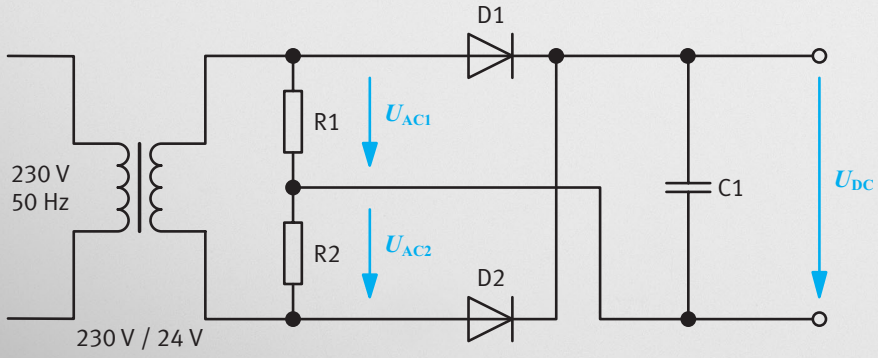
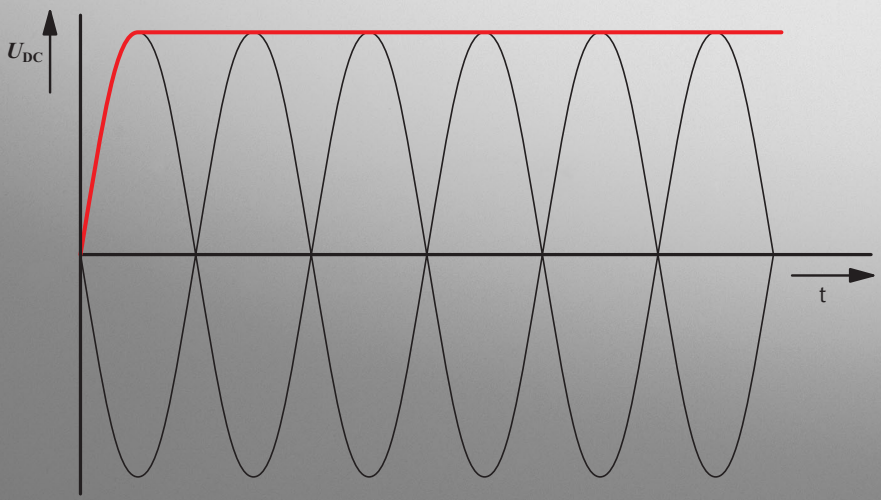
Basic electronics circuits

FESTO

Workbook

With CD-ROM





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Author: Karl-Heinz Drüke
Editor: Frank Ebel
Graphics: Anika Kuhn, Thomas Ocker, Doris Schwarzenberger
Layout: 12/2011, Frank Ebel, Beatrice Huber

© Festo Didactic GmbH & Co. KG, D-73770 Denkendorf, Germany, 2011
Internet: www.festo-didactic.com
e-mail: did@de.festo.com

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Use for intended purpose

The training package for “Basic principles of electrical engineering/electronics” may only be used:

- For its intended purpose in teaching and training applications
- When its safety functions are in flawless condition

The components included in the training package are designed in accordance with the latest technology as well as recognised safety rules. However, life and limb of the user and third parties may be endangered, and the components may be impaired, if they are used incorrectly.

The learning system from Festo Didactic has been developed and produced exclusively for training and further education in the field of automation technology. The training companies and/or trainers must ensure that all trainees observe the safety instructions described in this workbook.

Festo Didactic hereby excludes any and all liability for damages suffered by trainees, the training company and/or any third parties, which occur during use of the equipment sets in situations which serve any purpose other than training and/or vocational education, unless such damages have been caused by Festo Didactic due to malicious intent or gross negligence.

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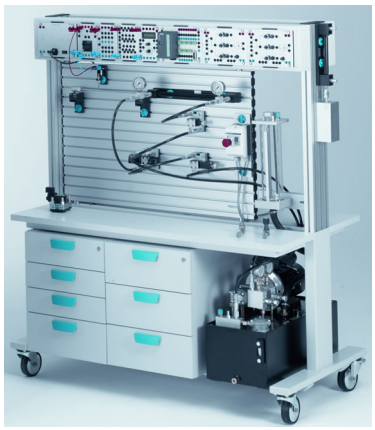
Preface

Festo Didactic's training system for automation and technology is geared towards various educational backgrounds and vocational requirements. The learning system is therefore broken down as follows:

- Technology-oriented training packages
- Mechatronics and factory automation
- Process automation and control technology
- Mobile robotics
- Hybrid learning factories

The training system for automation and technology is continuously updated and expanded in accordance with developments in the field of education, as well as actual professional practice.

The technology packages deal with various technologies including pneumatics, electro-pneumatics, hydraulics, electro-hydraulics, proportional hydraulics, programmable logic controllers, sensor technology, electrical engineering, electronics and electric drives.



The modular design of the training system allows for applications which go above and beyond the limitations of the individual training packages. For example, PLC actuation of pneumatic, hydraulic and electric drives is possible.

All training packages feature the following elements:

- Hardware
- Media
- Seminars

Hardware

The hardware in the training packages is comprised of industrial components and systems that are specially designed for training purposes. The components contained in the training packages are specifically designed and selected for the projects in the accompanying media.

Media

The media provided for the individual topics consist of a mixture of courseware and software. The courseware includes:

- Technical literature and textbooks (standard works for teaching basic knowledge)
- Workbooks (practical exercises with supplementary instructions and sample solutions)
- Lexicons, manuals and technical books (which provide technical information on groups of topics for further exploration)
- Transparencies and videos (for easy-to-follow, dynamic instruction)
- Posters (for presenting information in a clear-cut way)

Within the software, the following programmes are available:

- Digital training programmes (learning content specifically designed for virtual training)
- Simulation software
- Visualisation software
- Software for acquiring measurement data
- Project engineering and design engineering software
- Programming software for programmable logic controllers

The teaching and learning media are available in several languages. They are intended for use in classroom instruction, but are also suitable for self-study.

Seminars

A wide range of seminars covering the contents of the training packages round off the system for training and vocational education.

Do you have suggestions or criticism regarding this manual?

If so, send us an e-mail at did@de.festo.com.
The authors and Festo Didactic look forward to your comments.

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Introduction

This workbook is part of the learning system for automation and technology by Festo Didactic GmbH & Co. KG. The system provides a solid basis for practice-oriented training and continuing vocational education. The training package “Fundamentals of electrical engineering/electronics” (TP 1011) covers the following topics:

- Fundamentals of direct current technology
- Fundamentals of alternating current technology
- Fundamentals of semiconductors
- Basic electronic circuits

The workbook for basic electronic circuits completes the series of workbooks for “Basic principles of electrical engineering/electronics”. Particular emphasis is placed on the analytical examination of interaction between the components already covered in the first three books on the basic principles.

A laboratory workstation equipped with a fused mains power supply, two digital multimeters, a storage oscilloscope and safety laboratory cables is required for setting up and evaluating the circuits.

The circuits for all 10 exercises covering basic electronic circuits are set up using the TP 1011 equipment set.

Technical data for the various components (diodes, transistors, measuring devices etc.) is also available.

Work and safety instructions

General information

- Trainees should only work with the circuits under the supervision of a trainer.
- Observe specifications included in the technical data for the individual components, and in particular all safety instructions!
- Malfunctions which may impair safety must not be generated in the training environment and must be eliminated immediately.

Electrical components

- **Risk of death in case of interrupted protective earth conductor!**
  - The protective earth conductor (yellow/green) must never be interrupted, either inside or outside a device.
  - The insulation of the protective earth conductor must never be damaged or removed.
- German trade association regulations BGV A3, "Electrical systems and equipment", must be observed in commercial facilities.
- In schools and training facilities, the operation of power supply units must be responsibly monitored by trained personnel.
- **Caution!**
  The capacitors in the device may still carry a charge even after it has been disconnected from all power sources.
- When replacing fuses, use specified fuses only with the correct current rating.
- Never switch the power supply unit on immediately after it has been moved from a cold room to a warm room. Under unfavourable conditions, the condensate which forms as a result may damage the device. Leave the device switched off until it has reached room temperature.
- Use only extra-low voltage (max. 25 V DC) as the operating voltage for the circuits in the various exercises.
- Electrical connections may only be established in the absence of voltage.
- Electrical connections may only be interrupted in the absence of voltage.
- Use only connecting cables with safety plugs for electrical connections.
- Always pull the safety plug when disconnecting connecting cables – never pull the cable.

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Training package – Fundamentals of electrical engineering/electronics (TP 1011)

Training package TP 1011 consists of a multitude of training materials. The subject of this part of the TP 1011 training package is basic electronic circuits. Individual components included in training package TP 1011 may also be included in other packages.

Important components of TP 1011

- Permanent workstation with EduTrainer® universal patch panel
- Component set for electrical engineering/electronics with jumper plugs and safety laboratory cables
- EduTrainer® basic power supply unit
- Complete set of laboratory equipment

Media

The courseware for training package TP 1011 consists of four workbooks. The workbooks include exercise sheets for each exercise, the solutions to each individual worksheet and a CD-ROM. A set of ready-to-use exercise sheets and worksheets is included in each workbook for all of the exercises.

Data sheets for the hardware components are made available along with the training package, and on the CD-ROM.

Media	
Workbooks	Fundamentals of direct current technology Fundamentals of alternating current technology Fundamentals of semiconductors Basic electronic circuits
Digital training programmes	WBT Electrical engineering 1 – Fundamentals of electrical engineering WBT Electrical engineering 2 – Direct and alternating current circuits WBT Electronics 1 – Fundamentals of semiconductor technology WBT Electronics 2 – Integrated circuits WBT Electrical protective measures

Overview of media for training package TP 1011

Digital learning programmes available for training package TP 1011 include Electrical engineering 1, Electrical engineering 2, Electronics 1, Electronics 2 and Electrical protective measures. These programmes explore the basic principles of electrical engineering/electronics in detail. Training content is elucidated on the basis of practical case studies in a systematic, applications-oriented fashion.

The media are offered in several languages. You can find further training materials in our catalogue and on the Internet.

Allocation of learning objectives to exercises – basic electronic circuits

Exercise 1: Characteristic values of transistors

- You learn to test transistors for correct functioning.
- You learn to ascertain current amplification B for transistors.
- You become familiar with typical current amplification values for transistors.
- You learn to convert circuits for NPN transistors into circuits for PNP transistors.
- You learn to ascertain a circuit's voltage amplification.
- You become familiar with the effects of operating point adjustments.
- You become familiar with the effects of overdriving an amplifier.

Exercise 2: Basic transistor circuits

- You become familiar with the difference between an emitter follower and a common emitter circuit.
- You become familiar with the three basic transistor circuits.
- You learn to measure voltage amplification in transistor circuits.
- You become familiar with typical voltage amplification in basic transistor circuits.
- You know which basic transistor circuit causes a 180° phase shift.
- You know which basic transistor circuits are non-inverting.
- You learn to specify typical input and output resistance for the basic circuits.
- You learn to measure input and output resistance at amplification circuits.

Exercise 3: Multistage amplifiers

- You learn what a Darlington circuit is.
- You become familiar with complementary Darlington circuit.
- You learn to measure current in the nano-ampere range.
- You know what inverse feedback is.
- You learn to programme amplification gain with two resistors.
- You learn to generate measurement signals in the millivolt range.
- You learn to record an amplifier's frequency response.
- You learn to ascertain an amplifier's cut-off frequency.

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Exercise 4: Power amplifier

- You become familiar with operating point adjustment is circuits with positive and negative operating voltage.
- You learn to recognise inverse feedback.
- You learn which components determine a circuit's amplification gain G_U.
- You learn to recognise whether a given amplifier is a power amplifier or a voltage amplifier.
- You learn to recognise a push-pull output stage.
- You learn what crossover distortion is.
- You learn how inverse feedback effects signal distortion.
- You learn to differentiate between class B operation and class AB operation of an output stage.
- You learn to measure an output stage's quiescent current without an ammeter.
- You learn to determine an amplifier's output power.

Exercise 5: Differential and direct voltage amplifiers

- You learn to recognise the typical structure of a basic, differential amplifier circuit.
- You learn to indirectly determine current within circuits.
- You become familiar with the typical characteristics of a differential amplifier.
- You learn to record and draw the two characteristic curves – U_{out} = f (U_{in}) – of a differential amplifier.
- You learn the difference between differential amplification und common-mode amplification.
- You learn how to achieve a high common-mode rejection ratio, and where this attribute is necessary.
- You learn to recognise a constant current source/sink, and how to calculate constant current.
- You know what a comparator is.
- You learn to set up a twilight switch and explain its function.
- You learn what self-excitation is and what it does.
- You become familiar with the layout and typical characteristics of a direct voltage amplifier.
- You learn about offset and offset alignment.

Exercise 6: Pulse and sawtooth generators

- You learn to recognise the basic circuit of the classical astable multivibrator (AMV).
- You become familiar with the typical characteristics of an astable multivibrator.
- You become familiar with the characteristics of a trigger circuit.
- You learn to measure and calculate the trigger levels and hysteresis of a trigger circuit.
- You learn to convert a trigger circuit and an RC element into a square-wave generator
- You learn to measure and calculate pulse data for various square-wave generators.
- You learn what pulse-width modulation is (PWM) and how it is used.
- You become familiar with the characteristics of a monostable trigger circuit.
- You learn to measure the capacitance of capacitors.
- You learn to dimension the time-determining elements of various pulse circuits.
- You learn how a unijunction transistor (UJT) works and how to test it.
- You learn to convert curved sawtooth voltages into linearly rising sawtooth voltages.

Exercise 7: Sine-wave generators

- You learn the typical characteristics of an LC resonant circuit.
- You learn to measure and calculate the resonant frequency of a resonant circuit.
- You learn to recognise a resonant circuit with three-point connection.
- You learn to determine the coupling coefficient of a frequency determining circuit section.
- You learn to set up and commission LC oscillators.
- You learn how to determine the inductance of unknown coils with the help of an oscillator.
- You learn the working principle of inductive proximity sensors.
- You learn how to set up and commission a metal detector.
- You become familiar with the basic circuit and the characteristics of a Wien element.
- You become familiar with the layout of an RC sine-wave generator with Wien element.
- You become familiar with the problem of amplification settings for RC generators.

Exercise 8: Power pack circuits

- You learn the functions of the power pack in electronic devices.
- You become familiar with the most important rectifier circuits in power supply units.
- You learn the meanings of the terms half-wave rectifier und full-wave rectifier.
- You learn where the charging capacitor is located within a circuit.
- You learn to determine internal resistance or output resistance of voltage sources.
- You become familiar with the term “reference voltage”.
- You learn how an electronic voltage regulator works.
- You learn how to calculate the output voltage of voltage regulating circuits.
- You become familiar with the task and the operating function of the current limiter in power supply units.

Exercise 9: DC voltage converters

- You learn how current in a coil responds when direct voltage is applied.
- You learn how voltage at a coil responds when supply power is switched off.
- You learn to measure current characteristics in a coil indirectly, and display them at an oscilloscope.
- You learn to use a PNP transistor as an electronic switch for positive operating voltage.
- You learn to convert positive direct voltage into negative direct voltage.
- You can generate a large direct voltage from a small one.
- You learn to set up a blocking oscillator consisting of a transistor and a transformer.
- You know what a charge pump is.
- You learn how to stabilise output voltage at voltage transformers.

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Exercise 10: Thyristors and triacs

- You learn the difference between the performance of a thyristor and that of a transistor.
- You become familiar with the term “silicon controlled rectifier” (SCR).
- You learn the conditions under which a thyristor is “ignited”.
- You learn when a conducting thyristor is once again rendered non-conductive.
- You learn to test a thyristor for correct functioning with the help of simple means.
- You learn the difference between a thyristor and a triac.
- You learn how to activate thyristors in a potential-free or isolated manner.
- You learn how to switch direct current and alternating current with thyristors.
- You become familiar with the function of a semiconductor relay.
- You become familiar with the function of a phase-fired controller.

Equipment set

The workbook for fundamentals of electrical engineering/electronics imparts knowledge regarding layout, function and performance of amplifier circuits, power pack circuits, flip-flops and circuits used in power electronics.

The equipment set for fundamentals of electrical engineering/electronics (TP 1011) contains all the components required to achieve the specified learning objectives. Two digital multimeters, a digital storage oscilloscope and safety laboratory cables are also required for setting up and evaluating functional circuits.

Equipment set – Fundamentals of electrical engineering/electronics, order no. 571780

Component	Order no.	Quantity
EduTrainer® basic power supply unit	567321	1
EduTrainer® universal patch panel	567322	1
Component set for electrical engineering/electronics	567306	1
Safety jumper plugs, 19 mm, grey-black	571809	1

Overview of the component set for electrical engineering/electronics, order no. 567306

Component	Quantity
Resistor, 10 Ω / 2 W	1
Resistor, 22 Ω / 2 W	2
Resistor, 33 Ω / 2 W	1
Resistor, 100 Ω / 2 W	2
Resistor, 220 Ω / 2 W	1
Resistor, 330 Ω / 2 W	1
Resistor, 470 Ω / 2 W	2
Resistor, 680 Ω / 2 W	1
Resistor, 1 kΩ / 2 W	3
Resistor, 2.2 kΩ / 2 W	2
Resistor, 4.7 kΩ / 2 W	2
Resistor, 10 kΩ / 2 W	3
Resistor, 22 kΩ / 2 W	3
Resistor, 47 kΩ / 2 W	2
Resistor, 100 kΩ / 2 W	2
Resistor, 1 MΩ / 2 W	1
Potentiometer, 1 kΩ / 0.5 W	1
Potentiometer, 10 kΩ / 0.5 W	1
Thermistor (NTC), 4.7 kΩ / 0.45 W	1
Light-dependent resistor (LDR), 100 V / 0.2 W	1
Voltage-dependent resistor (VDR), 14 V / 0.05 W	1
Capacitor, 100 pF / 100 V	1
Capacitor, 10 nF / 100 V	2
Capacitor, 47 nF / 100 V	1
Capacitor, 0.1 µF / 100 V	2
Capacitor, 0.22 µF / 100 V	1
Capacitor, 0.47 µF / 100 V	2
Capacitor, 1.0 µF / 100 V	2
Capacitor, 10 µF / 250 V, polarised	2
Capacitor, 100 µF / 63 V, polarised	1
Capacitor, 470 µF / 50 V, polarised	1

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Component	Quantity
Coil, 100 mH/50 mA	1
Diode, AA118	1
Diode, 1N4007	6
Zener diode, ZPD 3.3	1
Zener diode, ZPD 10	1
Diac, 33 V / 1 mA	1
NPN transistor, BC140, 40 V / 1 A	2
NPN transistor, BC547, 50 V / 100 mA	1
PNP transistor, BC160, 40 V / 1 A	1
P-channel JFET transistor, 2N3820, 20 V / 10 mA	1
N-channel JFET transistor, 2N3819, 25 V / 50 mA	1
Unijunction transistor, 2N2647, 35 V / 50 mA	1
P-channel MOSFET transistor, BS250, 60 V / 180 mA	1
Thyristor, TIC 106, 400 V / 5 A	1
Triac, TIC206, 400 V / 4 A	1
Transformer coil, N = 200	1
Transformer coil, N = 600	2
Iron transformer core with holder	1
Signal lamp, 12 V / 62 mA	1
Light-emitting diode (LED), 20 mA, blue	1
Light-emitting diode (LED), 20 mA, red or green	1
Changeover switch	1

Graphic symbols, equipment set

Component	Graphic symbol
Resistor	
Potentiometer	
Thermistor (NTC)	
Light-dependent resistor (LDR)	
Voltage-dependent resistor (VDR)	
Capacitor	

Component	Graphic symbol
Zener diode	
DIAC	
NPN transistor	
PNP transistor	
P-channel JFET transistor	
N-channel JFET transistor	

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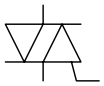
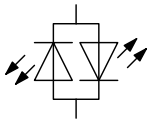
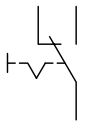
Component	Graphic symbol
Capacitor, polarised	
Coil	
Diode	
Triac	
Transformer coil	
Signal lamp	

Component	Graphic symbol
Unijunction transistor	
P-channel MOSFET transistor	
Thyristor	
Blue LED	
Red or green LED	
Changeover switch	

Allocation of components to exercises – basic electronic circuits

Exercise / Component	1	2	3	4	5	6	7	8	9	10
Diode, 1N4007				2	2	1	4	4	2	4
Electrolytic capacitor, 10 µF	1	2	2	1		1		1	1	
Electrolytic capacitor, 100 µF				1		1		1	1	
Electrolytic capacitor, 220 µF	1									
Electrolytic capacitor, 470 µF								1		
JFET transistor, 2N3819								1		
JFET transistor, 2N3820						1				
Capacitor, 1 nF			1							
Capacitor, 10 nF			1			2	2			1
Capacitor, 47 nF							1	2		
Capacitor, 0.1 µF			1			1	2			1
Capacitor, 0.22 µF				1			1			1
Capacitor, 0.47 µF								1		
Capacitor, 1 µF		1	1				1	1	1	1
Light-emitting diode, 20 mA, blue			1				1	1		
Light-emitting diode, 20 mA, red or green								1		
Signal lamp, 12 V / 62 mA					1	1				1
Potentiometer, 10 kΩ	1	1	1			1	1	1	1	1
Coil, 100 mH/50 mA							1			
Thyristor, TIC106										1
Triac, TIC206										1
Transformer coil, N = 200									1	1
Transformer coil, N = 600							1		1	1
Iron transformer core with holder									1	1
Transistor, BC140	1	1	1	2	2	2	2	2	2	2
Transistor, BC160	1		1	1	1	1	1	1	1	1
Transistor, BC547	1	1	1	1	1		1	1	1	1
Unijunction transistor, 2N2647						1				1
Changeover switch						1				1

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Component \ Exercise	1	2	3	4	5	6	7	8	9	10
Resistor, 10 Ω				1				1		2
Resistor, 33 Ω						1		1	1	1
Resistor, 100 Ω			1	1	2			1	1	1
Resistor, 220 Ω								1		1
Resistor, 330 Ω								1		
Resistor, 470 Ω		1				1		3		2
Resistor, 680 Ω					1		2			
Resistor, 1 kΩ	2	2	5	1	5	2		2		1
Resistor, 2.2 kΩ		2			3	2	1	1	1	4
Resistor, 22 kΩ	1	1		2	4	3	2	1	2	22
Resistor, 4.7 kΩ		1	1	2	2	2				
Resistor, 10 kΩ	2	1	2	1	6	3	4	4	2	3
Resistor, 47 kΩ	1	1	1	1	1	3	2	2	2	3
Resistor, 100 kΩ	1	1	4		2	1		1	2	1
Resistor, 1 MΩ			1				1			
Light-dependent resistor (LDR)					1					
Zener diode, ZPD 10								1	1	

Notes for the teacher/trainer

Learning objectives

The basic learning goal of this workbook is the setup and analysis of selected basic circuits. Amongst others, the circuits include power pack circuits, amplifier circuits, flip-flops and circuits used in power electronics. This direct interplay of theory and practice ensures fast progress and long-lasting learning. Concrete, individual learning objectives are assigned to each exercise.

Required time

The time required for working through the exercises depends on the learner's previous knowledge of the subject matter. Roughly 1 to 1½ hours should be scheduled for each exercise.

Equipment set components

The workbook and the equipment set are designed to be used together. All 10 exercises can be completed using components from one TP 1011 equipment set.

Standards

The following standards are applied in this workbook:

EN 60617-2 to EN 60617-8	Graphic symbols for diagrams
EN 81346-2	Industrial systems, installations and equipment and industrial products; structuring principles and reference designations
IEC 60364-1 (DIN VDE 0100-100)	Low-voltage electrical installations – Fundamental principles, Assessment of general characteristics, definitions
IEC 60346-4-41 (DIN VDE 0100-410)	Low-voltage electrical installations – Protective measures – Protection against electric shock

Identification in the workbook

Solutions and supplements in graphics or diagrams appear in red.
Exception: Information and evaluations regarding current are always in red; information and evaluations regarding voltage are always in blue.

Identification in the worksheets

Texts which require completion are identified with a grid or grey table cells.
Graphics and diagrams which require completion include a grid.

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Solutions
The solutions specified in this workbook result from test measurements. The results of your measurements may vary from these data.

Learning topics
For the vocation of electrician, the learning topic “basic electronic circuits” is assigned to field of learning 1 of the vocational school.

Structure of the exercises

All 10 exercises have the same structure and are broken down into:
- Title
- Learning objectives
- Problem description
- Circuit or positional sketch
- Project assignment
- Work aids
- Worksheets

The workbook contains the solutions for all exercises.

Component designations

The components in the circuit diagrams are identified in accordance with EN 81346-2. Letters are assigned as appropriate to each component. Multiple components of the same type within a single circuit are numbered.

Resistors:	R, R1, R2, ...
Capacitors:	C, C1, C2, ...
Indicators:	P, P1, P2, ...

Note
If resistors and capacitors are interpreted as physical variables, the letter identifying them is in italics (symbols). If digits are required for numbering, they are treated as indices and appear as subscript.

Contents of the CD-ROM

The workbook is included on the CD-ROM as a PDF file. The CD-ROM also provides you with additional media.

The CD-ROM contains the following folders:

- Operating instructions
- Illustrations
- Presentations
- Product information

Operating instructions
Operating instructions are provided for various components included in the training package. These instructions are helpful when using and commissioning the components.

Illustrations
Photos and graphics of components and industrial applications are made available. These can be used to illustrate individual tasks or to supplement project presentations.

Presentations
This directory contains short presentations for the circuits covered by the training package. These can be used, for example, to create project presentations.

Product information
Contains product information from the manufacturers of selected components. The representations and descriptions of the components in this format are intended to show how they would appear in an industrial catalogue. Additional information regarding the components is also included.

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Exercise 1

Examining characteristic values of transistors

Learning objectives

After completing this exercise:

- You will know how to test transistors for correct functioning.
- You will be able to ascertain current amplification B for transistors.
- You will be familiar with typical current amplification values for transistors.
- You will know how to convert circuits for NPN transistors into circuits for PNP transistors.
- You will be able to ascertain a circuit's voltage amplification.
- You will be familiar with the effects of operating point adjustments.
- You will be familiar with the effects of overdriving an amplifier.

Problem description

You work for a company that manufactures and repairs hi-fi amplifiers. During the course of initial training you will need to familiarise yourself with the performance of transistors and their typical characteristic values.

You will set up a test circuit to this end, which allows you to determine the degree to which transistors amplify power. After slightly modifying the circuit, you will then examine how a transistor can be used as a voltage amplifier.

Project assignments

1. Set up a test circuit with NPN transistor BC140 and ascertain the transistor's power amplification B with collector current values of I_C = 1 mA, 5 mA and 10 mA.
2. For purposes of comparison, determine power amplification B for transistor BC547.
3. Modify the test circuit so that it is suitable for testing PNP transistors, and ascertain power amplification B for transistor BC160.
4. Set sup a test circuit within which transistors are actuated non-destructively with direct voltage. Familiarise yourself with the basic principle of voltage amplification.
5. With the help of the test circuit, determine voltage amplification G_U when using transistors BC140 and BC547.
6. Expand the test circuit such that a BC140 transistor can be additionally actuated with alternating voltage. Familiarise yourself with the concept of alternating voltage amplification.
7. Examine the relationship between operating point setting and output signal distortion.
8. Find out whether the test circuit is a basic common emitter circuit, a basic fundamental circuit or a basic common collector.

Work aids

- Textbooks, books of tables
- Excerpts from manufacturers' catalogues
- Data sheets
- Internet
- WBT Electronics 1 and Electronics 2

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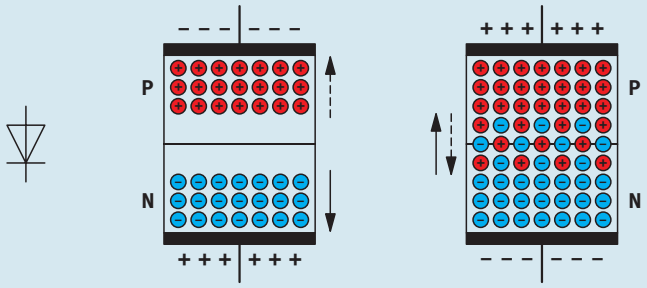
Information

Basic knowledge regarding diodes and transistors

Transistors and diodes consist of semiconductor materials, for the most part silicon. Semiconductors can be influenced by inserting dopants such that current flows within them either through **negative charge carriers** (electrons) or **positive charge carriers** (so-called "holes" or "defect electrons"). Semiconductors modified in this way are called **n-material** and **p-material** respectively.

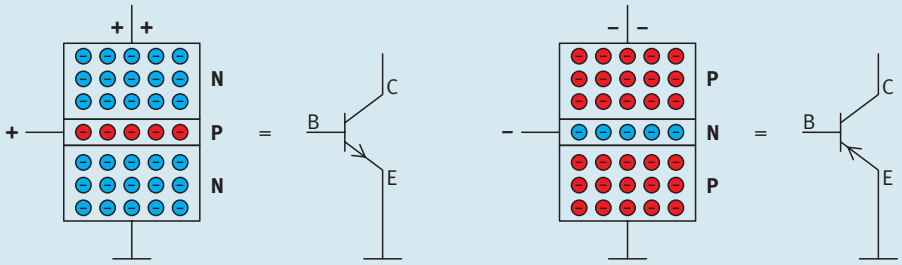
When p-material and n-material is joined, a **PN transition** occurs. The transition only allows electrical current to pass in one direction, and thus functions as an electrical valve or diode. The function of the diode can be readily explained with the basic electrical law which states that **"unlike charges attract each other and like charges repel each other"**.



Semiconductor diode – circuit symbol and layout

- **Blocked direction**
  If the n-region of the PN transition is connected to the plus pole of a voltage source and the p-zone is connected to the minus pole, the charge carriers in the semiconductor are drawn outward. As a result, a broad region which is free of charge carriers is created at the PN transition which functions as an insulating layer and prevents the flow of current. The PN transition (the diode) blocks flow.
- **Free-flow direction**
  If the polarity of the external voltage source is reversed (plus to p-region and minus to n-region), the charge carriers are driven towards each other in both regions and (after exceeding a given "threshold voltage") are capable of passing through the PN transition. Current flows. The diode is conductive.
- The diode terminal which is connected to the n-region is called the cathode, and the terminal connected to the p-region is called the anode.
- The arrow in the circuit symbol indicates the free-flow direction for the flow of current.

Transistors (more precisely “bipolar transistors”) consist of three semiconductor layers in one of the following orders: N-P-N or P-N-P. The middle layer is the base layer, and the two outside layers are known as the emitter and collector layers. This is why transistor terminals are usually designated with the abbreviations E, B and C.



NPN and PNP transistors – layout and circuit symbol

The polarity of a transistor’s operating voltage must always be set up such that the charge carriers from the emitter region are drawn to the collector. Due to the fact that unlike charges are attracted to each other, the following results:

- NPN transistors work with positive collector-emitter voltage U_{CE}
- PNP transistors work with negative collector-emitter voltage U_{CE}

However, without base voltage no flow of charge carriers takes place from the emitter to the collector. The base layer prevents the collector’s attractive force from extending into the emitter region. Only after charge carriers are lifted out of the emitter region into the (thin) base layer with the help of base voltage are they subjected to the influence of the collector’s attraction region, to which most of them then flow. In order to draw the charge carriers from the emitter to the base, base-emitter voltage U_{BE} must have the same polarity as collector-emitter voltage U_{CE}. This results in the following:

- NPN transistors become conductive in the case of positive base-emitter voltage U_{BE}.
- PNP transistors become conductive in the case of negative base-emitter voltage U_{BE}.

And thus the basic function of the transistor as an amplifier component can be explained as follows: With the help of relatively minimal base-emitter voltage U_{BE}, we can control how many charge carriers flow from the transistor’s emitter to its collector. However, base current I_B can also be specified in order to control collector current. Each specific base current value automatically results in a certain base-emitter voltage U_{BE}, which in turn dictates a given collector current I_C. Nevertheless, the relationship between collector current I_C and base current I_B is far more linear than the relationship between I_C and U_{BE}. Ratio I_C / I_B is know as transistor current amplification B. The ratio may vary from one transistor to the next, and usually lies within a range of 50 to 500.

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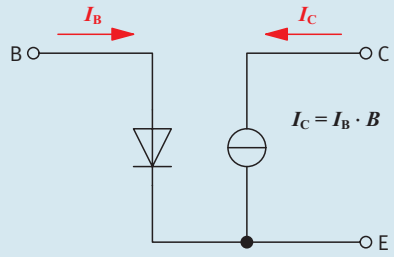
The equivalent circuit diagram of a transistor demonstrates its mode of operation in an even simpler fashion: The transistor's base-emitter path functions like a diode in the free-flow direction. Base current I_B flowing along this path increases current I_C between emitter and collector by a factor of B. The current source symbol indicates that collector current is for the most part independent of the collector voltage value.

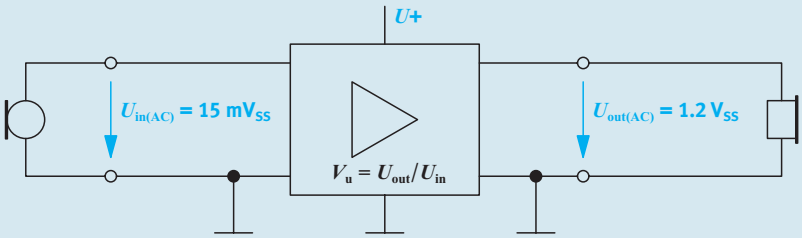


NPN transistor – equivalent circuit diagram

The **emitter** is identified with an **arrow** in the transistor symbol. Regardless of internal processes within the transistor, the direction of the arrow in the symbol nevertheless represents the actual direction of flow. The following applies in general to symbols for semiconductor components: The arrow points either towards a p-region or comes out of an n-region. (mnemonic aid: **P** = "**p**ointing" arrow, **N** = "adva**n**cing" arrow).

What does an amplifier do?

The microphone in a telephone converts sound waves created by, for example, speech or music, into alternating voltage in the millivolt range. However, this signal is too weak to drive a headphone or a loudspeaker directly. Several volts are required for good, audible reproduction with these devices. An amplifier must therefore be connected between the microphone and the headphone or loudspeaker. All amplifiers require (direct) operating voltage in order to generate an output signal.



Amplifier – circuit symbol

In the following pages you will learn how transistor amplifiers work.

1. Current amplification with NPN transistor BC140

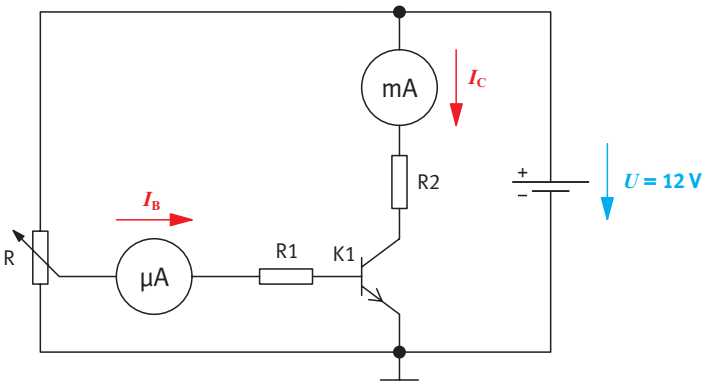
Information

The transistor as a current amplifier

You can test NPN transistors for correct functioning with the following circuit. Transistor base current I_B can be adjusted with the variable voltage divider (potentiometer). Assuming that the transistor is intact, any base current causes significantly increased collector current I_C. By dividing the measured value for I_C by the measured value for I_B, we arrive at current amplification gain B for the transistor under test.

$$B = \frac{I_C}{I_B}$$

Resistors R1 and R2 are so-called protective resistors. They limit base and collector current to values which are incapable of damaging the transistor, in the event that potentiometer R is operated without due care.



Test circuit for measuring current amplification B

Identification	Designation	Parameter
R1	Resistor	10 kΩ, 47 kΩ, 100 kΩ (depending on task)
R2	Resistor	1 kΩ
R	Potentiometer	10 kΩ
K1	Transistor	BC140, BC547, BC160 (depending on task)

Components list

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a) Set up the test circuit with a BC140 transistor and set I_C to a value of 1 mA. Read base current I_B and make a note of its value. Calculate current amplification B for the transistor under test on the basis of the measured values. Repeat measurement after setting I_C to a value of 5 mA and 10 mA. Enter the obtained values to the table under BC140 (1).

Transistor	BC140 (1)			BC140 (2)			BC547			BC160		
I_C [mA]	1	5	10	1	5	10	1	5	10	1	5	10
I_B [µA]	7.7	38.5	76.9	8.0	39.8	79.5	3.2	16.1	32.4	4.2	20.8	40.3
$B = I_C / I_B$	130	130	130	125	126	126	313	311	308	238	240	248

Table of measured values

b) A second BC140 transistor is included in the set of components furnished with the EduTrainer. Test it in the same way and ascertain current amplification B where I_C = 1 mA, 5 mA and 10 mA. Enter the values to the table under BC140 (2).
(It is entirely normal for current amplification gain to vary from on transistor to the next, even for transistors of the same type!)

2. Current amplification with NPN transistor BC547

a) Repeat the procedure with transistor BC547 and enter the values to the table.

3. Current amplification with PNP transistor BC160

a) Transistor BC160 is a PNP transistor. The measuring circuit used thus far must be slightly modified in order to assure that the transistor functions correctly. What needs to be done?

We only have to reverse operating voltage polarity. If the measuring devices are pointer instruments, their terminals must be reversed as well. Digital measuring instruments automatically change the preceding plus or minus signs at their displays.

b) Using the modified test circuit, ascertain the missing data for the BC160 transistor and enter them to the table.

c) Leave the transistor in the circuit in order to conduct research experiments.

1. What is the highest base current which can be selected with the potentiometer?

I_{Bmax} = approx. 240 µA

2. Try to calculate this value using data obtained with the test circuit.

Maximum voltage drop at R1 amounts to $U - U_{BE}$ = 12 V – 0.7 V = 11.3 V / 47 kΩ = 240 µA

3. What is the largest collector current value which can be set up with the circuit?

I_{Cmax} = approx. 12 mA

4. Try to calculate I_{Cmax} using the data obtained with the test circuit.

Maximum voltage drop at R2 amounts to $U - U_{Emin} \approx$ 12 V – 0 V = 12 V. In this case, current I_{Cmax} = 12 V / 1 kΩ = 12 mA flows through R2 and the series connected transistor.

5. Up to limit value I_{Cmax}, collector current I_C can be controlled by adjusting base current I_B. What is the designation for the transistor's state when it no longer responds to further control signal increases?

We say that the transistor is being overdriven, or has reached a state of saturation.
(It now functions like a switch in the on state. I_C is determined by U and R2.)

6. What has to be done in order to expand the test circuit for collector current of up to roughly 25 mA?

R2 must be reduced. $R_2 = U / I_{Cmax}$ = 12 V / 25 mA = 480 Ω → 470 Ω is selected

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4. The transistor as a voltage amplifier

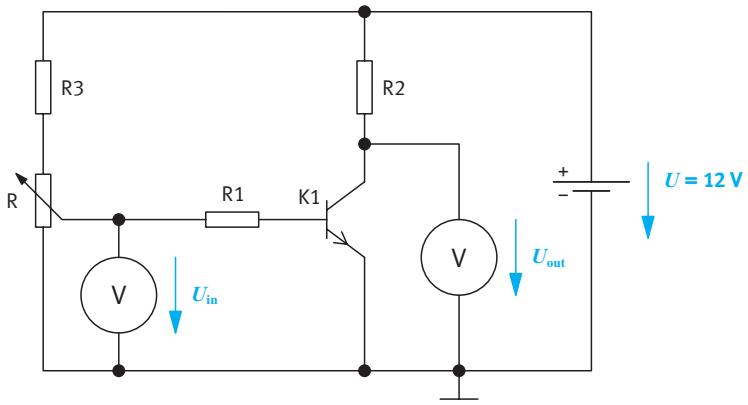
Information

With the help of (direct) operating voltage (designated U in this workbook), transistors can also be used as voltage amplifiers. However, they have to be combined with other components to this end, which convert current changes to voltage changes. In the simplest of all cases, "operating resistance R_A" is connected to the collector lead. The transistor and the resistor comprise a series connection through which collector current I_C flows. In accordance with Ohm's law, voltage drop over working resistance results from the equation $U_{RA} = R_A \cdot I_C$, and voltage drop U_{CE} results from the laws of series connection: $U_{CE} = U_C = U - U_{RA}$. In this way, input voltage U_{in} first of all controls base current I_B, and thus collector current I_C as well, and finally collector voltage U_C too, thanks to operating resistance R_A. Collector voltage then serves as output voltage U_{out}. With regard to a circuit's voltage amplification G_U we do not consider direct voltage at the input and the output, rather man the ratio of "voltage **change** at the output" to the "causative voltage **change** at the input. "Change" or difference is represented in formulas with the Greek letter Δ (delta). And thus the following notation results:

Voltage amplification $G_U = \dfrac{U_{out1} - U_{out2}}{U_{in1} - U_{in2}} = \dfrac{\Delta U_{out}}{\Delta U_{in}}$

5. Voltage amplification with NPN transistors BC140 and BC547

a) Convert the previously used test circuit into a voltage amplifier.



The transistor as a voltage amplifier

Identification	Designation	Parameter
R1	Resistor	47 kΩ
R2	Resistor	1 kΩ
R3	Resistor	22 kΩ
R	Potentiometer	10 kΩ
K1	Transistor	BC140, BC547

Components list

b) With the help of the new circuit, ascertain output voltage values for the input voltage values specified in the U_{in}/U_{out} table, and the input voltages for the specified U_{out} values.

U_{in}/U_{out} table, BC140									
U_{in} [V]	0	0.59	0.84	0.97	1.10	1.84	1.38	1.57	2.0
U_{out} [V]	12	11.8	10	8	6	4	2	0.2	0.1

c) Calculate difference ΔU_{out} using the 10 V und 2 V U_{out} values and difference ΔU_{in} on the basis of the associated U_{in} values. How high is voltage amplification G_U in the above circuit?

G_u = (10 V – 2 V) / (0.84 V – 1.38 V) = 8 V / -0.54 V = -14.8 ≈ 15
(Other values are possible!)

Note for the lesson
If voltage amplification G_U is negative, this is not necessarily an error. It simply indicates that the amplifier circuit is “inverting”, i.e. that an inverting amplifier is used. If U_{in} is made more positive, U_{out} becomes less positive or “more negative”, and vice versa.

d) Replace the BC140 transistor with a BC547 and repeat the measurements.

U_{in}/U_{out} table, BC547									
U_{in} [V]	0	0.621	0.738	0.828	0.908	0.99	1.08	1.57	2.0
U_{out} [V]	12	11.8	10	8	6	4	2	0.2	0.15

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e) Calculate difference ΔU_{out} using the 10 V und 2 V U_{out} values and difference ΔU_{in} on the basis of the associated U_{in} values. How high is voltage amplification G_U in the above circuit?

G_u = (10 V – 2 V) / (0.738 V – 1.08 V) = 8 V / -0.342 V = 23.4 ≈ 23
(Other values are possible!)

f) Evaluate the amplification characteristics of the BC140 and the BC547 transistors.

The circuit with the BC547 transistor provides higher voltage amplification, presumably because current amplification B is greater than it is for the BC140 transistor.

g) Represent the relationship between input and output voltage for the BC140 in diagram U_{out} = f (U_{in}). Sketch in thin reference lines by means of which the U_{in} values for U_{out} = 10 V und U_{out} = 2 V can be ascertained from the characteristic curve. Appropriately enter the designations ΔU_{out} and ΔU_{in} to the diagram as well.

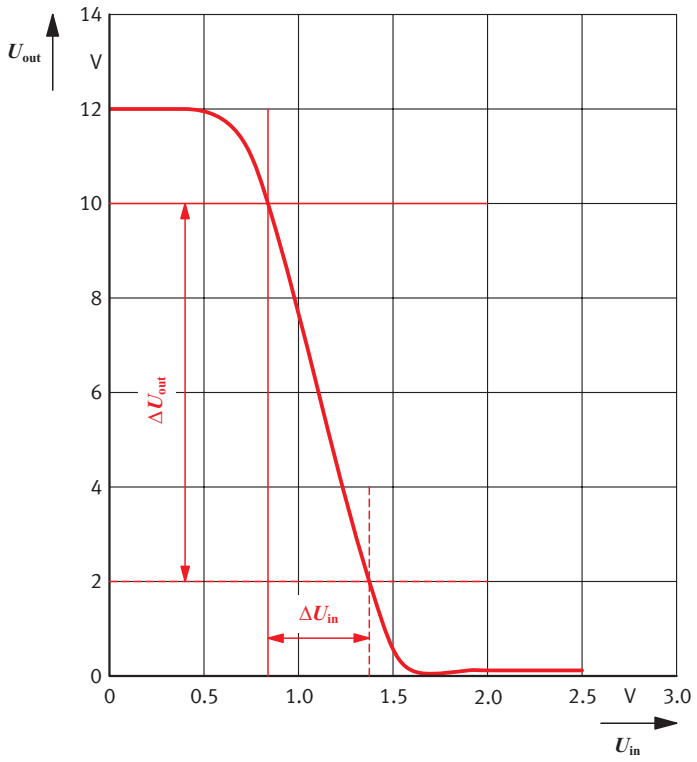


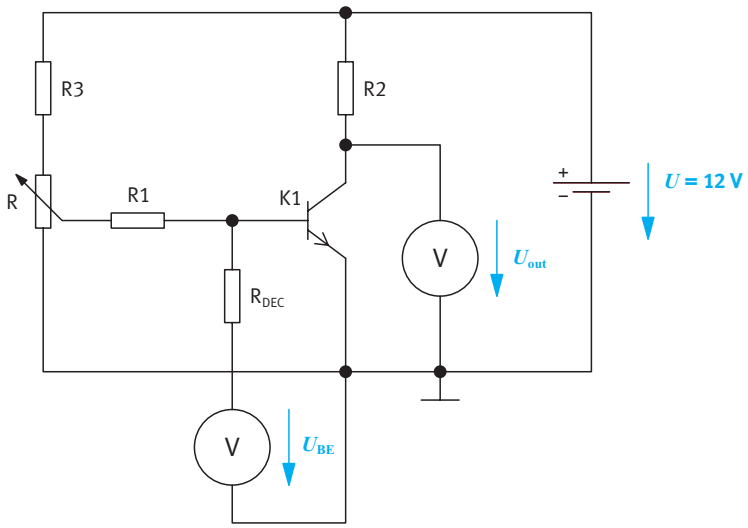
Diagram U_{out} = f (U_{in})

Information

In this circuit, resistor R1 protects the transistor from any excessive base current. Unfortunately, it also reduces voltage amplification G_U. However, theoretically possible amplification can also be ascertained in the protected circuit by measuring base-emitter voltage U_{BE} directly at the transistor instead of voltage U_{in} supplied by the potentiometer.

However, directly connecting a measuring instrument to the base lead at a modern transistor with long measuring cables results in the danger that the circuit will begin to oscillate in the 100 MHz range, and will thus be transformed into a VHF transmitter. This undesirable effect can even be detected without an oscilloscope if measured values change when the insulated measuring cables are touched, or if they react when your hand approaches the cables! This problem can be remedied by installing a decoupling resistor with a value of, for example, 1 to 10 kΩ between the base lead and the measuring cable (as close to base as possible!). Upstream from a high-impedance voltmeter ($R_i \geq 1$ MΩ), measured values remains practically undistorted by the resistor.

h) Modify the previous circuit accordingly.



Measuring U_{BE} via a decoupling resistor (parasitic suppressor)

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Identification	Designation	Parameter
R1	Resistor	47 kΩ
R2	Resistor	1 kΩ
R3	Resistor	22 kΩ
R_{DEC}	Resistor (decoupling resistor)	1 kΩ
R	Potentiometer	10 kΩ
K1	Transistor	BC547

Components list

i) Ascertain the missing values for the U_{BE}/U_{out} table with the help of the circuit.

U_{BE}/U_{out} table, BC547									
U_{BE} [mV]	0	595	675	691	702	712	722	747	751
U_{out} [V]	12	11.8	10	8	6	4	2	0.2	0.15

j) Calculate voltage amplification G_U on the basis of ΔU_{out} and ΔU_{BE}.
Use the measured values for U_{out} = 4 V and 8 V.

G_u = (8 V – 4 V) / (0.691 V – 0.712 V) = 4 V / -0.021 V = 190.5 ≈ 190 !

6. The transistor as alternating voltage amplifier

Information

Input voltage, which has thus far been adjusted manually with potentiometer R, can also be changed by injecting an alternating voltage. In order to assure that direct current flowing through R1 is not inadvertently drained off via the alternating voltage source, a so-called “coupling capacitor” (C1) is installed into the signal line. It has infinitely high resistance X_C for direct current, but allows alternating current to pass freely. Potentiometer R can now be used to set the amplifier’s operating point.

Due to the fact that small alternating voltages alone are not capable of rendering a transistor conductive, the transistor is influenced with a direct current such that collector voltage U_C is about halfway between its two extreme values, U_{Emax} and U_{Emin}, in the idle state. If a (small) alternating current is now added to direct base current, the direct current is then increased and reduced synchronous to the alternating signal cycles (undulating current occurs). Correspondingly, collector current I_C and collector voltage U_C oscillate around their quiescent values synchronous to the input signal.

The alternating voltage component is filtered back out of the undulating collector voltage with additional coupling capacitor C2, which is then used as output signal U_{out}. In this way, the amplifier circuit creates a considerably larger (amplified) alternating voltage signal at the output from a small one at the input (with identical frequency and waveform) – even though, in this case, the transistor works with positive operating voltage U only!

After measuring peak-to-peak values for the input and output signals with a oscilloscope, these values can be used to calculate the circuit’s alternating voltage amplification $G_{U(AC)}$.

Alternating voltage amplification gain $G_{U(AC)} = \frac{U_{out(ss)}}{U_{in(ss)}} = \frac{U_{out(eff)}}{U_{in(eff)}}$

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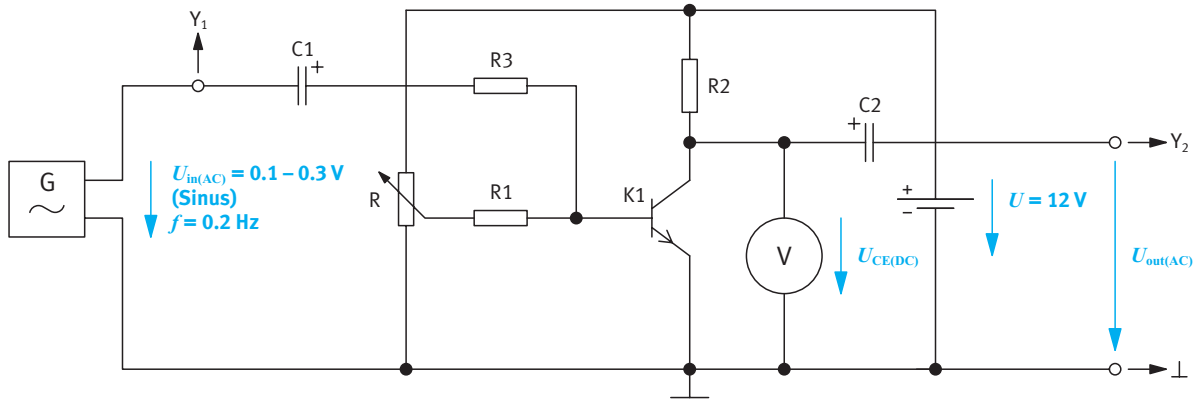

The transistor as an alternating voltage amplifier
Y_1: to oscilloscope, channel A
Y_2: to oscilloscope, channel B

Identification	Designation	Parameter
R1	Resistor	100 kΩ
R2	Resistor	1 kΩ
R3	Resistor	10 kΩ
R	Potentiometer	10 kΩ
C1	Capacitor	220 µF
C2	Electrolytic capacitor	10 µF
K1	Transistor	BC140

Components list

Notes

In order to be able to observe the operations which take place within the circuit in a relaxed fashion:

- Set the EduTrainer sine-wave generator to a very low frequency, for example 0.2 Hz.
- Roughly 0.1 to 0.3 V suffice for U_{in} (take from the 0 to 2 V output of the DDS waveform generator!).
- Adjust the oscilloscope such that both channels record two steady, uninterrupted lines, which move up and down synchronous to the input signal.
- Disconnect the sine-wave generator from C1 and set the circuit's operating point to U_{CE} = +6 V (50% of operating voltage) with the potentiometer.
- Reconnect the generator and adjust the amplitude of U_{in} such that transistor voltage U_{CE} oscillates between roughly +4 and +8 V.

a) Experiment with the circuit and then answer the following questions. Tick the correct answers.

☐ Input voltage $U_{in(AC)}$ and output voltage $U_{out(AC)}$ oscillate synchronously.
☑ Input voltage $U_{in(AC)}$ and output voltage $U_{out(AC)}$ oscillate oppositely.

☑ During the positive half-wave of $U_{in(AC)}$, more collector current I_C flows than during the negative half-wave of $U_{in(AC)}$.
☐ During the positive half-wave of $U_{in(AC)}$, less collector current IC flows than during the negative half-wave of $U_{in(AC)}$.

☐ When collector current in the transistor increases, collector-emitter voltage U_{CE} rises as well.
☑ When collector current in the transistor increases, collector-emitter voltage U_{CE} drops.

☑ An operating point U_C amounting to 50% of operating voltage is selected because from there, collector voltage can move up or down by the same amount.
☐ An operating point U_C amounting to 50% of operating voltage is selected because this is where amplification within the circuit is greatest.

☑ Coupling capacitors are intended to allow alternating signals to pass, but should not influence direct voltage.
☐ Coupling capacitors prevent unwanted high frequency oscillation within the circuit.

☑ The operating point is the basic setting for direct current within a circuit.
☐ The operating point is a the solder joint in the circuit diagram which connects the collector to the output.

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7. Relationship between operating point setting and output signal distortion

Information
The circuit is usually tested with signals which result in a stationary pattern at the oscilloscope. Increase the frequency of the input signal to 500 Hz to this end, and set the sweep at the oscilloscope such that one to two full periods for $U_{in(AC)}$ and $U_{out(AC)}$ can be viewed at the screen.

a) Adjust the input signal and the operating point such that a clean sinusoidal signal with 6 V peak-to-peak (6 V_{pp}) is generated at the output. Then measure the peak-to-peak value for $U_{in(AC)}$ and ascertain alternating voltage amplification $G_{U(AC)}$ for the circuit.

Where U_{out} = 6 V_{pp}, the amplifier requires an input voltage of U_{in} = 250 mV_{pp}.
The following results: G_u = 6 V_{pp} / 0.25 V_{pp} = 24

b) How many degrees does phase shifting amount to between $U_{in(AC)}$ and $U_{out(AC)}$?

U_{out} is displaced from U_{in} by one half-wave (180°). The negative half-wave of von U_{out} occurs during the positive half-wave of U_{in}, and vice versa.

c) What happens to the waveform of the output signal if the operating point is slowly adjusted up or down with potentiometer R?

The positive or negative peaks of the alternating output voltage are chopped.
The sinusoidal waveform is distorted.

d) Find the answer to the following question by changing $U_{in(AC)}$ and the operating point:
How much peak-to-peak voltage voltage can be delivered at the output without distorting the sinusoidal waveform?

Distortion is relatively minimal for output voltage of up to about 10 V_{pp}.

Information
The waveform of the output signal of a hi-fi amplifier must be identical to that of its input signal. However, signal inverting is not taken into consideration. If one channel can be inverted and Y deflection can be infinitely adjusted at your oscilloscope, you can attempt to bring the $U_{out(AC)}$ and $U_{in(AC)}$ signals into coincidence at the screen. The closer you come to succeeding, the better the amplifier is.

e) Test response characteristics with delta und square-wave voltage as well. Then evaluate whether or not the amplifier is suitable for hi-fi applications, at least under certain conditions.

With peak-to-peak output signals of just a few volts, the waveforms closely approximate each other, i.e. no visible distortion occurs. Deviation becomes greater as amplitude is increased. For this reason, the amplifier is only suitable for hi-fi applications under certain conditions.

8. Basic transistor circuits

Information
There are three basic transistor circuits. They are named after the transistor lead which serves as a common point of reference for the input and output signals. In the simplest of all cases, this is the transistor lead which is connected to ground. But there is frequently no direct connection from there to circuit grounding. In this case, the following method is helpful in determining the correct name: Find out to which transistor lead the input signal is applied, and from which lead the output signal is taken. The basic circuit is named after the remaining transistor lead.

a) Which type of basic transistor circuit was used in the preceding pages? Tick the correct answer.

☑ In the test and experimental circuits covered by exercise 1, the transistors were used in a common emitter circuit, or common emitter for short.
☐ In the test and experimental circuits covered by exercise 1, the transistors were used in a common base circuit, or base for short.
☐ In the test and experimental circuits covered by exercise 1, the transistors were used in a basic common collector, or common collector for short.

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Exercise 1

Examining characteristic values of transistors

Learning objectives

After completing this exercise:

- You will know how to test transistors for correct functioning.
- You will be able to ascertain current amplification B for transistors.
- You will be familiar with typical current amplification values for transistors.
- You will know how to convert circuits for NPN transistors into circuits for PNP transistors.
- You will be able to ascertain a circuit's voltage amplification.
- You will be familiar with the effects of operating point adjustments.
- You will be familiar with the effects of overdriving an amplifier.

Problem description

You work for a company that manufactures and repairs hi-fi amplifiers. During the course of initial training you will need to familiarise yourself with the performance of transistors and their typical characteristic values.

You will set up a test circuit to this end, which allows you to determine the degree to which transistors amplify power. After slightly modifying the circuit, you will then examine how a transistor can be used as a voltage amplifier.

Project assignments

1. Set up a test circuit with NPN transistor BC140 and ascertain the transistor's power amplification B with collector current values of I_C = 1 mA, 5 mA and 10 mA.
2. For purposes of comparison, determine power amplification B for transistor BC547.
3. Modify the test circuit so that it is suitable for testing PNP transistors, and ascertain power amplification B for transistor BC160.
4. Set sup a test circuit within which transistors are actuated non-destructively with direct voltage. Familiarise yourself with the basic principle of voltage amplification.
5. With the help of the test circuit, determine voltage amplification G_U when using transistors BC140 and BC547.
6. Expand the test circuit such that a BC140 transistor can be additionally actuated with alternating voltage. Familiarise yourself with the concept of alternating voltage amplification.
7. Examine the relationship between operating point setting and output signal distortion.
8. Find out whether the test circuit is a basic common emitter circuit, a basic fundamental circuit or a basic common collector.

Work aids

- Textbooks, books of tables
- Excerpts from manufacturers' catalogues
- Data sheets
- Internet
- WBT Electronics 1 and Electronics 2

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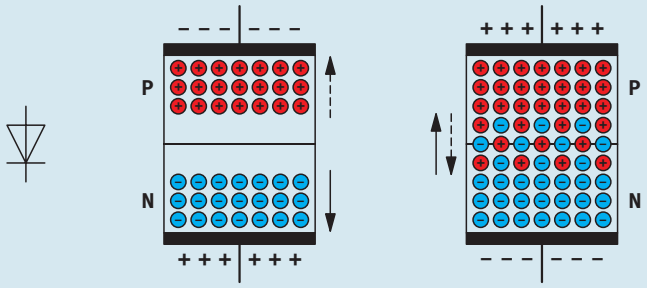
Information

Basic knowledge regarding diodes and transistors

Transistors and diodes consist of semiconductor materials, for the most part silicon. Semiconductors can be influenced by inserting dopants such that current flows within them either through **negative charge carriers** (electrons) or **positive charge carriers** (so-called "holes" or "defect electrons"). Semiconductors modified in this way are called **n-material** and **p-material** respectively.

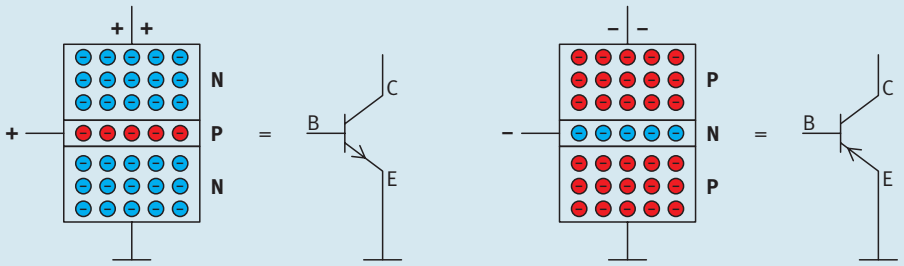
When p-material and n-material is joined, a **PN transition** occurs. The transition only allows electrical current to pass in one direction, and thus functions as an electrical valve or diode. The function of the diode can be readily explained with the basic electrical law which states that **"unlike charges attract each other and like charges repel each other"**.



Semiconductor diode – circuit symbol and layout

- **Blocked direction**
  If the n-region of the PN transition is connected to the plus pole of a voltage source and the p-zone is connected to the minus pole, the charge carriers in the semiconductor are drawn outward. As a result, a broad region which is free of charge carriers is created at the PN transition which functions as an insulating layer and prevents the flow of current. The PN transition (the diode) blocks flow.
- **Free-flow direction**
  If the polarity of the external voltage source is reversed (plus to p-region and minus to n-region), the charge carriers are driven towards each other in both regions and (after exceeding a given "threshold voltage") are capable of passing through the PN transition. Current flows. The diode is conductive.
- The diode terminal which is connected to the n-region is called the cathode, and the terminal connected to the p-region is called the anode.
- The arrow in the circuit symbol indicates the free-flow direction for the flow of current.

Transistors (more precisely “bipolar transistors”) consist of three semiconductor layers in one of the following orders: N-P-N or P-N-P. The middle layer is the base layer, and the two outside layers are known as the emitter and collector layers. This is why transistor terminals are usually designated with the abbreviations E, B and C.



NPN and PNP transistors – layout and circuit symbol

The polarity of a transistor’s operating voltage must always be set up such that the charge carriers from the emitter region are drawn to the collector. Due to the fact that unlike charges are attracted to each other, the following results:

- NPN transistors work with positive collector-emitter voltage U_{CE}
- PNP transistors work with negative collector-emitter voltage U_{CE}

However, without base voltage no flow of charge carriers takes place from the emitter to the collector. The base layer prevents the collector’s attractive force from extending into the emitter region. Only after charge carriers are lifted out of the emitter region into the (thin) base layer with the help of base voltage are they subjected to the influence of the collector’s attraction region, to which most of them then flow. In order to draw the charge carriers from the emitter to the base, base-emitter voltage U_{BE} must have the same polarity as collector-emitter voltage U_{CE}. This results in the following:

- NPN transistors become conductive in the case of positive base-emitter voltage U_{BE}.
- PNP transistors become conductive in the case of negative base-emitter voltage U_{BE}.

And thus the basic function of the transistor as an amplifier component can be explained as follows: With the help of relatively minimal base-emitter voltage U_{BE}, we can control how many charge carriers flow from the transistor’s emitter to its collector. However, base current I_B can also be specified in order to control collector current. Each specific base current value automatically results in a certain base-emitter voltage U_{BE}, which in turn dictates a given collector current I_C. Nevertheless, the relationship between collector current I_C and base current I_B is far more linear than the relationship between I_C and U_{BE}. Ratio I_C / I_B is know as transistor current amplification B. The ratio may vary from one transistor to the next, and usually lies within a range of 50 to 500.

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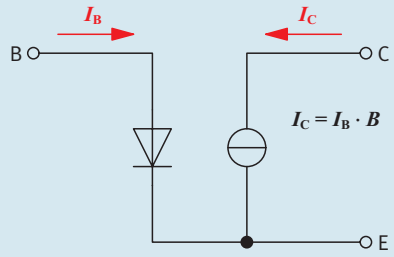
The equivalent circuit diagram of a transistor demonstrates its mode of operation in an even simpler fashion: The transistor's base-emitter path functions like a diode in the free-flow direction. Base current I_B flowing along this path increases current I_C between emitter and collector by a factor of B. The current source symbol indicates that collector current is for the most part independent of the collector voltage value.

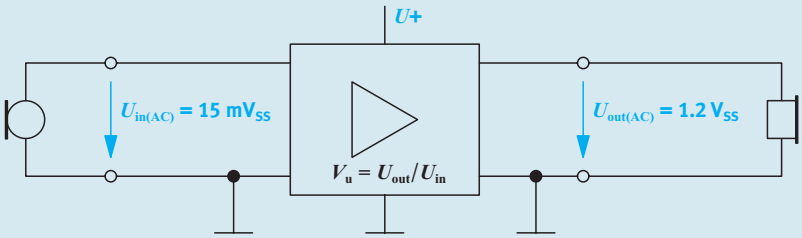


NPN transistor – equivalent circuit diagram

The **emitter** is identified with an **arrow** in the transistor symbol. Regardless of internal processes within the transistor, the direction of the arrow in the symbol nevertheless represents the actual direction of flow. The following applies in general to symbols for semiconductor components: The arrow points either towards a p-region or comes out of an n-region. (mnemonic aid: **P** = "**p**ointing" arrow, **N** = "adva**n**cing" arrow).

What does an amplifier do?

The microphone in a telephone converts sound waves created by, for example, speech or music, into alternating voltage in the millivolt range. However, this signal is too weak to drive a headphone or a loudspeaker directly. Several volts are required for good, audible reproduction with these devices. An amplifier must therefore be connected between the microphone and the headphone or loudspeaker. All amplifiers require (direct) operating voltage in order to generate an output signal.



Amplifier – circuit symbol

In the following pages you will learn how transistor amplifiers work.

1. Current amplification with NPN transistor BC140

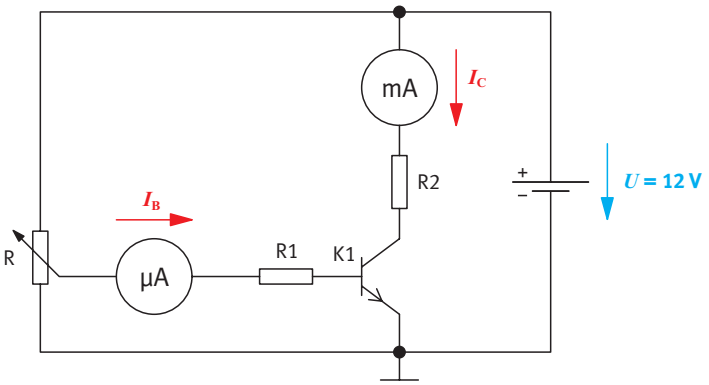
Information

The transistor as a current amplifier

You can test NPN transistors for correct functioning with the following circuit. Transistor base current I_B can be adjusted with the variable voltage divider (potentiometer). Assuming that the transistor is intact, any base current causes significantly increased collector current I_C. By dividing the measured value for I_C by the measured value for I_B, we arrive at current amplification gain B for the transistor under test.

$$B = \frac{I_C}{I_B}$$

Resistors R1 and R2 are so-called protective resistors. They limit base and collector current to values which are incapable of damaging the transistor, in the event that potentiometer R is operated without due care.



Test circuit for measuring current amplification B

Identification	Designation	Parameter
R1	Resistor	10 kΩ, 47 kΩ, 100 kΩ (depending on task)
R2	Resistor	1 kΩ
R	Potentiometer	10 kΩ
K1	Transistor	BC140, BC547, BC160 (depending on task)

Components list

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a) Set up the test circuit with a BC140 transistor and set I_C to a value of 1 mA. Read base current I_B and make a note of its value. Calculate current amplification B for the transistor under test on the basis of the measured values. Repeat measurement after setting I_C to a value of 5 mA and 10 mA. Enter the obtained values to the table under BC140 (1).

Transistor	**BC140 (1)**			**BC140 (2)**			**BC547**			**BC160**		
I_C **[mA]**	1	5	10	1	5	10	1	5	10	1	5	10
I_B **[µA]**												
$B = I_C / I_B$												

Table of measured values

b) A second BC140 transistor is included in the set of components furnished with the EduTrainer. Test it in the same way and ascertain current amplification B where I_C = 1 mA, 5 mA and 10 mA. Enter the values to the table under BC140 (2).
(It is entirely normal for current amplification gain to vary from on transistor to the next, even for transistors of the same type!)

2. Current amplification with NPN transistor BC547

a) Repeat the procedure with transistor BC547 and enter the values to the table.

3. Current amplification with PNP transistor BC160

a) Transistor BC160 is a PNP transistor. The measuring circuit used thus far must be slightly modified in order to assure that the transistor functions correctly. What needs to be done?

b) Using the modified test circuit, ascertain the missing data for the BC160 transistor and enter them to the table.

c) Leave the transistor in the circuit in order to conduct research experiments.

1. What is the highest base current which can be selected with the potentiometer?

2. Try to calculate this value using data obtained with the test circuit.

3. What is the largest collector current value which can be set up with the circuit?

4. Try to calculate I_{Cmax} using the data obtained with the test circuit.

5. Up to limit value I_{Cmax}, collector current I_C can be controlled by adjusting base current I_B. What is the designation for the transistor's state when it no longer responds to further control signal increases?

6. What has to be done in order to expand the test circuit for collector current of up to roughly 25 mA?

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4. The transistor as a voltage amplifier

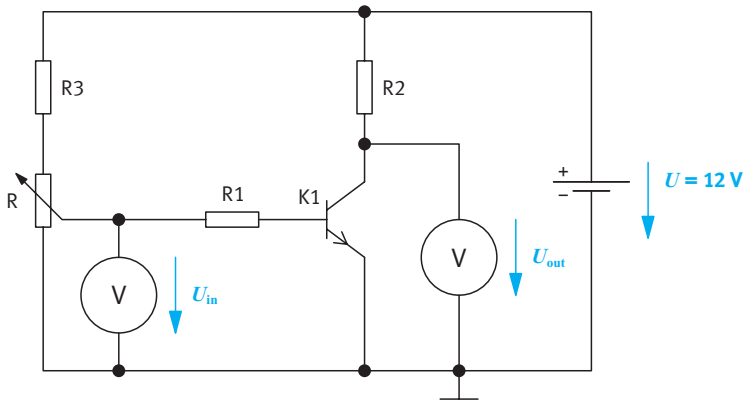
Information

With the help of (direct) operating voltage (designated U in this workbook), transistors can also be used as voltage amplifiers. However, they have to be combined with other components to this end, which convert current changes to voltage changes. In the simplest of all cases, "operating resistance R_A" is connected to the collector lead. The transistor and the resistor comprise a series connection through which collector current I_C flows. In accordance with Ohm's law, voltage drop over working resistance results from the equation $U_{RA} = R_A \cdot I_C$, and voltage drop U_{CE} results from the laws of series connection: $U_{CE} = U_C = U - U_{RA}$. In this way, input voltage U_{in} first of all controls base current I_B, and thus collector current I_C as well, and finally collector voltage U_C too, thanks to operating resistance R_A. Collector voltage then serves as output voltage U_{out}. With regard to a circuit's voltage amplification G_U we do not consider direct voltage at the input and the output, rather man the ratio of "voltage **change** at the output" to the "causative voltage **change** at the input. "Change" or difference is represented in formulas with the Greek letter Δ (delta). And thus the following notation results:

Voltage amplification $G_U = \dfrac{U_{out1} - U_{out2}}{U_{in1} - U_{in2}} = \dfrac{\Delta U_{out}}{\Delta U_{in}}$

5. Voltage amplification with NPN transistors BC140 and BC547

a) Convert the previously used test circuit into a voltage amplifier.



The transistor as a voltage amplifier

Identification	Designation	Parameter
R1	Resistor	47 kΩ
R2	Resistor	1 kΩ
R3	Resistor	22 kΩ
R	Potentiometer	10 kΩ
K1	Transistor	BC140, BC547

Components list

b) With the help of the new circuit, ascertain output voltage values for the input voltage values specified in the U_{in}/U_{out} table, and the input voltages for the specified U_{out} values.

U_{in}/U_{out} table, BC140									
U_{in} [V]	0								2.0
U_{out} [V]		11.8	10	8	6	4	2	0.2	

c) Calculate difference ΔU_{out} using the 10 V und 2 V U_{out} values and difference ΔU_{in} on the basis of the associated U_{in} values. How high is voltage amplification G_U in the above circuit?

d) Replace the BC140 transistor with a BC547 and repeat the measurements.

U_{in}/U_{out} table, BC547									
U_{in} [V]	0								2.0
U_{out} [V]		11.8	10	8	6	4	2	0.2	

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e) Calculate difference ΔU_{out} using the 10 V und 2 V U_{out} values and difference ΔU_{in} on the basis of the associated U_{in} values. How high is voltage amplification G_U in the above circuit?

f) Evaluate the amplification characteristics of the BC140 and the BC547 transistors.

g) Represent the relationship between input and output voltage for the BC140 in diagram U_{out} = f (U_{in}). Sketch in thin reference lines by means of which the U_{in} values for U_{out} = 10 V und U_{out} = 2 V can be ascertained from the characteristic curve. Appropriately enter the designations ΔU_{out} and ΔU_{in} to the diagram as well.

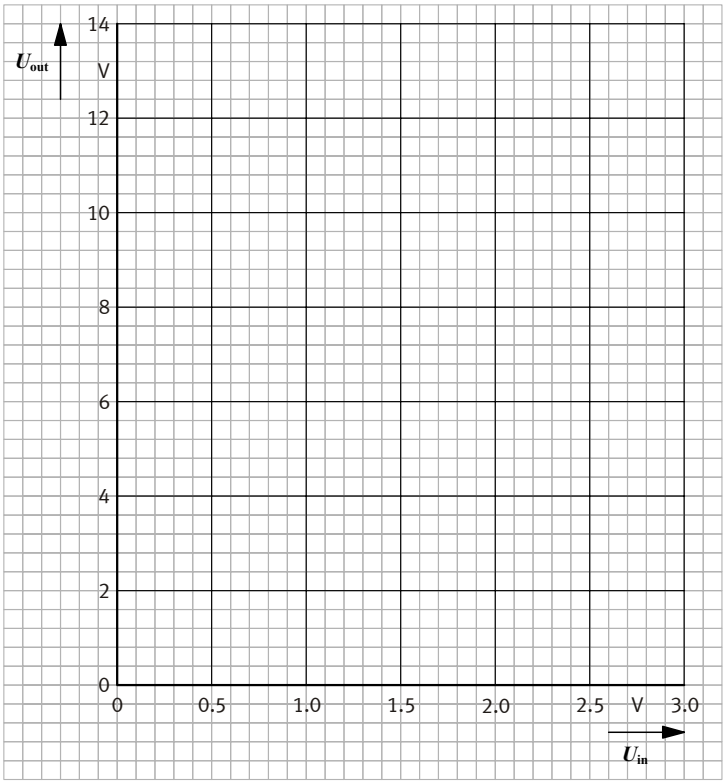


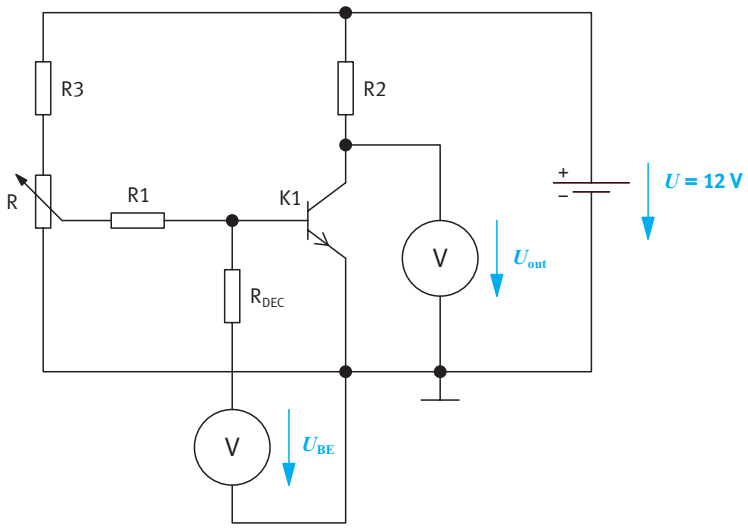
Diagram U_{out} = f (U_{in})

Information

In this circuit, resistor R1 protects the transistor from any excessive base current. Unfortunately, it also reduces voltage amplification G_U. However, theoretically possible amplification can also be ascertained in the protected circuit by measuring base-emitter voltage U_{BE} directly at the transistor instead of voltage U_{in} supplied by the potentiometer.

However, directly connecting a measuring instrument to the base lead at a modern transistor with long measuring cables results in the danger that the circuit will begin to oscillate in the 100 MHz range, and will thus be transformed into a VHF transmitter. This undesirable effect can even be detected without an oscilloscope if measured values change when the insulated measuring cables are touched, or if they react when your hand approaches the cables! This problem can be remedied by installing a decoupling resistor with a value of, for example, 1 to 10 kΩ between the base lead and the measuring cable (as close to base as possible!). Upstream from a high-impedance voltmeter ($R_i \geq 1$ MΩ), measured values remains practically undistorted by the resistor.

h) Modify the previous circuit accordingly.



Measuring U_{BE} via a decoupling resistor (parasitic suppressor)

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Identification	Designation	Parameter
R1	Resistor	47 kΩ
R2	Resistor	1 kΩ
R3	Resistor	22 kΩ
R_{DEC}	Resistor (decoupling resistor)	1 kΩ
R	Potentiometer	10 kΩ
K1	Transistor	BC547

Components list

i) Ascertain the missing values for the U_{BE}/U_{out} table with the help of the circuit.

U_{BE}/U_{out} table, BC547									
U_{BE} [mV]	0								
U_{out} [V]		11.8	10	8	6	4	2	0.2	0.15

j) Calculate voltage amplification G_U on the basis of ΔU_{out} and ΔU_{BE}.
Use the measured values for U_{out} = 4 V and 8 V.

6. The transistor as alternating voltage amplifier

Information

Input voltage, which has thus far been adjusted manually with potentiometer R, can also be changed by injecting an alternating voltage. In order to assure that direct current flowing through R1 is not inadvertently drained off via the alternating voltage source, a so-called “coupling capacitor” (C1) is installed into the signal line. It has infinitely high resistance X_C for direct current, but allows alternating current to pass freely. Potentiometer R can now be used to set the amplifier’s operating point.

Due to the fact that small alternating voltages alone are not capable of rendering a transistor conductive, the transistor is influenced with a direct current such that collector voltage U_C is about halfway between its two extreme values, U_{Emax} and U_{Emin}, in the idle state. If a (small) alternating current is now added to direct base current, the direct current is then increased and reduced synchronous to the alternating signal cycles (undulating current occurs). Correspondingly, collector current I_C and collector voltage U_C oscillate around their quiescent values synchronous to the input signal.

The alternating voltage component is filtered back out of the undulating collector voltage with additional coupling capacitor C2, which is then used as output signal U_{out}. In this way, the amplifier circuit creates a considerably larger (amplified) alternating voltage signal at the output from a small one at the input (with identical frequency and waveform) – even though, in this case, the transistor works with positive operating voltage U only!

After measuring peak-to-peak values for the input and output signals with a oscilloscope, these values can be used to calculate the circuit’s alternating voltage amplification $G_{U(AC)}$.

Alternating voltage amplification gain $G_{U(AC)} = \frac{U_{out(ss)}}{U_{in(ss)}} = \frac{U_{out(eff)}}{U_{in(eff)}}$

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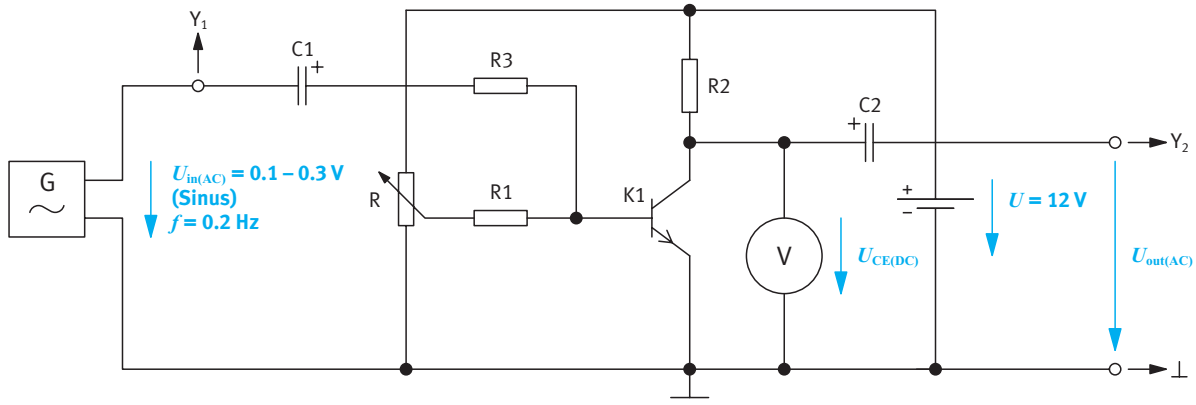

The transistor as an alternating voltage amplifier
Y_1: to oscilloscope, channel A
Y_2: to oscilloscope, channel B

Identification	Designation	Parameter
R1	Resistor	100 kΩ
R2	Resistor	1 kΩ
R3	Resistor	10 kΩ
R	Potentiometer	10 kΩ
C1	Capacitor	220 µF
C2	Electrolytic capacitor	10 µF
K1	Transistor	BC140

Components list

Notes

In order to be able to observe the operations which take place within the circuit in a relaxed fashion:

- Set the EduTrainer sine-wave generator to a very low frequency, for example 0.2 Hz.
- Roughly 0.1 to 0.3 V suffice for U_{in} (take from the 0 to 2 V output of the DDS waveform generator!).
- Adjust the oscilloscope such that both channels record two steady, uninterrupted lines, which move up and down synchronous to the input signal.
- Disconnect the sine-wave generator from C1 and set the circuit's operating point to U_{CE} = +6 V (50% of operating voltage) with the potentiometer.
- Reconnect the generator and adjust the amplitude of U_{in} such that transistor voltage U_{CE} oscillates between roughly +4 and +8 V.

a) Experiment with the circuit and then answer the following questions. Tick the correct answers.

☐ Input voltage $U_{in(AC)}$ and output voltage $U_{out(AC)}$ oscillate synchronously.
☐ Input voltage $U_{in(AC)}$ and output voltage $U_{out(AC)}$ oscillate oppositely.

☐ During the positive half-wave of $U_{in(AC)}$, more collector current I_C flows than during the negative half-wave of $U_{in(AC)}$.
☐ During the positive half-wave of $U_{in(AC)}$, less collector current IC flows than during the negative half-wave of $U_{in(AC)}$.

☐ When collector current in the transistor increases, collector-emitter voltage U_{CE} rises as well.
☐ When collector current in the transistor increases, collector-emitter voltage U_{CE} drops.

☐ An operating point U_C amounting to 50% of operating voltage is selected because from there, collector voltage can move up or down by the same amount.
☐ An operating point U_C amounting to 50% of operating voltage is selected because this is where amplification within the circuit is greatest.

☐ Coupling capacitors are intended to allow alternating signals to pass, but should not influence direct voltage.
☐ Coupling capacitors prevent unwanted high frequency oscillation within the circuit.

☐ The operating point is the basic setting for direct current within a circuit.
☐ The operating point is a the solder joint in the circuit diagram which connects the collector to the output.

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7. Relationship between operating point setting and output signal distortion

Information
The circuit is usually tested with signals which result in a stationary pattern at the oscilloscope. Increase the frequency of the input signal to 500 Hz to this end, and set the sweep at the oscilloscope such that one to two full periods for $U_{in(AC)}$ and $U_{out(AC)}$ can be viewed at the screen.

a) Adjust the input signal and the operating point such that a clean sinusoidal signal with 6 V peak-to-peak (6 V_{pp}) is generated at the output. Then measure the peak-to-peak value for $U_{in(AC)}$ and ascertain alternating voltage amplification $G_{U(AC)}$ for the circuit.

b) How many degrees does phase shifting amount to between $U_{in(AC)}$ and $U_{out(AC)}$?

c) What happens to the waveform of the output signal if the operating point is slowly adjusted up or down with potentiometer R?

d) Find the answer to the following question by changing $U_{in(AC)}$ and the operating point:
How much peak-to-peak voltage voltage can be delivered at the output without distorting the sinusoidal waveform?

Information
The waveform of the output signal of a hi-fi amplifier must be identical to that of its input signal. However, signal inverting is not taken into consideration. If one channel can be inverted and Y deflection can be infinitely adjusted at your oscilloscope, you can attempt to bring the $U_{out(AC)}$ and $U_{in(AC)}$ signals into coincidence at the screen. The closer you come to succeeding, the better the amplifier is.

e) Test response characteristics with delta und square-wave voltage as well. Then evaluate whether or not the amplifier is suitable for hi-fi applications, at least under certain conditions.

8. Basic transistor circuits

Information
There are three basic transistor circuits. They are named after the transistor lead which serves as a common point of reference for the input and output signals. In the simplest of all cases, this is the transistor lead which is connected to ground. But there is frequently no direct connection from there to circuit grounding. In this case, the following method is helpful in determining the correct name: Find out to which transistor lead the input signal is applied, and from which lead the output signal is taken. The basic circuit is named after the remaining transistor lead.

a) Which type of basic transistor circuit was used in the preceding pages? Tick the correct answer.

☐ In the test and experimental circuits covered by exercise 1, the transistors were used in a common emitter circuit, or common emitter for short.
☐ In the test and experimental circuits covered by exercise 1, the transistors were used in a common base circuit, or base for short.
☐ In the test and experimental circuits covered by exercise 1, the transistors were used in a basic common collector, or common collector for short.

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