SMALL SIGNAL TRANSISTOR AMPLIFIER

In addition to this instructions, please read the following chapters in the book 'Basic electronics for scientists and engineers' by D. L. Eggleston:

4.3. DC and switching applications (repetition)

4.4. Amplifiers:

- 4.4.3. AC equivalents for bipolar junction transistors (repetition)
- 4.4.4. Applying the AC equivalents: the common-emitter amplifier
- 4.4.7. Other properties of transistor amplifiers
- 4.4.9. Feedback

Additional resources:

https://www.electronics-tutorials.ws/amplifier/amp_2.html
https://www.electronics-tutorials.ws/amplifier/emitter-resistance.html
https://www.electronics-tutorials.ws/amplifier/amp_1.html

UNSTABILIZED COMMON EMITTER AMPLIFIER

Transistor is an active electronic element mainly used to amplify electronic signals such as input voltages and currents in all modern devices and instruments. Transistor is the most important single electronic element in modern technology. Its discovery and application has started a new industrial revolution that has led the civilization into the era of information and computer technology. Transistors triggered development of modern computers and started miniaturization of all electrical devices, including computing devices and data storage. Digital technology is based on transistor effect. Modern central processing unit (CPU) of a computer can have 80 million transistors per mm^2 and transistor dimensions of only 7 nm (Apple A12 Bionic). For comparison, Pentium 4 in 2006 had 2 million transistors per mm^2, and Intel 486 in 1989 had only 7000 transistors per mm^2.

If emitter electrode is grounded, base electrode connected with the input signal and collector electrode with the output signal, transistor can be used as a voltage amplifier. Such circuit configuration is called common emitter circuit, and voltage amplifier is a common emitter amplifier. If common collector circuit is used, the common collector amplifier can amplify input current so it acts as a current amplifier. Common emitter amplifier (fig. 1) will amplify small variations of the input base voltage U_{BE} into much larger variations of the output collector voltage U_{CE}. Therefore, transistor amplifier does not amplify DC voltage component of U_{BE}, but only amplitude (variations) of AC component of U_{BE}.

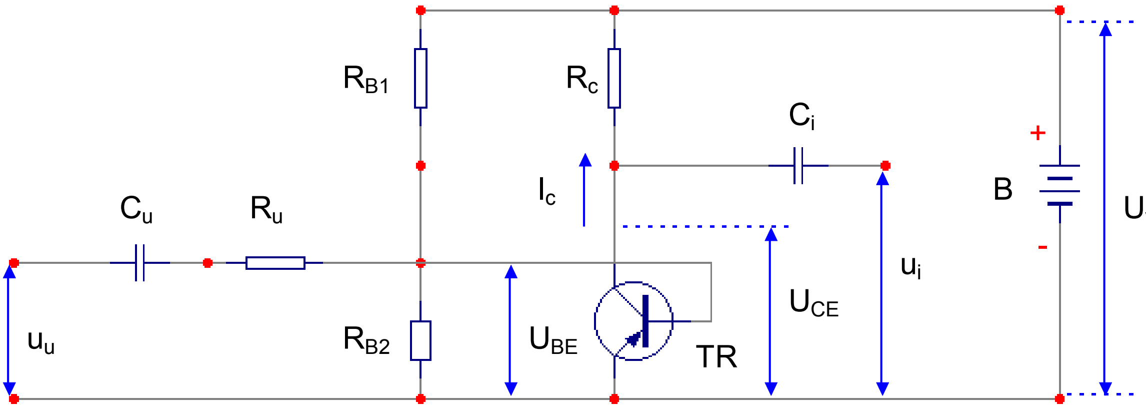


Figure 1. *Unstabilized common-emitter (voltage) amplifier*

Characteristics of the transistor and elements in the circuit determine operation of the common-emitter amplifier. Input circuit is also called **control loop**, while output circuit is called **supply loop**. From figure 1 and for the supply loop (output circuit) consisting of the battery U_v, resistance R_C and voltage drop U_{CE} across collector and emitter, follows:

$$U_v = I_C R_C + U_{CE} \qquad (1)$$

Relation (1) represents a linear equation $I_C = f(U_{CE})$ and is called **load line**. Operating point of the transistor must satisfy both conditions for a proper operation of the transistor: it must lay both on the load line and on the characteristic curve of the transistor. Load line is drawn together with the output characteristics in figure 2. Load line describes dependency of the DC voltages and currents in the supply loop (output circuit): collector current I_C vs. collector voltage U_{CE}. Besides, relation between collector current I_C and collector voltage U_{CE} is also, at the same time, determined by the output characteristic for a given value of the base current I_B. Therefore, the only allowed values of the output collector current I_c and of the output collector voltage U_{CE} are those that satisfy both the load line and the output characteristic for the given base current I_B. Operating or Q-point is found somewhere on the output characteristic for a given base current. At the same time, operating or Q-point must satisfy the load line. So, the operating or Q-point is found at the intersection of the output characteristic for a given base current and the load line.

Therefore, position of the operating point is determined by the base current and the slope and y-interception of the load line. The load line is determined by the external electronic elements: voltage of the battery (power supply) U_v and collector resistance R_C determine the slope of the load line, while the voltage of the battery U_v determines the y-intercept. Therefore, we can see that the operating point can be chosen by appropriate choice of external electronic elements: U_v and R_C. In order for transistor to operate as a voltage amplifier, operating point or Q-point must be chosen in the middle of the linear active region, far from the cutoff and saturation regions. Inside linear active region, emitter-base junction is forward biased while base-collector junction is reverse biased and the variations of the collector current are proportional and linear to the variations of the base current:

$$\Delta I_C = \beta \Delta I_B$$

In the linear active region, output collector current I_C depends very weakly on output collector voltage U_{CE}, while it strongly varies with the input base current I_B.

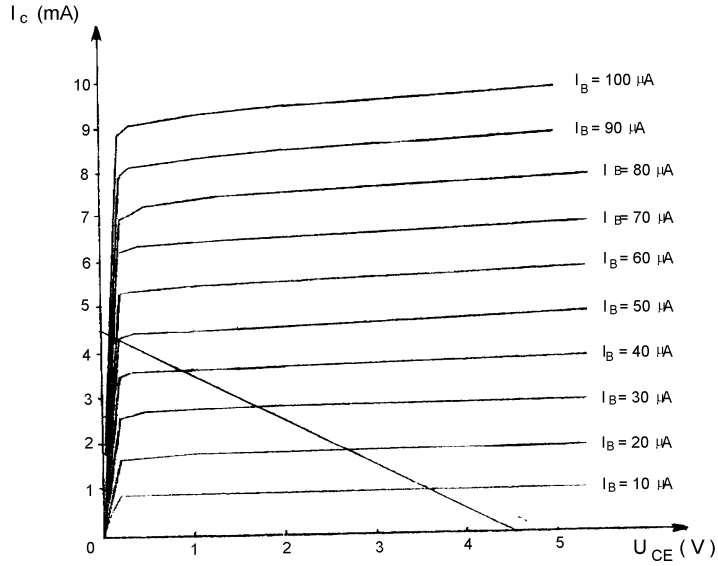


Figure 2. *Output characteristics of the transistor in common-emitter amplifier and the load line*

As already mentioned, operating point should be chosen in the middle of the linear active region in order to avoid any distortion of the AC signal $u_u = U_u \sin \omega t$ due to the large signal amplitude or closeness to the cutoff or saturation region. Time-varying input signal is connected to the transistor input across the capacitor C_u and it varies the base voltage U_{BEQ} of the operating or Q-point for a value U_{BE} that depends on the amplitude U_u of the input signal. Amplification of the varying input voltage is shown on figure 3. Input voltage varies base voltage U_{BE} that causes base current I_B to vary around the operating point I_{BQ}. Variation in the base current causes variation of the collector current I_C according to the above relation, which in turn causes variation of the collector voltage U_{CE}. Consequently, the input voltage is amplified to the value of the output voltage. If the variation of the input signal causes the operating point to move to the non-linear part of the forward gain current characteristic (to the saturation or cutoff regions), the average value of the collector current becomes different than the quiescent collector current I_{CQ} of the operating point. Therefore, Q-point will also change as it is determined by the average value of the collector current.

If the operating point is chosen in the middle of the active region and with the appropriate amplitude of the input signal, the quiescent collector current I_{CQ} is the same as the average collector current and the operating point does not vary. For amplification to be linear and independent of the amplitude of the input AC voltage U_u, amplitude U_v must be small enough. This additional condition is the consequence of the non-linearity of the characteristics that will cause distortion of the large-amplitude signals. Factor of the voltage amplification or voltage gain β_u depends on the amplitude of the input signal as:

$$\beta_u = \frac{\Delta U_{CE}}{\Delta U_{BE}} \cong \beta_{uQ} \left(1 + \frac{1}{2}\frac{U_u}{U_T}\right)$$

where $U_u \equiv \Delta U_{BE}$ is the amplitude of the AC input signal which also corresponds to the variation of the input base voltage U_{BE} in the operating point, while $U_T = \frac{kT}{q}$ is called temperature equivalent and is determined by the operating temperature of the transistor. At the room temperature of 300 K, temperature equivalent is 26 mV.

Voltage amplification will be linear, i.e. factor of the voltage amplification or voltage gain will be constant ($\beta_u = \beta_{uQ}$) only for input signals with adequately small amplitudes such as $U_u << U_T$ = 26 mV. This is **small signal transistor amplifier**.

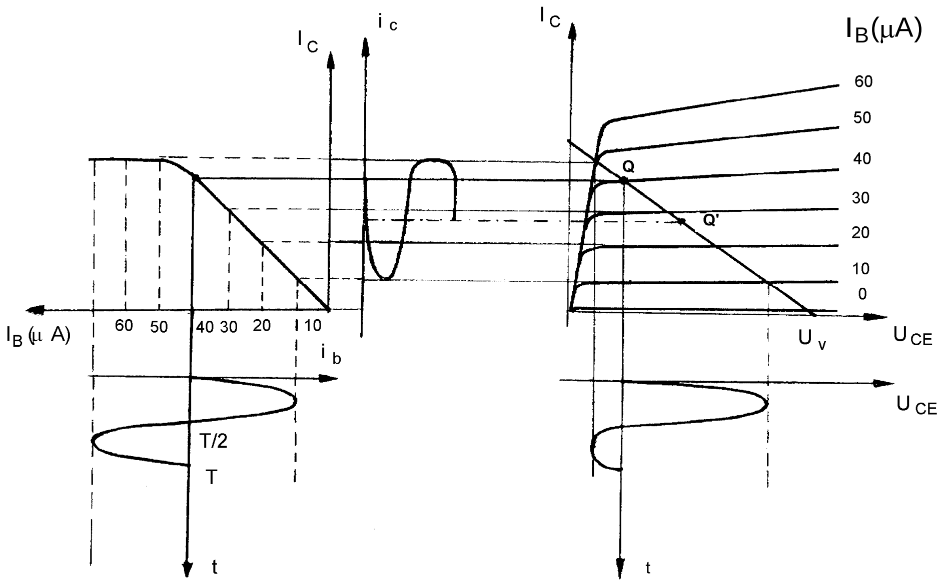


Figure 3. *Determination of the voltage amplification by the use of transistor characteristics and the load line. Non-linearity of the voltage amplification and signal distortions are also shown.*

INFLUENCE OF THE EXTERNAL ELECTRONIC ELEMENTS IN AMPLIFIER CIRCUIT

Battery (power supply) U_v, Ohmic resistances and capacitors are all used as external electronic elements in the circuit of the common-emitter voltage amplifier (fig. 1). They determine normal operation of the transistor and they must be optimally chosen as their values affect characteristics of the amplifier.

Base resistance between the base and the battery, as well as the battery voltage adjust the operating point. Values of the voltages and currents of the operating point can be determined from the intersection of the output characteristic and the load line (fig. 2). Capacitors C_u and C_i are used for feedback. The purpose of the capacitor C_u is to separate source of the AC input signal from the DC voltages supplied by the battery and needed to correctly bias the two PN junctions in the transistor. Without that capacitor, DC component would influence the input signal and lower its amplification and the voltage gain. Similarly, the purpose of the second capacitor, C_i, is to separate the output from the DC component so that only amplified AC signal is carried over to the output and to the next stage of the electronic circuit.

Input resistance R_u is used to obtain better linearity of the amplification (gain), although it lowers amplification factor (gain) due to its voltage drop.

Capacitors C_u and C_i will influence the frequency characteristics (gain vs frequency) of the amplifier circuit due to the capacitive reactance X_C:

$$|X_C| = \frac{1}{2\pi f C}$$

where f is the frequency of the amplified signal. It is clear that the capacitive reactance depends on the frequency of the input signal and capacity of the capacitor. If we consider input circuit (supply loop) on figure 1, than the AC voltage drop u_{BE} between base and emitter is:

$$u_{BE} = u_u - u_C$$

where u_u is the AC input voltage and u_c is AC voltage drop on the capacitor C_u. Common-emitter amplifier amplifies not the AC input voltage of the circuit (u_u) but the AC input voltage u_{BE} passed to the base of the transistor. Consequently, if the voltage drop u_C on the capacitor is large, AC voltage on the base u_{BE} will be small and much smaller than the AC input voltage u_u ($u_{BE} < u_u$), so the voltage amplification will be small. Oppositely, if voltage drop u_C is very small ($u_C \approx 0$), than $u_{BE} \approx u_u$ and the voltage amplification will be maximal. Ideally, voltage drop on capacitor C_u should be as small as possible in order to obtain highest amplification, while still having the necessary separation between the signal source and the DC component. Voltage drop u_C will be small if capacitive reactance is small, and highest amplification will be obtained. Capacitive reactance is small for higher frequencies of the signal and for large capacitance of the capacitor C_u. Therefore, factor of amplification will increase with the frequency and with the capacitance of the capacitor. The frequency characteristics A = f (f) increases for low frequencies, until the maximum factor of amplification is reached.

For higher frequencies, amplification will not further increase due to the internal capacitance of the transistor. Depletion region formed on the emitter-base junction across which the electric field is established, acts as plates of a capacitor with the electric field in-between. The same happens in the depletion region of the base-collector junction. Therefore, transistor has its own base-collector and emitter-base junction capacitances. If the potential barrier of the PN junction is lowered (by forward bias), the width of the depletion region is decreased and the junction barrier capacitance is increased as in a plate capacitor when the plates are brought closer. In reverse bias, potential barrier and the width of depletion region of the PN junction are increased, while the junction barrier capacitance is decreased. Height of the potential barrier and width of the depletion region depend on the bias voltage and not on the frequency of the signal. Therefore, junction barrier capacitances of the transistor depend on the bias voltage.

On the other hand, diffusion capacitance will depend on the frequency of the signal. Diffusion between emitter and base causes majority charge carriers in emitter semiconductor to flow into the base and to form diffusion current. Therefore, diffusion current accumulates additional charge carriers in the base, which forms diffusion capacitance. Majority charge carriers in emitter are now accumulated in the base where they become minority charge carriers and recombine with majority charge carriers. In order for current to flow through the transistor, these charges need to move through the barrier and through the base to reach the collector. AC signal varies the direction of the current flow, so AC emitter current fills and empties the barrier and the base as the current changes direction. Charges that enter base from the emitter will flow back to the emitter when the direction of the AC signal is changed. Charges need enough time in order to pass through the barrier and the base and reach the collector before the direction of the AC signal is changed. If the frequency is too high, the charges will not have enough time to pass through the barrier and the base and reach the collector. So, if the signal half-period is shorter than the time the charges need to reach the collector, the collector current and the amplification will decrease. Therefore, amplification decreases for higher frequencies due to the diffusion capacitance.

To summarize, amplification will be maximal for a certain frequency. Amplification will decrease for lower frequencies due to the increase of the reactive capacitance of capacitor C_u. Amplification will also decrease for higher frequencies due to the diffusion capacitance of the transistor.

STABILIZATION OF THE OPERATING POINTS

Unstabilized common-emitter amplifier can be modified in order to improve the characteristics of the amplifier so that the factor of amplification and the stability of the operating point depend more on electronic elements in the circuit than the characteristic of the transistor. Such a stabilized common-emitter amplifier is shown in figure 4. Stabilization of the operating point is achieved by shunt negative feedback.

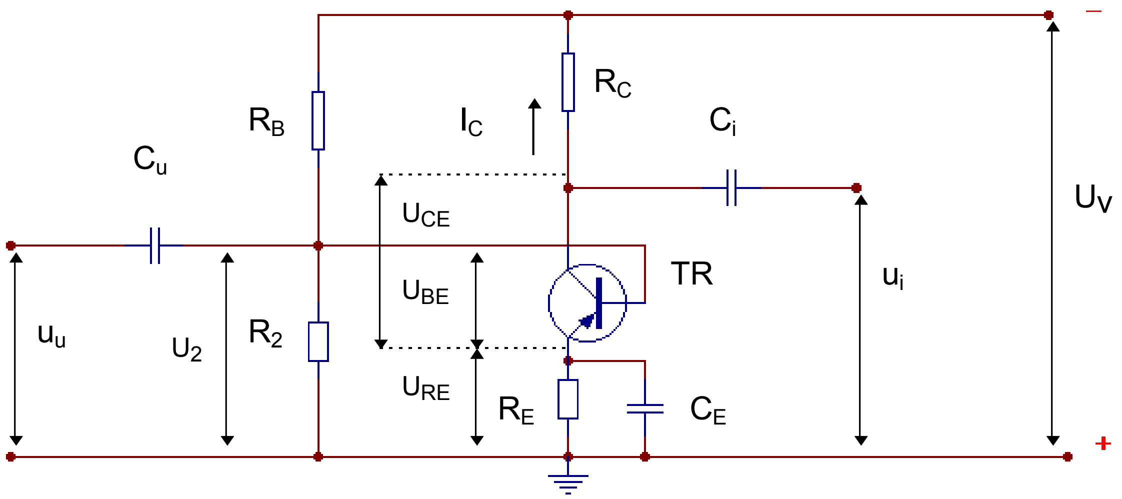


Figure 4. *Stabilized common-emitter amplifier*

The goal of the stabilized amplifier is to stabilize operating point so that it does not vary under the variable external conditions such as the temperature. Variation of the operational temperature of the transistor will greatly affect operation of the bipolar transistor. Operation of the bipolar transistor is based on injection of the minority charge carriers into the base and their transport through the emitter-base barrier and through the base until the collector is reached. Minority charge carriers are formed or removed mainly by generation and recombination processes between holes and electrons in the base. In order to form an electron-hole pair, covalent bond between atoms must be broken. Therefore, an increase in the temperature will cause more breakings of the covalent bonds and formation of more electron-hole pairs, thus increasing the concentration and the current of the minority charge carriers, which corresponds to the base current.

If the operational temperature of the transistor is lowered, the base current decreases, which in turn decreases reverse bias current of the base-collector junction (collector current). If collector current decreases, voltage drop on resistor R_C will also decrease and voltage U_{CE} will increase according to the equation of the load line (relation 1). Operating point moves towards larger U_{CE} and smaller I_C and nearer to the cutoff region. This can affect linearity of the amplification and cause distortion of the amplified signal as it moves to the cutoff region (see output characteristics of the transistor, figure 2).

Stabilized common-emitter amplifier with negative current feedback (figure 4) differs from the unstabilized amplifier (fig. 1) in two ways:

1. Resistor R_2 is connected in parallel with the base and acts as a voltage divider. It divides DC voltage U_v of the power supply (battery) in the ratio of the R_B and R_2:

$$U_2 = \frac{R_2}{R_B + R_2} U_v$$

   This means that the voltage drop U_2 is constant and determined only by resistors R_2 and R_B ad by the power supply.

2. Additional resistor R_E is connected to the emitter, so emitter is not grounded anymore. It can be seen that:

$$U_2 = U_{BE} + U_{R_E}$$

   where U_{RE} is the voltage drop across the resistor R_E. Resistor R_E provides DC negative feedback to stabilize the emitter current and hence the operating point of the transistor.

As already mentioned, decrease in the operational temperature causes decrease of the collector current I_C and of the emitter current I_E (because emitter current is $I_E = I_B + I_C$). Decreased emitter current I_E also decreases voltage drop U_{RE} on resistor R_E. As the voltage drop U_2 is constant, decrease in U_{RE} leads to the increase of the voltage drop U_{BE} of the base-emitter junction. Furthermore, larger U_{BE} causes an increase of the base current I_B, which in turn lead to the increase of the collector current I_C. This increase of the collector current I_C due to the feedback by the emitter resistor R_E compensates decrease of the collector current due to the lower operational temperature. Therefore, operating point is stabilized on the load line and the DC collector current does not vary with the change of the operational temperature. Operating point of such an amplifier with temperature stabilization is stabilized by the negative current feedback because the output collector current I_C affects the input base current I_B (feedback) in such a way that decrease in output current causes its increase in the feedback (negative feedback).

Stabilization is required only for the DC component and negative feedback must be removed for AC component. Therefore, capacitor C_E is connected with the resistor R_E in parallel. It does not influence DC component, and negative feedback can be achieved. If capacitance C_E is large enough, the AC current will flow freely through the capacitor even for low frequency of the AC signal, and the capacitor C_E will be short-circuited. Therefore, no voltage drop will arise for AC component on resistor R_E and negative feedback will not affect AC component (all of the emitter current flows through the short-circuited capacitor C_E as it has much lower capacitive reactance than the resistance of the resistor R_E). Factor of amplification will decrease if the negative feedback influences AC component of the signal.

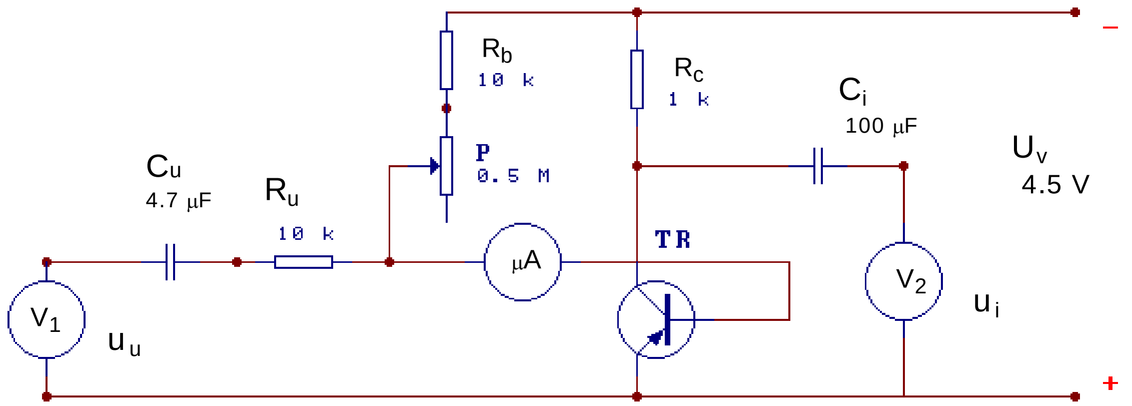
Influence of different electronic elements (C_u, C_E) in the circuit of the common-emitter amplifier on the factor of amplification and on the frequency characteristic of the amplifier circuit are studied, as well as stabilization of the operating point in a circuit with negative current feedback.

ASSIGNMENT I:

1. Assembly the common-emitter amplifier circuit with transistor AC 550 according to the circuit diagram shown below. Determine the operating or Q-point of the amplifier by the use of the output characteristics of the AC 550 transistor obtained in the previous assignment 'Characteristics of the bipolar junction transistor' and the load line for the base current I_B = 15 μA. Measure collector current I_C and voltage U_{CE} for I_B = 15 μA in order to determine the operating point experimentally. Compare the measured values of the operating point with the values determined from the output characteristic and the load line.

Notes:

- Use input signal with the frequency of 1 kHz, supplied by the frequency generator
- Vary input voltage from 1 mV to 20 mV
- AC voltmeter instrument should be connected parallel with the frequency generator (input signal source)
- Output voltage u_i should be measured by the second AC voltmeter.



2. Measure frequency characteristics of the unstabilized common-emitter amplifier, i.e. measure factor of the voltage amplification (voltage gain) $\beta_u = |u_i|/|u_u|$ vs. frequency for different values of capacitance of the capacitor C_u. Use always the same amplitude of the input signal.

Notes:

- Use input signal with the amplitude u_u = 1 mV which can be set on the frequency generator

- Vary the frequency of the input signal from the minimal to the maximal value (20 Hz – 200 kHz)
- Determine frequency characteristics for three different values of capacitance C_u (4.7 μF, 0.1 μF and 0.01 μF)

ASSIGNMENT II:

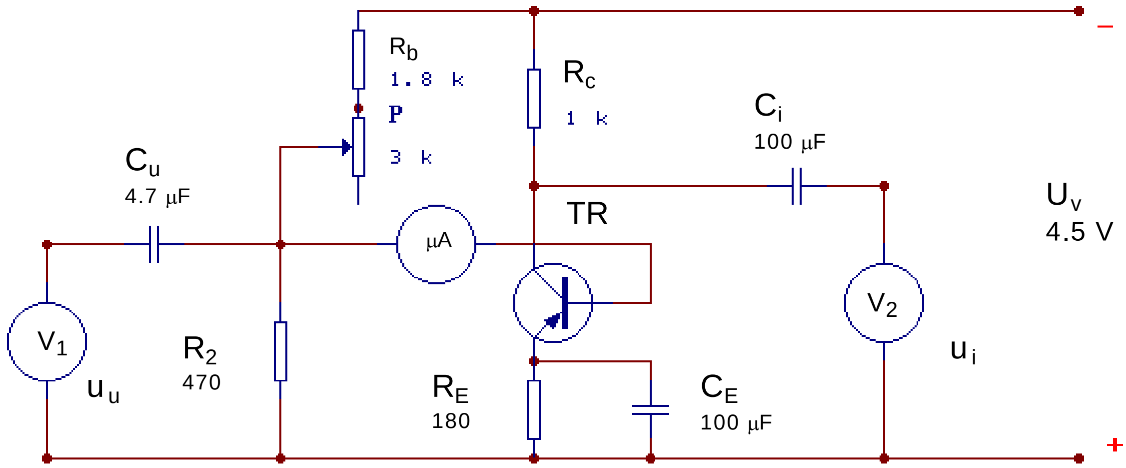
By the use of the stabilized common-emitter amplifier with the negative current feedback shown on the diagram below, and at the operating point used in assignment 1, determine the following:

1. Determine dependence of the output voltage u_i on input voltage u_u at f = 1 kHz:
   a. without capacitor C_E
   b. with capacitor C_E = 100 μF

Notes:
- connect frequency generator at the input and use f = 1 kHz
- vary input voltage from 1 mV to 20 mV
- connect AC voltmeter parallel with the frequency generator
- use the second AC voltmeter to measure output voltage u_i

2. Measure frequency characteristics (dependence of β_u on frequency) for constant amplitude od the input voltage u_u = 1 mV
   a. without capacitor C_E
   b. with capacitor C_E = 100 μF

Notes:
- connect frequency generator at the input and use f = 1 kHz
- vary the frequency of the input signal from the minimal to the maximal value (20 Hz – 200 kHz)
- determine frequency characteristic with and without the capacitor C_E



All results and measurements from assignments I and II should be shown on diagrams and discussed.