Small Signal Amplifier with Bipolar Junction Transistor

This tutorial will teach you in very easy steps how to design class-A amplifiers. Starting with the results of bias point design we get the following circuit

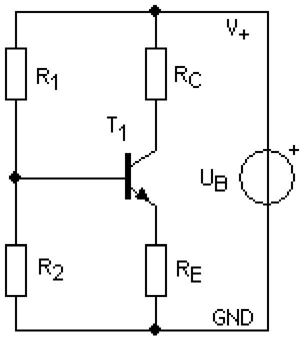

Figure 1: Basic circuit with npn-transistor

The most important rule developing such an amplifier is to distinguish between the DC-analysis as done during bias point calculation and AC-analysis starting at this point.

The source impedance of an ideal voltage source is 0 Ω which means, that the positive power line V+ and the ground line GND are short circuited for AC-signals. The result is the next circuit schematic.

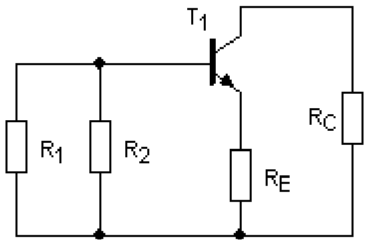

Figure 2: Equivalent AC-circuit

It is the equivalent circuit for AC-analysis. Bypass capacitors may be placed in parallel to each resistor in that sense, that the regarding transistor port is connected to ground (grounded) for AC-signals. The AC-voltage drop along the capacitor is very small and can be neglected. The coupling capacitors C_{C1} and C_{C2} prevent DC current flow through the source and respectively load. The bias point is independent from source and load impedance.

- If the emitter is grounded by a capacitor C_E, we get the common emitter circuit. The emitter is both used for input and output, the base pin is the input node, the collector pin is the output node.

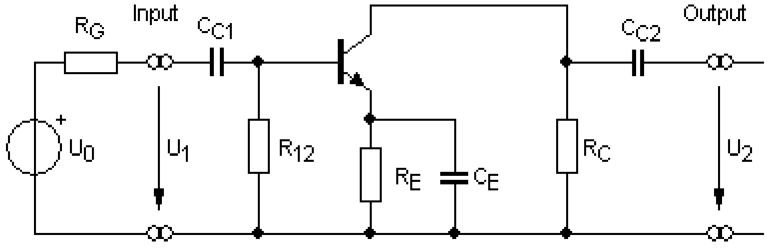

Figure 3: Common emitter circuit

- If the collector is grounded by a capacitor C_C, we get the common collector circuit. The collector is both used for input and output, the base pin is the input-node, the emitter pin is the output node.

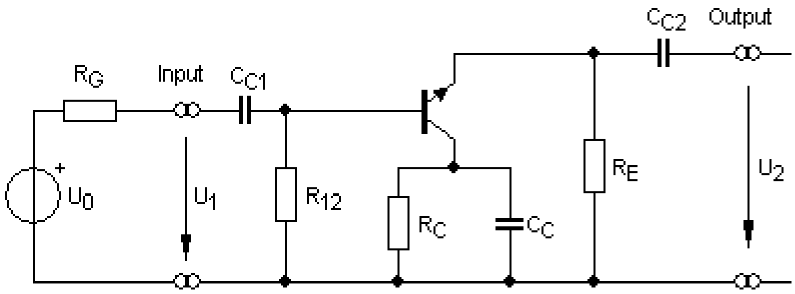

Figure 4: Common collector circuit

- If the base is grounded by a capacitor C_B, we get the common base circuit. The base is both used for input and output, the emitter pin is the input node, the collector pin is the output node.

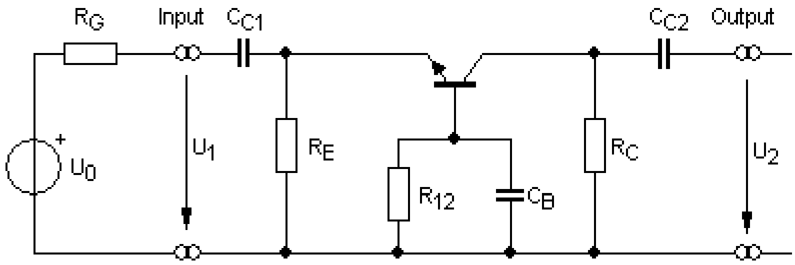

Figure 5: Common base circuit

Note: There are three more circuit options by exchange of the input and output pins but these circuits are not relevant in this tutorial.

The common emitter circuit

The main current $I_E \approx I_C$ passes through the output section. A small current I_B in the input section controls the main current. There is a high current gain as well as a high voltage gain depending on the resistor R_C. This also results in a very high power gain. It is the most frequently used circuit in small signal amplifiers.

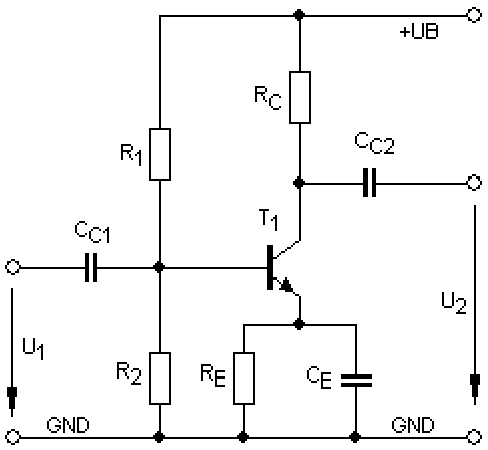

Figure 6: Physical circuit

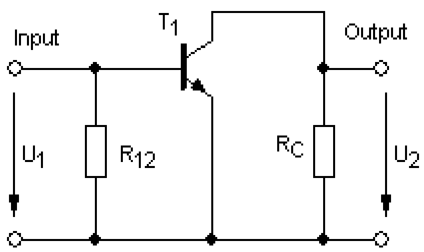

Figure 7: Equivalent AC-circuit

The input impedance is due to a parallel connection of resistor R_{12} (which itself is a parallel connection of R_1 and R_2) and due to the input impedance of the transistor. The input impedance of the transistor can be easily derived from the pn-junction equation

$$I_B = I_s\left(e^{\frac{U_{BE}}{U_T}} - 1\right)$$

and for small signals

$$\frac{dI_B}{dU_{BE}} = I_S\left(e^{\frac{U_{BE}}{U_T}} - 1 + 1\right)\frac{1}{U_T} = \frac{I_S}{U_T}\left(e^{\frac{U_{BE}}{U_T}} - 1\right) + \frac{I_S}{U_T} = \frac{I_B}{U_T} + \frac{I_S}{U_T} \quad .$$

Since the base-emitter junction is forward biased, we get $I_B \gg I_S$ and

$$\frac{dI_B}{dU_{BE}} \approx \frac{I_S}{U_T}\left(e^{\frac{U_{BE}}{U_T}} - 1\right) = \frac{I_B}{U_T} = g_{BE}$$

the value of the input conduction of the bipolar junction transistor if small signals are applied at low frequencies . Finally one gets the AC input resistance as

$$r_{BE} = \frac{1}{g_{BE}} = \frac{U_T}{I_B} \quad .$$

The collector current I_C is $I_C = B\, I_B$ and therefore

$$I_C = B\, I_B = B\, I_s\left(e^{\frac{U_{BE}}{U_T}} - 1\right) \quad ,$$

and for small signals

$$\frac{dI_C}{dU_{BE}} = B\frac{I_S}{U_T}\left(e^{\frac{U_{BE}}{U_T}} - 1\right) + B\frac{I_S}{U_T} = \frac{I_C}{U_T} + B\frac{I_S}{U_T}$$

and one gets for forward biased base emitter junction

$$\frac{dI_C}{dU_{BE}} \approx B\frac{I_S}{U_T}\left(e^{\frac{U_{BE}}{U_T}} - 1\right) = \frac{I_C}{U_T} = g_M \quad ,$$

the mutual conduction, a relation between input voltage change to output current change. Since there is a very little difference between the DC current gain B and the AC current gain β, B is replaced with β in the following equations.

Now we have reached the point, where a very simple equivalent circuit for AC analysis at the bias point can be built:

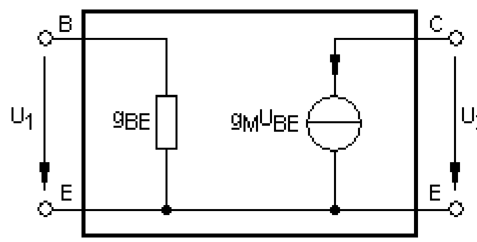

Figure 8: Very simple equivalent circuit

If this simple equivalent circuit is used, the physical circuit shown in Figure 6 can be transformed to the circuit in Figure 9:

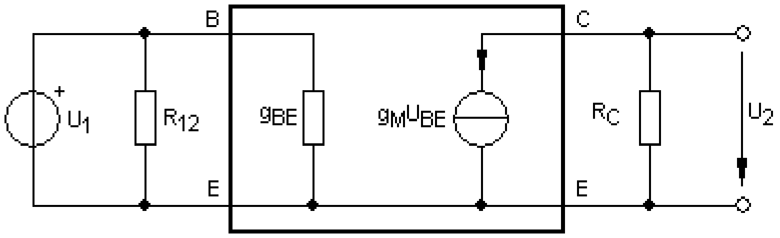

Figure 9: Very simple circuit to determine the properties

It is easy to derive the equation for the input resistance and the result is

$$R_{\text{in}}=\frac{\beta R_{12}}{g_M R_{12}+\beta} \quad .$$

Starting at $U_2=-I_C * R_C=-g_M U_{BE} R_C$ and $U_{BE}=U_1$ one gets

$$V_U=\frac{U_2}{U_1}=-g_M R_C$$

for the voltage gain V_U.

Because the bipolar junction transistors width of the base is slightly dependent of the voltage applied between collector and emitter, the output conductance g_o must be taken into account. The output conductance for small AC signals is the rise of the collector current I_C as a function of the applied voltage between collector and emitter U_{CE}.

$$g_o=\frac{dI_c}{d U_{CE}}=\frac{I_C}{U_{CE}-U_{early}}=\frac{I_C}{U_T}\frac{U_T}{U_{CE}-U_{early}}=g_M \eta_C \quad .$$

The influence of a change of U_{CE} on the change of I_C is called the output conductance.

$$\eta_C=\frac{U_T}{U_{CE}-U_{early}} \quad .$$

If the base width changes with respect to the output voltage, the voltage drop on the base emitter junction changes too. There is a reverse influence of the output voltage U_{CE} to the input voltage U_{BE}

$$\eta_B=\frac{d U_{BE}}{d U_{CE}}\approx\eta_C \quad .$$

Finally, we get an equivalent transistor circuit for small signals at low frequencies.

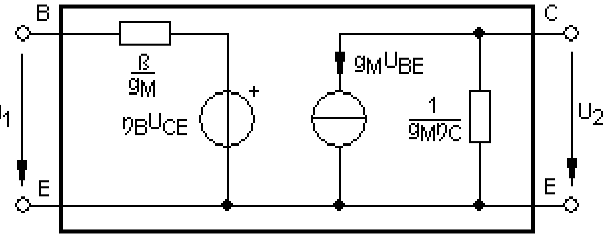

Figure 10: small signal equivalent circuit

Replacing the transistor in Figure 7 leads to the following circuit:

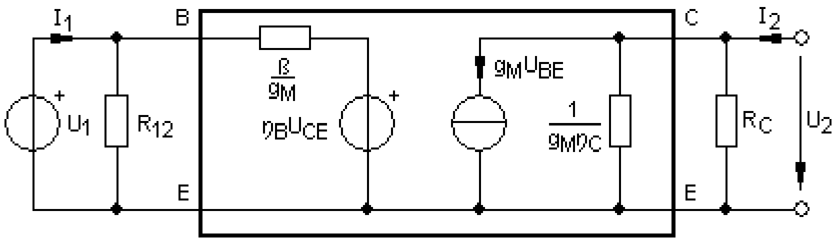

Figure 11: Equivalent circuit of Figure 6

The current $g_M U_{BE}$ flows through the parallel connected resistors $\frac{1}{g_M \eta_C}$ and R_C .

Therefore, the resulting output voltage is $U_2 = -U_1 \frac{g_M R_C}{1 + g_M \eta_C R_C}$ and the voltage gain equals

$$\boxed{V_U = \frac{U_2}{U_1} = -\frac{g_M R_C}{1 + g_M \eta_C R_C}} \; .$$

The input resistance of the biased transistor is defined as the voltage applied at the base pin divided by the current which flows into the base pin

$$\boxed{R_{Tin} = \frac{U_{BE}}{I_B} = \frac{\beta}{g_m} \frac{1 + g_M \eta_C R_C}{1 + (\eta_B + \eta_C) g_M R_C}} \; .$$

The input resistance is defined as the voltage applied at the input port divided by the current which flows into the input port and results in the parallel connection of R_{Tin} and R_{12}.

$$\boxed{R_{\text{in}} = \frac{R_{Tin} R_{12}}{R_{Tin} + R_{12}}}$$

The output resistance is defined as the voltage applied at the output port divided by the current which flows into the output port

$$\boxed{R_{\text{out}} = \frac{U_2}{I_2} = R_C \frac{g_M R_{12} + \beta}{(1 + g_M \eta_C R_C)(g_M R_{12} + \beta) + \eta_B g_M^2 R_{12} R_C}} \; .$$

Due to a slight change in the base width, there is a resulting influence of the collector resistor R_C on the input resistance R_{in}. The output resistance depends on the parallel connection of the resistors R_1 and R_2. The voltage gain V_U becomes reduced due to the base width modulation. The temperature stability of the voltage gain depends on bias point and temperature, because the mutual conductance $g_M = \frac{I_C}{U_T}$ changes with temperature. A possible goal of correct biasing is the temperature stability of g_M. In order to increase the overall temperature stability, a negative feedback might be applied to the circuit.

The common emitter circuit with R_E

The resistor $R_E = R_E' + R_E''$ is split into two parts. Both parts act as DC resistance. One part (R_E') additionally acts as negative feedback for AC signals.

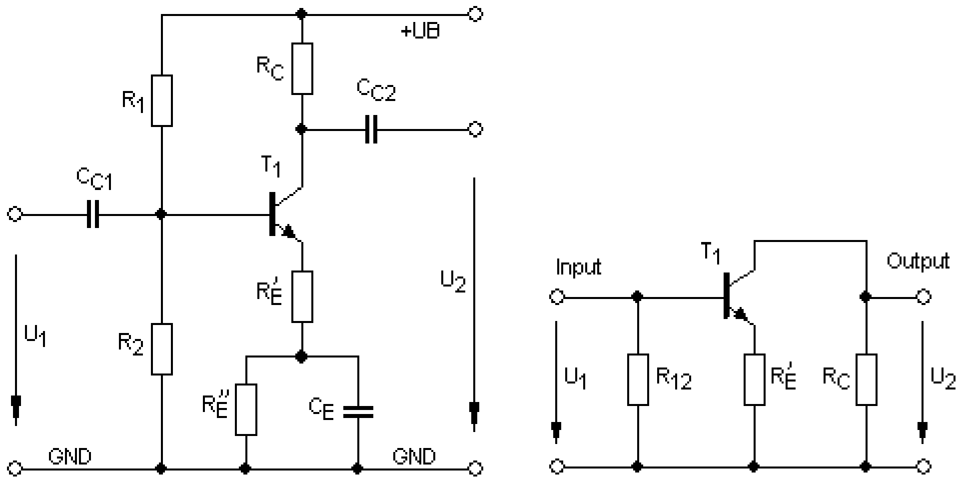

Figure 12: Physical circuit and equivalent circuit with negative AC-feedback

The next step in determining the circuit properties is if the physical transistor is replaced by the equivalent small signal transistor model for low frequencies.

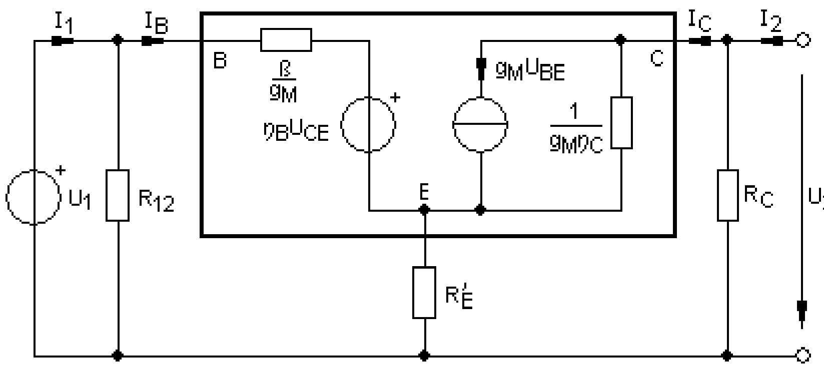

Figure 13: Equivalent circuit of Figure 12

Applying of Norton's Theorem two meshes to solve for the unknown currents can be found. In the following equations the resistor R_E' is renamed by R_E. Otherwise the equations need more than one line for printing which results in unreadable forms. Applying Ohm's law and after some irksome substitutions the transistor input resistance can be found as

$$R_{Tin} = \frac{U_1}{I_B} = \frac{\beta \eta_C}{g_M(\eta_B+\eta_C)} + R_E + \left(R_E + \frac{\eta_B}{g_M(\eta_B+\eta_C)}\right) \frac{\beta - R_E g_M(\eta_B+\eta_C)}{(R_E+R_C) g_M (\eta_B+\eta_C)+1} \quad .$$

Negligence of reverse voltage gain η_B results in

$$R_{Tin} = \frac{U_1}{I_B} = R_E\left(1 + \frac{\beta - R_E g_M \eta_C}{(R_E+R_C) g_M \eta_C + 1}\right) + \frac{\beta}{g_M}$$

and for vanishing base width modulation η_B and η_C

$$\boxed{R_{Tin}=(1+\beta)R_E+\frac{\beta}{g_M}}$$

The input resistance is defined as the voltage applied at the input port divided by the current which flows into the input port and results in the parallel connection of R_{Tin} and R_{12}.

$$\boxed{R_{in}=\frac{R_{Tin}R_{12}}{R_{Tin}+R_{12}}}$$

The transistor current gain is

$$\frac{I_C}{I_B}=\frac{\beta-R_E g_M(\eta_B+\eta_C)}{(R_E+R_C)g_M(\eta_B+\eta_C)+1} \quad ,$$

for neglecting reverse voltage gain η_B

$$\frac{I_C}{I_B}=\frac{\beta-R_E g_M \eta_C}{(R_E+R_C)g_M \eta_C+1}$$

can be derived. Without base width modulation

$$\boxed{\frac{I_C}{I_B}=\beta}$$

After some laborious substitutions the voltage gain V_U equals

$$V_U=\frac{U_2}{U_1}=\frac{-I_C R_C}{U_1}\frac{I_B}{I_B}=-R_C\frac{I_C}{I_B}\frac{I_B}{U_1}=$$

$$=\frac{-R_C\left(\beta-R_E g_M(\eta_B+\eta_C)\right)}{\left(R_E+\frac{\beta}{g_M}\frac{\eta_C}{\eta_B+\eta_C}\right)\left((R_E+R_C)g_M(\eta_B+\eta_C)+1\right)+\left(R_E+\frac{1}{g_M}\frac{\eta_B}{\eta_B+\eta_C}\right)\left(\beta-R_E g_M(\eta_B+\eta_C)\right)}$$

Neglect of reverse voltage gain η_B results in

$$V_U=\frac{-R_C\beta}{\left(R_E+\frac{\beta}{g_M}\right)\left((R_E+R_C)g_M\eta_C+1\right)+R_E(\beta-R_E g_M\eta_C)}$$

In the case of vanishing base width modulation we get handsome equations:

$$\boxed{V_U=-\frac{g_M R_C}{g_M R_E\frac{(\beta+1)}{\beta}+1}} \quad ,$$

for large AC current gain β

$$\boxed{V_U=-\frac{g_M R_C}{g_M R_E+1}} \quad ,$$

and for $g_M R_E \gg 1$ the voltage gain is simply

$$\boxed{V_U=-\frac{R_C}{R_E}} \quad .$$