Anfängerpraktikum für Physiker 2
Bipolartransistor and the emitter circuit (TRA)

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Contents

1 Introduction

This protocol is about the bipolar transistor and the emitter circuit. Different circuits were built and measured to better understand the transistor and learn about semiconductor physics.

2 Theoretical Background

2.1 Doped silicon

Silicon is an ideal insulator at low temperatures and forms a perfect grid since it has four valence electrons. But if you swap some silicon atoms for donors, atoms with an additional valence electron, the grid becomes n-doped. If you swap some silicon for acceptors, atoms with one less valence electron, the grid becomes p-doped. If a p-doped and a n-doped material border each other and a pn-gate is created. If you apply voltage to this insulator it becomes conductive.

2.2 Bipolar transistor

The bipolar transistor is an electric component consisting of two pn-gates and a shared middle zone. The middle zone is called basis. The two other ports are called emitter (higher doping) and collector (lower doping). There is pnp-transistors and npn-transistors:

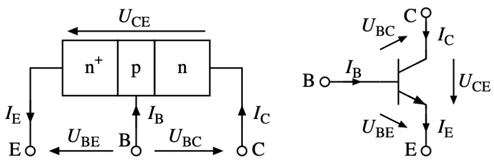

Figure 1: NPN-Transistor

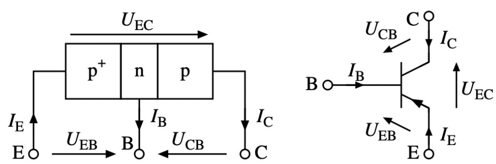

Figure 2: PNP-Transistor

Without current flowing through the base, the transistor is not conductive. But if minimum amount of current flows through the base it becomes conductive. The transistor works as an amplifier until its saturated.

2.3 Two-port network

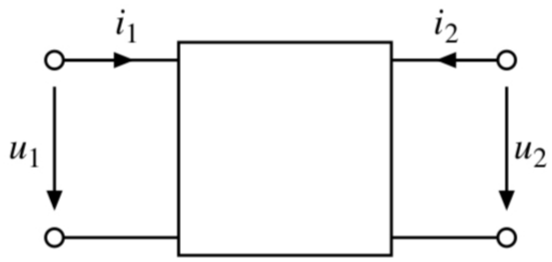

Figure 3: Two-port

A two-port is section of a linear circuit where in each case two conductors lead in and out and the sum of all currents in and out are is the same. The currents i_1 and i_2 can be described can be described by the following funktion.

$$\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \tag{1}$$

It is also possible to describe the equation with the h-parameters. Where u_1 and i_2 are function of i_1 and u_2

$$\begin{pmatrix} u_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \begin{pmatrix} i_1 \\ u_2 \end{pmatrix} \tag{2}$$

A transistor amplifier is a two gate, where one of the theretransistor clamps in both gates.

2.4 Small signal model

The Ebers-Moll Modell is an aquivalent circuit for the mathematical description of the npn-transistor and contains two current sources and two diods. The equations of the Ebers-Moll modell can be substituted with the y parameters to show the two-gate display of the transistor and the differential values of the transistor currents and voltages can be Received.

$$\begin{pmatrix} dI_B \\ dI_C \end{pmatrix} = \begin{pmatrix} \frac{\partial I_B}{\partial U_{BE}}|_{U_{CE}} & \frac{\partial I_B}{\partial U_{CE}}|_{U_{BE}} \\ \frac{\partial I_C}{\partial U_{BE}}|_{U_{CE}} & \frac{\partial I_C}{\partial U_{CE}}|_{U_{BE}} \end{pmatrix} \begin{pmatrix} dU_{BE} \\ dU_{CE} \end{pmatrix} \tag{3}$$

With the differential input resistance r_{BE} and $\frac{1}{r_{BE}} = \frac{\partial I_B}{\partial U_{BE}}|_{U_{CE}}$ and the differential output resistenc r_{CE} and $\frac{1}{r_{CE}} = \frac{\partial I_C}{\partial U_{CE}}|_{U_{BE}}$. And the slope $S = .\frac{\partial I_C}{\partial U_{BE}}|_{U_{CE}}$ and the reverse slop $S_r = \frac{\partial I_B}{\partial U_{CE}}|_{U_{BE}}$ results to the following equation.

$$\begin{pmatrix} dI_B \\ dI_c \end{pmatrix} = \begin{pmatrix} \frac{\partial I_B}{\partial U_{BE}}|_{U_{CE}} & \frac{\partial I_B}{\partial U_{CE}}|_{U_{BE}} \\ \frac{\partial I_C}{\partial U_{BE}}|_{U_{CE}} & \frac{\partial I_C}{\partial U_{CE}}|_{U_{BE}} \end{pmatrix} \begin{pmatrix} dU_{BE} \\ dU_{CE} \end{pmatrix} \tag{4}$$

The differential values dI and dU are small signal values but they are written as i and u if we neglected the the reverse slope ($S \approx 0$) we get the following equation:

$$\begin{pmatrix} i_b \\ i_c \end{pmatrix} = \begin{pmatrix} \frac{1}{r_{BE}} & 0 \\ S & \frac{1}{r_{CE}} \end{pmatrix} \begin{pmatrix} u_{BE} \\ u_{CE} \end{pmatrix} \tag{5}$$

and with the collector current:

$$I_C = I_S \cdot exp\left(\frac{qU_{BE}}{k_b T}\right) \tag{6}$$

we receive for the slope S following relations

$$S = \left.\frac{\partial I_C}{\partial U_{BE}}\right|_{U_{CE}} = \frac{qI_C}{k_B T} \tag{7}$$

q should be the elementary charge.

2.5 Emitter circuit

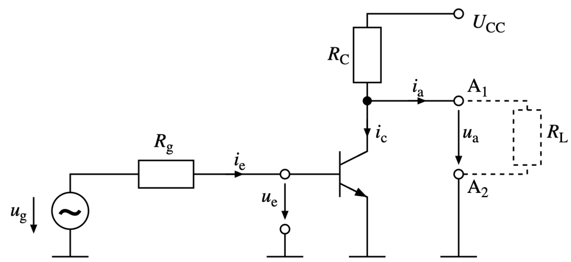

Figure 4: Emitter circuit

An emitter circuit like in figure 5 has an alternating current signal on the input u_a and convert it to an amplified output signal. The change of the output voltage is equivalent to the negative change of the voltage itself. Wich is caused by i_c and R_C. $dU_a = -dI_C \cdot R_C$ in combination with equation 5 follows the equation with amplification A:

$$A = \frac{dU_a}{dU_e} = -S \cdot (R_C || r_{CE}) \tag{8}$$

If a load resistance R_L is build in the circuit:

$$A = \frac{dU_a}{dU_e} = -S \cdot (R_C || r_{CE} || R_L) \tag{9}$$

$$A \approx -\frac{R_C || R_L}{R_E} \tag{10}$$

When the input signal's frequency is high enough for R_E to be short-circuited by C_E, equation 9 is used. The amplification of the basis emitter votage drift is calculated with formula 10 In addition, the equations below apply to the emitter circuit in figure 5 (u_{re} is the potential difference around R_E:

$$S(u_e - u_{re}) = \beta i_b \tag{11}$$

$$u_e = i_b r_{BE} + (1 + \beta) i_b R_E \tag{12}$$

2.6 working point

It's crucial to tune the emitter circuit to an acceptable working point because a high I_B can induce the transistor's saturation, which can result in an output signal with cut-off peaks. The state of the emitter circuit when there is no input signal is the operation point.

3 Conducting the experiment

3.1 Setting the working point

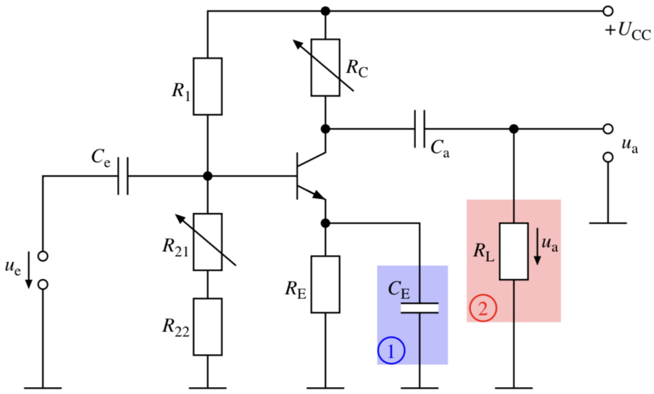

Figure 5: emitter circuit

The emitter circuit was build like in figure 5, but without R_L. The resistor R_c was set to $10K\Omega$.The input signal should be a sine signal. The signal should operate at $5,5KHz$ and an amplitude of about $10V$. The potentiometer R_{21} is tuned to the point where the amplitude of the exiting signal is maximised while the output signal is not distorted. Afterwards the resistor $R21$ is being measured outside and inside of the circuit. Then U_{BE}, U_{CE} and I_C (Figure ?)are measured for each value of the adjustable Resistor $R_C = 1K\Omega, 5K\Omega$ and $10K\Omega$

3.2 Amplification of the emitter circuit

The entry signal is being set to $5,5KHz$.And the Amplitude of the input and output signal should be measured with oscilloscope. The resistor R_C vary from $1K\Omega$ to $10K\Omega$. The measurements should be done with 3 configurations on the circuit from figur 5:
1. with the capacitor C_E but without R_L
2. without capacitor C_E but with R_L
3. with capacitor C_E and with R_L

3.3 Frequency response

The frequency of the Input voltage is being varied to determine the amplitude. Again the circuit of figure 5 is used with $R_c = 10K\Omega$. The frequency should be in-between $6Hz - 250KHz$. While the frequency is being varied at the input and output signal needs to be measured.

3.4 characteristics lines of the transistor

A picture Charakteristic lines on the entry $I_B = f(U_{BE})\mid_{U_{BE}}$ was taken. The circuit in figure 6 was used and for I_B, U_{BE} und U_CE there was a multimeter connected. $R_1 = 1K\Omega$, $R_2 = 220\Omega$ as a potentiometers and $R_X = 1K\Omega$ also as potentiometer. U_{CE} was put on the same value as in experiment 3.1 Setting the working point. And $R_C = 5K\Omega$. U_{BE} was measured between $0 \leq 670mV$, I_B was measured as well.

Afterwards a picture of the Characteristic lines of the exit $I_C = f(U_{BE})\mid_{U_{BE}}$ was taken. And again figuer 6 was in use but with multimeter on I_C, U_{BE} and U_{CE}. This time U_{BE} was put on the same value as in experiment 3.1 Setting the working point. And U_{CE} was measured between $0 \leq 10V$, I_C was measured as well.

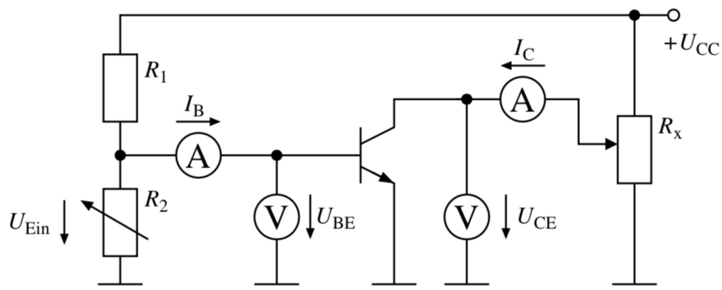

Figure 6: Characteristic lines

4 Evaluation and results

4.1 Characteristic lines of the transistor (Assignment 7)

The characteristic input curve (figure 7) is plotted to determine the resistance r_{BE} and the transistor's operating temperature T, while the characteristic output (figure 8) curve is plotted to calculate r_{CE}. For both curves, a linear approximation at the value of the operation point is also plotted. With equation 5 and the curve fit of the slope we receive the value $r_{BE} = (3361 \pm 7)\Omega$. And with equation 6 and the fitting parameters we also receive $T = (321,51 \pm 0,68)K$. With the help of equation S can be calculated for the different values of R_C.

R_C in $K\Omega$	S in $\frac{1}{\Omega}$
1	0,02
5	0,02
10	0,02

$r_{CE} = 1256281 \pm 50\Omega$ is calculated when is $R_C = 10K\Omega$. The enormous value was anticipated because there should be no current flowing from point E to point C (figure 14).

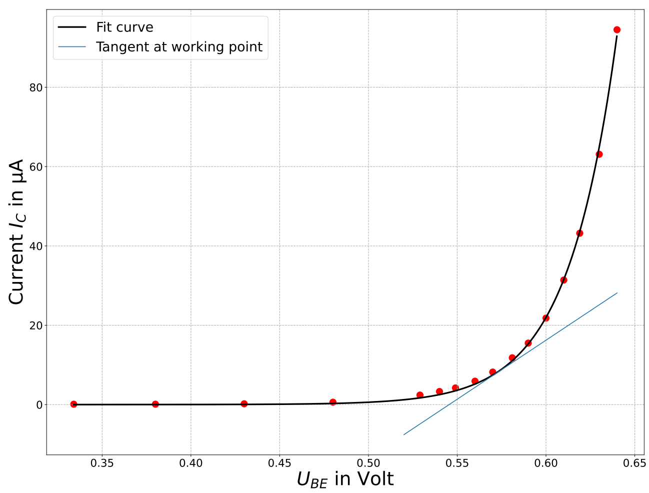

Figure 7: Bipoler-Transistor with parasitic elements

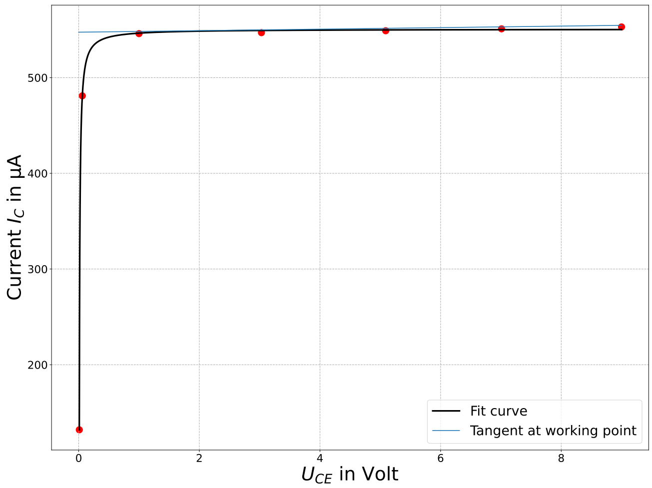

Figure 8: Bipolar-Transistor with parasitic elements

4.2 Amplification of the emitter circuit (Assignment 8)

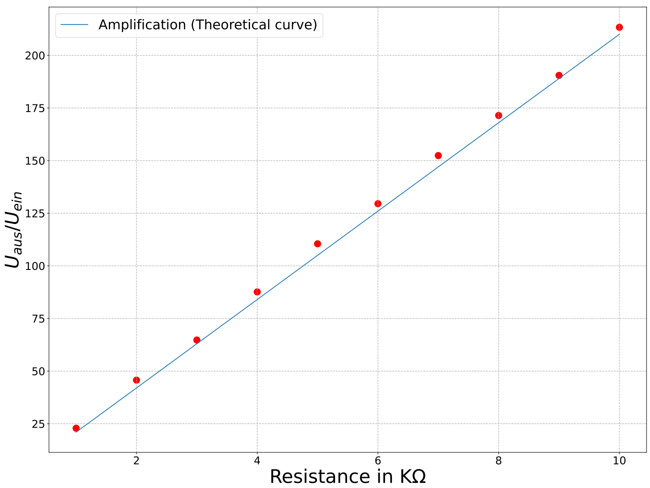

Figure 9: Transfer curve of the emitter circuit with a capacitor C_E and without the R_L resistor and its amplification curve

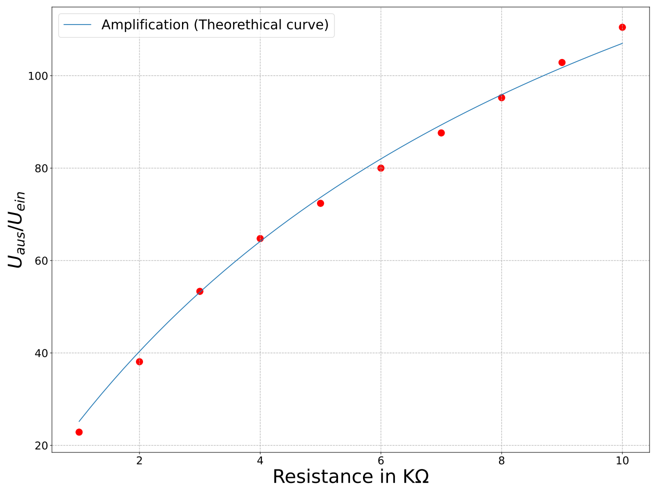

Figure 10: Transfer curve of the emitter circuit with a capacitor C_E and the resistor R_L and its amplification curve

To calculate the voltage amplification A displayed in Figure 9 and 10 one uses equation 9. This is due to the capacitor just becoming conducting at high frequencies.

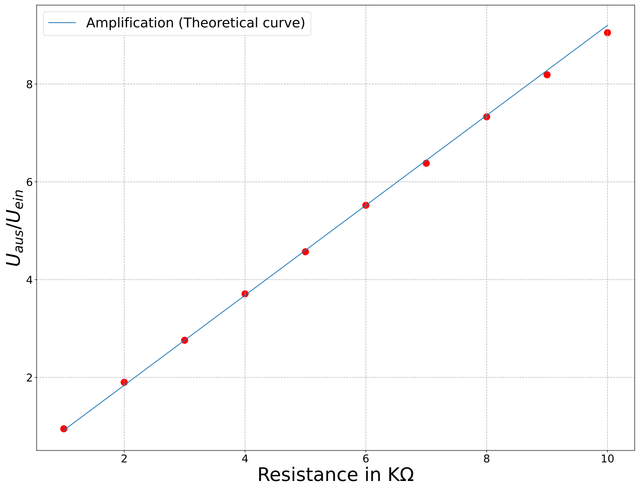

Figure 11: Transfer curve of the emitter circuit without the capacitor C_E and the resistor R_L and its amplification curve

To calculate the voltage amplification of the circuit without the the capacitor one uses equation 10, since it is just the base emitter voltage drift.
The measurements have no significant error when compared to the theoretical curve. While figure 9 and 11 display a linear growing amplification, figure 10 displays a growth that slows down over time. This is due to the resistor R_L included in this circuit.

4.3 Frequency response in the emitter circuit (Assignment 9)

The voltage amplification of the emitter circuit is displayed in figure 12. The amplification in this emitter-circuit behaves like the amplification of a highpassfilter for frequencies from o Hz to 10^3 Hz, since only high frequencies get amplified. It behaves like a lowpassfilter from there on, because only low frequencies are amplified. The interval where it acts like a lowpassfilter is 10^3 Hz to $2 \cdot 10^5$ Hz.
A_{max} is located at $1,06 \cdot 10^3$ Hz and has a value of $A_{max} = 220$. So the amplification is bigger than $\frac{1}{\sqrt{2}} \cdot A_{max} \approx 155,56$ for the interval from about 50Hz to $9,5 \cdot 10^4$ Hz.

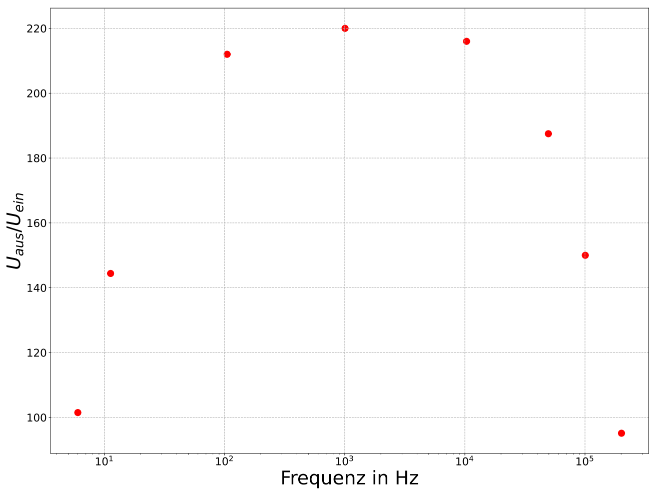

Figure 12: Transfer function depending on frequency

4.4 High- and lowpassfilter (assignment 10)

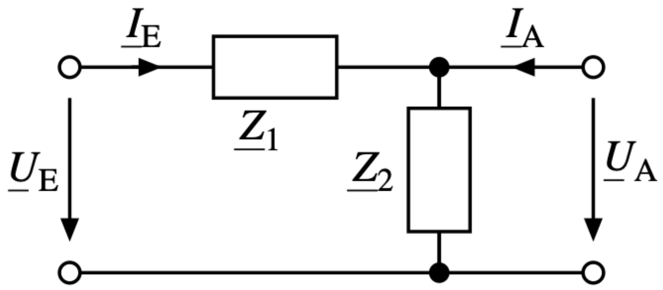

Figure 13: Two gate example

With a two-gate, a straightforward highpass- or lowpassfilter can be implemented. The relation between voltage and current with y-parameters are:

$$\begin{pmatrix} I_e \\ I_a \end{pmatrix} = \begin{pmatrix} \frac{1}{Z_1} & -\frac{1}{Z_1} \\ \frac{1}{Z_1} & \frac{1}{Z_1} + \frac{1}{Z_2} \end{pmatrix} \begin{pmatrix} U_e \\ U_a \end{pmatrix} \tag{13}$$

and the transfer function is defined as

$$g(Z_1, Z_2) = \frac{U_E}{U_A} \tag{14}$$

And when $I_A = 0$ then $U_e = \left(\frac{Z_1}{Z_2} + 1\right) U_a$ and the transfer function gets converted to

$$g(Z_1, Z_2) = \frac{Z_1}{Z_1 + Z_2} \tag{15}$$

The circuit's two impedances are a capacitor C and a resistance R. After that it can be assumed for the High- and the lowpass

$$g_{High} = \frac{R}{j\omega + R} \tag{16}$$

$$g_{Low} = \frac{j\omega}{j\omega + R} \tag{17}$$

5 Questions

5.1 Bipoler- transistor(Preliminary consideration 1)

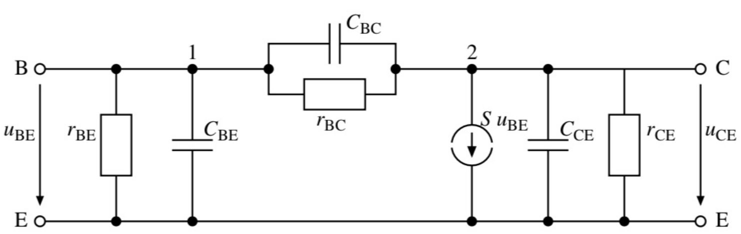

Figure 14: Bipoler-Transistor with parasitic elements

To determine the values r_{BE} and C_{BE}, r_{CE} and C_{CE} and r_{BC} and C_{BC} from figure 7 it is necessary to connect a multimeter on the points BE, BC and CE. r_{BE} are voltage dependant resistances and C_{BE} and C_{CE} are capacities. Every time the resistance and the capacities are measured. But this method does not work because it does not consider Kischoff's law. This results in small shifts in the values of the multimeters because they are connected to the howl circuit. As observered in exercise 1 where the same resistance was measured in the circuit and outside of it. The values where completely different. $R_{IN} = 131,8K\Omega$ and $R_{OUT} = 5,46K\Omega$.

5.2 Y- and h parameters (Preliminary consideration 2)

The following relations are utilized to simplify the y-parameter representation

$$y_{11} = \frac{1}{h_{11}} \tag{18}$$

$$y_{12} = -\frac{h_{12}}{h_{11}} \tag{19}$$

$$y_{21} = \frac{h_{21}}{h_{11}} \tag{20}$$

$$y_{22} = \frac{h_{11}h_{22} - h_{12}h_{21}}{h_{11}} \tag{21}$$

Equation 5 can be convicted to:

$$\begin{pmatrix} u_{BE} \\ i_c \end{pmatrix} = \begin{pmatrix} r_{BE} & 0 \\ S \cdot r_{BE} & \frac{1}{r_{CE}} \end{pmatrix} \begin{pmatrix} i_b \\ u_{CE} \end{pmatrix} \tag{22}$$

The relaion between S and β can be determined with the equation 11 and 12:

$$\beta = r_{BE} \cdot S \tag{23}$$

6 Literature

[1]"Faculty of Physics TUM" https://www.ph.tum.de/academics/org/labs/ap/ap2/TRA.pdf

7 Appendix