Transistors

1.0 The Bipolar Junction Transistor

The transistor is another type of semiconductor with a nonlinear current-voltage relationship. It has three connections (see Figure 1), known as the base (B), collector (C) and emitter (E). The base-emitter part of the transistor acts like a diode, in the sense that no current flows in the device if $V_{BE}$ is less than 0.6 to 0.7V. If $V_{BE}$ is greater than 0.6 to 0.7V and the collector voltage is greater than the base voltage, then the transistor is said to be in the ‘forward active’ mode. Due to the physical properties of the transistor (explored in detail in later electrical engineering courses), a transistor in the ‘forward active’ mode acts as a current amplifier, such that

$$I_C = \beta I_B$$

![Figure 1.](image)

$\beta$ (sometimes denoted as $H_{FE}$ or $h_{FE}$) is a positive constant known as the current gain. The term “gain” is used in electrical engineering to represent multiplication of a quantity by some constant, usually voltage gain or current gain. $\beta$ is usually fairly large, for example 50 to 200, and depends on each individual device.

This equation tells us an important thing about the transistor: if we control the (input) base current $I_B$, then we can control the larger (output) collector current $I_C$. So if we have a small current at the input (small currents often occur in electronic circuits), we can use it to control the (larger) output current, which can be used to power something that requires a lot of current, for example a loudspeaker or motor. Thus, we can think of the base-emitter side of the transistor as the “input”, which has a small current, and the collector-emitter side of the transistor as the “output”, which has a large current.

Since the sum of currents leaving a node (here the “node” is the transistor itself) is equal to the sum of currents entering the node, we also have

$$I_E = I_B + I_C = (\beta + 1)I_B = \frac{(\beta + 1)}{\beta}I_C$$

This equation tells us another important thing about transistor operation in the forward active mode. Since $\beta$ is large, most of the current flowing through the transistor is going from the collector to the emitter.
2.0 Analysis of Transistor Circuits

Consider the circuit in Figure 2. The first thing to notice about this circuit is that it has two voltage sources. Virtually all transistor circuits include a fixed DC (direct current) supply between the emitter and collector, often with resistances between the supply and the transistor, and this supply is almost always shown as $V_{CC}$. The input voltage, $V_{in}$, often varies, and in many cases, is an AC (alternating current) voltage. Note that voltages marked on a circuit diagram without ‘+’ and ‘-’ shown, such as $V_C$ below, are conventionally interpreted as the voltage at that node relative to ground. Note also that in the example below, we assume $V_{CC} > V_{BE}$ (often much larger) in order to allow the transistor to be in the forward active mode if $V_{BE} > 0.7V$. The circuit in Figure 2 is known as a common-emitter configuration.

![Figure 2](image)

The principles of analysis are somewhat similar to those for the diode, in that there are two cases depending on the input voltage relative to $V_{BE}$ in the forward active mode:

If $V_{in} > 0.7V$ :

$$I_B = \frac{V_{in} - V_{BE}}{R_B}, \quad \text{so} \quad I_C = \beta I_B = \beta \frac{V_{in} - V_{BE}}{R_B},$$

$$I_E = (\beta + 1)I_B = (\beta + 1) \frac{V_{in} - V_{BE}}{R_B} \quad \text{and} \quad V_C = V_{CC} - R_CI_C = V_{CC} - \beta R_C \frac{V_{in} - V_{BE}}{R_B}$$

If $V_{in} < 0.7V$ : The base-emitter junction is reverse-biased, so no current flows.

$$I_B = I_C = I_E = 0 \quad \text{and} \quad V_C = V_{CC} - R_CI_C = V_{CC}.$$ 

Finally, you may be wondering physically how it is that the transistor can magically increase the collector current, given a much smaller base current. The above circuit explains this: the large collector and emitter currents are actually supplied by the power supply $V_{CC}$, and the transistor is simply a circuit element that draws current from this supply.

3.0 Transistors as Switches

In the example above, setting $V_{in}$ to a high voltage, e.g. $V_{CC}$, causes a large base current $I_B$, and hence an even larger collector current $I_C$. In this instance, $R_C I_C$ will be large, so that $V_C = V_{CC} - R_CI_C$ is small. Depending on the resistance values $R_B$ and $R_C$,
the collector current $I_C$ may even be large enough that $R_C I_C \approx V_{CC}$, so that $V_C \approx 0$. In practise, when $0 < V_C < V_{BE}$, the transistor enters a mode known as saturation, which imposes a minimum voltage $V_{CE(sat)}$ on $V_C$. In practice, this just means that the minimum voltage for $V_C$ is $V_{CE(sat)}$, which depends on $I_C$ and $I_B$, but a typical value might be 0.2V.

In the example above, setting $V_{in}$ to a low voltage, specifically less than 0.7V, the transistor enters a mode known as cutoff. Here, $V_C = V_{CC}$ as in section 2.

To summarise:

\[
\begin{align*}
V_{in} & \text{ HIGH } \Rightarrow V_C \text{ LOW} \\
V_{in} & \text{ LOW } \Rightarrow V_C \text{ HIGH}
\end{align*}
\]

The analysis example given section 2 thus suggests a very important application of the transistor: a switch. In this case, the switch exhibits an inverting behaviour: the output is high when the input is low, and vice versa.

### 4.0 Transistors as Amplifiers or Current-Control Devices

We have just examined the behaviour of the transistor for extreme operating conditions. If we ensure that $V_{CE(sat)} \approx 0.2V < V_C < V_{CC}$, then we have a range over which the (output) voltage $V_C$ can be linearly controlled by the input voltage $V_{in}$, according to

\[
V_C = V_{CC} - \beta R_C \frac{V_{in} - V_{BE}}{R_B}.
\]

Equivalently, the (output) current $I_C$ (or $I_E$ in some circuits) can be linearly controlled by $V_{in}$, according to

\[
I_C = \beta \frac{V_{in} - V_{BE}}{R_B}.
\]

In both cases, the above constraint on $V_C$ implies that the corresponding constraint on the input voltage is

\[
V_{BE} < V_{in} < V_{BE} + \frac{R_B}{\beta R_C} (V_{CC} - V_{CE(sat)}).
\]

In practise it is possible to select values of $R_B$ and/or $R_C$ to try to allow operation in this region, and verify these in the lab by looking at the variation of $V_C$ when applying typical values of the input voltage. If $V_C$ reaches saturation or cutoff for the input voltages in your application, then think carefully about the values of $R_B$ and/or $R_C$ and change one accordingly.

Once $R_B$ and $R_C$ are selected, the circuit can operate as a voltage amplifier or as a current-control device. This can be handy if $R_C$ is actually a light bulb, loudspeaker, motor etc.
Why not simply connect $R_C$ up directly to $V_{in}$, use $V_{in}$ to control the voltage/current in $R_C$, and forget about the transistor, $V_{CC}$ and $R_B$? Often in electronic circuits, the input current is very small, because it comes from a logic circuit, sensor, integrated circuit etc that cannot produce a large amount of current. The circuit in Figure 2 is an example of a transistor circuit that allows a small-current signal to power some large-current load (here you can think of $R_C$ as the load).

5.0 Practical Considerations

5.1 Other Transistor Configurations

Your research will turn up many different variations on the circuit of Figure 2. Each have different advantages and disadvantages. Try to take the time to understand the basic principles of operation described in these notes, to give you the best chance of assessing the various options and in particular, debugging them in the lab.

5.2 NPN and PNP

Throughout sections 1 to 3, we have referred to the transistor as shown in Figure 1. In fact this is an NPN transistor, which is one of two possible transistor configurations. The other, shown in Figure 3, is the PNP transistor. Its operation is similar to that of the NPN transistor, except that the base-emitter junction has the opposite orientation, so that we require $V_{BE} \leq -0.6$ to -0.7 V for the transistor to be forward active region. Consequently, the currents all flow in the opposite direction to the arrows indicated, i.e. with respect to the directions shown in Figure 3, $I_B$, $I_C$ and $I_E$ are all negative. The PNP transistor is thus complementary to the NPN.

5.3 Special Transistors

One special transistor you may come across is known as the Darlington pair. This can be realised either using two transistors (the second one usually has a high power rating), or they can be bought in a single package. A Darlington pair basically consists of two transistors (with current gains $\beta_1$ and $\beta_2$) connected to behave as though they are just a single transistor with current gain $\beta_1\beta_2$. Obviously these are good in applications that require a very high current gain.

5.4 Data Sheets

Transistors are not all the same; there are various different packages intended for different purposes. Each type of transistor from each manufacturer comes with its
own instruction manual: the data sheet. If you want to know the likely current gain of your transistor, look up the data sheet (if you need to know it exactly, you will either need a component analyzer or to measure it yourself in the lab). If you want to know anything about your transistor or how it can be used, look up the data sheet. Example data sheets can be found at http://engg1000.ee.unsw.edu.au/components.html; in general you can find data sheets by searching the web.

5.5 Power Ratings

Transistors cannot provide an infinite output current ($I_C$ or $I_E$); beyond a certain current they will start to burn. The maximum current rating of a transistor is listed in the data sheets and should be consulted. Low-current transistors include the BC549 (max. around 100 mA); higher current transistors include the BD139.

Some high-power transistors are designed to operate under heat and have a special hole where you can attach a heatsink. Mount the heatsink so it contacts the exposed metal side of the transistor, and ensure that the heatsink does not touch any other component leads, as it is active (effectively an extension of the collector of the transistor).

Please note: These notes are intended to give the key basic knowledge required to get started in ENGG1000. They are certainly not comprehensive, and very likely you will need to consult other sources even just to complete your project in this course.