Transistors

- They are unidirectional current carrying devices with capability to control the current flowing through them
- The switch current can be controlled by either current or voltage
- Bipolar Junction Transistors (BJT) control current by current
- Field Effect Transistors (FET) control current by voltage
- They can be used either as switches or as amplifiers

NPN Bipolar Junction Transistor

- One N-P (Base Collector) diode one P-N (Base Emitter) diode

![NPN Bipolar Junction Transistor diagram](image)
PNP Bipolar Junction Transistor

• One P-N (Base Collector) diode one N-P (Base Emitter) diode

NPN BJT Current flow

Figure 13.3 Only a small fraction of the emitter current flows into the base (provided that the collector-base junction is reverse biased and the base-emitter junction is forward biased).
BJT $\alpha$ and $\beta$

- From the previous figure $i_E = i_B + i_C$
- Define $\alpha = i_C / i_E$
- Define $\beta = i_C / i_B$
- Then $\beta = i_C / (i_E - i_C) = \alpha / (1 - \alpha)$
- Then $i_C = \alpha i_E$; $i_B = (1 - \alpha) i_E$

- Typically $\beta \approx 100$ for small signal BJTs (BJTs that handle low power) operating in active region (region where BJTs work as amplifiers)

BJT in Active Region

- Called CE because emitter is common to both $V_{BB}$ and $V_{CC}$
BJT in Active Region (2)

• Base Emitter junction is forward biased

• Base Collector junction is reverse biased

• For a particular $i_B$, $i_C$ is independent of $R_{CC}$

  $\Rightarrow$ transistor is acting as current controlled current source ($i_C$ is controlled by $i_B$, and $i_C = \beta i_B$)

• Since the base emitter junction is forward biased, from Shockley equation

\[
i_C = I_{CS} \exp \left( \frac{V_{BE}}{V_T} \right) - 1
\]

Early Effect and Early Voltage

• As reverse-bias across collector-base junction increases, width of the collector-base depletion layer increases and width of the base decreases (base-width modulation).

• In a practical BJT, output characteristics have a positive slope in forward-active region; collector current is not independent of $V_{CE}$.

• Early effect: When output characteristics are extrapolated back to point of zero $i_C$, curves intersect (approximately) at a common point $V_{CE} = -V_A$ which lies between 15 V and 150 V. ($V_A$ is named the Early voltage)

• Simplified equations (including Early effect):

\[
i_C = I_s \exp \left[ \frac{V_{BE}}{V_T} \right] \left( 1 + \frac{V_{CE}}{V_A} \right) \quad \beta_P = \beta_{PO} \left[ 1 + \frac{V_{CE}}{V_A} \right] \quad i_B = \frac{I_s}{\beta_{PO}} \exp \left( \frac{V_{BE}}{V_T} \right)
\]
BJT in Active Region (3)

- Normally the above equation is never used to calculate $i_C$, $i_B$
  Since for all small signal transistors $v_{BE} \approx 0.7$. It is only useful for deriving the small signal characteristics of the BJT.

- For example, for the CE connection, $i_B$ can be simply calculated as,

$$i_B = \frac{V_{BB} - V_{BE}}{R_{BB}}$$

or by drawing load line on the base–emitter side

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Deriving BJT Operating points in Active Region – An Example

In the CE Transistor circuit shown earlier $V_{BB} = 5V$, $R_{BB} = 107.5$ kΩ, $R_{CC} = 1$ kΩ, $V_{CC} = 10V$. Find $I_B, I_C, V_{CE}, \beta$ and the transistor power dissipation using the characteristics as shown below

By Applying KVL to the base emitter circuit

$$I_B = \frac{V_{BB} - V_{BE}}{R_{BB}}$$

By using this equation along with the $i_B / v_{BE}$ characteristics of the base emitter junction, $I_B = 40 \mu A$
Deriving BJT Operating points in Active Region –An Example (2)

By Applying KVL to the collector emitter circuit

\[ I_C = \frac{V_{CC} - V_{CE}}{R_{CC}} \]

By using this equation along with the \( i_C / v_{CE} \) characteristics of the base collector junction, \( i_C = 4 \text{ mA}, V_{CE} = 6V \)

\[ \beta = \frac{I_C}{I_B} = \frac{4 \text{ mA}}{40 \mu A} = 100 \]

Transistor power dissipation = \( V_{CE}I_C = 24 \text{ mW} \)

We can also solve the problem without using the characteristics if \( \beta \) and \( V_{BE} \) values are known

BJT in Cutoff Region

• Under this condition \( i_B = 0 \)

• As a result \( i_C \) becomes negligibly small

• Both base-emitter as well base-collector junctions may be reverse biased

• Under this condition the BJT can be treated as an off switch
BJT in Saturation Region

• Under this condition $i_C / i_B < \beta$ in active region

• Both base emitter as well as base collector junctions are forward biased

• $V_{CE} \approx 0.2$ V

• Under this condition the BJT can be treated as an on switch

BJT in Saturation Region (2)

• A BJT can enter saturation in the following ways (refer to the CE circuit)

• For a particular value of $i_B$, if we keep on increasing $R_{CC}$

• For a particular value of $R_{CC}$, if we keep on increasing $i_B$

• For a particular value of $i_B$, if we replace the transistor with one with higher $\beta$
BJT in Saturation Region – Example 1

In the CE Transistor circuit shown earlier $V_{BB} = 5V$, $R_{BB} = 107.5 \text{k}\Omega$, $R_{CC} = 10 \text{k}\Omega$, $V_{CC} = 10V$. Find $I_B, I_C, V_{CE}$, $\beta$ and the transistor power dissipation using the characteristics as shown below.

Here even though $I_B$ is still 40 $\mu A$; from the output characteristics, $I_C$ can be found to be only about 1mA and $V_{CE} \approx 0.2V$ ($\Rightarrow V_{BC} \approx 0.5V$ or base collector junction is forward biased (how?))

$$\beta = \frac{I_C}{I_B} = \frac{1mA}{40 \mu A} = 25 < 100$$

BJT in Saturation Region – Example 2

In the CE Transistor circuit shown earlier $V_{BB} = 5V$, $R_{BB} = 43 \text{k}\Omega$, $R_{CC} = 1 \text{k}\Omega$, $V_{CC} = 10V$. Find $I_B, I_C, V_{CE}, \beta$ and the transistor power dissipation using the characteristics as shown below.

Here $I_B$ is 100 $\mu A$ from the input characteristics; $I_C$ can be found to be only about 9.5 mA from the output characteristics and $V_{CE} \approx 0.5V$ ($\Rightarrow V_{BC} \approx 0.2V$ or base collector junction is forward biased (how?))

$$\beta = \frac{I_C}{I_B} = \frac{9.5 \text{mA}}{100 \mu A} = 95 < 100$$

Transistor power dissipation = $V_{CE}I_C \approx 4.7 \text{mW}$

Note: In this case the BJT is not in very hard saturation.
BJT in Saturation Region – Example 2

(2)

In the CE Transistor circuit shown earlier $V_{BB} = 5V$, $V_{BE} = 0.7V$ $R_{BB} = 107.5 \, k\Omega$, $R_{CC} = 1 \, k\Omega$, $V_{CC} = 10V$, $\beta = 400$. Find $I_B, I_C, V_{CE}$, and the transistor power dissipation using the characteristics as shown below.

By Applying KVL to the base emitter circuit

$$I_B = \frac{V_{BB} - V_{BE}}{R_{BB}} = 40\mu A$$

Then $I_C = \beta I_B = 400 \times 40 \, \mu A = 16000 \, \mu A$

and $V_{CE} = V_{CC} - R_{CC} \times I_C = 10 - 0.016 \times 1000 = -6V(?)$

But $V_{CE}$ cannot become negative (since current can flow only from collector to emitter).

Hence the transistor is in saturation.

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BJT in Saturation Region – Example 3

In the CE Transistor circuit shown earlier $V_{BB} = 5V$, $V_{BE} = 0.7V$ $R_{BB} = 107.5 \, k\Omega$, $R_{CC} = 1 \, k\Omega$, $V_{CC} = 10V$, $\beta = 400$. Find $I_B, I_C, V_{CE}$, and the transistor power dissipation using the characteristics as shown below.

By Applying KVL to the base emitter circuit

$$I_B = \frac{V_{BB} - V_{BE}}{R_{BB}} = 40\mu A$$

Then $I_C = \beta I_B = 400 \times 40 \, \mu A = 16000 \, \mu A$

and $V_{CE} = V_{CC} - R_{CC} \times I_C = 10 - 0.016 \times 1000 = -6V(?)$

But $V_{CE}$ cannot become negative (since current can flow only from collector to emitter).

Hence the transistor is in saturation.
BJT in Saturation Region – Example 3(2)

Hence $V_{CE} \approx 0.2\,\text{V}$

$\therefore I_C = (10 - 0.2)/1 = 9.8\,\text{mA}$

Hence the operating $\beta = 9.8\,\text{mA} / 40\,\mu\text{A} = 245$

BJT Operating Regions at a Glance (1)

![Diagram showing BJT operating regions]

**Figure 13.12** Amplification occurs in the active region. Clipping occurs when the instantaneous operating point enters saturation or cutoff. In saturation, $V_{CE} \geq 0.2\,\text{V}$. 
BJT Operating Regions at a Glance (2)

Figure 13.17 Regions of operation on the characteristics of an npn BJT.

BJT Large-signal (DC) model

Figure 13.16 BJT large-signal models. (Note: Values shown are appropriate for typical small-signal silicon devices at a temperature of 300 K.)
BJT ‘Q’ Point (Bias Point)

• Q point means Quiescent or Operating point

• Very important for amplifiers because wrong ‘Q’ point selection increases amplifier distortion

• Need to have a stable ‘Q’ point, meaning the operating point should not be sensitive to variation to temperature or BJT β, which can vary widely

Four Resistor bias Circuit for Stable ‘Q’ Point

By far best circuit for providing stable bias point
Analysis of 4 Resistor Bias Circuit

\[ V_B = V_{TH} = \frac{V_{cc} R_2}{R_1 + R_2} \]
\[ R_B = R_{TH} = \frac{R_1 R_2}{R_1 + R_2} \]

Analysis of 4 Resistor Bias Circuit (2)

Applying KVL to the base-emitter circuit of the Thevenized Equivalent form

\[ V_B - I_B R_B - V_{BE} - I_E R_E = 0 \quad (1) \]

Since \( I_E = I_B + I_C = I_B + \beta I_B = (1 + \beta)I_B \quad (2) \)

Replacing \( I_E \) by \( (1 + \beta)I_B \) in (1), we get

\[ I_B = \frac{V_B - V_{BE}}{R_B + (1 + \beta)R_E} \quad (3) \]

If we design \((1 + \beta)R_E >> R_B\) (say \((1 + \beta)R_E >> 100R_B\))

Then \( I_B \approx \frac{V_B - V_{BE}}{(1 + \beta)R_E} \quad (4) \)
Analysis of 4 Resistor Bias Circuit (3)

\[ I_C = I_E \approx \frac{V_B - V_{BE}}{R_E} \]  \hspace{1cm} \text{for large } \beta \hspace{1cm} (5)

Hence \( I_C \) and \( I_E \) become independent of \( \beta \)!

Thus we can setup a Q-point independent of \( \beta \) which tends to vary widely even within transistors of identical part number (For example, \( \beta \) of 2N2222A, a NPN BJT can vary between 75 and 325 for \( I_C = 1 \) mA and \( V_{CE} = 10V \))

4 Resistor Bias Circuit -Example

A 2N2222A is connected as shown with \( R_1 = 6.8 \text{ k}\Omega \), \( R_2 = 1 \text{ k}\Omega \), \( R_C = 3.3 \text{ k}\Omega \), \( R_E = 1 \text{ k}\Omega \) and \( V_{CC} = 30V \). Assume \( V_{BE} = 0.7V \).
Compute \( V_{CC} \) and \( I_C \) for \( \beta = 100 \) and ii) 300
4 Resistor Bias Circuit –Example (1)

   i) $\beta = 100$

\[
V_B = V_{TH} = \frac{Vcc \cdot R_2}{R_1 + R_2} = \frac{30 \cdot 1}{6.8 + 1} = 3.85V
\]

\[
R_B = R_{TH} = \frac{R_1 \cdot R_2}{R_1 + R_2} = \frac{6.8 \cdot 1}{6.8 + 1} = 0.872k\Omega
\]

\[
I_B = \frac{V_B - V_{BE}}{R_B + (1 + \beta)R_E} = \frac{3.85 - 0.7}{0.872 + 101 \cdot 1} = 30.92\mu A
\]

\[
I_{CQ} = \beta I_B = 3.09 \text{ mA}
\]

\[
I_{EQ} = (1 + \beta)I_B = 3.12 \text{ mA}
\]

\[
V_{CEQ} = V_{CC} - I_C R_C - I_E R_E = 30 - 3.09 \cdot 3.3 - 3.12 \cdot 1 = 16.68V
\]

4 Resistor Bias Circuit –Example (2)

   i) $\beta = 300$

\[
V_B = V_{TH} = \frac{Vcc \cdot R_2}{R_1 + R_2} = \frac{30 \cdot 1}{6.8 + 1} = 3.85V
\]

\[
R_B = R_{TH} = \frac{R_1 \cdot R_2}{R_1 + R_2} = \frac{6.8 \cdot 1}{6.8 + 1} = 0.872k\Omega
\]

\[
I_B = \frac{V_B - V_{BE}}{R_B + (1 + \beta)R_E} = \frac{3.85 - 0.7}{0.872 + 301 \cdot 1} = 10.43\mu A
\]

\[
I_{CQ} = 300I_B = 3.13 \text{ mA}
\]

\[
I_{EQ} = (1 + \beta)I_B = 3.14 \text{ mA}
\]

\[
V_{CEQ} = V_{CC} - I_C R_C - I_E R_E = 30 - 3.13 \cdot 3.3 - 3.14 \cdot 1 = 16.53V
\]
4 Resistor Bias Circuit – Example (3)

<table>
<thead>
<tr>
<th></th>
<th>$\beta = 100$</th>
<th>$\beta = 300$</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCEQ</td>
<td>16.68 V</td>
<td>16.53 V</td>
<td>0.9 %</td>
</tr>
<tr>
<td>ICQ</td>
<td>3.09 mA</td>
<td>3.13 mA</td>
<td>1.29 %</td>
</tr>
</tbody>
</table>

The above table shows that even with wide variation of $\beta$ the bias points are very stable.

Four-Resistor Bias Network for BJT

\[ V_{EQ} = V_{CC} \left( \frac{R_1}{R_1 + R_2} \right) \]
\[ R_{EQ} = R_1 \left[ \frac{R_2}{R_1 + R_2} \right] \]
\[ 4 = 12,000 I_B + 0.7 + 16,000 (\beta_F + 1) I_B \]
\[ \therefore I_B = \frac{V_{EQ} - V_{BE}}{\frac{R_{EQ}}{R_E} + (\beta_F + 1) R_E} = \frac{4\text{V} - 0.7\text{V}}{1.23 \times 10^6\Omega} = 2.68 \mu\text{A} \]
\[ I_C = \beta_F I_B = 201 \mu\text{A} \]

\[ I_E = (\beta_F + 1) I_B = 204 \mu\text{A} \]
\[ V_{CE} = V_{CC} - R_C I_C - R_E I_E \]
\[ = 4.32 \text{V} \]

F. A. region correct - Q-point is (201 $\mu$A, 4.32 V)
Four-Resistor Bias Network for BJT (cont.)

- All calculated currents > 0, $V_{BC} = V_{BE} - V_{CE} = 0.7 - 4.32 = -3.62$ V
- Hence, base-collector junction is reverse-biased.

\[
V_{BC} = V_{BE} - V_{CE} = 0.7 - 4.32 = -3.62 \text{ V}
\]

\[
\Rightarrow \text{base-collector junction is reverse-biased.}
\]

The two points needed to plot the load line are (0, 12 V) and (314 μA, 0).

- Resulting load line is plotted on common-emitter output characteristics.

- Current in base voltage divider network is limited by choosing $I_2 < \frac{I_C}{5}$. This ensures that power dissipation in bias resistors is < 17 % of total quiescent power consumed by circuit and $I_2 >> I_B$ for $\beta > 50$. 

Four-Resistor Bias Network for BJT: Design Objectives

- We know that

\[
I_E = \frac{V_{EQ} - V_{BE} - R_{EQ} I_B}{R_E} = \frac{V_{EQ} - V_{BE}}{R_E} \quad \text{for} \quad R_{EQ} I_B << (V_{EQ} - V_{BE})
\]

- This implies that $I_B << I_2$, so that $I_2 = I_1$. So base current doesn’t disturb voltage divider action. Thus, Q-point is independent of base current as well as current gain.

- Also, $V_{EQ}$ is designed to be large enough that small variations in the assumed value of $V_{BE}$ won’t affect $I_E$.

- Current in base voltage divider network is limited by choosing $I_2 \leq I_C/5$. This ensures that power dissipation in bias resistors is < 17 % of total quiescent power consumed by circuit and $I_2 >> I_B$ for $\beta > 50$. 

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Four-Resistor Bias Network for BJT: Design Guidelines

- Choose Thévenin equivalent base voltage $\frac{V_{cc}}{4} \leq V_{eq} \leq \frac{V_{cc}}{2}$
- Select $R_1$ to set $I_1 = 9I_B$. $R_1 = \frac{V_{eq}}{9I_B}$
- Select $R_2$ to set $I_2 = 10I_B$. $R_2 = \frac{V_{cc} - V_{eq}}{10I_B}$
- $R_E$ is determined by $V_{eq}$ and desired $I_C$. $R_E \approx \frac{V_{eq} - V_{BE}}{I_C}$
- $R_C$ is determined by desired $V_{CE}$. $R_C \approx \frac{V_{cc} - V_{CE} - R_E}{I_C}$

Four-Resistor Bias Network for BJT: Example

- **Problem:** Design 4-resistor bias circuit with given parameters.
- **Given data:** $I_C = 750 \mu A$, $\beta_F = 100$, $V_{cc} = 15 V$, $V_{CE} = 5 V$
- **Assumptions:** Forward-active operation region, $V_{BE} = 0.7 V$
- **Analysis:** Divide $(V_{cc} - V_{CE})$ equally between $R_E$ and $R_C$. Thus, $V_E = 5 V$ and $V_C = 10 V$

\[
R_C = \frac{V_{cc} - V_C}{I_C} = 6.67 \ \text{k} \Omega \\
R_E = \frac{V_E}{I_E} = 6.60 \ \text{k} \Omega \\
V_B = V_E + V_{BE} = 5.7 V \\
I_B = \frac{I_C}{\beta_F} = 7.5 \ \mu A
\]

\[
I_2 = 10I_B = 75.0 \ \mu A \\
I_1 = 9I_B = 67.5 \ \mu A \\
R_1 = \frac{V}{9I_B} = 84.4 \ \text{k} \Omega \\
R_2 = \frac{V_{cc} - V_B}{10I_B} = 124 \ \text{k} \Omega
\]
Two-Resistor Bias Network for BJT: Example

- **Problem:** Find Q-point for *pnp* transistor in 2-resistor bias circuit with given parameters.
- **Given data:** $\beta_F = 50$, $V_{CC} = 9$ V
- **Assumptions:** Forward-active operation region, $V_{EB} = 0.7$ V
- **Analysis:**
  
  $9 = V_{EB} + 18,000 I_B + 1000 (I_C + I_B)$  
  $\therefore 9 = V_{EB} + 18,000 I_B + 1000 (51)I_B$  
  
  $\therefore I_B = \frac{9V - 0.7V}{69,000 \, \Omega} = 120 \, \mu A$  
  $I_C = 50 I_B = 6.01 \, mA$  
  
  $V_{EC} = 9 - 1000 (I_C + I_B) = 2.88 \, V$  
  $V_{BC} = 2.18 \, V$  

  **Forward-active region operation is correct Q-point is:** (6.01 mA, 2.88 V)