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.
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M. B. Patil, IIT Bombay
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![Diagram of Bipolar Junction Transistors](image-url)
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![Bipolar Junction Transistor Circuit](image)

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

Assuming $V_{on} = 0.7$ V for $D_1$, we get $I_1 = 5 \text{ V} - 0.7 \text{ V} = 4.3 \text{ mA}$, $I_2 = 0$ (since $D_2$ is reverse biased), and $I_3 \approx I_1 = 4.3 \text{ mA}$. 

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![Circuit Diagram](image)

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![Diode Circuit Diagram](image)

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

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Using a more accurate equivalent circuit for the BJT, we obtain,

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\begin{align*}
    \text{I}_1 &= \frac{5 \text{ V} - 0.7 \text{ V}}{R_1} = 4.3 \text{ mA} \\
    \text{I}_2 &= \alpha \text{I}_1 \approx 4.3 \text{ mA} \\
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The values of \text{I}_2 and \text{I}_3 are dramatically different than the ones obtained earlier.

Conclusion: A BJT is NOT the same as two diodes connected back-to-back (although it does have two p-n junctions).
Using a more accurate equivalent circuit for the BJT, we obtain,

\[ I_1 = \frac{5 \text{ V} - 0.7 \text{ V}}{R_1} = 4.3 \text{ mA} \text{ (as before)}, \]

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* However, in a BJT, exactly the opposite is true. For a higher performance, the base region is made as short as possible (subject to certain constraints), and the two diodes therefore cannot be treated as independent devices.

* 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, $V_{EB} > 0$ V, and $V_{CB} < 0$ 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.
* Analog circuits, including amplifiers, are generally designed to ensure that the BJTs are operating in the active mode.
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In the active mode, \[ I_C = \alpha I_E, \quad \alpha \approx 1 \] (slightly less than 1).

\[ I_B = I_E - I_C = I_E (1 - \alpha) \]

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

\[ \beta = \frac{I_C}{I_B} = \alpha / (1 - \alpha) \]

\( \beta \) 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 \(\beta \Rightarrow I_B \ll I_C \text{ or } I_E\) when the transistor is in the active mode.
Assume the BJT to be in the active mode ⇒ $V_{BE} = 0.7\text{V}$ and $I_C = \alpha I_E = \beta I_B$.

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

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

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

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

$V_{BC} = V_B - V_C = 0.7\text{V} - 8.7\text{V} = -8\text{V}$, i.e., the B-C junction is indeed under reverse bias.
A simple BJT circuit

\[ V_{BB} = 2 \text{ V} \]
\[ V_{CC} = 10 \text{ V} \]
\[ V_{CE} = 10 \text{ V} \]
\[ \beta = 100 \]

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

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.

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 $\beta = \alpha/(1 - \alpha)$. 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.
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Reverse active mode: B–E in r. b., B–C in f. b.

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The two \(\alpha\)'s, \(\alpha_F\) ("forward\(\alpha\)) and \(\alpha_R\) ("reverse\(\alpha\)) are generally quite different. Typically, \(\alpha_F > 0\) 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 \(\beta = \alpha/(1 - \alpha)\). 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
Ebers-Moll model for a *pnp* transistor

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

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\[
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 & \text{B} \downarrow \text{I}_B \\
 & \text{I}_E \rightarrow \text{I}_C
\end{align*}
\]

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

\[
\begin{align*}
 & \text{E} \rightarrow \text{p} \rightarrow \text{n} \rightarrow \text{p} \rightarrow \text{C} \\
 & \text{B} \uparrow \text{I}_B \\
 & \text{I}_E \rightarrow \text{I}_C
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Ebers-Moll model for a pnp transistor

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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.

The currents $I'_E$ and $I'_C$ are given by the Shockley diode equation:

$$I'_E = I_{ES} \exp \left( \frac{V_{EB}}{V_T} \right) - 1,$$

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<table>
<thead>
<tr>
<th>Mode</th>
<th>B-E</th>
<th>B-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward active</td>
<td>forward</td>
<td>reverse</td>
</tr>
<tr>
<td>Reverse active</td>
<td>reverse</td>
<td>forward</td>
</tr>
<tr>
<td>Saturation</td>
<td>forward</td>
<td>forward</td>
</tr>
<tr>
<td>Cut-off</td>
<td>reverse</td>
<td>reverse</td>
</tr>
</tbody>
</table>
For an npn transistor, the same model holds with current directions and voltage polarities suitably changed.

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I_E &= I_{ES} \left[ \exp \left( \frac{V_{BE}}{V_T} \right) - 1 \right] \\
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For an npn transistor, the same model holds with current directions and voltage polarities suitably changed.
$I_C - V_{CE}$ characteristics

A BJT is a three-terminal device, and its $I-V$ characteristics can therefore be represented in several different ways. The $I_C$ versus $V_{CE}$ characteristics are very useful in amplifiers.

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To start with, we consider a single point, $I_B = 10 \, \mu A$, $V_{CE} = 5 \, V$. 

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There are several ways to assign \( V_{BE} \) and \( V_{CB} \) so that they satisfy the constraint:

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V_{CB} + V_{BE} = (V_C - V_B) + (V_B - V_E) = V_{CE} = 5 \, V.
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Let us consider some of these possibilities.
$I_C - V_{CE}$ characteristics

Constraints: $I_B = 10 \, \mu A$, $V_{CE} = 5 \, V$. 

$I'_E = I_{ES} \left[ \exp \left( \frac{V_{BE}}{V_T} \right) - 1 \right]$ 

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$I_C - V_{CE}$ characteristics

Constraints: $I_B = 10 \mu A$, $V_{CE} = 5 \text{ V}$.

D1 and D2 are both off, and we cannot satisfy the condition, $I_B = 10 \mu A$, since all currents are much smaller than $10 \mu A$. 

\[ I'_E = I_{ES} \left[ \exp \left( \frac{V_{BE}}{V_T} \right) - 1 \right] \]
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M. B. Patil, IIT Bombay
\( I_C - V_{CE} \) characteristics

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D1 and D2 are both off, and we cannot satisfy the condition, \( I_B = 10 \, \mu\text{A} \), since all currents are much smaller than \( 10 \, \mu\text{A} \).

\( \Rightarrow \) This possibility (and similarly others with both junctions reverse biased) is ruled out.

M. B. Patil, IIT Bombay
$I_C - V_{CE}$ characteristics

$\alpha_F = 0.99, \quad I_{SE} = 1 \times 10^{-14} \text{ A}$

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D1 and D2 are both conducting; however, the forward bias for the B-E junction is impossibly large.
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D1 and D2 are both conducting; however, the forward bias for the B-E junction is impossibly large.

⇒ This possibility is also ruled out.
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D1 is on, D2 is off. This is a realistic possibility. Since the B-C junction is under reverse bias, $I'_C$ and $\alpha_R I'_C$ are much smaller than $I'_E$, and therefore the lower branches in the Ebers-Moll model can be dropped (see next slide).
(The actual values for \( V_{BE} \) and \( V_{CB} \) obtained by solving the Ebers-Moll equations are \( V_{BE} = 0.656 \text{ V} \) and \( V_{CB} = 4.344 \text{ V} \).)

The BJT is in the active mode, and therefore

\[
I_C = \beta I_B = \frac{\alpha_F}{1 - \alpha_F} \quad I_B = 99 \times 10 \mu A = 0.99 \text{ mA}.
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If $V_{CE}$ is reduced to, say, 4 V, and $I_B$ kept at 10 $\mu$A, our previous argument holds, and once again, we find that $I_C = \beta I_B = 0.99$ mA.
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Thus, the plot of $I_C$ versus $V_{CE}$ is simply a horizontal line.
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\( I_C - V_{CE} \) characteristics

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Thus, the plot of \( I_C \) versus \( V_{CE} \) is simply a horizontal line.

However, as \( V_{CE} \to 0 \) V, things change (see next slide).
When $V_{CE} \approx 0.7 \, V$ (and $I_B$ kept at $10 \, \mu A$), the B-C drop is about $0 \, V$. 
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As $V_{CE}$ is reduced further, the B-C junction gets forward biased. For example, with $V_{CE} = 0.3$ V, we may have a voltage distribution shown in the figure.

(The numbers are only representative; the actual $V_{BE}$ and $V_{BC}$ values can be obtained by solving the E-M equations.)
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Now, the component $I'_C$ in the E-M model becomes significant, $I_C = \alpha_F I'_E - I'_C$ reduces, and $I_C$ becomes smaller than $\beta I_B$. 

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$I_C$-$V_{CE}$ characteristics
$I_C - V_{CE}$ characteristics

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Now, the component $I'_C$ in the E-M model becomes significant, $I_C = \alpha_F I'_E - I'_C$ reduces, and $I_C$ becomes smaller than $\beta I_B$.

The region where $I_C < \beta I_B$ is called the “saturation region.”
If $I_B$ is doubled (from 10 $\mu$A to 20 $\mu$A), $I_C = \beta I_B$ changes by a factor of 2 in the linear region. Apart from that, there is no qualitative change in the $I_C - V_{CE}$ plot.
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Clearly, the $I_C - V_{CE}$ behaviour of a BJT is not represented by a single curve but by a family of curves, known as the “$I_C - V_{CE}$ characteristics.”
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Clearly, the $I_C - V_{CE}$ behaviour of a BJT is not represented by a single curve but by a family of curves, known as the “$I_C - V_{CE}$ characteristics.”

The $I_E - V_{CB}$ and $I_C - V_{BE}$ characteristics of a BJT are also useful in understanding BJT circuits.
A simple BJT circuit (revisited)

We are now in a position to explain what happens when $R_B$ is decreased from 100 k to 10 k in the above circuit.
A simple BJT circuit (revisited)

We are now in a position to explain what happens when $R_B$ is decreased from 100 kΩ to 10 kΩ in the above circuit.

Let us plot $I_C - V_{CE}$ curves for $I_B \approx \frac{V_{BB} - 0.7 \, V}{R_B}$ for the two values of $R_B$. 
A simple BJT circuit (revisited)

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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.
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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.

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 \( I_C = 9.8 \, mA \).