Bipolar Junction Transistors

- Bipolar: both electrons and holes contribute to conduction
- Junction: device includes two p-n junctions (as opposed to a "point-contact" transistor, the first transistor)
- Transistor: "transfer resistor" When Bell Labs had an informal contest to name their new invention, one engineer pointed out that it acts like a resistor, but a resistor where the voltage is transferred across the device to control the resulting current.
- Invented in 1947 by Shockley, Bardeen, and Brattain at Bell Laboratories.
- BJT is still used extensively, and anyone interested in electronics must have at least a working knowledge of this device.
- "A BJT is two diodes connected back-to-back." WRONG! Let us see why.

M. B. Patil, IIT Bombay
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  WRONG! Let us see why.
Consider a \textit{pnp} BJT in the following circuit:

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{circuit.png}
\end{figure}

If the transistor is replaced with two diodes connected back-to-back, we get:

Assuming $V_{on} = 0.7\,\text{V}$ for $D1$, we get $I_1 = 5\,\text{V} - 0.7\,\text{V}$, $I_2 = 0$ (since $D2$ is reverse biased), and $I_3 \approx I_1 = 4.3\,\text{mA}$.

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Consider a \( pnp \) BJT in the following circuit:

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Assuming \( V_{on} = 0.7 \) V for \( D1 \), we get

\[ I_1 = \frac{5 \text{ V} - 0.7 \text{ V}}{1 \text{ k}\Omega} = 4.3 \text{ mA}, \]

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![Bipolar Junction Transistor Circuit](image)

If the transistor is replaced with two diodes connected back-to-back, we get

![Diodes Connected Back-to-Back](image)

Assuming $V_{on} = 0.7$ V for D1, we get

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l_1 = \frac{5 \, \text{V} - 0.7 \, \text{V}}{R_1} = 4.3 \, \text{mA},
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$l_2 = 0$ (since D2 is reverse biased), and $l_3 \approx l_1 = 4.3$ mA.
Using a more realistic equivalent circuit for the BJT, we obtain,

\[ I_1 = 5 \text{ V} - 0.7 \text{ V} \]
\[ R_1 = 4.3 \text{ mA} \text{ (as before)}, \]
\[ I_2 = \alpha I_1 \approx 4.3 \text{ mA} \text{ (since} \alpha \approx 1 \text{ for a typical BJT), and} \]
\[ I_3 = I_1 - I_2 = (1 - \alpha) I_1 \approx 0 \text{ A} \]

The values of \( I_2 \) and \( I_3 \) are dramatically different than the ones obtained earlier, viz., \( I_2 \approx 0 \), \( I_3 \approx 4.3 \text{ mA} \).

Conclusion: A BJT is NOT the same as two diodes connected back-to-back (although it does have two p-n junctions).
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What is wrong with the two-diode model of a BJT?

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* Later, we will look at the “Ebers-Moll model” of a BJT, which is a fairly accurate representation of the transistor action.
In the active mode of a BJT, the B-E junction is under forward bias, and the B-C junction is under reverse bias.

- For a pnp transistor, $V_{BE} > 0$ $V$ and $V_{BC} < 0$ $V$.

- For an npn transistor, $V_{BE} > 0$ $V$ and $V_{BC} < 0$ $V$.

Since the B-E junction is under forward bias, the voltage (magnitude) is typically 0.6 to 0.75 $V$.

The B-C voltage can be several Volts (or even hundreds of Volts), and is limited by the breakdown voltage of the B-C junction.

The symbol for a BJT includes an arrow for the emitter terminal, its direction indicating the current direction when the transistor is in active mode.

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In the active mode, $I_C = \alpha I_E$, $\alpha \approx 1$ (slightly less than 1).

The ratio $I_C/I_B$ is defined as the current gain $\beta$ of the transistor.

$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1 - \alpha}$.

$\beta$ is a function of $I_C$ and temperature. However, we will generally treat it as a constant, a useful approximation to simplify things and still get a good insight.
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Transistors are generally designed to get a high value of \(\beta\) (typically 100 to 250, but can be as high as 2000 for "super-\(\beta\)" transistors). A large \(\beta\) \(\Rightarrow\) \(i_B \ll i_C\) or \(i_E\) when the transistor is in the active mode.
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*\( \beta \) increases substantially as \( \alpha \rightarrow 1 \).*
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Assume the BJT to be in the active mode ⇒ $V_{BE} = 0.7\text{ V}$ and $I_C = \alpha I_E = \beta I_B$.

$I_B = V_{BB} - V_{BE} R_B = 2\text{ V} - 0.7\text{ V} \times 100\text{ k}\Omega = 13\mu\text{ A}$.

$I_C = \beta \times I_B = 100 \times 13\mu\text{ A} = 1.3\text{ mA}$.

$V_C = V_{CC} - I_C R_C = 10\text{ V} - 1.3\text{ mA} \times 1\text{ k}\Omega = 8.7\text{ V}$.

Let us check whether our assumption of active mode is correct. We need to check whether the B-C junction is under reverse bias.

$V_{BC} = V_B - V_C = 0.7\text{ V} - 8.7\text{ V} = -8.0\text{ V}$, i.e., the B-C junction is indeed under reverse bias.
A simple BJT circuit

Assume the BJT to be in the active mode ⇒ $V_{BE} = 0.7$ V and $I_C = \alpha I_E = \beta I_B$.

$I_B = V_{BB} - V_{BE} R_B = 2 V - 0.7 V 100 k = 13 \mu A$.

$I_C = \beta I_B = 100 \times 13 \mu A = 1.3$ mA.

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What happens if $R_B$ is changed from 100 k to 10 k?
A simple BJT circuit: continued

What happens if $R_B$ is changed from 100 k to 10 k?

Assuming the BJT to be in the active mode again, we have $V_{BE} \approx 0.7 \, V$, and $I_C = \beta I_B$. 

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$\rightarrow V_{BC} = V_B - V_C = 0.7 \text{ V} - (-3) \text{ V} = 3.7 \text{ V}.$
What happens if $R_B$ is changed from 100 k to 10 k?

Assuming the BJT to be in the active mode again, we have $V_{BE} \approx 0.7$ V, and $I_C = \beta I_B$.

\[
I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{2 \text{ V} - 0.7 \text{ V}}{10 \text{ k}} = 130 \, \mu\text{A} \rightarrow I_C = \beta \times I_B = 100 \times 130 \, \mu\text{A} = 13 \text{ mA}.
\]

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V_C = V_{CC} - I_C R_C = 10 \text{ V} - 13 \text{ mA} \times 1 \text{ k} = -3 \text{ V}
\]

$V_{BC} = V_B - V_C = 0.7 \text{ V} - (-3) \text{ V} = 3.7 \text{ V}$.

$V_{BC}$ is not only positive, it is huge!

$\rightarrow$ The BJT cannot be in the active mode, and we need to take another look at the circuit.
Ebers-Moll model for a pnp transistor

Active mode ("forward" active mode): B-E in f.b. B-C in r.b.

\[ I_C = \alpha I_E \]

Reverse active mode: B-E in r.b. B-C in f.b.

In the reverse active mode, emitter $\leftrightarrow$ collector. (However, we continue to refer to the terminals with their original names.)

The two $\alpha$'s, $\alpha_F$ (forward $\alpha$) and $\alpha_R$ (reverse $\alpha$) are generally quite different. Typically, $\alpha_F > 0.98$, and $\alpha_R$ is in the range from 0.02 to 0.5.

The corresponding current gains ($\beta_F$ and $\beta_R$) differ significantly, since $\beta = \alpha/(1 - \alpha)$.
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In amplifiers, the BJT is biased in the forward active mode (simply called the "active mode") in order to make use of the higher value of $\beta$ in that mode.

M. B. Patil, IIT Bombay
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In amplifiers, the BJT is biased in the forward active mode (simply called the "active mode") in order to make use of the higher value of \( \beta \) in that mode.
The Ebers-Moll model combines the forward and reverse operations of a BJT in a single comprehensive model.

\[ I_{EC} = I_{ES} \left[ \exp \left( \frac{V_{EB}}{V_T} \right) - 1 \right], \quad I_{IC} = I_{CS} \left[ \exp \left( \frac{V_{CB}}{V_T} \right) - 1 \right]. \]
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The currents $I'_E$ and $I'_C$ are given by the Shockley diode equation:

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<table>
<thead>
<tr>
<th>Mode</th>
<th>B-E</th>
<th>B-C</th>
<th>$I'_E \gg I'_C$</th>
<th>$I'_C \gg I'_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward active</td>
<td>forward</td>
<td>reverse</td>
<td>$I'_E \gg I'_C$</td>
<td>$I'_C \gg I'_E$</td>
</tr>
<tr>
<td>Reverse active</td>
<td>reverse</td>
<td>forward</td>
<td>$I'_C \gg I'_E$</td>
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</tr>
<tr>
<td>Saturation</td>
<td>forward</td>
<td>forward</td>
<td>$I'_E$ and $I'_C$ are comparable.</td>
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**Ebers-Moll Model Equations**

For a **pnp transistor**:

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Ebers-Moll model

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M. B. Patil, IIT Bombay
Ebers-Moll model in active mode

\[ I_{C} = \alpha F I_{E} = \beta F I_{B} \]

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\[ I_{E}' = I_{E} \left[ \frac{e^{V_{BE}/V_{T}} - 1}{e^{V_{BE}/V_{T}} - 1} \right] \]

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Since BJT is a three-terminal device, its behavior can be described in many different ways, e.g.,

- $I_C$ versus $V_{CB}$ for different values of $I_E$
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The $I-V$ relationship for a BJT is not a single curve but a "family" of curves or "characteristics."

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BJT $I-V$ characteristics

\[ \alpha_F = 0.99 \rightarrow \beta_F = \frac{\alpha_F}{1 - \alpha_F} = 99 \]

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\[\text{**Linear Region:** B-E under forward bias, B-C under reverse bias, } I_C = \beta_F I_B\]

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$I_B = 10 \mu A$

$I_C (mA)$

$V_{CE} (Volts)$

$V_{BE} (Volts)$

$V_{BC} (Volts)$
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In addition to the BJT $I_C - V_{CE}$ curve, the circuit variables must also satisfy the constraint, $V_{CC} = V_{CE} + I_C R_C$, a straight line in the $I_C - V_{CE}$ plane.
A simple BJT circuit (revisited)

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The intersection of the load line and the BJT characteristics gives the solution for the circuit. For $R_B = 10$ k, note that the BJT operates in the saturation region, leading to $V_{CE} \approx 0.2$ V, and $I_C = 9.8$ mA.
Assuming the transistor to be operating in the active region, find $R_E$ and $R_C$ to obtain $I_E = 2 \text{ mA}$, and $V_{BC} = 1 \text{ V}$ ($\alpha \approx 1$).

\begin{equation}
I_E R_E = V_{EE} - V_{EB} = 5 \text{ V} - 0 = 5 \text{ V} \Rightarrow R_E = 4.3 \text{ k}\Omega.
\end{equation}

\begin{equation}
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