A transistor is somewhat like a valve used to control liquid current. In this analogy we find:

<table>
<thead>
<tr>
<th>This</th>
<th>...is (sort of) like...</th>
<th>this</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric current</td>
<td>Liquid current</td>
<td></td>
</tr>
<tr>
<td>Voltage</td>
<td>Pressure</td>
<td></td>
</tr>
<tr>
<td>Collector</td>
<td>Valve Input</td>
<td></td>
</tr>
<tr>
<td>Emitter</td>
<td>Valve Output</td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td>Valve Control Knob</td>
<td></td>
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</tbody>
</table>

![Diagram of transistor and valve analogy]

- Collector
- Emitter
- Base
- $i_C$
- $V_{CE}$
- $P_{CE}$
- Current (liquid)
- Pressure
**Cutoff** is analogous to the value being completely closed—no current will flow through the value, regardless of how much pressure ($v_{CE}$) is applied.

**Saturation** is analogous to the value being completely open—it takes almost no pressure ($v_{CE}$) to get a lot of current to flow through the valve.

**Active** mode is analogous to having the value partially open—it requires some pressure ($v_{CE}$) to get current to flow. Moreover, this current can be increased by further opening the valve (increasing base current $i_B$) or decreased by further closing the valve (decreasing base current $i_B$).

We will find that BJT behavior is in many ways similar to MOSFET behavior!

**ACTIVE MODE**

We found earlier that forward biasing the emitter-base junction (EBJ) results in collector (drift) current. The junction voltage for the EBJ is $v_{BE}$ (for npn).

Thus, in active mode, the voltage base-to-emitter $v_{BE}$ controls the collector current $i_C$. Specifically, we find that:

$$i_C = I_s e^{v_{BE}/V_t} \quad (npn)$$

$$i_C = I_s e^{v_{EB}/V_t} \quad (pnp)$$
Here we should note two things:

1. The active mode equation is very similar to the p-n junction diode equation.

No surprise here! The collector current is directly proportional to the diffusion current across the EBJ. That’s why the equation is just like the diffusion current equation for a pn junction.

In fact, $I_S$ is scale current (a device parameter), and $V_T$ is the thermal voltage (25 mV)—the same values used to describe junction diodes!

2. A BJT in ACTIVE mode is analogous to a MOSFET in SATURATION mode.

Recall that for a MOSFET in SATURATION, the drain current $i_D$ is “controlled” by the gate-to-source voltage $V_{GS}$. Likewise, for a BJT in ACTIVE mode, the collector current $i_C$ is “controlled” by the base-to-emitter voltage $V_{BE}$.

Note the analogies!

\[
\begin{align*}
  i_D & \text{ analogous to } i_C \\
  v_{BE} & \text{ analogous to } v_{GS} \\
  \text{ACTIVE} & \text{ analogous to SATURATION}
\end{align*}
\]
Note also that a **necessary** (but not sufficient) condition for a *npn* BJT to be in **ACTIVE** mode is that $v_{BE} > 0$ (i.e., the EBJ is forward biased).

This is **analogous** to an NMOS in **SATURATION** mode, where a **necessary** (but not sufficient) condition is that $v_{GS} > V_t$ (i.e., the channel is conducting).
Likewise, for a BJT to be in the ACTIVE mode, the CBJ must be in reverse bias (i.e., $\nu_{BC} < 0$). Assuming that the forward biased EBJ results in $\nu_{BE} \approx 0.7 \, \text{V}$, we can use KVL to determine that the CBJ will be reverse biased only when:

\[
\begin{align*}
\nu_{CE} &> 0.7 \, \text{V} \quad \text{for } npn \text{ in ACTIVE} \\
\nu_{EC} &> 0.7 \, \text{V} \quad \text{for } pnp \text{ in ACTIVE}
\end{align*}
\]

These statements above are analogous to the MOSFET inequality $\nu_{DS} > \nu_{GS} - \nu_t$ for MOSFET SAT. (more on this later!).

Now, we are tempted to make another analogy between base current $i_B$ and gate current $i_G$, but here the analogies end!

Recall $i_G = 0$ always, but for BJTs we find that $i_B$ is not equal to zero (generally).

Instead, we found that although most of the charge carriers (e.g., holes or free electrons) diffusing across the EBJ end up “drifting” across the CBJ into the collector, some charge carriers do “exit” the base terminal.
Recall, however, that for every one charge carrier that leaves the base terminal, there are typically 50 to 250 (depending on the BJT) charge carriers that drift into the collector.

As a result, the collector current for ACTIVE mode is typically 50 to 250 times larger than the base current! I.E.:

$$50 < \frac{i_C}{i_B} < 250 \text{ typically, for BJT ACTIVE}$$

The precise value of this ratio is the device parameter $\beta$ (beta):

$$\beta = \frac{i_C}{i_B} \quad \text{for BJT ACTIVE mode}$$

Thus, we find that the base current can be expressed as:

For (npn):

$$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{\frac{v_{BE}}{V_T}}$$

For (pnp):

$$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{\frac{v_{EB}}{V_T}}$$
Likewise, from KCL, we can determine the emitter current for a BJT in the ACTIVE mode:

\[
i_E = i_c + i_B \\
= \beta i_B + i_B \\
= (\beta + 1)i_B
\]

Or similarly,

\[
i_E = i_c + i_B \\
i_c \left(1 + \frac{1}{\beta}\right) \\
= \left(\frac{\beta + 1}{\beta}\right)i_c
\]

An alternative to device parameter \(\beta\) is the device parameter \(\alpha\), defined as:

\[
\alpha = \frac{\beta}{\beta + 1}
\]

Note that the value of \(\alpha\) will be just slightly less than one.

We can thus alternatively express the current relationships as:

\[
i_c = \alpha i_E \quad i_B = (1 - \alpha)i_E
\]
And therefore:

\[
i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{\frac{v_{BE}}{V_T}} \quad (nnp)
\]

\[
i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{\frac{v_{EB}}{V_T}} \quad (ppn)
\]

Recall that the exponential expression for a \textit{pn} junction turned out to be of \textit{limited} use, as it typically led to unsolvable \textit{transcendental equations}.

The \textit{same} is true for these exponential equations! We will thus generally use the equations below to approximate the behavior of a BJT in the \text{ACTIVE} mode:

\[
\begin{align*}
\nu_{BE} &\approx 0.7 \quad i_C = \beta i_B \quad \nu_{CE} > 0.7 \quad (nnp \text{ in ACTIVE}) \\
\nu_{EB} &\approx 0.7 \quad i_C = \beta i_B \quad \nu_{EC} > 0.7 \quad (ppn \text{ in ACTIVE})
\end{align*}
\]

\textbf{SATURATION MODE}

Recall for BJT SATURATION mode that both the CBJ and the EBJ are \textit{forward biased}.

Thus, the collector current is due to \textit{two} physical mechanisms, the \textit{first} being charge carriers (holes or free-electrons) that
drift across the CBJ (just like ACTIVE mode), and the second being charge carriers that diffuse across the forward biased CBJ!

As a result, a second term appears in our mathematical description of collector current (when the BJT is in SATURATION):

\[
i_c = I_s e^{v_{BE}/V_t} - \left(\frac{I_s}{\alpha_R}\right) e^{v_{BC}/V_t} \quad \text{(nnp)}
\]

\[
i_c = I_s e^{v_{EB}/V_t} - \left(\frac{I_s}{\alpha_R}\right) e^{v_{CB}/V_t} \quad \text{(pnp)}
\]

where \(\alpha_R\) represents the same device parameter \(\alpha\) discussed earlier (for ACTIVE mode), with the only difference that it specifies the value of \(\alpha\) specifically for the CBJ.

This second term describes the current due to diffusion across the CBJ. Note that this current is in the opposite direction of the drift current (the first term), hence the minus sign in the second term.

Now using KVL (i.e., \(v_{CE} = v_{CB} + v_{BE}\)), we can write this collector current equation as:
\[ i_C = I_S e^{\frac{V_{BE}}{V_T}} - \left( \frac{I_S}{\alpha R} \right) e^{\frac{(V_{BE} - V_{CE})}{V_T}} \]

\[ = I_S e^{\frac{V_{BE}}{V_T}} \left( 1 - e^{\frac{-V_{CE}}{V_T}} \right) \]

Thus, we can conclude:

\[ i_C = I_S e^{\frac{V_{BE}}{V_T}} \left( 1 - e^{\frac{-V_{CE}}{V_T}} \right) \quad \text{for } npn \text{ in SAT.} \]

\[ i_C = I_S e^{\frac{V_{EB}}{V_T}} \left( 1 - e^{\frac{-V_{EC}}{V_T}} \right) \quad \text{for } pnp \text{ in SAT.} \]

It is thus clear that for a BJT in SATURATION, the collector current \( i_C \) is dependent on both \( V_{BE} \) and \( V_{CE} \).

This is precisely analogous to the TRIODE mode for MOSFETS!

Recall for triode mode, drain current \( i_D \) is dependent on both \( V_{GS} \) and \( V_{DS} \). We thus have discovered two new analogies:
$v_{CE}$ analogous to $v_{DS}$

SATURATION analogous to TRIODE

\[ i_C = I_S e^{\frac{v_{BE}}{V_T}} \left( 1 - e^{-\frac{v_{CE}}{V_T}} \right) \]

\[ i_D = K \left[ 2(v_{GS} - V_t) v_{DS} - v_{DS}^2 \right] \]

nnp in SAT. mode

NMOS in TRIODE mode
Now, a BJT is in SATURATION mode if both the CBJ and the EBJ are forward biased. Assuming that $v_{BE} \approx 0.7$ V if the EBJ is forward biased, the CBJ voltage $v_{BC}$ will be positive only if (using KVL):

\[ v_{BC} > 0 \]
\[ v_{BE} - v_{CE} > 0 \]
\[ 0.7 - v_{CE} > 0 \]
\[ v_{CE} < 0.7 \]

Thus, we can conclude that a necessary (but not sufficient) condition for a BJT to be in SATURATION is:

\[
\begin{align*}
    v_{CE} &< 0.7 & \text{for } npn \text{ in SAT.} \\
    v_{EC} &< 0.7 & \text{for } pnp \text{ in SAT.}
\end{align*}
\]

These inequalities are analogous to the MOSFET inequalities:

\[
\begin{align*}
    v_{DS} &< v_{GS} - V_t & \text{for } NMOS \text{ in Triode} \\
    v_{DS} &> v_{GS} - V_t & \text{for } PMOS \text{ in Triode}
\end{align*}
\]

Now, we note for the BJT SATURATION mode that the collector current will always be less than that in ACTIVE mode with the same value of $v_{BE}$.
Thus, we can equivalently state that the collector current in SATURATION will be less than the value $\beta i_B$: 

$$i_C < \beta i_B \quad \text{for BJT in SAT.}$$

This of course means that the base current in SAT. is greater than $i_C / \beta$ (i.e., the base current in active): 

$$i_B > \frac{i_C}{\beta} \quad \text{for BJT in SAT.}$$

Likewise, this means that:

$$i_E < (\beta + 1) i_B \quad \text{and} \quad i_C < \alpha i_E \quad \text{for BJT in SAT.}$$

But remember KCL is still valid for BJTs in SATURATION (it's always valid!):

$$i_E = i_B + i_C \quad \text{(KCL)}$$

Finally, we should again note that the exponential equations presented for SATURATION mode are not particularly useful for analyzing BJT circuits (that transcendental equation thing again!).
Thus, we describe a BJT in SATURATION with some approximate equations. Since both CBJ and EBJ are forward biased, we assume that $v_{BE} \approx 0.7V$ and that $v_{BC} \approx 0.5V$, resulting in the following approximate description for a BJT in SATURATION:

\[
\begin{align*}
    v_{BE} &\approx 0.7V & v_{CE} &\approx 0.2V & i_c &< \beta i_b & \text{for npn in SAT.} \\
    v_{EB} &\approx 0.7V & v_{EC} &\approx 0.2V & i_c &< \beta i_b & \text{for pnp in SAT.}
\end{align*}
\]

**CUTOFF MODE**

Cutoff mode for BJTs is obviously analogous to cutoff mode for MOSFETS.

In both cases the transistor currents are zero!

\[
i_E = i_B = i_C = 0 \quad \text{for BJTs in CUTOFF}
\]

Note that a BJT is in cutoff if both EBJ and CBJ are in reverse bias. This is true if:
\[ \nu_{BE} < 0 \quad \text{and} \quad \nu_{BC} < 0 \quad \text{for} \quad npn \quad \text{in CUTOFF} \]

\[ \nu_{EB} < 0 \quad \text{and} \quad \nu_{CB} < 0 \quad \text{for} \quad pnp \quad \text{in CUTOFF} \]