# 11   Semiconductors - Transistors

The transistor was invented in the late 1940s. Credit for its invention is given to three Bell Laboratories scientists, John Bardeen, Walter Brattain, and William Shockley. Transistor is a contraction of the word "transfer" and the word "resistor."

There are two types of transistor, the bi-polar junction (BJT) and metal-oxide field-effect (MOSFET). We will only discuss the BJT in this chapter. Two types of BJT exist. They are the **NPN** and the **PNP**. We will discuss the NPN and not the PNP.

Symbols, Pins, and Construction

The BJT NPN transistor has the three pin arrangement shown in the figure below at left. The PNP is shown at right. These devices have three terminals. Pins on the BJT are labelled C (collector), B (base) and E (Emitter).
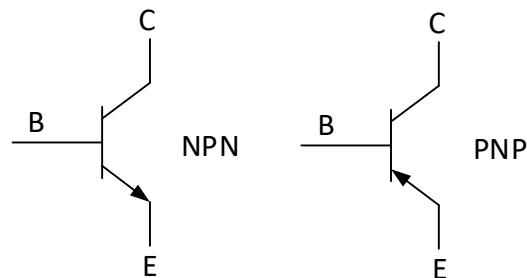
One can remember the NPN with the saying:

NPN: **N**ot **P**ointing i**N**

Transistors are like diodes in that they are not linear devices. They have four modes of operation from which we will concentrate on the first three. These modes are:
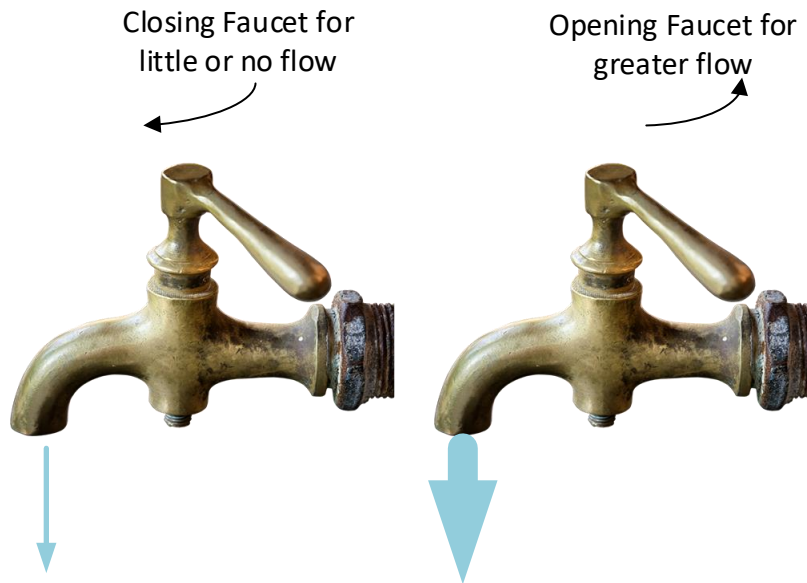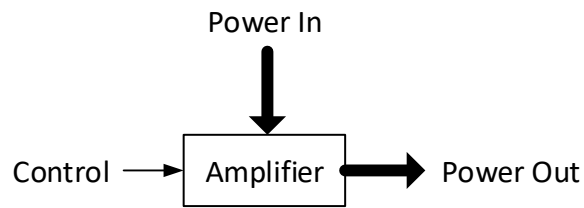
- **Saturation** – This mode acts as a **short circuit** with current flow from C to E.
- **Cut-off** – This mode acts as an **open circuit** with no current flow from C to E.
- **Active** – In this mode, the current in C is an amplification of the current in B.
- **Reverse-Active** – In this mode, current in C is an amplification of the current in B but in the reverse direction.

As mentioned before, BJT transistors control the flow of current. MOSFET transistors, on the other hand, control voltage. While the discussion of BJT transistors is fundamental to further study, most transistors used are MOSFET's since they typically do not use the higher currents (and more heat) of the BJTs.

A BJT transistor consists of three doped regions. The base is sandwiched between the collector and emitter with metal contacts attached to all three. The transistor is referred toas a bipolar transistor because both holes and electrons act as current carriers.

Emitter (n)	
:---:	
Collector (n)	
Substrate (no doping)	

Base (p) very thin layer
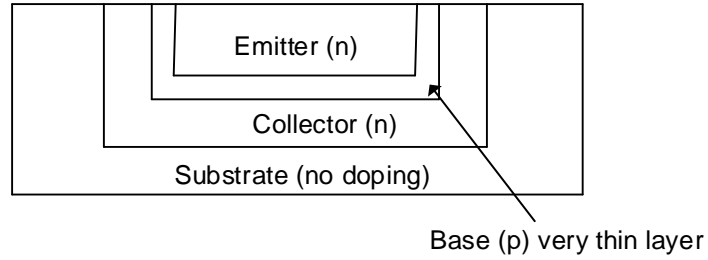
The junction between the base-to-emitter and base-to-collector form junctions with the base being very thin and lightly doped. The base furnishes the control current that changes the current flow from C to E. It acts as an amplifier control device. This is shown in the diagram below as well as the faucet example.

Power In

Control → Amplifier → Power Out

Closing Faucet for little or no flow

Opening Faucet for greater flow

If the current is small into the base, a relatively small current is allowed from the Collector terminal to the Emitter terminal. If the current into the base increases, the current flow from C to E increases as well.
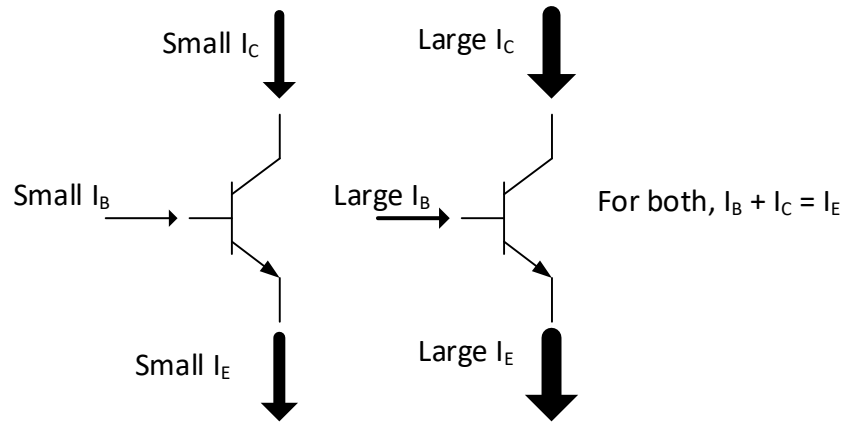
This is shown in the diagram below with the flow of electrons (opposite positive current shown above) with the emitter electrons flowing upward mainly through the collector at the top with only a small current of electrons flowing outward through the base.

Biasing

The figure below shows a BJT transistor with voltages attached to the B and C terminals through resistors. The B-E junction is forward biased (B>E) and the B-C junction is reverse biased (B<C). The result is a forward-biased transistor.
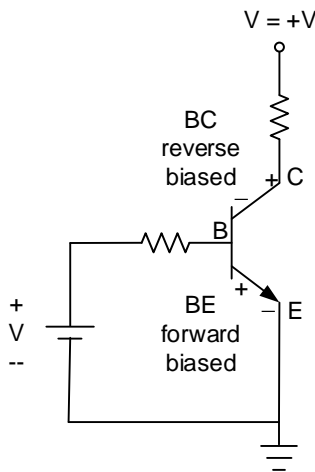
With the B-E junction forward biased more than the .7 V of the bias of the diode for climbing the "electron hill", the current can flow easily from C to E. The base has "a low density of holes" which allows this current to flow. The majority current is also aided by a flow of holes in the opposite direction. We call this minority carrier flow. Both flows are present in the transistor when forward biased. The direction of transistor electron currents is reversed from the current arrows we typically draw for positive flow. We can now write, however:

$$I_E = I_C + I_B$$

Where the current I_B is very small in comparison to I_E or I_C.
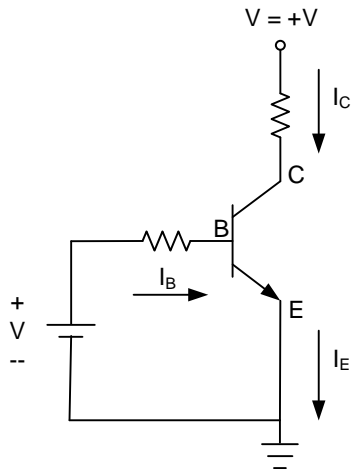
The current gain of the circuit is defined as β. Since we are presently dealing with dc currents, the value is expressed as β$_{DC}$. The relationship is:

$$\beta_{DC} = \frac{I_C}{I_B}$$

Knowing the formula for β$_{DC}$, a value for β$_{DC}$ and $I_E = I_C + I_B$, we can find the currents and voltages of the circuit above. For example:
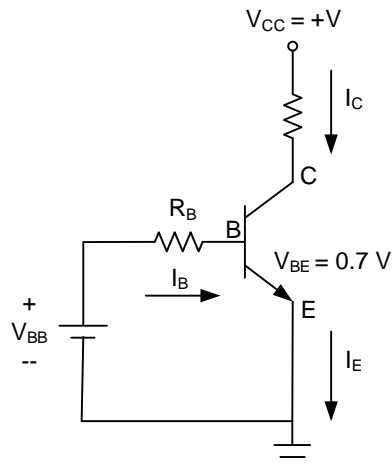
For an npn BJT transistor, we are given $I_B = 50\ \mu A$ and $I_C = 3.65\ mA$. Then:

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3.65\ mA}{50\ \mu A} = 73$$

and

$$I_E = I_C + I_B = 3.65\ mA + 50\ \mu A = 3.70\ mA$$

Now, if the V$_{BB}$ is greater than 0.7 V, there is a flow of current through the R$_B$ from left to right.

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We can write: $V_{R_B} \cong 0.7\ V$

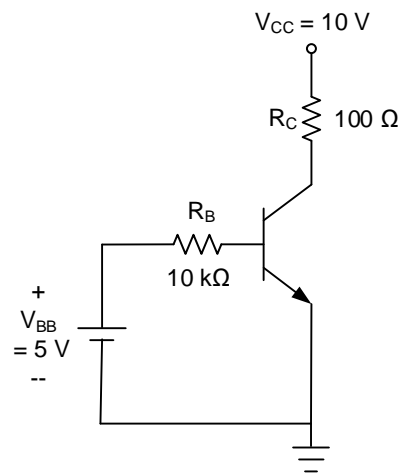We also know: $V_{R_B} = V_{BB} - V_{BE}$

and $I_B = \frac{V_{BB} - V_{BE}}{R_B}$

We can also write: $V_{CE} = V_{CC} - V_{R_C}$

and $V_{CE} = V_{CC} - I_C R_C$

An example:

Determine $I_B, I_C, I_E, V_{BE}, V_{CE}$, and V_{CB} in the circuit below if β_{DC} = 150.

Since V_{BB} > 0.7 V, we can write: $V_{R_B} \cong 0.7\ V$

and $I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\ V - 0.7\ V}{10\ k\Omega} = 430\ \mu A$

$I_C = \beta_{DC} I_B = (150)(430\ \mu A) = 64.5\ mA$

$I_E = I_C + I_B = 64.5\ mA + 430\ \mu A = 64.9\ mA$

Now $V_{CE} = V_{CC} - I_C R_C = 10\ V - (64.5\ mA)(100\Omega) = 10\ V - 6.45\ V = 3.55\ V$

and $V_{CB} = V_{CE} - V_{BE} = 3.55\ V - 0.7\ V = 2.85\ V$

Try the same circuit with the following changes:

R_B = 22 kΩ, R_C = 220 Ω, V_{BB} = 6 V, , V_{CC} = 9 V, and β_{DC} = 90.

If we design a circuit using the BJT transistor and the circuit above, we notice that regions exist that define the transistor's action. It is similar to a ball field with a high wall along each foul line shown below:

Left
Field
Foul
LIne

Right Field Foul LIne
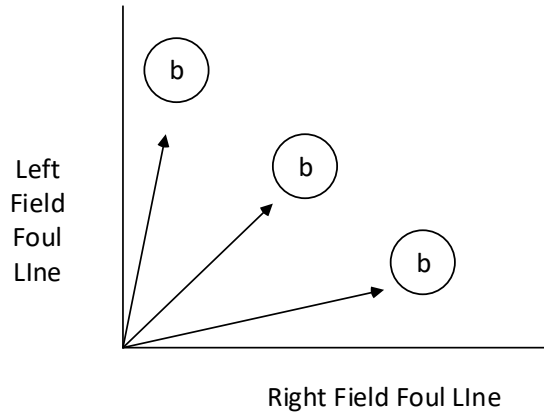
You will notice that the ball can be hit anywhere in the field but will not cross the foul line either on the left field or right field. Also, you will notice that with the circuit, the ball will fall along a line. This is called the DC load line. Also notice that the ball can land along the foul line. The transistor name for these two are called cut-off and saturation.
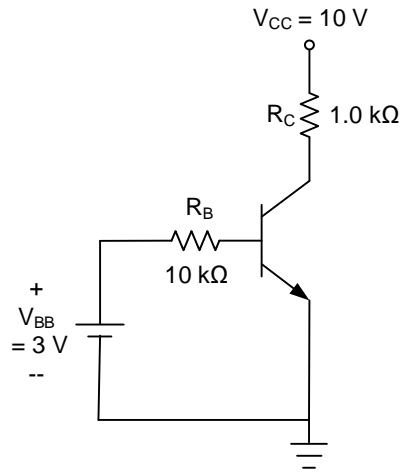
Saturation

Left
Field
Foul
LIne

Cut-off

Right Field Foul LIne
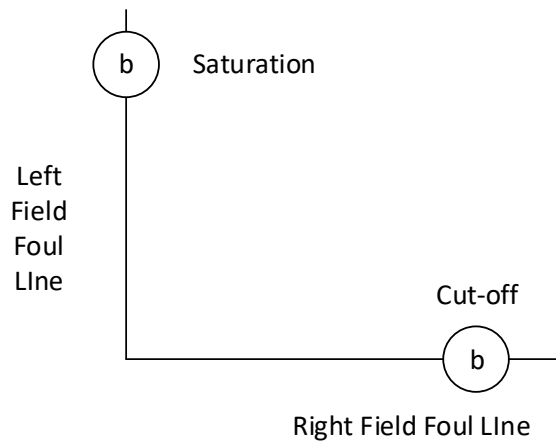
If we replace our ball-field with a graph of I_C vs V_{CE}, we see a similar result.

I_C

Saturation

DC Load Line

Cut-off V_{CE}
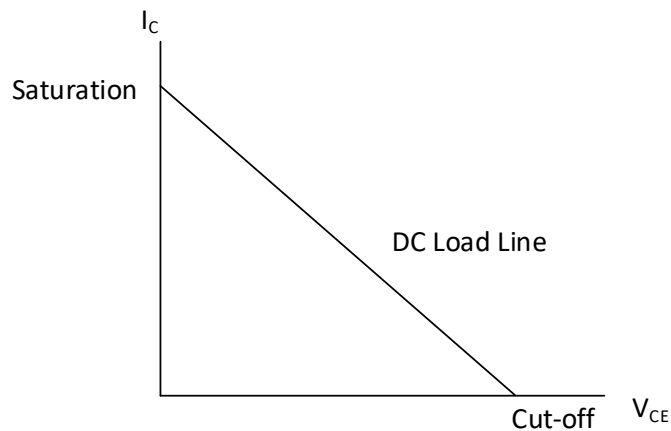
We see that if the transistor turns on and I_C x R_C >= V_{CC}, we are in saturation. We hit the wall. If the transistor is turned off, the V_{CE} wall is hit. If the transistor is on, the I_C wall is hit. There is a small value of V_{CE}(sat) that also is given so the above equation becomes I_C x R_C >= V_{CC} + $V_{CE(sat)}$.

In the following example, determine the state of the circuit and see whether it is in saturation:

First, determine a value of $V_{CE(sat)}$. Assume .2 V.
Then find $I_{C(sat)}$:

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{10\ V - 0.2\ V}{1.0\ k\Omega} = 9.8\ mA$$

Next, find I_B:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3\ V - 0.7\ V}{10\ k\Omega} = \frac{2.3\ V}{10\ k\Omega} = 0.23\ mA$$
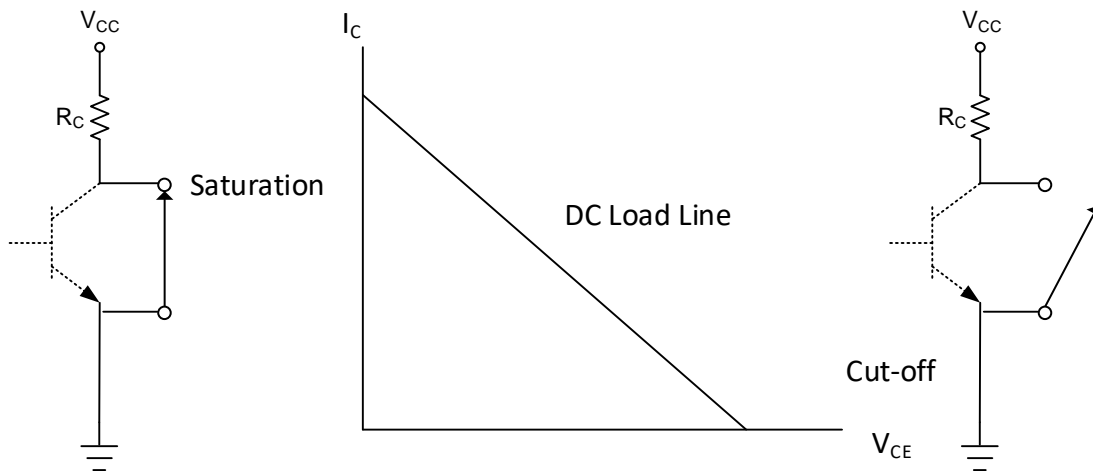
$$I_C = \beta_{DC} I_B = (50)(0.23\ mA) = 11.5\ mA$$

Now, if I_C > I_{Csat}, then saturation occurs. The circuit is saturated. It acts as a switch. The wall was hit.

As an exercise, for the following values, find if the circuit is saturated:

$\beta_{DC} = 125, V_{BB} = 1.5\ V, R_B = 6.8\ k\Omega, R_C = 180\ k\Omega$, and $V_{CC} = 12\ V$

The transistor is seen as a switch below in saturation and cut-off. Notice the switch is closed when in saturation and open in cut-off:

A good rule to follow is that for a 5 V value of V_{CC}, we use a 1 kΩ resistor to ensure the transistor is acting as a switch. For 10 V, 2K, etc.

Problems

1. For I_E = 5.34 mA and I_B = 475 μA, find I_C.
2. For I_C = 25 mA and I_B = 200 μA, find $β_{DC}$.
3. For I_C = 20.3 mA and I_E = 20.5 mA, find $β_{DC}$.
4. For the following circuit, I_B = 50 μA, R_C = 5V (value of voltage measured across R_C), determine $β_{DC}$.
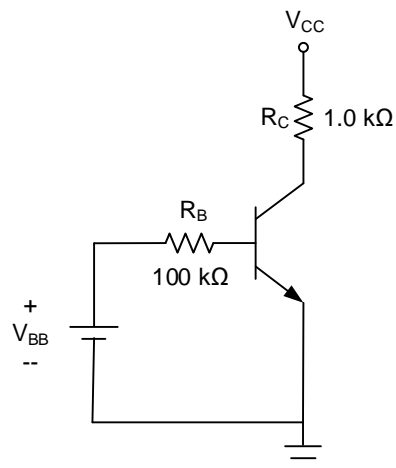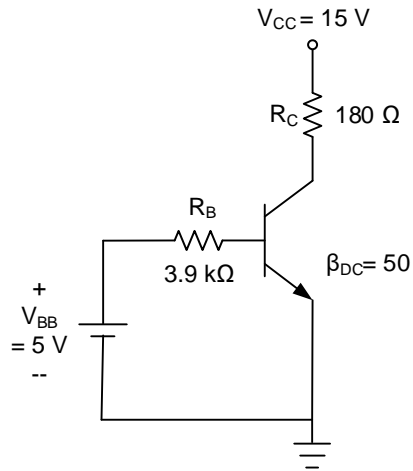

5. For the circuit above, find I_B, IC, IE and VCE given:

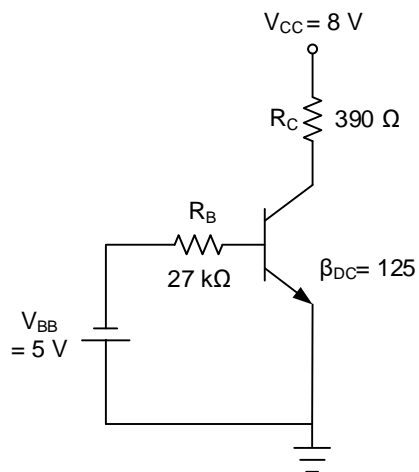$$β_{DC} = 200, V_{BB} = 3.0\ V, \text{and } V_{CC} = 10\ V$$

6. Increase V_{CC} to 15 V and recalculate the problem above.
7. Find the currents in the diagram below (I_B, I_C, and I_E). Also, calculate β_{DC}.

$V_{CC} = 24$ V

R_C ⟩ 470 Ω

R_B
4.7 kΩ

+
8V
−

+
V_{BB}
= 4 V
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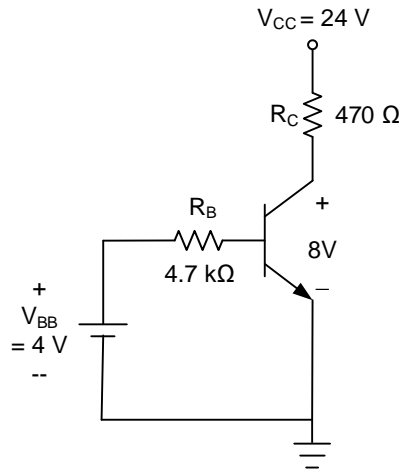
8. For the circuit below, find V_{CE}, V_{BE} and V_{CB}:

$V_{CC} = 15$ V

R_C ⟩ 180 Ω

R_B
3.9 kΩ

$\beta_{DC} = 50$

+
V_{BB}
= 5 V
--

9. Again, find V_{CE}, V_{BE} and V_{CB}:

$V_{CC} = 8$ V

R_C ⟩ 390 Ω

R_B
27 kΩ

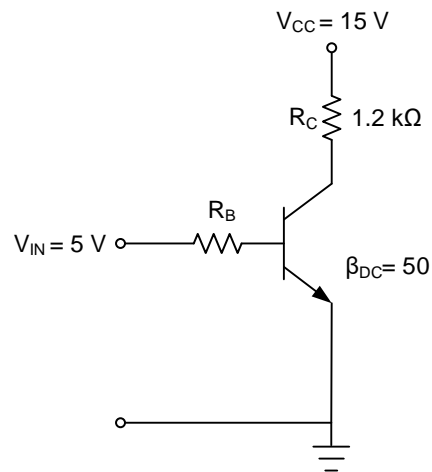$\beta_{DC} = 125$

V_{BB}
= 5 V

10. Are either of the circuits above saturated?

11. Find $I_{C(sat)}$ and I_B necessary for saturation. Also, find the minimum value of V_{IN} to produce saturation.

$V_{CC} = 5$ V

R_C 10 kΩ

R_B

V_{IN} ○ —WW—

1.0 MΩ

$β_{DC} = 150$
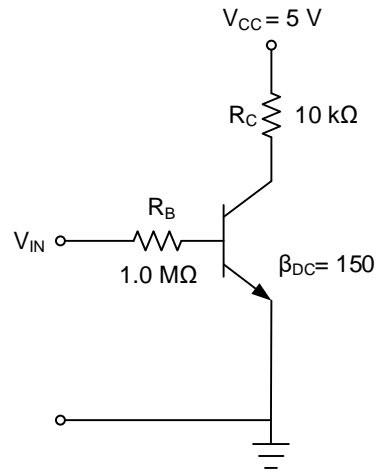
12. For the following, find R_B to give saturation.

$V_{CC} = 15$ V

R_C 1.2 kΩ

R_B

$V_{IN} = 5$ V ○ —WW—

$β_{DC} = 50$