - V_{BE}}{R_B} = \frac{12\text{ V} - 0.7\text{ V}}{240\text{ k}\Omega} = \mathbf{47.08\ \mu A}$$

Eq. (4.5): $$I_{C_Q} = \beta I_{BQ} = (50)(47.08\ \mu\text{A}) = \mathbf{2.35\ mA}$$

b. Eq. (4.6): $$\begin{aligned} V_{CE_Q} &= V_{CC} - I_C R_C \\ &= 12\text{ V} - (2.35\text{ mA})(2.2\text{ k}\Omega) \\ &= \mathbf{6.83\ V} \end{aligned}$$

c. $V_B = V_{BE} = \mathbf{0.7\ V}$
$V_C = V_{CE} = \mathbf{6.83\ V}$

d. Using double-subscript notation yields

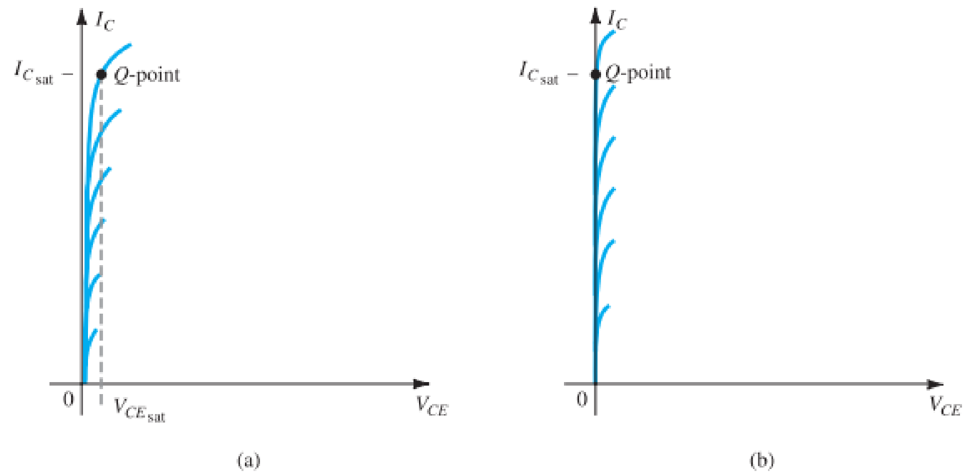
$$\begin{aligned} V_{BC} &= V_B - V_C = 0.7\text{ V} - 6.83\text{ V} \\ &= \mathbf{-6.13\ V} \end{aligned}$$

with the negative sign revealing that the junction is reversed-biased, as it should be for linear amplification.

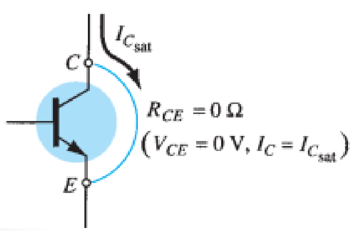
Fixed-Bias Configuration …

- **Transistor Saturation**

- Saturation regions:
  (a) Actual
  (b) approximate.

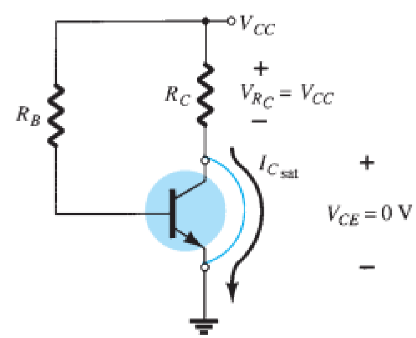


- Determining I_{Csat}



$$R_{CE} = \frac{V_{CE}}{I_C} = \frac{0\text{ V}}{I_{C_{sat}}} = 0\,\Omega$$

- Determining I_{Csat} for the fixed-bias configuration.



$$I_{C_{sat}} = \frac{V_{CC}}{R_C}$$

Fixed-Bias Configuration …

- **Load Line Analysis**

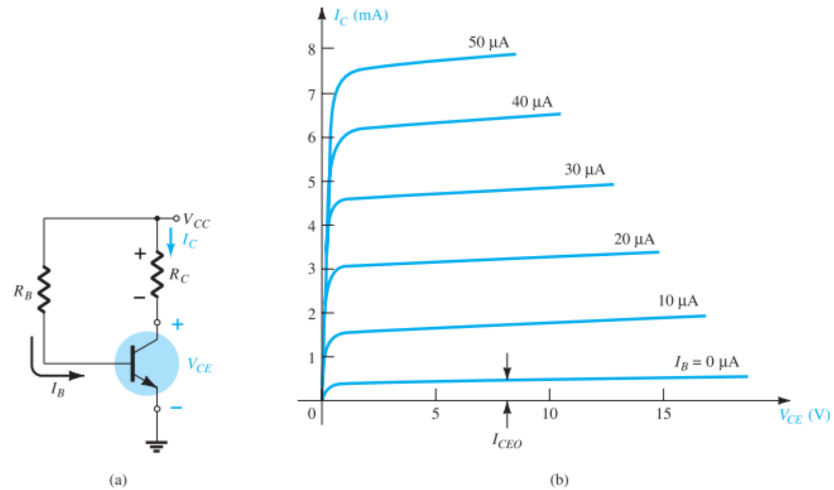
$$V_{CE} = V_{CC} - I_C R_C$$

$$V_{CE} = V_{CC} - (0)R_C$$

$$V_{CE} = V_{CC}\big|_{I_C = 0\text{ mA}}$$

$$0 = V_{CC} - I_C R_C$$

$$I_C = \frac{V_{CC}}{R_C}\bigg|_{V_{CE} = 0\text{ V}}$$



Load-line analysis: (a) the network; (b) the device characteristics.

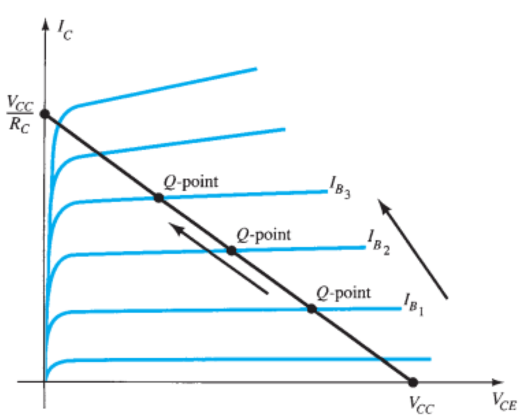


FIG. 4.13
Movement of the Q-point with increasing level of I_B.

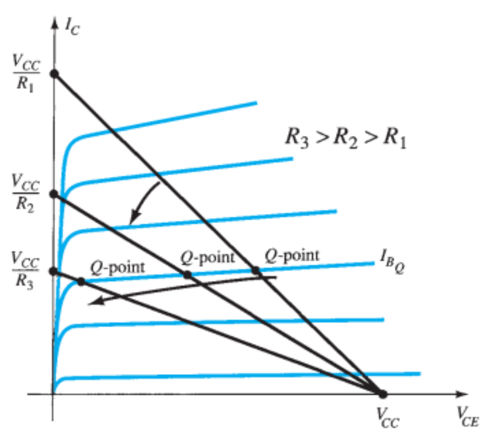


FIG. 4.14
Effect of an increasing level of R_C on the load line and the Q-point.

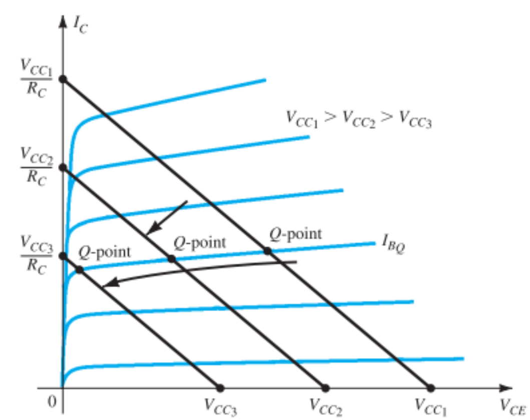
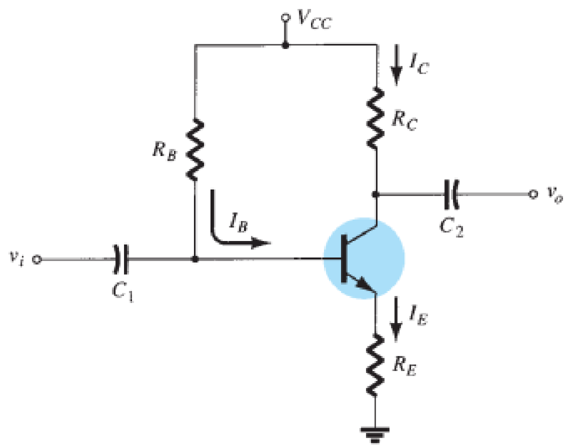


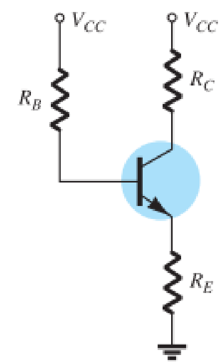
FIG. 4.15
Effect of lower values of V_{CC} on the load line and the Q-point.

Emitter-Bias Configuration

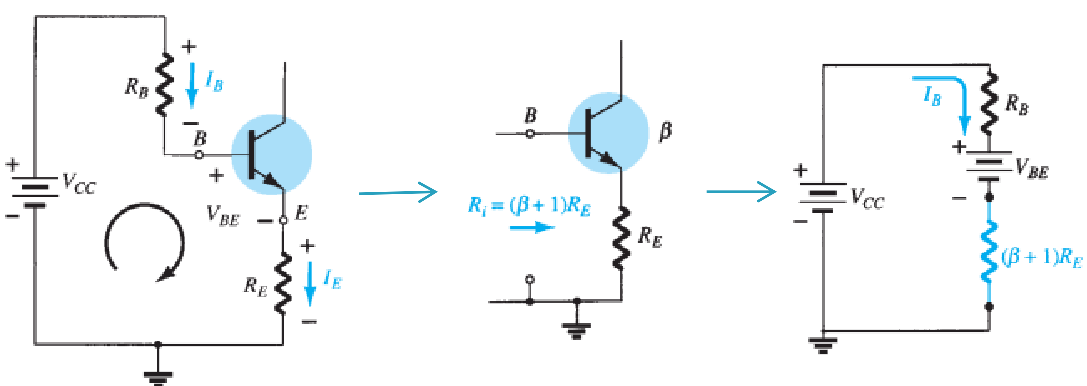
- BJT bias circuit with emitter resistor.



- DC equivalent ct



- Base-Emitter Loop



$$+V_{CC} - I_B R_B - V_{BE} - I_E R_E = 0$$

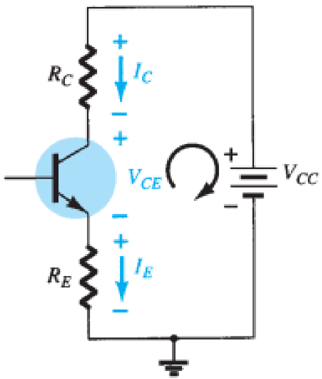
$$I_E = (\beta + 1)I_B$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E}$$

$$R_i = (\beta + 1)R_E$$

Emitter-Bias Configuration

Collector-Emitter Loop



$$+I_E R_E + V_{CE} + I_C R_C - V_{CC} = 0$$

$$I_E \cong I_C$$

$$V_{CE} = V_{CC} - I_C(R_C + R_E)$$

$$V_E = I_E R_E$$

$$V_{CE} = V_C - V_E$$

$$V_C = V_{CE} + V_E$$

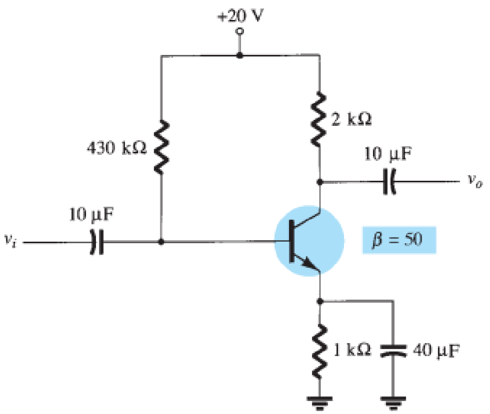
$$V_B = V_{CC} - I_B R_B$$

$$V_C = V_{CC} - I_C R_C$$

$$V_B = V_{BE} + V_E$$

EXAMPLE 4.4 For the emitter-bias network of Fig. 4.23, determine:

a. I_B.
b. I_C.
c. V_{CE}.
d. V_C.
e. V_E.
f. V_B.
g. V_{BC}.



Solution:

a. Eq. (4.17): $I_B = \dfrac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E} = \dfrac{20\text{ V} - 0.7\text{ V}}{430\text{ k}\Omega + (51)(1\text{ k}\Omega)}$

$= \dfrac{19.3\text{ V}}{481\text{ k}\Omega} = \mathbf{40.1\ \mu A}$

b. $I_C = \beta I_B$
$= (50)(40.1\ \mu\text{A})$
$\cong \mathbf{2.01\ mA}$

c. Eq. (4.19): $V_{CE} = V_{CC} - I_C(R_C + R_E)$
$= 20\text{ V} - (2.01\text{ mA})(2\text{ k}\Omega + 1\text{ k}\Omega) = 20\text{ V} - 6.03\text{ V}$
$= \mathbf{13.97\ V}$

d. $V_C = V_{CC} - I_C R_C$
$= 20\text{ V} - (2.01\text{ mA})(2\text{ k}\Omega) = 20\text{ V} - 4.02\text{ V}$
$= \mathbf{15.98\ V}$

e. $V_E = V_C - V_{CE}$
$= 15.98\text{ V} - 13.97\text{ V}$
$= \mathbf{2.01\ V}$

or $V_E = I_E R_E \cong I_C R_E$
$= (2.01\text{ mA})(1\text{ k}\Omega)$
$= \mathbf{2.01\ V}$

f. $V_B = V_{BE} + V_E$
$= 0.7\text{ V} + 2.01\text{ V}$
$= \mathbf{2.71\ V}$

g. $V_{BC} = V_B - V_C$
$= 2.71\text{ V} - 15.98\text{ V}$
$= \mathbf{-13.27\ V}$ (reverse-biased as required)

Emitter-Bias Configuration

- Improved bias stability (check example 4.5)

The addition of the emitter resistor to the dc bias of the BJT provides improved stability, that is, the dc bias currents and voltages remain closer to where they were set by the circuit when outside conditions, such as temperature and transistor beta, change.

Effect of β variation on the response of the fixed-bias configuration of Fig. 4.7.

β	I_B (μA)	I_C (mA)	V_{CE} (V)
50	47.08	2.35	6.83
100	47.08	4.71	1.64

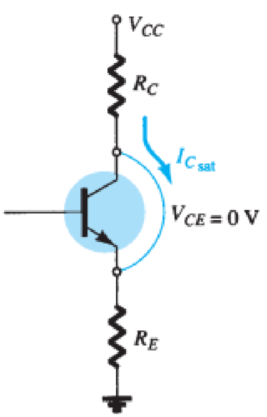
The BJT collector current is seen to change by 100% due to the 100% change in the value of β. The value of I_B is the same, and V_{CE} decreased by 76%.

Effect of β variation on the response of the emitter-bias configuration of Fig. 4.23.

β	I_B (μA)	I_C (mA)	V_{CE} (V)
50	40.1	2.01	13.97
100	36.3	3.63	9.11

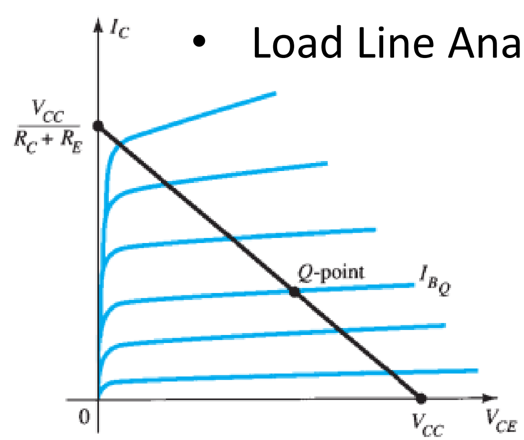
Now the BJT collector current increases by about 81% due to the 100% increase in β. Notice that I_B decreased, helping maintain the value of I_C—or at least reducing the overall change in I_C due to the change in β. The change in V_{CE} has dropped to about 35%. The network of Fig. 4.23 is therefore more stable than that of Fig. 4.7 for the same change in β.

- Saturation Level



$$I_{C_{sat}} = \frac{V_{CC}}{R_C + R_E}$$

- Load Line Analysis

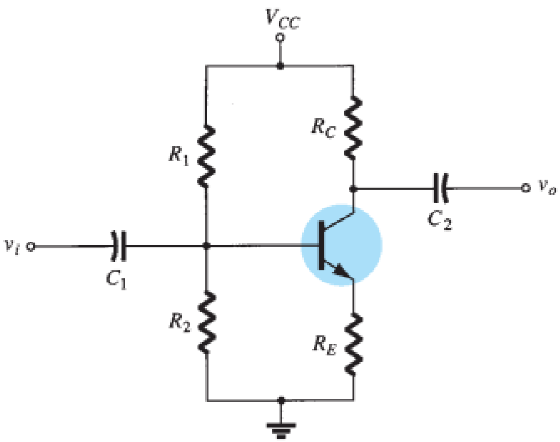


$$V_{CE} = V_{CC}\big|_{I_C = 0\text{ mA}}$$

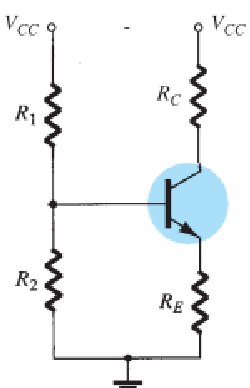
$$I_C = \frac{V_{CC}}{R_C + R_E}\bigg|_{V_{CE} = 0\text{ V}}$$

Voltage-Divider Configuration

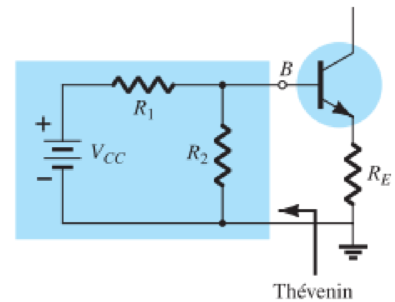
- Voltage-divider bias configuration.

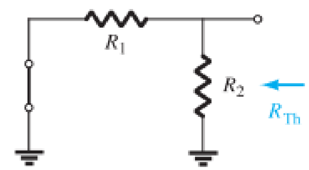


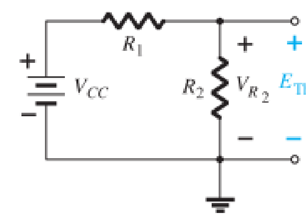
- DC components of the voltage-divider configuration.



- Exact Analysis

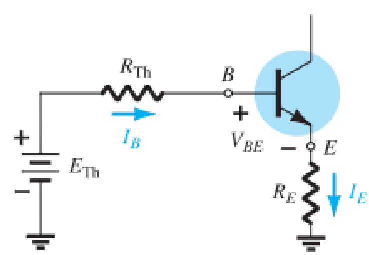






$$R_{Th} = R_1 \| R_2$$

$$E_{Th} = V_{R_2} = \frac{R_2 V_{CC}}{R_1 + R_2}$$

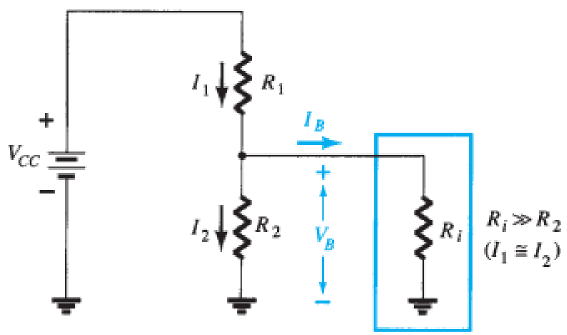


$$I_B = \frac{E_{Th} - V_{BE}}{R_{Th} + (\beta + 1)R_E}$$

$$V_{CE} = V_{CC} - I_C(R_C + R_E)$$

Voltage-Divider Configuration

- Approximate Analysis



$$V_B = \frac{R_2 V_{CC}}{R_1 + R_2}$$

$$R_i = (\beta + 1)R_E \cong \beta R_E$$

$$\beta R_E \geq 10 R_2$$

$$V_E = V_B - V_{BE}$$

$$I_E = \frac{V_E}{R_E}$$

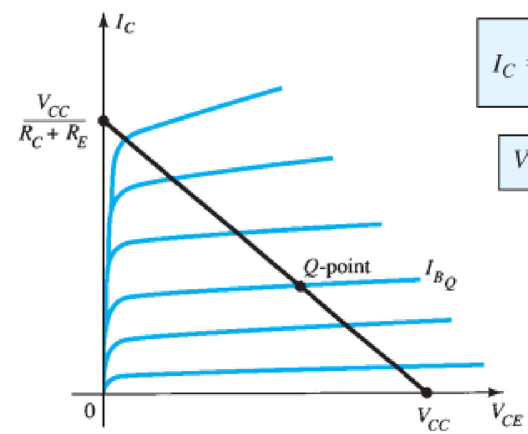
$$I_{C_Q} \cong I_E$$

$$V_{CE_Q} = V_{CC} - I_C(R_C + R_E)$$

- Transistor Saturation

$$I_{C_{sat}} = I_{C_{max}} = \frac{V_{CC}}{R_C + R_E}$$

- Load-Line Analysis



$$I_C = \left.\frac{V_{CC}}{R_C + R_E}\right|_{V_{CE}=0\ \text{V}}$$

$$V_{CE} = V_{CC}\big|_{I_C=0\ \text{mA}}$$

Voltage-Divider Configuration Example

EXAMPLE 4.11 Determine the levels of I_{C_Q} and V_{CE_Q} for the voltage-divider configuration of Fig. 4.37 using the exact and approximate techniques and compare solutions. In this case, the conditions of Eq. (4.33) *will not be satisfied* and the results will reveal the difference in solution if the criterion of Eq. (4.33) is ignored.

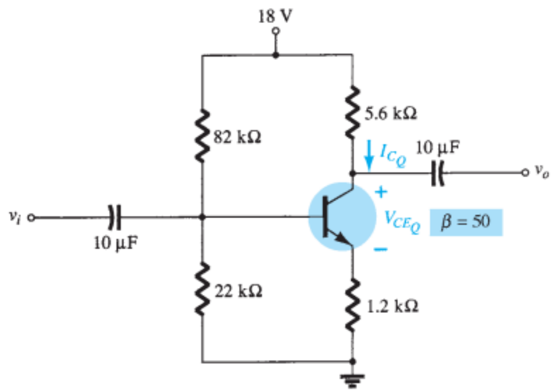


FIG. 4.37
Voltage-divider configuration for Example 4.11.

Solution: Exact analysis:

Eq. (4.33):

$$\beta R_E \geq 10R_2$$
$$(50)(1.2\,\text{k}\Omega) \geq 10(22\,\text{k}\Omega)$$
$$60\,\text{k}\Omega \ngeq 220\,\text{k}\Omega \ (\textit{not satisfied})$$
$$R_{Th} = R_1 \| R_2 = 82\,\text{k}\Omega \| 22\,\text{k}\Omega = 17.35\,\text{k}\Omega$$
$$E_{Th} = \frac{R_2 V_{CC}}{R_1 + R_2} = \frac{22\,\text{k}\Omega(18\,\text{V})}{82\,\text{k}\Omega + 22\,\text{k}\Omega} = 3.81\,\text{V}$$
$$I_B = \frac{E_{Th} - V_{BE}}{R_{Th} + (\beta + 1)R_E} = \frac{3.81\,\text{V} - 0.7\,\text{V}}{17.35\,\text{k}\Omega + (51)(1.2\,\text{k}\Omega)} = \frac{3.11\,\text{V}}{78.55\,\text{k}\Omega} = 39.6\,\mu\text{A}$$
$$I_{C_Q} = \beta I_B = (50)(39.6\,\mu\text{A}) = \mathbf{1.98\,mA}$$
$$V_{CE_Q} = V_{CC} - I_C(R_C + R_E)$$
$$= 18\,\text{V} - (1.98\,\text{mA})(5.6\,\text{k}\Omega + 1.2\,\text{k}\Omega)$$
$$= \mathbf{4.54\,V}$$

Approximate analysis:

$$V_B = E_{Th} = 3.81\,\text{V}$$
$$V_E = V_B - V_{BE} = 3.81\,\text{V} - 0.7\,\text{V} = 3.11\,\text{V}$$
$$I_{C_Q} \cong I_E = \frac{V_E}{R_E} = \frac{3.11\,\text{V}}{1.2\,\text{k}\Omega} = \mathbf{2.59\,mA}$$
$$V_{CE_Q} = V_{CC} - I_C(R_C + R_E)$$
$$= 18\,\text{V} - (2.59\,\text{mA})(5.6\,\text{k}\Omega + 1.2\,\text{k}\Omega)$$
$$= \mathbf{3.88\,V}$$

Comparing the exact and approximate approaches.

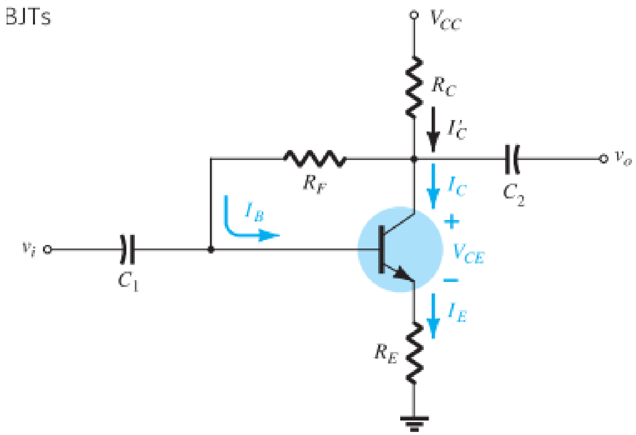
	I_{C_Q} *(mA)*	V_{CE_Q} *(V)*
Exact	1.98	4.54
Approximate	2.59	3.88

The results reveal the difference between exact and approximate solutions. I_{C_Q} is about 30% greater with the approximate solution, whereas V_{CE_Q} is about 10% less. The results are notably different in magnitude, but even though βR_E is only about three times larger than R_2, the results are still relatively close to each other. For the future, however, our analysis will be dictated by Eq. (4.33) to ensure a close similarity between exact and approximate solutions.

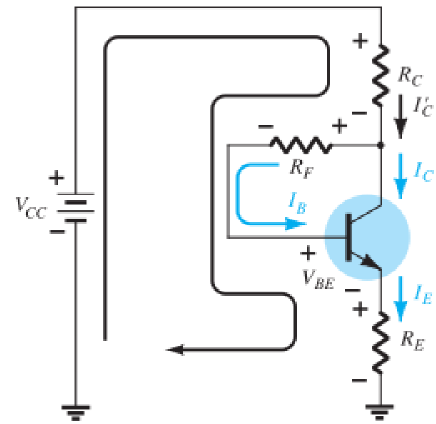
$$\boxed{\beta R_E \geq 10R_2} \qquad \textbf{(4.33)}$$

Collector Feedback Configuration

- DC bias circuit with voltage feedback.



- Base–Emitter Loop



$$V_{CC} - V_{BE} - \beta I_B(R_C + R_E) - I_B R_F = 0$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_F + \beta(R_C + R_E)}$$

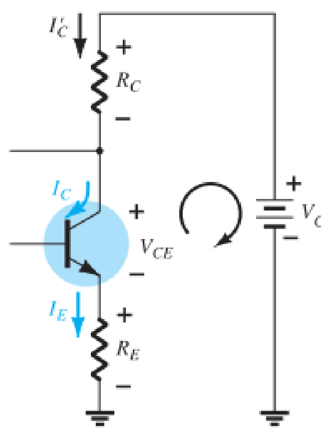
$$I_B = \frac{V'}{R_F + \beta R'}$$

$$R' = R_E.$$

$$I_{C_Q} = \frac{\beta V'}{R_F + \beta R'} = \frac{V'}{\frac{R_F}{\beta} + R'}$$

$$I_{C_Q} \cong \frac{V'}{R'}$$

- Collector–Emitter Loop



$$I_E R_E + V_{CE} + I'_C R_C - V_{CC} = 0$$

Because $I'_C \cong I_C$ and $I_E \cong I_C$, we have

$$I_C(R_C + R_E) + V_{CE} - V_{CC} = 0$$

and

$$V_{CE} = V_{CC} - I_C(R_C + R_E)$$

Collector Feedback Configuration

- Saturation Conditions

Using the approximation $I'_C = I_C$

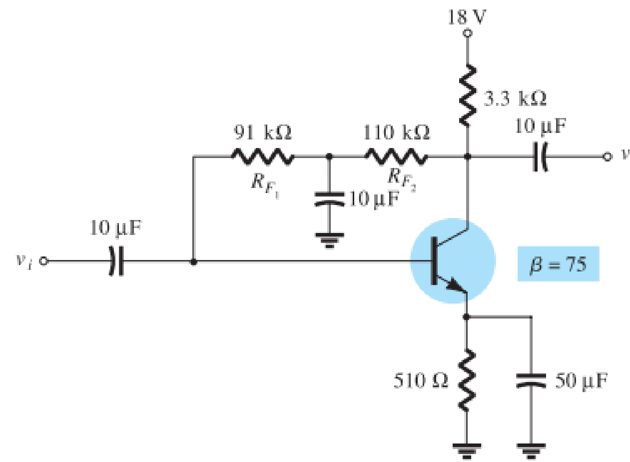
$$I_{C_{sat}} = I_{C_{max}} = \frac{V_{CC}}{R_C + R_E}$$

- Load-Line Analysis

Continuing with the approximation $I'_C = I_C$ results in the same load line defined for the voltage-divider and emitter-biased configurations.

The level of I_{BQ} is defined by the chosen bias configuration.

EXAMPLE 4.14 Determine the dc level of I_B and V_C for the network of Fig. 4.42.



Solution: In this case, the base resistance for the dc analysis is composed of two resistors with a capacitor connected from their junction to ground. For the dc mode, the capacitor assumes the open-circuit equivalence, and $R_B = R_{F_1} + R_{F_2}$.

Solving for I_B gives

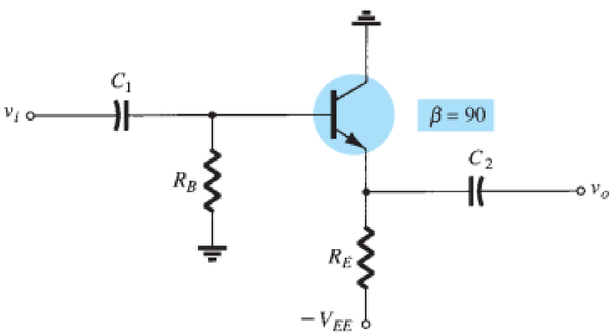
$$\begin{aligned} I_B &= \frac{V_{CC} - V_{BE}}{R_B + \beta(R_C + R_E)} \\ &= \frac{18\text{ V} - 0.7\text{ V}}{(91\text{ k}\Omega + 110\text{ k}\Omega) + (75)(3.3\text{ k}\Omega + 0.51\text{ k}\Omega)} \\ &= \frac{17.3\text{ V}}{201\text{ k}\Omega + 285.75\text{ k}\Omega} = \frac{17.3\text{ V}}{486.75\text{ k}\Omega} \\ &= \mathbf{35.5\ \mu A} \end{aligned}$$

$$\begin{aligned} I_C &= \beta I_B \\ &= (75)(35.5\ \mu\text{A}) \\ &= 2.66\text{ mA} \end{aligned}$$

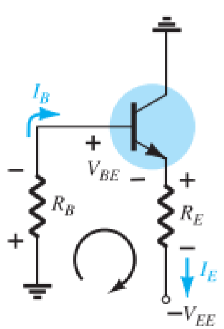
$$\begin{aligned} V_C &= V_{CC} - I'_C R_C \cong V_{CC} - I_C R_C \\ &= 18\text{ V} - (2.66\text{ mA})(3.3\text{ k}\Omega) \\ &= 18\text{ V} - 8.78\text{ V} \\ &= \mathbf{9.22\ V} \end{aligned}$$

Emitter-Follower Configuration

- Common-collecter (emitter-follower) configuration.



- dc equivalent ct



i/p ct

$$-I_BR_B - V_{BE} - I_ER_E + V_{EE} = 0$$

$$I_BR_B + (\beta + 1)I_BR_E = V_{EE} - V_{BE}$$

$$\boxed{I_B = \frac{V_{EE} - V_{BE}}{R_B + (\beta + 1)R_E}}$$

o/p ct

$$-V_{CE} - I_ER_E + V_{EE} = 0$$

$$\boxed{V_{CE} = V_{EE} - I_ER_E}$$

EXAMPLE 4.16 Determine V_{CE_Q} and I_{E_Q} for the network of Fig. 4.48.

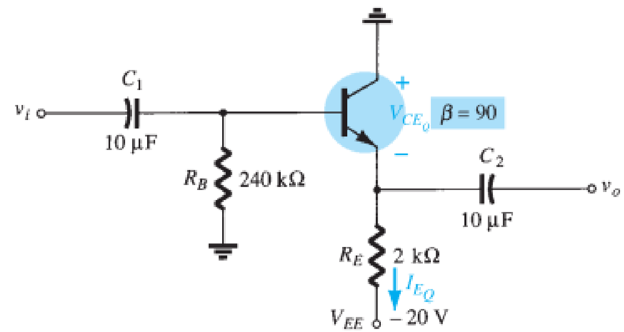


FIG. 4.48
Example 4.16.

Solution:

Eq. 4.44:

$$I_B = \frac{V_{EE} - V_{BE}}{R_B + (\beta + 1)R_E}$$

$$= \frac{20\text{ V} - 0.7\text{ V}}{240\text{ k}\Omega + (90 + 1)2\text{ k}\Omega} = \frac{19.3\text{ V}}{240\text{ k}\Omega + 182\text{ k}\Omega}$$

$$= \frac{19.3\text{ V}}{422\text{ k}\Omega} = 45.73\ \mu\text{A}$$

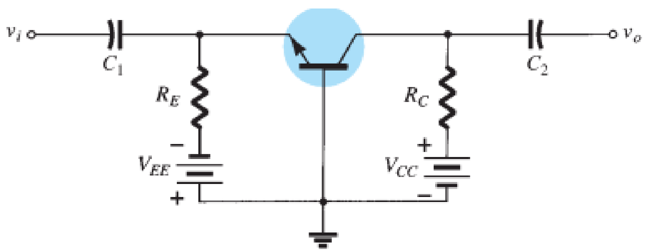
and Eq. 4.45:

$$V_{CE_Q} = V_{EE} - I_ER_E$$
$$= V_{EE} - (\beta + 1)I_BR_E$$
$$= 20\text{ V} - (90 + 1)(45.73\ \mu\text{A})(2\text{ k}\Omega)$$
$$= 20\text{ V} - 8.32\text{ V}$$
$$= \mathbf{11.68\ V}$$

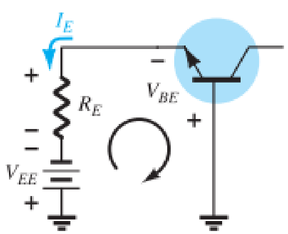
$$I_{E_Q} = (\beta + 1)I_B = (91)(45.73\ \mu\text{A})$$
$$= 4.16\text{ mA}$$

Common-Base Configuration

- Common-base configuration



- i/p ct



$$-V_{EE} + I_E R_E + V_{BE} = 0$$

$$\boxed{I_E = \frac{V_{EE} - V_{BE}}{R_E}}$$

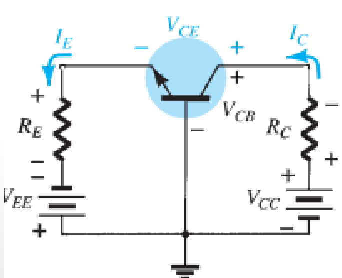
$$-V_{EE} + I_E R_E + V_{CE} + I_C R_C - V_{CC} = 0$$

$$V_{CE} = V_{EE} + V_{CC} - I_E R_E - I_C R_C$$

$$I_E \cong I_C$$

$$\boxed{V_{CE} = V_{EE} + V_{CC} - I_E(R_C + R_E)}$$

- Determining V_{CB} & V_{CE}



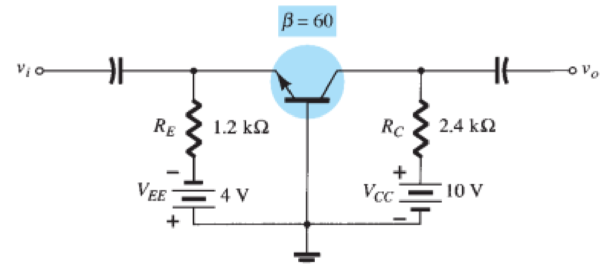
$$V_{CB} + I_C R_C - V_{CC} = 0$$

$$V_{CB} = V_{CC} - I_C R_C$$

$$I_C \cong I_E$$

$$\boxed{V_{CB} = V_{CC} - I_C R_C}$$

EXAMPLE 4.17 Determine the currents I_E and I_B and the voltages V_{CE} and V_{CB} for the common-base configuration of Fig. 4.52.



Solution: Eq. 4.46:

$$I_E = \frac{V_{EE} - V_{BE}}{R_E} = \frac{4\text{ V} - 0.7\text{ V}}{1.2\text{ k}\Omega} = \mathbf{2.75\text{ mA}}$$

$$I_B = \frac{I_E}{\beta + 1} = \frac{2.75\text{ mA}}{60 + 1} = \frac{2.75\text{ mA}}{61} = \mathbf{45.08\ \mu A}$$

Eq. 4.47:

$$\begin{aligned} V_{CE} &= V_{EE} + V_{CC} - I_E(R_C + R_E) \\ &= 4\text{ V} + 10\text{ V} - (2.75\text{ mA})(2.4\text{ k}\Omega + 1.2\text{ k}\Omega) \\ &= 14\text{ V} - (2.75\text{ mA})(3.6\text{ k}\Omega) \\ &= 14\text{ V} - 9.9\text{ V} \\ &= \mathbf{4.1\text{ V}} \end{aligned}$$

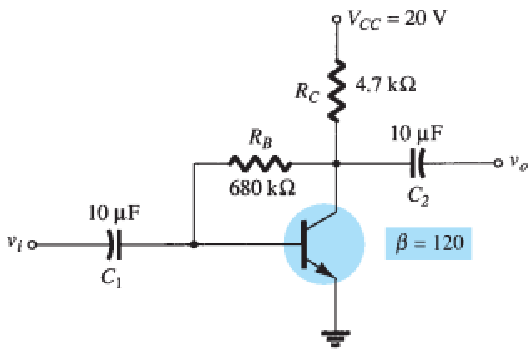
Eq. 4.48:

$$\begin{aligned} V_{CB} &= V_{CC} - I_C R_C = V_{CC} - \beta I_B R_C \\ &= 10\text{ V} - (60)(45.08\ \mu\text{A})(24\text{ k}\Omega) \\ &= 10\text{ V} - 6.49\text{ V} \\ &= \mathbf{3.51\text{ V}} \end{aligned}$$

MISCELLANEOUS BIAS CONFIGURATIONS

EXAMPLE 4.18 For the network of Fig. 4.53:

a. Determine I_{C_Q} and V_{CE_Q}.
b. Find V_B, V_C, V_E, and V_{BC}.



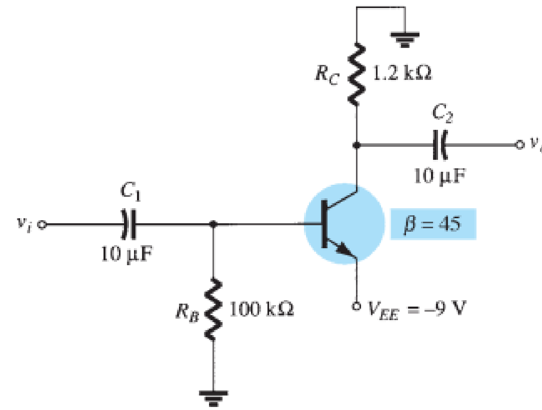
Solution:

a. The absence of R_E reduces the reflection of resistive levels to simply that of R_C, and the equation for I_B reduces to

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \beta R_C}$$
$$= \frac{20\text{ V} - 0.7\text{ V}}{680\text{ k}\Omega + (120)(4.7\text{ k}\Omega)} = \frac{19.3\text{ V}}{1.244\text{ M}\Omega}$$
$$= \mathbf{15.51\ \mu A}$$
$$I_{C_Q} = \beta I_B = (120)(15.51\ \mu\text{A})$$
$$= \mathbf{1.86\ mA}$$
$$V_{CE_Q} = V_{CC} - I_C R_C$$
$$= 20\text{ V} - (1.86\text{ mA})(4.7\text{ k}\Omega)$$
$$= \mathbf{11.26\ V}$$

b.
$$V_B = V_{BE} = \mathbf{0.7\ V}$$
$$V_C = V_{CE} = \mathbf{11.26\ V}$$
$$V_E = \mathbf{0\ V}$$
$$V_{BC} = V_B - V_C = 0.7\text{ V} - 11.26\text{ V}$$
$$= \mathbf{-10.56\ V}$$

EXAMPLE 4.19 Determine V_C and V_B for the network of Fig. 4.54.



Solution: Applying Kirchhoff's voltage law in the clockwise direction for the base–emitter loop results in

$$-I_B R_B - V_{BE} + V_{EE} = 0$$

and

$$I_B = \frac{V_{EE} - V_{BE}}{R_B}$$

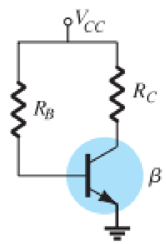
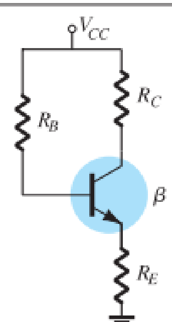
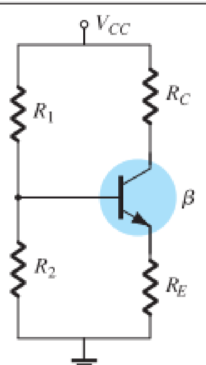
Substitution yields

$$I_B = \frac{9\text{ V} - 0.7\text{ V}}{100\text{ k}\Omega}$$
$$= \frac{8.3\text{ V}}{100\text{ k}\Omega}$$
$$= 83\ \mu\text{A}$$

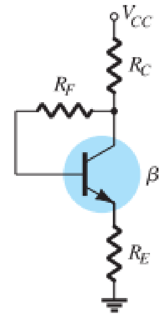
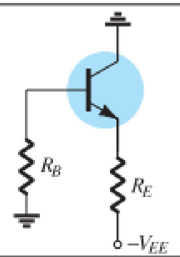
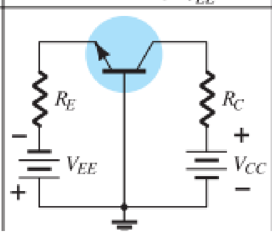
$$I_C = \beta I_B$$
$$= (45)(83\ \mu\text{A})$$
$$= 3.735\text{ mA}$$
$$V_C = -I_C R_C$$
$$= -(3.735\text{ mA})(1.2\text{ k}\Omega)$$
$$= \mathbf{-4.48\ V}$$
$$V_B = -I_B R_B$$
$$= -(83\ \mu\text{A})(100\text{ k}\Omega)$$
$$= \mathbf{-8.3\ V}$$

Summary Table

BJT Bias Configurations

Type	Configuration	Pertinent Equations
Fixed-bias		$I_B = \dfrac{V_{CC} - V_{BE}}{R_B}$ $I_C = \beta I_B, I_E = (\beta + 1)I_B$ $V_{CE} = V_{CC} - I_C R_C$
Emitter-bias		$I_B = \dfrac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E}$ $I_C = \beta I_B, I_E = (\beta + 1)I_B$ $R_i = (\beta + 1)R_E$ $V_{CE} = V_{CC} - I_C(R_C + R_E)$
Voltage-divider bias		EXACT: $R_{Th} = R_1 \| R_2, E_{Th} = \dfrac{R_2 V_{CC}}{R_1 + R_2}$ $I_B = \dfrac{E_{Th} - V_{BE}}{R_{Th} + (\beta + 1)R_E}$ $I_C = \beta I_B, I_E = (\beta + 1)I_B$ $V_{CE} = V_{CC} - I_C(R_C + R_E)$ APPROXIMATE: $\beta R_E \geq 10R_2$ $V_B = \dfrac{R_2 V_{CC}}{R_1 + R_2}, V_E = V_B - V_{BE}$ $I_E = \dfrac{V_E}{R_E}, I_B = \dfrac{I_E}{\beta + 1}$ $V_{CE} = V_{CC} - I_C(R_C + R_E)$

Summary Table..

Collector-feedback		$I_B = \dfrac{V_{CC} - V_{BE}}{R_F + \beta(R_C + R_E)}$ $I_C = \beta I_B, I_E = (\beta + 1)I_B$ $V_{CE} = V_{CC} - I_C(R_C + R_E)$
Emitter-follower		$I_B = \dfrac{V_{EE} - V_{BE}}{R_B + (\beta + 1)R_E}$ $I_C = \beta I_B, I_E = (\beta + 1)I_B$ $V_{CE} = V_{EE} - I_E R_E$
Common-base		$I_E = \dfrac{V_{EE} - V_{BE}}{R_E}$ $I_B = \dfrac{I_E}{\beta + 1}, I_C = \beta I_B$ $V_{CE} = V_{EE} + V_{CC} - I_E(R_C + R_E)$ $V_{CB} = V_{CC} - I_C R_C$

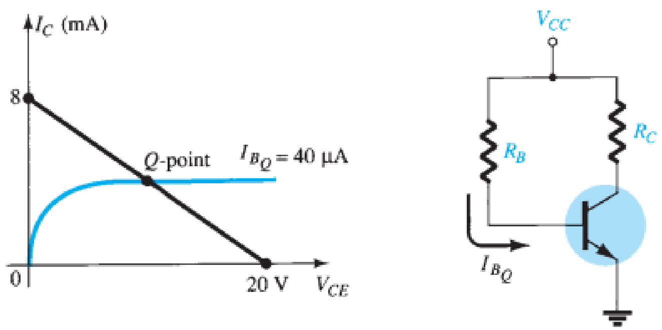
DESIGN OPERATION

Design Operations

- Discussions thus far have focused on the analysis of existing networks. All the elements are in place, and it is simply a matter of solving for the current and voltage levels of the configuration.
- The design process is one where a current and/or voltage may be specified and the elements required to establish the designated levels must be determined.
- The design sequence is obviously sensitive to the components that are already specified and the elements to be determined. If the transistor and supplies are specified, the design process will simply determine the required resistors for a particular design.
- Once the theoretical values of the resistors are determined, the nearest standard commercial values are normally chosen and any variations due to not using the exact resistance values are accepted as part of the design.

Design Operations Example

EXAMPLE 4.21 Given the device characteristics of Fig. 4.59a, determine V_{CC}, R_B, and R_C for the fixed-bias configuration of Fig. 4.59b.



(a) (b)

Solution: From the load line

$$V_{CC} = \mathbf{20\ V}$$

$$I_C = \left.\frac{V_{CC}}{R_C}\right|_{V_{CE}=0\ V}$$

and

$$R_C = \frac{V_{CC}}{I_C} = \frac{20\ V}{8\ mA} = \mathbf{2.5\ k\Omega}$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

with

$$R_B = \frac{V_{CC} - V_{BE}}{I_B}$$

$$= \frac{20\ V - 0.7\ V}{40\ \mu A} = \frac{19.3\ V}{40\ \mu A}$$

$$= \mathbf{482.5\ k\Omega}$$

Standard resistor values are

$$R_C = 2.4\ k\Omega$$

$$R_B = 470\ k\Omega$$

Using standard resistor values gives

$$I_B = 41.1\ \mu A$$

which is well within 5% of the value specified.

Design Operations Example..

- Design of a Current-Gain-Stabilized (Beta-Independent) Circuit

EXAMPLE 4.25 Determine the levels of R_C, R_E, R_1, and R_2 for the network of Fig. 4.63 for the operating point indicated.

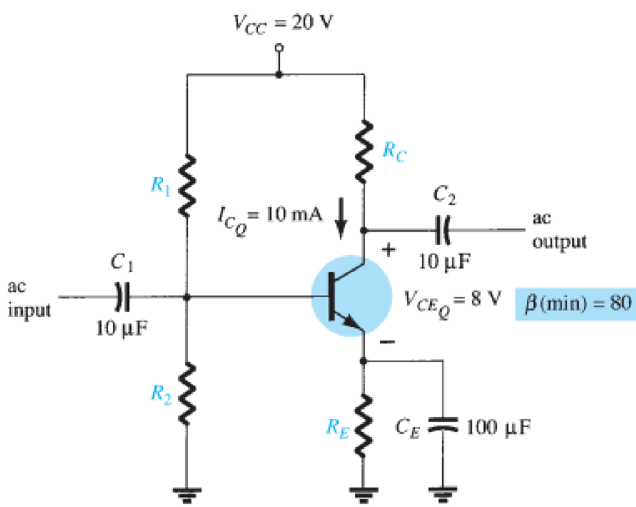


FIG. 4.63
Current-gain-stabilized circuit for design considerations.

Solution:

$$V_E = \tfrac{1}{10}V_{CC} = \tfrac{1}{10}(20\text{ V}) = 2\text{ V}$$

$$R_E = \frac{V_E}{I_E} \cong \frac{V_E}{I_C} = \frac{2\text{ V}}{10\text{ mA}} = \mathbf{200\ \Omega}$$

$$R_C = \frac{V_{R_C}}{I_C} = \frac{V_{CC} - V_{CE} - V_E}{I_C} = \frac{20\text{ V} - 8\text{ V} - 2\text{ V}}{10\text{ mA}} = \frac{10\text{ V}}{10\text{ mA}}$$

$$= \mathbf{1\ k\Omega}$$

$$V_B = V_{BE} + V_E = 0.7\text{ V} + 2\text{ V} = 2.7\text{ V}$$

$$R_2 \le \tfrac{1}{10}\beta R_E$$

and

$$V_B = \frac{R_2}{R_1 + R_2}V_{CC}$$

Substitution yields

$$R_2 \le \tfrac{1}{10}(80)(0.2\text{ k}\Omega)$$

$$= \mathbf{1.6\ k\Omega}$$

$$V_B = 2.7\text{ V} = \frac{(1.6\text{ k}\Omega)(20\text{ V})}{R_1 + 1.6\text{ k}\Omega}$$

$$2.7R_1 + 4.32\text{ k}\Omega = 32\text{ k}\Omega$$

$$2.7R_1 = 27.68\text{ k}\Omega$$

$$R_1 = \mathbf{10.25\ k\Omega} \quad (\text{use } 10\text{ k}\Omega)$$

VARIOUS BJT CIRCUITS

- MULTIPLE BJT NETWORKS
- CURRENT MIRRORS
- CURRENT SOURCE CIRCUITS
  - Bipolar Transistor Constant-Current Source
  - Transistor/Zener Constant-Current Source
- PNP TRANSISTORS
- TRANSISTOR SWITCHING NETWORKS

MULTIPLE BJT NETWORKS

- **R–C coupling**

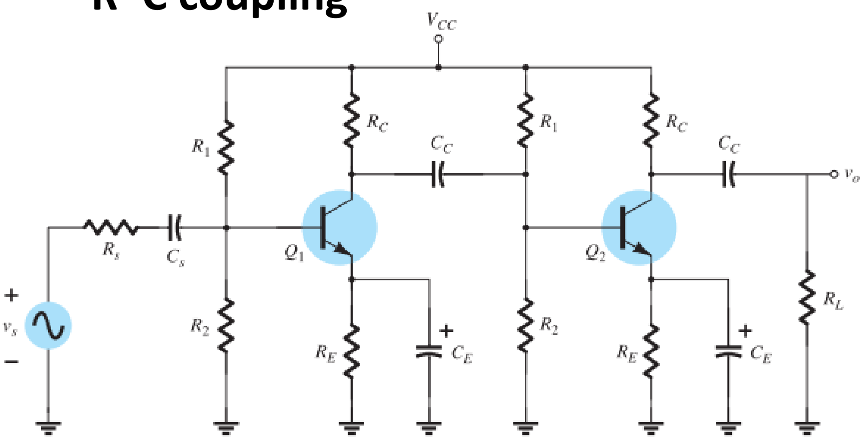


FIG. 4.64
R–C coupled BJT amplifiers.

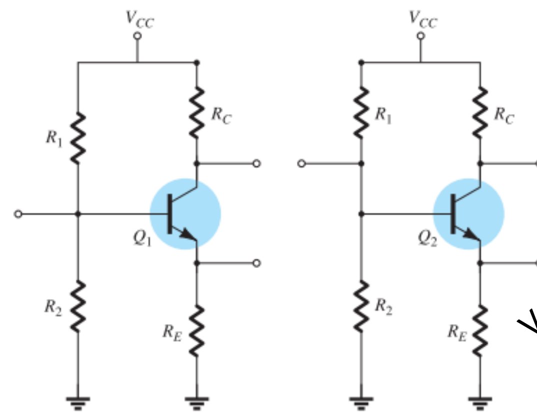


FIG. 4.65
DC equivalent of Fig. 4.64.

Voltage divider ;)

- **Darlington configuration**

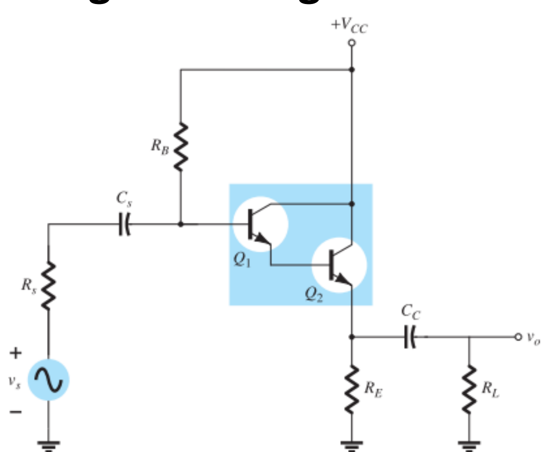


FIG. 4.66
Darlington amplifier.

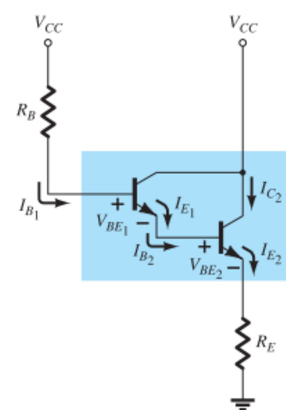


FIG. 4.67
DC equivalent of Fig. 4.66.

$$\beta_D = \beta_1\beta_2$$

$$I_{B_1} = \frac{V_{CC} - V_{BE_1} - V_{BE_2}}{R_B + (\beta_D + 1)R_E}$$

$$V_{BE_D} = V_{BE_1} + V_{BE_2}$$

$$I_{B_1} = \frac{V_{CC} - V_{BE_D}}{R_B + (\beta_D + 1)R_E}$$

$$I_{C_2} \cong I_{E_2} = \beta_D I_{B_1}$$

$$V_{E_2} = I_{E_2}R_E$$

$$V_{C_2} = V_{CC}$$

$$V_{CE_2} = V_{C_2} - V_{E_2}$$

$$V_{CE_2} = V_{CC} - V_{E_2}$$

MULTIPLE BJT NETWORKS..

- Cascode configuration

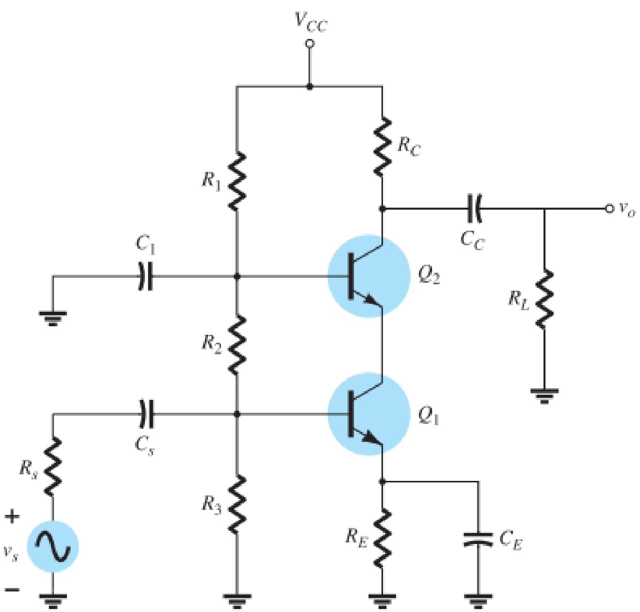


FIG. 4.68
Cascode amplifier.

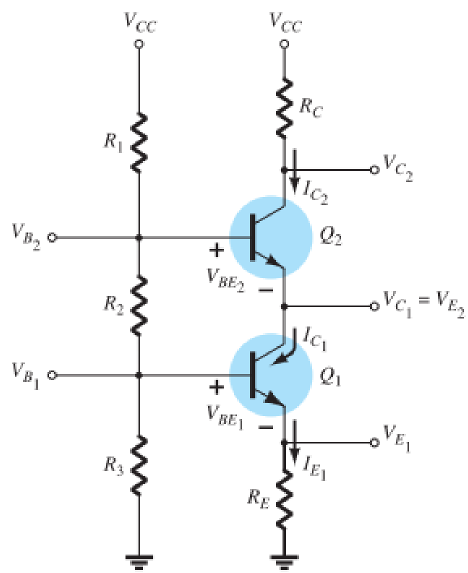


FIG. 4.69
DC equivalent of Fig. 4.68.

$$I_{R_1} \cong I_{R_2} \cong I_{R_3} \gg I_{B_1} \text{ or } I_{B_2}$$

$$V_{B_1} = \frac{R_3}{R_1 + R_2 + R_3} V_{CC}$$

$$V_{B_2} = \frac{(R_2 + R_3)}{R_1 + R_2 + R_3} V_{CC}$$

$$V_{E_1} = V_{B_1} - V_{BE_1}$$

$$V_{E_2} = V_{B_2} - V_{BE_2}$$

$$I_{C_2} \cong I_{E_2} \cong I_{C_1} \cong I_{E_1} = \frac{V_{B_1} - V_{BE_1}}{R_{E_1} + R_{E_2}}$$

$$V_{C_1} = V_{B_2} - V_{BE_2}$$

$$V_{C_2} = V_{CC} - I_{C_2} R_C$$

$$I_{R_1} \cong I_{R_2} \cong I_{R_3} = \frac{V_{CC}}{R_1 + R_2 + R_3}$$

$$I_{B_1} = \frac{I_{C_1}}{\beta_1} \qquad I_{B_2} = \frac{I_{C_2}}{\beta_2}$$

MULTIPLE BJT NETWORKS…

- **Feedback Pair**

$$I_{B_2} = I_{C_1} = \beta_1 I_{B_1}$$
$$I_{C_2} = \beta_2 I_{B_2}$$

$$\boxed{I_{C_2} \cong I_{E_2} = \beta_1\beta_2 I_{B_1}}$$

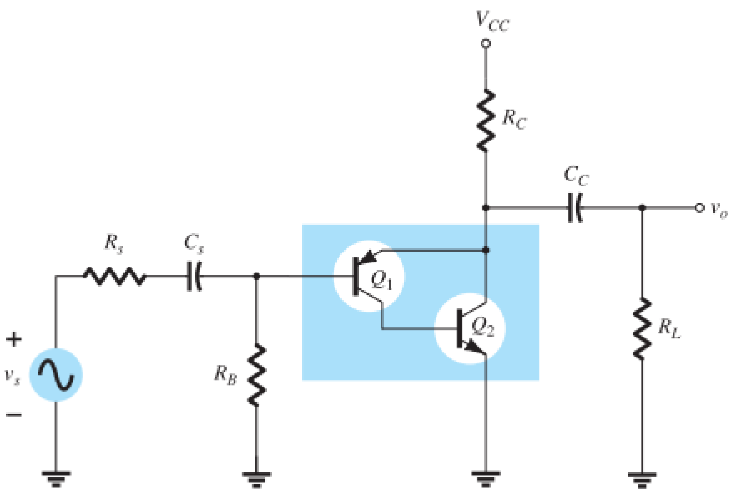


FIG. 4.70
Feedback Pair amplifier.

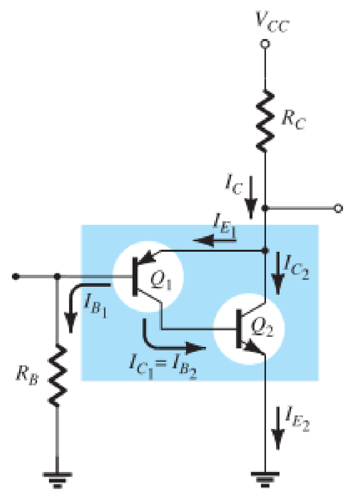


FIG. 4.71
DC equivalent of Fig. 4.70.

$$I_C = I_{E_1} + I_{E_2}$$
$$\cong \beta_1 I_{B_1} + \beta_1\beta_2 I_{B_1}$$
$$= \beta_1(1 + \beta_2) I_{B_1}$$

$$\boxed{I_C \cong \beta_1\beta_2 I_{B_1}}$$

$$V_{CC} - I_C R_C - V_{EB_1} - I_{B_1} R_B = 0$$
$$V_{CC} - V_{EB_1} - \beta_1\beta_2 I_{B_1} R_C - I_{B_1} R_B = 0$$

$$\boxed{I_{B_1} = \frac{V_{CC} - V_{EB_1}}{R_B + \beta_1\beta_2 R_C}}$$

$$\boxed{V_{B_1} = I_{B_1} R_B} \qquad \boxed{V_{C_2} = V_{CC} - I_C R_C}$$

$$\boxed{V_{B_2} = V_{BE_2}} \qquad \boxed{V_{C_1} = V_{BE_2}}$$

$$\boxed{V_{CE_2} = V_{C_2}}$$

$$V_{EC_1} = V_{E_1} - V_{C_1}$$

$$\boxed{V_{EC_1} = V_{C_2} - V_{BE_2}}$$

MULTIPLE BJT NETWORKS….

- **Direct Coupled**

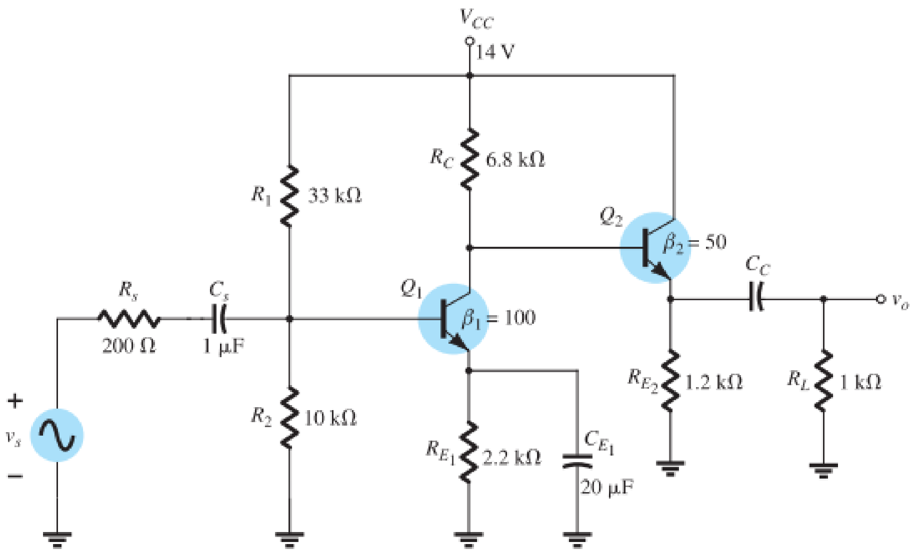


FIG. 4.72
Direct-coupled amplifier.

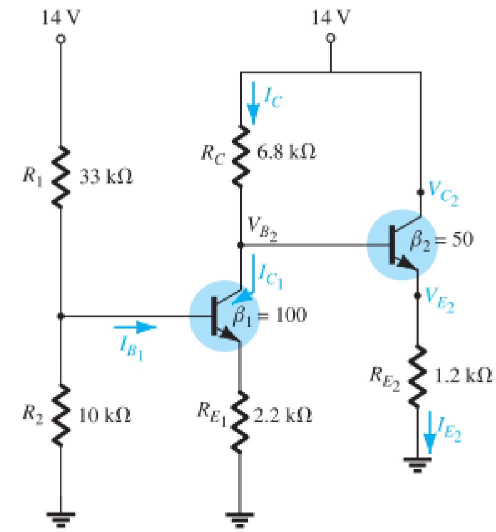


FIG. 4.73
DC equivalent of Fig. 4.72.

$$I_{B_1} = \frac{E_{Th} - V_{BE}}{R_{Th} + (\beta + 1)R_{E_1}}$$

$$R_{Th} = R_1 \| R_2$$

$$E_{Th} = \frac{R_2 V_{CC}}{R_1 + R_2}$$

$$\boxed{V_{B_2} = V_{CC} - I_C R_C}$$

$$V_{E_2} = V_{B_2} - V_{BE_2}$$

$$\boxed{I_{E_2} = \frac{V_{E_2}}{R_{E_2}}}$$

$$\boxed{V_{C_2} = V_{CC}}$$

$$V_{CE_2} = V_{C_2} - V_{E_2}$$

$$\boxed{V_{CE_2} = V_{CC} - V_{E_2}}$$

CURRENT MIRRORS

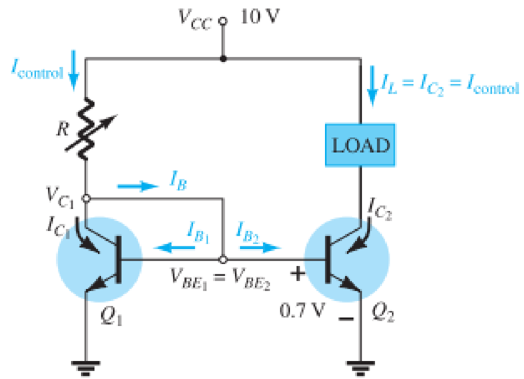


FIG. 4.74
Current mirror using back-to-back BJTs.

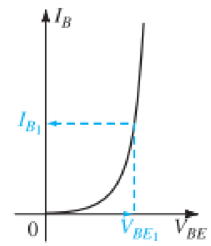
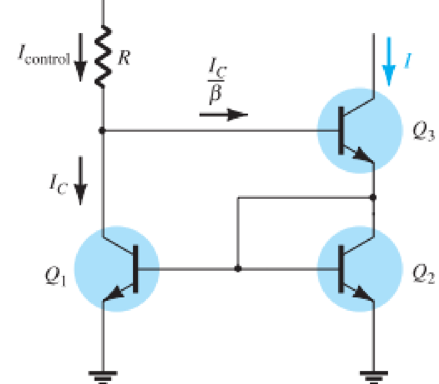


FIG. 4.75
Base characteristics for transistor Q_1 (and Q_2).

$$I_{control} = \frac{V_{CC} - 2V_{BE}}{R} \approx I_C + \frac{I_C}{\beta} = \frac{\beta + 1}{\beta} I_C \approx I_C$$



$$I \approx I_C = I_{control}$$

FIG. 4.78
Current mirror circuit with higher output

$$I_{control} = I_{C_1} + I_B = I_{C_1} + 2I_{B_1}$$

$$I_{C_1} = \beta_1 I_{B_1}$$

$$I_{control} = \beta_1 I_{B_1} + 2I_{B_1} = (\beta_1 + 2)I_{B_1}$$

β_1 is typically $\gg 2$, $I_{control} \cong \beta_1 I_{B_1}$

$$I_{B_1} = \frac{I_{control}}{\beta_1}$$

$$I_L = I_{C_2} = \beta I_{B_2}$$

$$I_{control} = \frac{V_{CC} - V_{BE}}{R}$$

$I_L \uparrow I_{C_2} \uparrow I_{B_2} \uparrow V_{BE_2} \uparrow V_{CE_1} \downarrow, I_R \downarrow, I_B \downarrow, I_{B_2} \downarrow I_{C_2} \downarrow I_L \downarrow$

Note

$$I = I_{DSS}$$

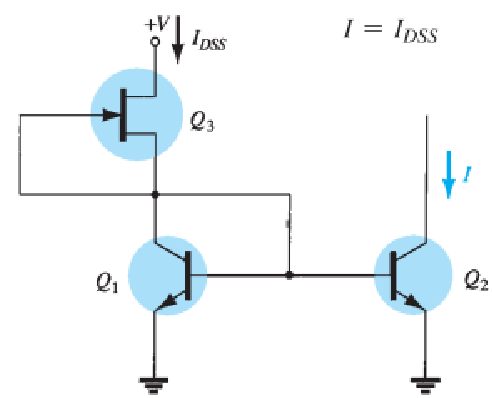
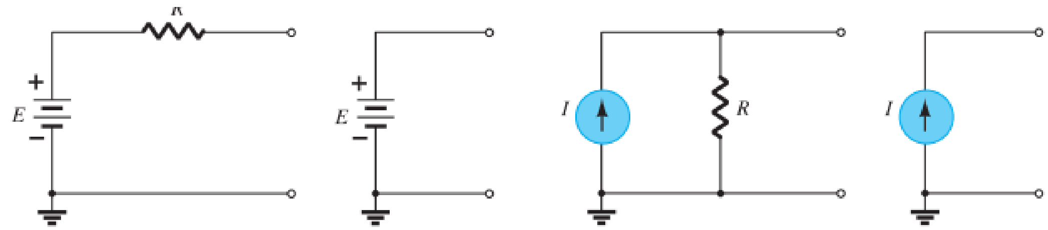


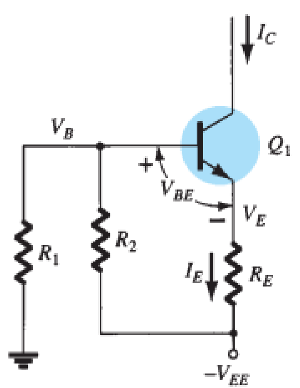
FIG. 4.79
Current mirror connection.

CURRENT SOURCE CIRCUITS



Practical voltage source | Ideal voltage source | Practical current source | Ideal current source

- **Bipolar Transistor Constant-Current Source**



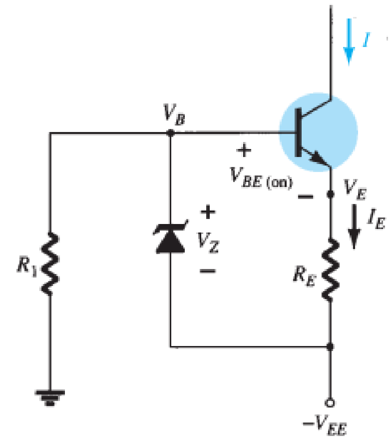
$$V_B = \frac{R_1}{R_1 + R_2}(-V_{EE})$$

$$V_E = V_B - 0.7\text{ V}$$

$$I_E = \frac{V_E - (-V_{EE})}{R_E} \approx I_C$$

FIG. 4.81
Discrete constant-current source.

- **Transistor/Zener Constant-Current Source**



$$I \approx I_E = \frac{V_Z - V_{BE}}{R_E}$$

FIG. 4.83
Constant-current circuit using Zener diode.

pnp TRANSISTORS

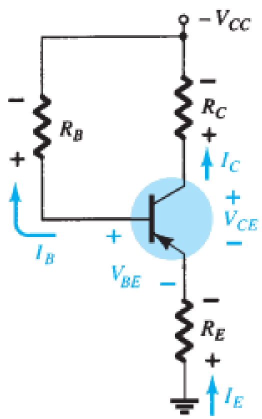


FIG. 4.85
pnp transistor in an emitter-stabilized configuration.

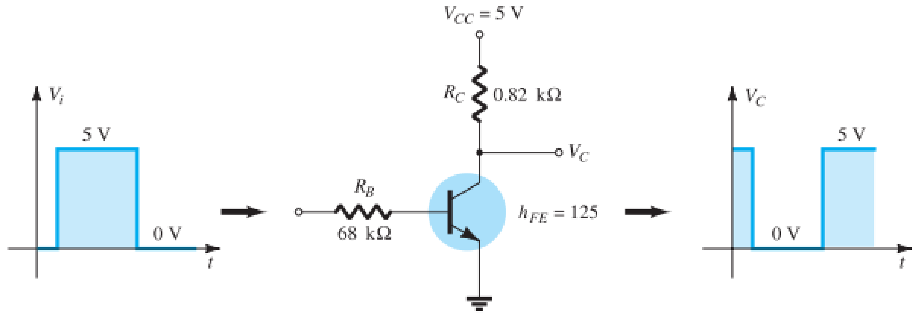
$$-I_ER_E + V_{BE} - I_BR_B + V_{CC} = 0$$

$$I_B = \frac{V_{CC} + V_{BE}}{R_B + (\beta + 1)R_E}$$

$$-I_ER_E + V_{CE} - I_CR_C + V_{CC} = 0$$

$$V_{CE} = -V_{CC} + I_C(R_C + R_E)$$

TRANSISTOR SWITCHING NETWORKS

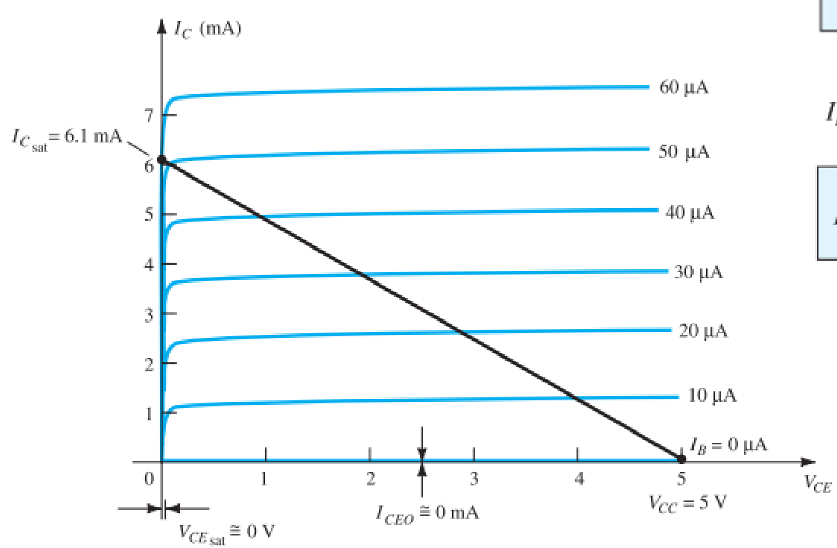


(a)

$$I_{C_{sat}} = \frac{V_{CC}}{R_C}$$

$$I_{B_{max}} \cong \frac{I_{C_{sat}}}{\beta_{dc}}$$

$$I_B > \frac{I_{C_{sat}}}{\beta_{dc}}$$



(b)

FIG. 4.87
Transistor inverter.

TRANSISTOR SWITCHING NETWORKS..

$$R_{sat} = \frac{V_{CE_{sat}}}{I_{C_{sat}}}$$

and is depicted in Fig. 4.88.

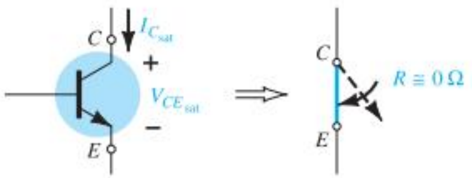


FIG. 4.88
Saturation conditions and the resulting terminal resistance.

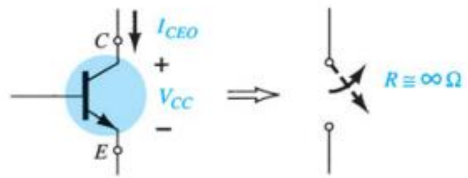


FIG. 4.89
Cutoff conditions and the resulting terminal resistance.

Using a typical average value of $V_{CE_{sat}}$ such as 0.15 V gives

$$R_{sat} = \frac{V_{CE_{sat}}}{I_{C_{sat}}} = \frac{0.15\text{ V}}{6.1\text{ mA}} = 24.6\ \Omega$$

$$R_{cutoff} = \frac{V_{CC}}{I_{CEO}} = \frac{5\text{ V}}{0\text{ mA}} = \boldsymbol{\infty\ \Omega}$$

$$R_{cutoff} = \frac{V_{CC}}{I_{CEO}} = \frac{5\text{ V}}{10\ \mu\text{A}} = \mathbf{500\ k\Omega}$$

$$t_{on} = t_r + t_d$$

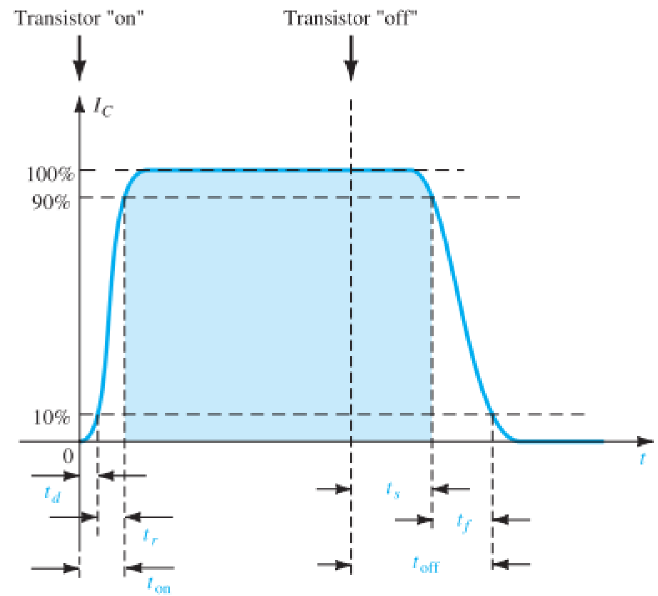


FIG. 4.91
Defining the time intervals of a pulse waveform.

$$t_{off} = t_s + t_f$$

TROUBLESHOOTING TECHNIQUES

TROUBLESHOOTING TECHNIQUES

- For an "on" transistor, the voltage V_{BE} should be in the neighborhood of 0.7 V.
- For the typical transistor amplifier in the active region, V_{CE} is usually about 25% to 75% of V_{CC} .

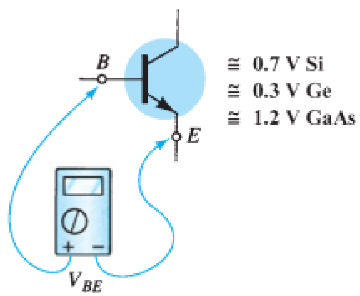


FIG. 4.92
Checking the dc level of V_{BE}.

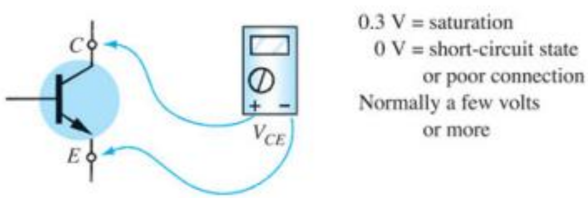


FIG. 4.93
Checking the dc level of V_{CE}.

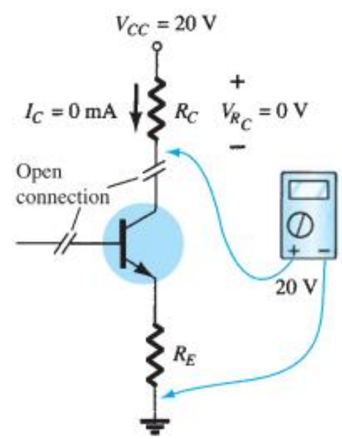


FIG. 4.94
Effect of a poor connection or damaged device.

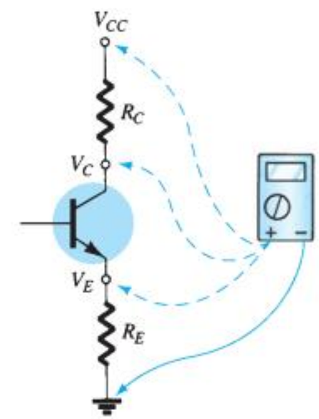


FIG. 4.95
Checking voltage levels with respect to ground.

BIAS STABILIZATION

- The stability of a system is a measure of the sensitivity of a network to variations in its parameters.
- In any amplifier employing a transistor the collector current I_C is sensitive to each of the following parameters:

β: increases with increase in temperature

$|V_{BE}|$: decreases about 2.5 mV per degree Celsius (°C) increase in temperature

I_{CO} (reverse saturation current): doubles in value for every 10°C increase in temperature

Variation of Silicon Transistor Parameters with Temperature

T (°C)	I_{CO} (nA)	β	V_{BE} (V)
−65	0.2×10^{-3}	20	0.85
25	0.1	50	0.65
100	20	80	0.48
175	3.3×10^{3}	120	0.3

Stability Factors $S(I_{CO})$, $S(V_{BE})$, and $S(\beta)$

$$S(I_{CO}) = \frac{\Delta I_C}{\Delta I_{CO}}$$

$$S(V_{BE}) = \frac{\Delta I_C}{\Delta V_{BE}}$$

$$S(\beta) = \frac{\Delta I_C}{\Delta \beta}$$

The higher the stability factor, the more sensitive is the network to variations in that parameter.

BIAS STABILIZATION .. $S(I_{co})$

Fixed-Bias Configuration

$$S(I_{CO}) \cong \beta$$

Emitter-Bias Configuration

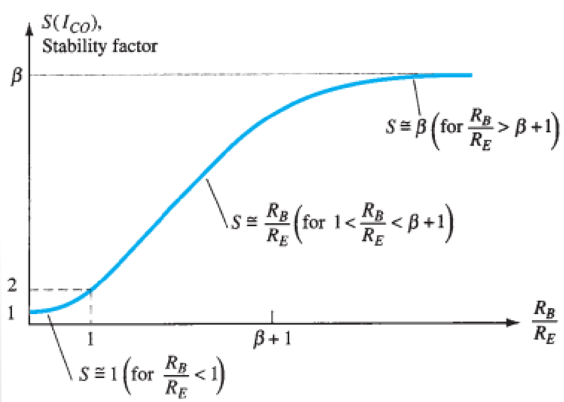
$$S(I_{CO}) \cong \frac{\beta(1 + R_B/R_E)}{\beta + R_B/B_E}$$

$$S(I_{CO}) \cong \beta \quad R_B/R_E \gg \beta$$

$$S(I_{CO}) \cong 1 \quad R_B/R_E \ll 1$$

$$S(I_{CO}) \cong \frac{R_B}{R_E}$$

R_B/R_E ranges between 1 and $(\beta + 1)$



Voltage-Divider Bias Configuration

$$S(I_{CO}) \cong \frac{\beta(1 + R_{Th}/R_E)}{\beta + R_{Th}/R_E}$$

Feedback-Bias Configuration ($R_E = 0\ \Omega$)

$$S(I_{CO}) \cong \frac{\beta(1 + R_B/R_C)}{\beta + R_B/R_C}$$

Physical Impact

- fixed-bias configuration

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

$$I_C = \beta I_B + (\beta + 1)I_{CO}$$

the level of I_C would continue to rise with temperature, with I_B maintaining a fairly constant value—a very unstable situation.

- emitter-bias configuration

$$I_B\downarrow = \frac{V_{CC} - V_{BE} - V_E\uparrow}{R_B}$$

there is a reaction to an increase in I_C that will tend to oppose the change in bias conditions.

- feedback configuration

$$I_B\downarrow = \frac{V_{CC} - V_{BE} - V_{R_C}\uparrow}{R_B}$$

a stabilizing effect as described for the emitter-bias configuration.

- voltage-divider bias

$$\beta R_E \gg 10R_2$$

The most stable of the configurations

BIAS STABILIZATION .. $S(V_{BE})$ & $S(\beta)$

$$S(V_{BE}) = \frac{\Delta I_C}{\Delta V_{BE}}$$

Fixed-Bias Configuration

$$S(V_{BE}) \cong \frac{-\beta}{R_B}$$

$$S(\beta) = \frac{I_{C_1}}{\beta_1}$$

Emitter-Bias Configuration

$$S(V_{BE}) \cong \frac{-\beta/R_E}{\beta + R_B/R_E}$$

$\beta \gg R_B/R_E$

$$S(V_{BE}) \cong \frac{-\beta/R_E}{\beta} = -\frac{1}{R_E}$$

$$S(\beta) = \frac{\Delta I_C}{\Delta\beta} = \frac{I_{C_1}(1 + R_B/R_E)}{\beta_1(\beta_2 + R_B/R_E)}$$

Voltage-Divider Bias Configuration

$$S(V_{BE}) = \frac{-\beta/R_E}{\beta + R_{Th}/R_E}$$

$$S(\beta) = \frac{I_{C_1}(1 + R_{Th}/R_E)}{\beta_1(\beta_2 + R_{Th}/R_E)}$$

Feedback-Bias Configuration ($R_E = 0\ \Omega$)

$$S(V_{BE}) = \frac{-\beta/R_C}{\beta + R_B/R_C}$$

$$S(\beta) = \frac{I_{C_1}(R_B + R_C)}{\beta_1(R_B + \beta_2 R_C)}$$

Summary

$$\Delta I_C = S(I_{CO})\Delta I_{CO} + S(V_{BE})\Delta V_{BE} + S(\beta)\Delta\beta$$

For fixed-bias

$$\Delta I_C = \beta\Delta I_{CO} - \frac{\beta}{R_B}\Delta V_{BE} + \frac{I_{C_1}}{\beta_1}\Delta\beta$$

General Conclusion:

The ratio R_B/R_E or R_{Th}/R_E should be as small as possible with due consideration to all aspects of the design, including the ac response.

- BJT Diode Usage and Protective Capabilities
- Relay Driver
- Light Control
- Maintaining a Fixed Load Current
- Alarm System with a CCS
- Voltage Level Indicator
- Logic Gates

PRACTICAL APPLICATION

Practical Application

- BJT Diode Usage and Protective Capabilities

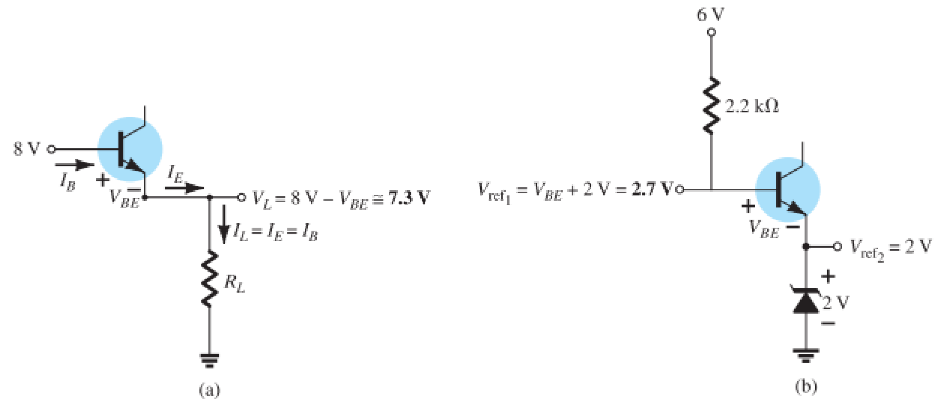


FIG. 4.102
BJT applications as a diode: (a) simple series diode circuit; (b) setting a reference level.

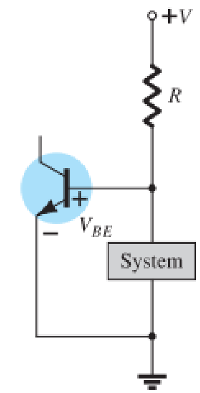


FIG. 4.103
Acting as a protective device.

- Relay Driver

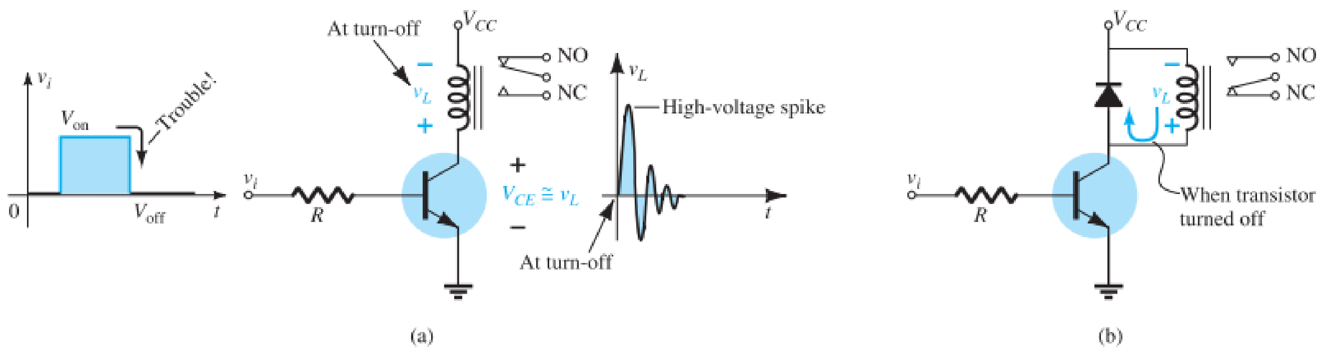


FIG. 4.104
Relay driver: (a) absence of protective device; (b) with a diode across the relay coil.

Practical Application..

- Light Control

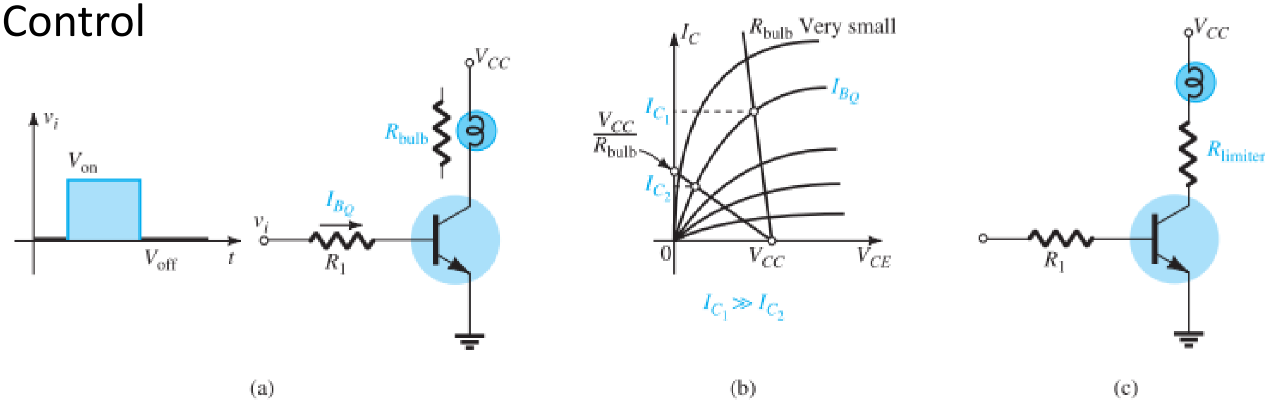


FIG. 4.105
Using the transistor as a switch to control the on–off states of a bulb: (a) network; (b) effect of low bulb resistance on collector current; (c) limiting resistor.

- Maintaining a Fixed Load Current

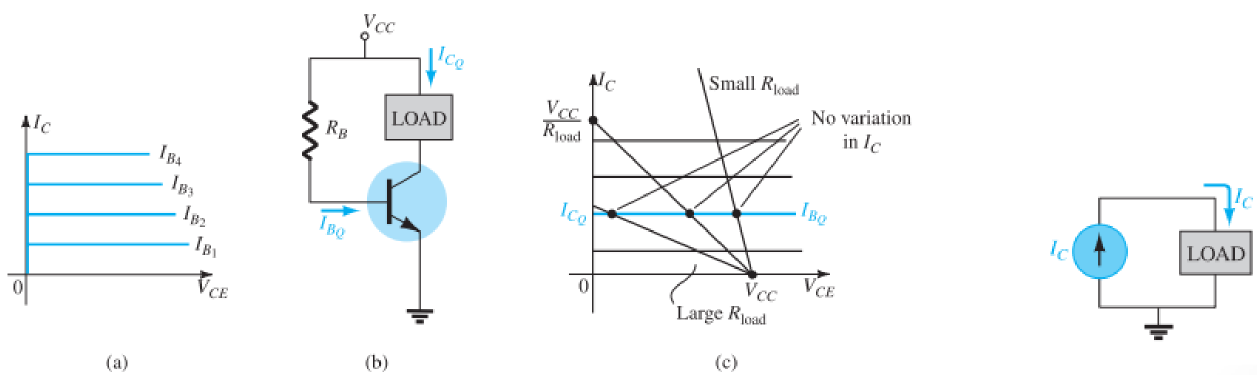


FIG. 4.106
Building a constant-current source assuming ideal BJT characteristics: (a) ideal characteristics; (b) network; (c) demonstrating why I_C remains constant.

Practical Application…

- Alarm System with a CCS

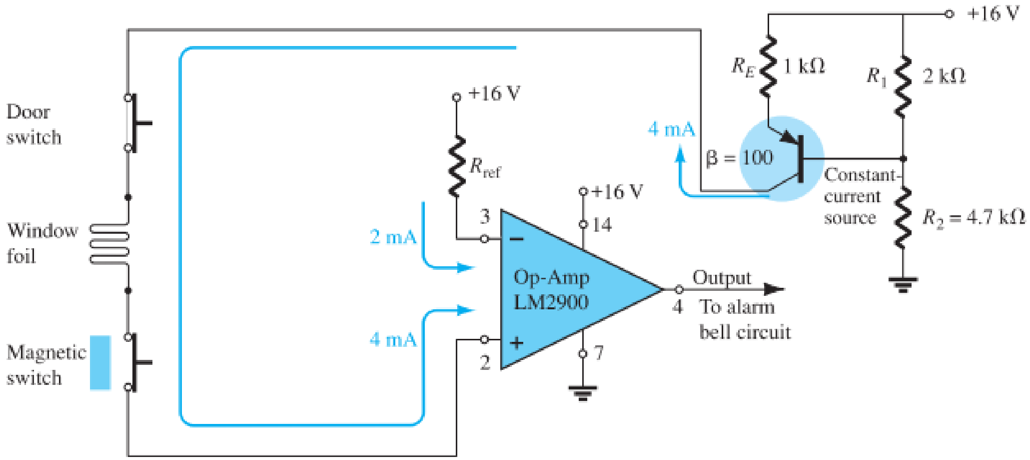


FIG. 4.108
An alarm system with a constant-current source and an op-amp comparator.

- Voltage Level Indicator

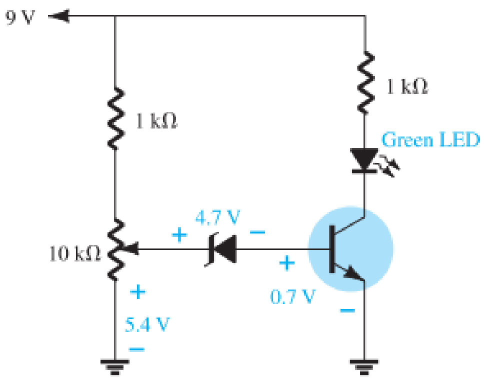
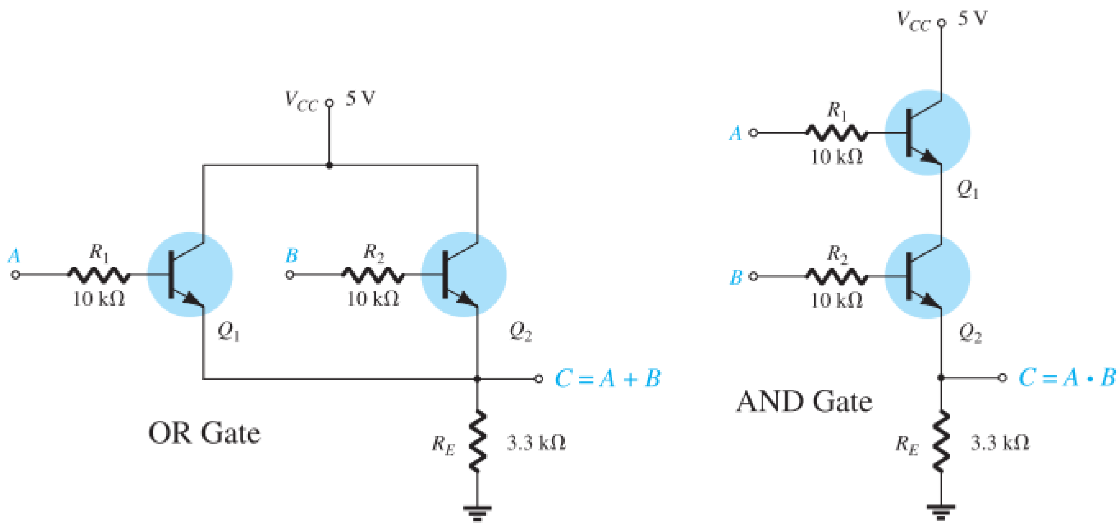


FIG. 4.112
Voltage level indicator.

Practical Application….

- Logic Gates



A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

1 = high
0 = low

(a)

A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

(b)

FIG. 4.111
BJT logic gates: (a) OR; (b) AND.

- For more details, refer to:
  - Chapter 4 at R. Boylestad, **Electronic Devices and Circuit Theory**, 11th edition, Prentice Hall.
- The lecture is available online at:
  - https://speakerdeck.com/ahmad_elbanna
- For inquires, send to:
  - ahmad.elbanna@fes.bu.edu.eg
  - ahmad.elbanna@ejust.edu.eg