There are two major families of transistors, bipolar junction transistors (BJT) and field-effect transistors (FET). These notes will be restricted to BJTs.

Bipolar transistors have 3 terminals and come in two varieties, as NPN and as PNP transistors. The N and the P stand for negatively and positively doped semiconductor materials, respectively. A PN junction forms a semiconductor diode and in this sense a BJT can be thought of as consisting of two back-to-back (or front-to-front) connected diodes. This is shown in the figures below together with the schematic symbols and the names of the terminals.

If a NPN transistor is measured with an ohmmeter, then current can flow from the base to the emitter and from the base to the collector. For a PNP transistor current can flow from the emitter to the base and from the collector to the base.
For normal power/signal amplification the base-emitter junction diode $D_{BE}$ is forward biased and the base-collector junction diode $D_{BC}$ is reverse biased.

The simplified cross section of a NPN BJT looks as follows:

- $N+$: N region with high concentration of electrons
- Electrons attracted to upper N region by $+V_{CC}$
- Electrons that recombine with holes in P region

The emitter region consists of a N-type semiconductor material with a high concentration of excess electrons ($N+$). The collector is also made from N-type semiconductor material, but with a smaller concentration of excess electrons ($N$). In-between is the base region that uses P-type semiconductor material with a small concentration of excess holes ($P$).
The base-emitter junction acts like a diode. If a voltage $V_{BE}$ is applied as shown in the figure, then the emitter current $i_E$ can be computed using Shockley's equation as

$$i_E = i_S \left( e^{\frac{V_{BE}}{V_T}} - 1 \right)$$

where

- $i_E$: Emitter current
- $i_S$: Reverse saturation current, $i_S \approx 10^{-12} \text{ to } 10^{-15} \text{ A}$
- $V_{BE}$: Base-emitter voltage
- $V_T$: Thermal voltage, $V_T = \frac{kT}{q} = 26 \text{ mV at room temperature}$

Define

$$\alpha = \frac{i_C}{i_E} \quad \text{common base current transfer ratio}$$

$$\beta = \frac{i_C}{i_B} \quad \text{current gain } \beta$$

Using $\alpha$, $i_C$ and $i_B$ can be expressed as (note: $i_E = i_C + i_B$)

$$i_C = \alpha i_E = \alpha i_S \left( e^{\frac{V_{BE}}{V_T}} - 1 \right)$$

$$i_B = i_E - i_C = (1 - \alpha) i_S \left( e^{\frac{V_{BE}}{V_T}} - 1 \right)$$

Note that

$$\beta = \frac{i_C}{i_B} = \frac{\alpha i_S \left( e^{\frac{V_{BE}}{V_T}} - 1 \right)}{(1 - \alpha) i_S \left( e^{\frac{V_{BE}}{V_T}} - 1 \right)} = \frac{\alpha}{1 - \alpha} \left( 1 - \frac{i_S \left( e^{\frac{V_{BE}}{V_T}} - 1 \right)}{i_S \left( e^{\frac{V_{BE}}{V_T}} - 1 \right)} \right) \uparrow \text{ term drops out} \Rightarrow \text{linearized model}$$
This leads to two equivalent circuit models for the BJT, one nonlinear and based on Shockley's equation and one linear and based on the current gain \( \beta = i_e/i_b \).

**NPN BJT**

Schematic Symbol

Nonlinear Model

Linear Model

Note that the models are only valid for the active mode of the transistor, i.e. if \( i_b > 0 \) and \( V_{CE} < 0.5V \). For PNP transistors the models are:

**PNP BJT**

Schematic Symbol

Nonlinear Model

Linear Model
For small signal transistors such as 2N2222 (NPN) and 2N2907 (PNP), the current gain is in the range of 100 - 200. However, $\beta$ is temperature dependent and can vary quite a lot between transistors from different batches. Good transistor circuits should only depend on the fact that $\beta \gg 1$ and not on the exact value of $\beta$.

**Measurement of ic-Vce Characteristic for NPN BJT**

The following circuit was used in LTspice to measure ic and vce for different base-emitter voltages VBE.

In the simulation, V2 is varied from 0 to 15V so that VCE can cover a whole range from 0 to about 10V. VBE is stepped from 0.66V to 0.72V in increments of 0.02V.
The resulting graph is shown below. Note that Hspice assumes a temperature of 25°C as default.

**NPN Transistor: $i_C - v_{CE}$ Characteristic, Parameter $v_{BE}$**

![Graph showing $i_C$ vs. $v_{CE}$ for different $v_{BE}$ values.]

Note that $i_C$ is approximately constant and can be modeled by a controlled current source for $v_{CE} > 0.4\,V$ (for fixed $v_{BE}$). Note also that equal increments in $v_{BE}$ do not give equal increments in $i_C$ due to the exponential relationship in Shockley's equation:

$$i_C = A i_s (e^{v_{BE}/(v_T)} - 1)$$

The next page shows the $i_C$-$v_{CE}$ characteristic of a NPN BJT when $i_B$ is stepped from 100μA to 500μA in 100μA increments. Note that in this case $i_C$ increases approximately proportional with $i_B$. This is what leads to the (linear) current gain model of the BJT in active mode.
NPN Transistor: Measurement of $i_C$ - $v_{CE}$ Characteristic

\[ V(N_002) = v_{CE} \]

NPN Transistor: $i_C$ - $v_{CE}$ Characteristic, Parameter $i_B$

Transistor in active mode if $v_{CE} \approx 0.4V$

Collector - Emitter Voltage $v_{CE}$

Note: Approximately equal increments of $i_C$ for equal increments of $i_B$ in linear model.
NPN Transistor: Measurement of Current Gain beta

Circuit for measuring $i_C$, $i_C$ for different fixed values of $V_{CE}$

Current gain $\beta = \frac{i_C}{i_B}$ depends on temperature $T_c$, $i_C$ and $V_{CE}$. $\beta$ decreases as $i_C$ increases.

Current Gain beta versus $i_C$, Parameter $V_{CE}$

Collector Current $i_C$
Common Emitter Amplifier using NPN BJT

**KVL:** \( -V_s + R_B i_B + V_{BE} = 0 \)

\[ i_B = \frac{V_s - V_{BE}}{R_B} \]

\[ V_c = V_{CC} - \frac{R_C}{R_B} (V_s - V_{BE}) \]

**Voltage gain:** \( \frac{dV_c}{dV_s} = -\frac{R_C}{R_B} \)

**Current gain:** \( \beta \)

\[ R_{in} = \frac{V_s}{i_B} = \frac{V_s}{V_s - V_{BE}} < R_B \]

\[ R_{load} = R_C \]

Note: \( i_B > 0 \) and \( \frac{R_C}{R_B} (V_s - V_{BE}) < V_{CC} \)

\[ V_{BE} < V_s < \frac{R_B}{R_C} V_{CC} + V_{BE} \]
NPN Transistor: Common Emitter Amplifier

Voltage gain: \( \frac{dV_C}{dV_S} \)

Gain = -17.6

\( V_C = V_{CE} \)

\( V_S \)

\( I_S > 0 \) for active mode

Both needed for active mode!
Common Collector Amplifier also called emitter followers

Voltage gain < 1, current gain $\beta$ (large!)

\[ KVL: \quad -V_s + R_b i_b + V_{BE} + (\beta + 1) R_e i_b = 0 \]

\[ \Rightarrow (R_b + (\beta + 1) R_e) i_b = V_s - V_{BE} \quad \Rightarrow \quad i_b = \frac{V_s - V_{BE}}{R_b + (\beta + 1) R_e} \]

\[ \Rightarrow \quad V_e = (\beta + 1) R_e \cdot \frac{V_s - V_{BE}}{R_b + (\beta + 1) R_e} \]

Voltage gain: \[ \frac{dV_e}{dV_s} = \frac{(\beta + 1) R_e}{R_b + (\beta + 1) R_e} \quad \text{if } i_b > 0 \text{ and } \quad V_e < V_{CC} \]

Current gain: $\beta + 1$

\[ R_{in} = \frac{V_s}{i_b} = \frac{(R_b + (\beta + 1) R_e)V_s}{V_s - V_{BE}} = \frac{R_b + (\beta + 1) R_e}{V_{CC} + V_{BE}} \]

\[ R_{load} = R_e \] 

Note: $R_{in}$ is actively increased by current gain $\beta$ of transistor.
NPN Transistor: Common Collector Amplifier

Provides current gain!

or Emilio follower

Voltage gain: \( \frac{\delta V_E}{\delta V_S} \)

Voltage gain: 0.576

need \( i_B > 0 \) and \( V_{CE} > 0.5V \)

for active region of BJT
Another Useful Transistor Circuit

Current Source using PNP BJT

Choose $R_1$ for a constant $2V_F$ voltage drop across diodes

KVL: $V_{BE} - 2V_F + (\beta+1)R_Ei_B = 0$

$\Rightarrow (\beta+1)R_Ei_B = 2V_F - V_{BE} \Rightarrow i_B = \frac{2V_F - V_{BE}}{(\beta+1)R_E}$

$\Rightarrow i_C = \beta i_B = \frac{\beta}{(\beta+1)R_E}(2V_F - V_{BE}) = \frac{2V_F - V_{BE}}{R_E}$

$V_F, V_{BE} = 0.6 - 0.7 V \text{ for Silicon}$

Example: $V_F = V_{BE} = 0.6 V, \quad R_E = 560 \Omega$

$\Rightarrow i_C = \frac{0.6}{560} = 1.07 mA$
PNP Transistor: Current Source

Step $R_L$ for values $R_L = 1k, 3k, 5k, 7k, 9k, 11k$

Current is constant through $R_L (R_3)$ stays within range $922 \mu A - 941 \mu A$ for change of $R_2$ and $V_1 = V_{cc}$
OpAmps Made from Transistors (BJTs and FETs)

Schematic Diagram
LM741 OpAmp

Overall voltage gain of OpAmps (w/o feedback) is $\approx 10^5$.

Simplified Schematic
LF 356 OpAmp

*3pF in LF357 series.