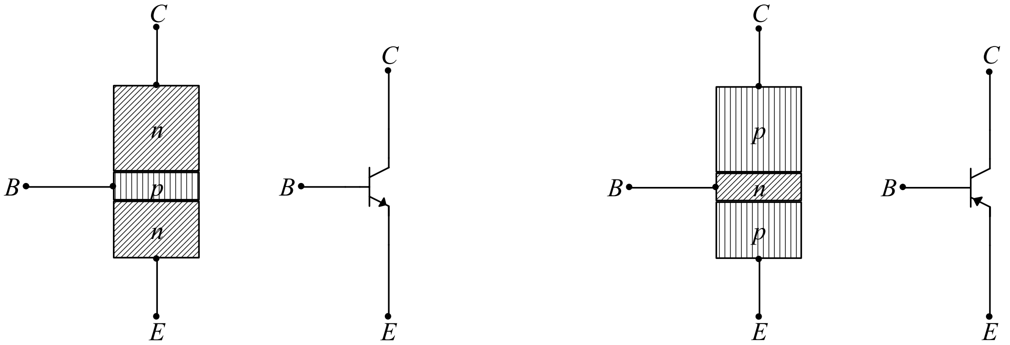
Transistors:
Bipolar Junction Transistors (BJT)

General configuration and definitions

The transistor is the main building block “element” of electronics. It is a semiconductor device and it comes in two general types: the Bipolar Junction Transistor (BJT) and the Field Effect Transistor (FET). Here we will describe the system characteristics of the BJT configuration and explore its use in fundamental signal shaping and amplifier circuits.

The BJT is a three terminal device and it comes in two different types. The ***npn*** BJT and the ***pnp*** BJT. The BJT symbols and their corresponding block diagrams are shown on Figure 1. The BJT is fabricated with three separately doped regions. The npn device has one p region between two n regions and the pnp device has one n region between two p regions.
The BJT has two junctions (boundaries between the n and the p regions). These junctions are similar to the junctions we saw in the diodes and thus they may be forward biased or reverse biased. By relating these junctions to a diode model the pnp BJT may be modeled as shown on Figure 2.

The three terminals of the BJT are called the Base (B), the Collector (C) and the Emitter (E).



(a) ***npn*** transistor (b) ***pnp*** transistor

Figure 1. BJT schematics and structures. (a) *npn* transistor, (b) *pnp* transistor

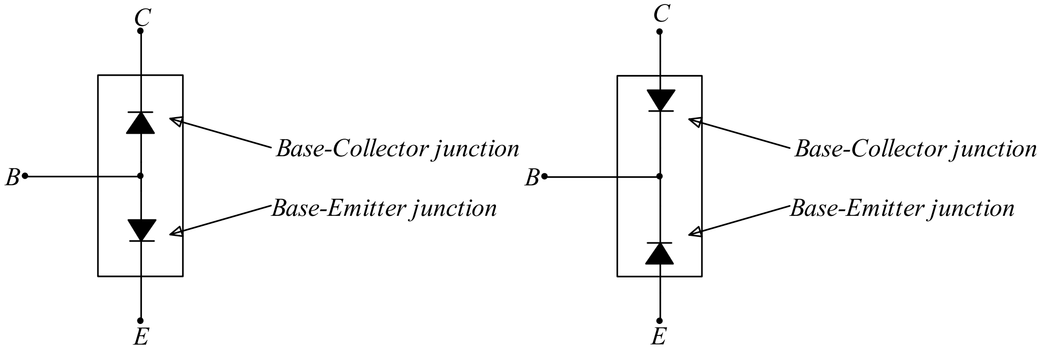


Figure 2

Since each junction has two possible states of operation (forward or reverse bias) the BJT with its two junctions has four possible states of operation.

For a detailed description of the BJT structure see: Jaeger and Blalock, Microelectronic Circuit Design, McGraw Hill.
Here it is sufficient to say that the structure as shown on Figure 1 is not symmetric. The n and p regions are different both geometrically and in terms of the doping concentration of the regions. For example, the doping concentrations in the collector, base and emitter may be, $10^{15}, 10^{17}$ and 10^{19} respectively. Therefore the behavior of the device is not electrically symmetric and the two ends cannot be interchanged.

Before proceeding let's consider the BJT ***npn*** structure shown on Figure 3.

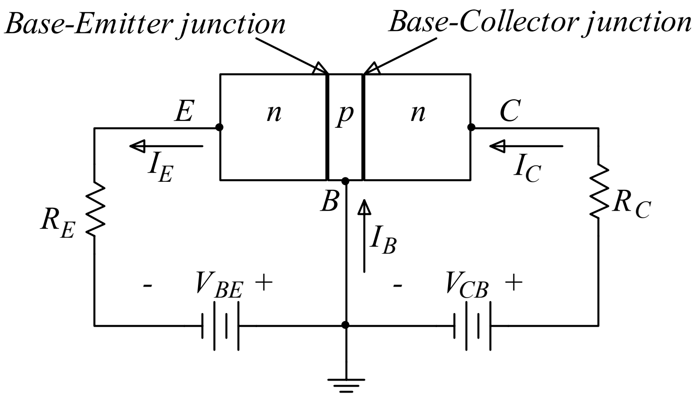


Figure 3. Biasing voltages of *npn* transistor

With the voltage V_{BE} and V_{CB} as shown, the Base-Emitter (B-E) junction is forward biased and the Base-Collector (B-C) junction is reverse biased.

The current through the B-E junction is related to the B-E voltage as

$$I_E = I_s\left(e^{V_{BE}/V_T} - 1\right) \tag{1.1}$$

Due to the large differences in the doping concentrations of the emitter and the base regions the electrons injected into the base region (from the emitter region) results in the emitter current I_E. Furthermore the number of electrons injected into the collector region is directly related to the electrons injected into the base region from the emitter region.

Therefore, the collector current is related to the emitter current which is in turn a function of the B-E voltage.

The voltage between two terminals controls the current through the third terminal.

This is the basic principle of the BJT

The collector current and the base current are related by

$$I_C = \beta I_B \tag{1.2}$$

And by applying KCL we obtain

$$I_E = I_C + I_B \tag{1.3}$$

And thus from equations (1.2) and (1.3) the relationship between the emitter and the base currents is

$$I_E = (1+\beta)I_B \tag{1.4}$$

And equivalently

$$I_C = \frac{\beta}{1+\beta} I_E \tag{1.5}$$

The fraction $\frac{\beta}{1+\beta}$ is called α.

For the transistors of interest $\beta = 100$ which corresponds to $\alpha = 0.99$ and $I_C \simeq I_E$.

The direction of the currents and the voltage polarities for the ***npn*** and the ***pnp*** BJTs are shown on Figure 4.

(a) ***npn*** transistor

(b) ***pnp*** transistor

Figure 4. Current directions and voltage polarities for *npn* (a) and *pnp* (b) BJTs

Transistor i-v characteristics

A. Transistor Voltages

Three different types of voltages are involved in the description of transistors and transistor circuits. They are:

Transistor supply voltages: V_{CC} , V_{BB} .

Transistor terminal voltages: V_C , V_C , V_E

Voltages across transistor junctions: V_{BE} , V_{CE} , V_{CB}

All of these voltages and their polarities are shown on Figure 5 for the ***npn*** BJT.

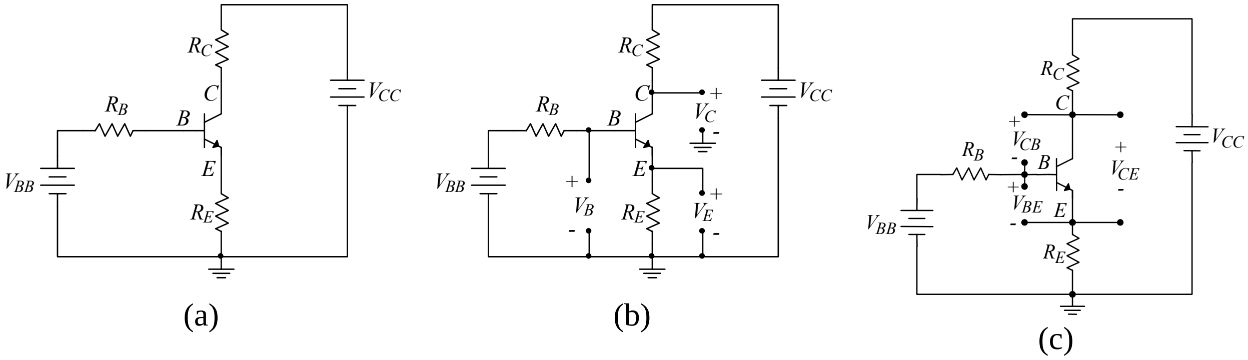


Figure 5

Transistor Operation and Characteristic i-v curves

The three terminals of the transistors and the two junctions, present us with multiple operating regimes. In order to distinguish these regimes we have to look at the i-v characteristics of the device.

The most important characteristic of the BJT is the plot of the collector current, I_C, versus the collector-emitter voltage, V_{CE}, for various values of the base current, I_B as shown on the circuit of Figure 6.

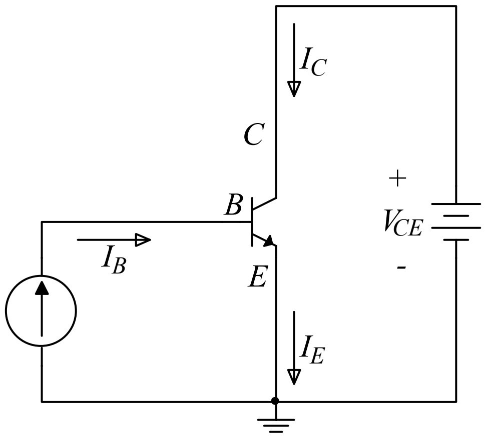


Figure 6. Common emitter BJT circuit for determining output characteristics

Figure 7 shows the qualitative characteristic curves of a BJT. The plot indicates the four regions of operation: the saturation, the cutoff, the active and the breakdown. Each family of curves is drawn for a different base current and in this plot $I_{B4} > I_{B3} > I_{B2} > I_{B1}$

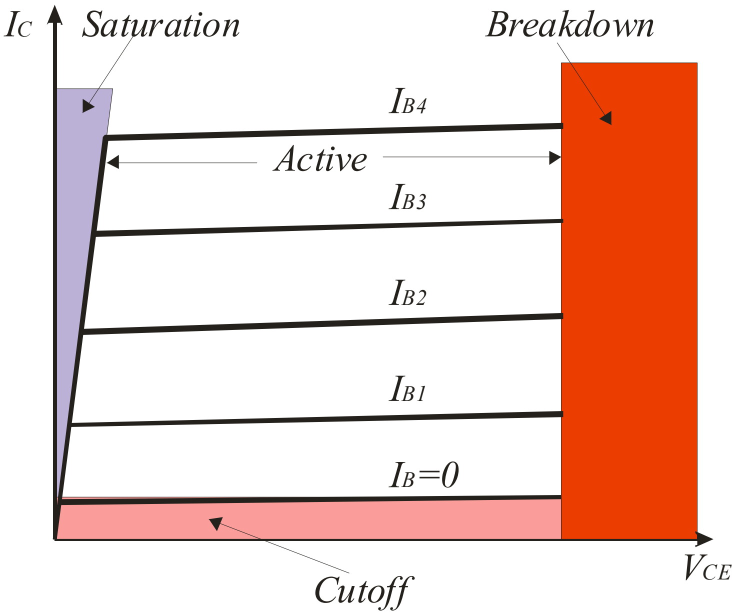


Figure 7. BJT characteristic curve

The characteristics of each region of operation are summarized below.

1. **cutoff region:**
   Base-emitter junction is reverse biased. No current flow

2. **saturation region:**
   Base-emitter junction forward biased
   Collector-base junction is forward biased
   I_c reaches a maximum which is independent of I_B and β.
   No control.
   $V_{CE} < V_{BE}$

3. **active region:**
   Base-emitter junction forward biased
   Collector-base junction is reverse biased
   Control, $I_C = \beta I_B$ (as can be seen from Figure 7 there is a small slope of I_C with V_{CE}.
   $V_{BE} < V_{CE} < V_{CC}$

4. **breakdown region:**
   I_C and V_{CE} exceed specifications
   damage to the transistor

Basic BJT Applications

Switch

Consider the circuit shown on Figure 8. If the voltage v_i is less than the voltage required to forward bias the base-emitter junction then the current $I_B = 0$ and thus the transistor is in the cutoff region and $I_C = 0$. Since $I_C = 0$ the voltage drop across *Rc* is zero and so *Vo=Vcc.*

If the voltage v_i increases so that V_{BE} forward biases the base-emitter junction the transistor will turn on and

$$I_B = \frac{v_i - V_{BE}}{R_B} \tag{1.6}$$

Once the transistor is on we still do not know if it is operating in the active region or in the saturation region. However, KVL around the C-E loop gives

$$V_{CC} = I_C R_C + V_{CE} \tag{1.7}$$

And so

$$V_{CE} = V_{CC} - I_C R_C \tag{1.8}$$

Note that $V_{CE} = V_0$ as shown on Figure 8.

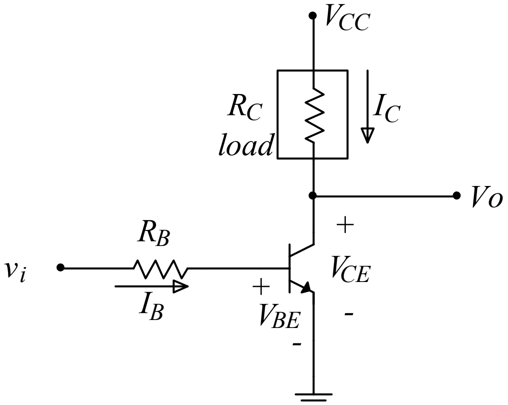


Figure 8. npn BJT switch circuit

Equation (1.8) is the load line equation for this circuit. In graphical form it is shown on Figure 9.

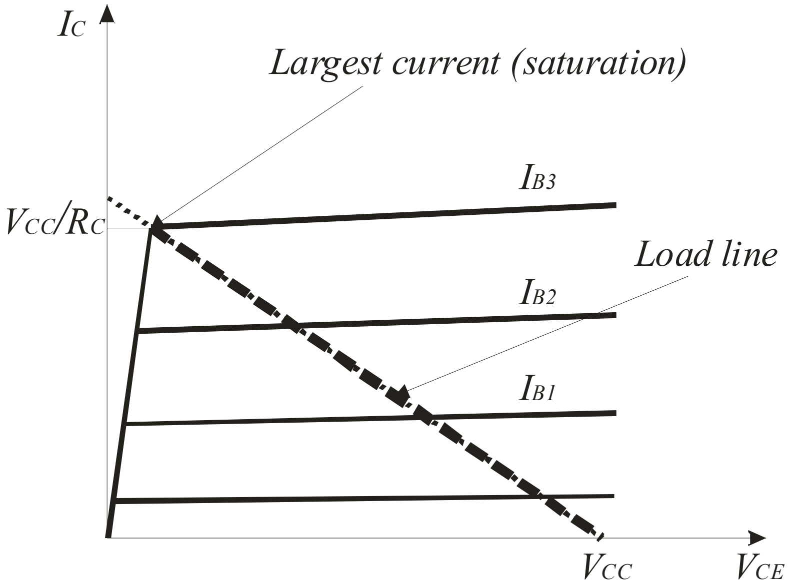


Figure 9

As the base current increases the transistor may operate at points along the load line (thick dashed line on Figure 9). In the limit, the base current I_{B3} results in the largest current I_C. This is the saturation current and when the transistor operates at this point it is said to be biased in the saturation mode. In saturation, the base-collector junction is forward biased and the relationship between the base and the collector current is not linear.
Therefore the collector current at saturation is

$$I_C(sat) = \frac{V_{CC} - V_{CE}(sat)}{R_C} \tag{1.9}$$

In saturation the collector-emitter voltage, V_{CE}, is less than the V_{BE}. Typically, the V_{CE} at saturation is about 0.2 Volts.

Digital Logic.

The circuit on Figure 10 shows the fundamental inverter circuit.

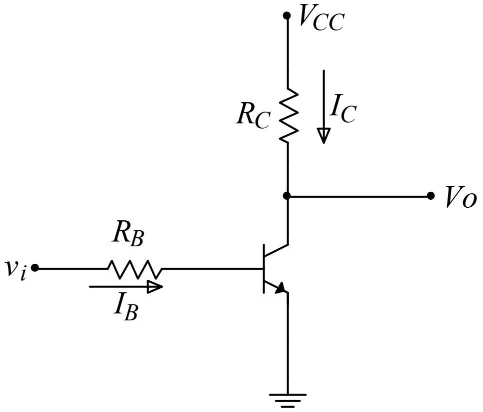


Figure 10. Basic BJT inverter circuit

If the voltage v_i is zero (**low**) the transistor is in the cutoff region, the current $I_C = 0$ and the voltage $V_0 = V_{CC}$ (**high**).

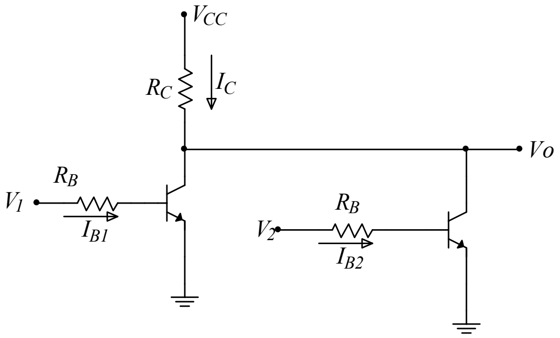
By contrast if the voltage v_i is **high**, say equal to V_{CC}, the transistor is driven into saturation and the output is equal to $V_{CE}(sat)$ which is **low**.

With this fundamental circuit as the basis we are able to construct any other logic operation.

Problem:

For the circuit shown below, complete the logic table:

V_1	V_2	V_0
High	Low	
Low	High	
Low	Low	
high	high	



Amplifier Circuit.

The basic inverter circuit also forms the basic amplifier circuit. The voltage transfer curve (output voltage as a function of the input voltage) is the fundamental characterization of an amplifier. For the circuit shown on Figure 11 the voltage transfer curve is shown on Figure 12.

Note the large slope of the curve in the active mode. A small change in the input voltage V_I induces a large change on the output V_0 – an amplification. (we will explore this in the laboratory)

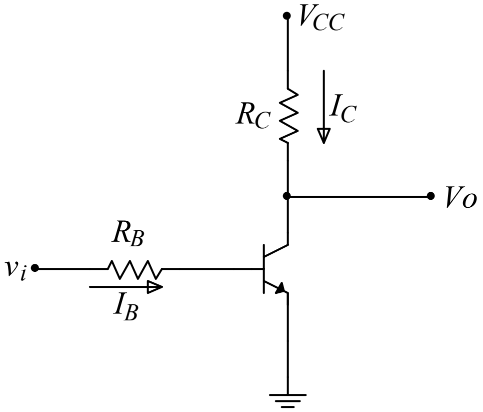


Figure 11. BJT inverter amplifier

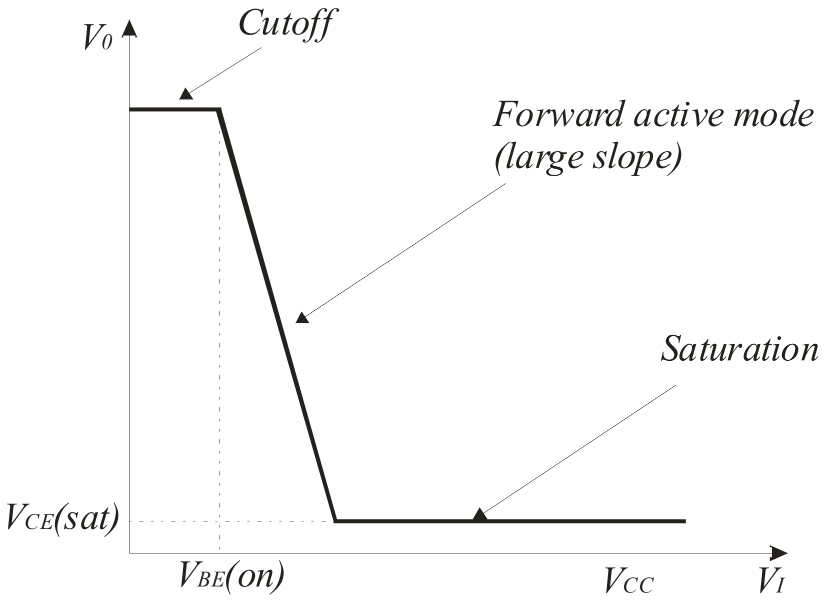


Figure 12. Inverter amplifier voltage transfer characteristic curve