

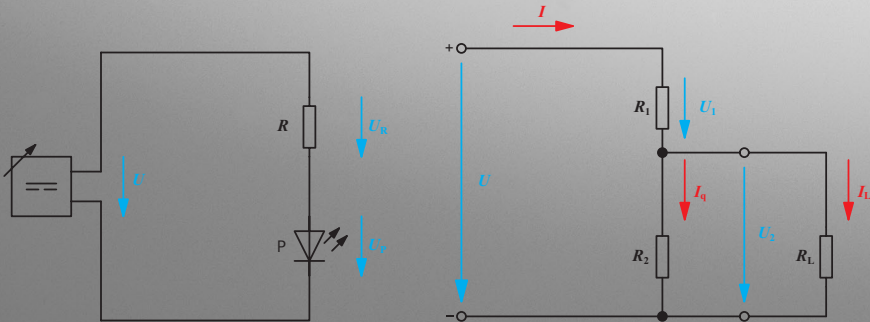
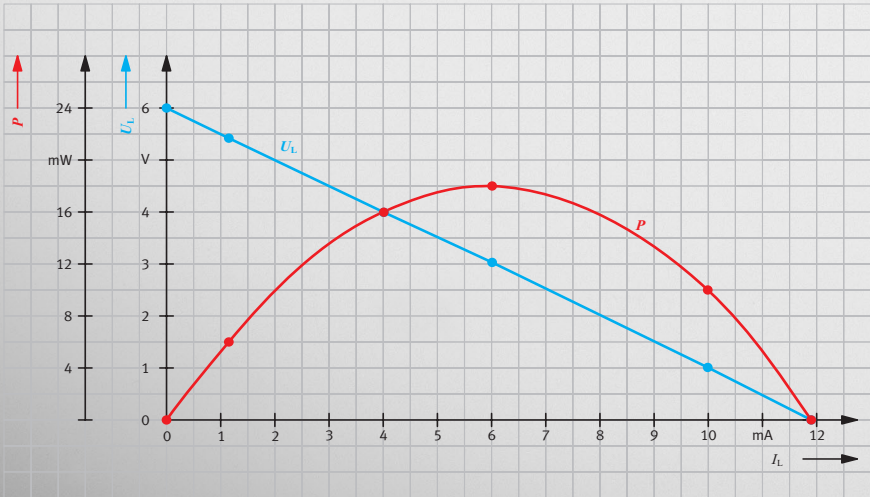
Fundamentals of direct current technology



Workbook



With CD-ROM



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Use for intended purpose

The training package Fundamentals 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 fields of automation and 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.

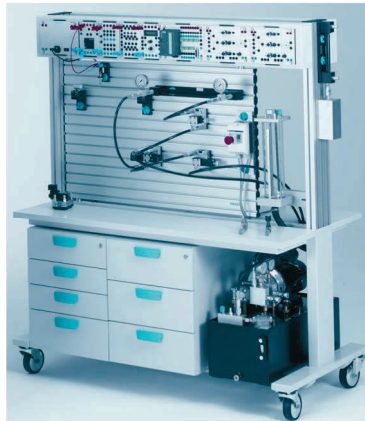
Preface

Festo Didactic's learning 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 learning system for automation and technology will be updated and extended in parallel with developments in the area of training and professional practice.

The technology packages deal with various technologies including pneumatics, electropneumatics, hydraulics, electrohydraulics, proportional hydraulics, programmable logic controllers, sensors, electrical engineering, electronics and electric drives.



The modular design of the learning 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 components:

- Hardware
- Media
- Seminars

Hardware

The hardware in the training packages consists 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 teachware and software. The teachware includes:

- Technical books and textbooks (standard works for teaching basic knowledge)
- Workbooks (practical exercises with supplementary instructions and sample solutions)
- Glossaries, manuals and technical books (providing more in-depth information on the various topics)
- Sets of transparencies and videos (for clear and dynamic instruction)
- Posters (for clear-cut illustration of facts)

Within the software, the following programs are available:

- Digital training programs (learning content specifically prepared for the purpose of 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 systems for training and vocational education.

Do you have tips, feedback or suggestions for improving this workbook?

If so, please send us an e-mail at did@festo.com.

The authors and Festo Didactic look forward to your feedback.

Introduction

This workbook is part of the learning system for automation and technology by Festo Didactic. The system provides a solid basis for practice-oriented basic and further training. 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 Fundamentals of direct current technology provides the introduction to the topic of electrical engineering/electronics. Its focus is on offering an understanding of the basic electrical variables. Among the variables covered are voltage, current, resistance and conductance as well as energy and capacity. A detailed explanation of Ohm's law is also provided. Particular emphasis is placed on the use of measuring devices.

A laboratory workstation equipped with a protected power supply, two digital multimeters, a storage oscilloscope and safety laboratory cables is needed to build and evaluate the circuits.

All circuits for the 10 exercises in Fundamentals of direct current technology are built using the equipment set TP 1011. The basic theoretical principles needed to understand these exercises are covered by technical textbooks.

Technical data for the individual components (linear and non-linear resistors, capacitors, measuring equipment, etc.) is also available.

Work and safety instructions



General information

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

Electrical components

- **Risk of fatal injury from interrupted protective earth conductor**
 - The protective earth conductor (yellow/green) must not be interrupted either outside or inside the device.
 - The insulation of the protective earth conductor must not be damaged or removed.
- In industrial facilities, the regulations BGV A3 "Electrical systems and equipment" of the German institute for health and safety must be observed.
- In schools and training facilities, the operation of power supply units must be responsibly monitored by trained personnel.
- **Caution!**

The capacitors in the device can still be charged even if the device has been disconnected from all power sources.
- When replacing fuses: only use specified fuses with the correct rated current.
- Never switch on the power supply unit immediately after it has been moved from a cold room to a warm one. The condensate that forms can, under unfavourable conditions, damage your device. Leave the device switched off until it has reached room temperature.
- Only use voltages of max. 60 V DC and 25 V AC as the operating voltage for the circuits in the individual exercises. Note also the information on the maximum operating voltage of the components used.
- The power must be disconnected before establishing electrical connections.
- The power must be disconnected before breaking electrical connections.
- Only use connecting cables with safety plugs for electrical connections.
- Only pull the safety plugs when disconnecting connecting cables – never pull the cable.
- Always connect the storage oscilloscope to the power supply using an isolating transformer.

Training package Fundamentals of direct current technology (TP 1011)

The training package TP 1011 consists of a multitude of individual training materials. This part of the training package TP 1011 deals with the fundamentals of direct current technology. Individual components included in the training package TP 1011 can 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
- Basic power supply unit EduTrainer®
- Complete set of laboratory equipment

Media

The teachware for the training package TP 1011 consists of technical textbooks, books of tables and workbooks. The textbooks clearly communicate the fundamentals of direct current technology. The workbooks contain the worksheets for each of the exercises, the solutions to each individual worksheet and a CD-ROM. A set of ready-to-use exercise sheets and worksheets for each exercise is supplied with each workbook.

Technical data for the hardware components is made available along with the training package and on the CD-ROM.

Media	
Textbooks	Technical expertise for electrical professions Electrical engineering
Book of tables	Electrical engineering/electronics
Workbooks	Fundamentals of direct current technology Fundamentals of alternating current technology Fundamentals of semiconductors Basic electronic circuits
Digital learning programs	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 the training package TP 1011

The digital learning programs Electrical engineering 1, Electrical engineering 2, Electronics 1, Electronics 2 and Electrical protective measures are available as software for the training package TP 1011. These learning programs deal in detail with the fundamentals of electrical engineering/electronics. The learning content is conveyed both by descriptions of the topics and by application using practical case studies.

The media are offered in numerous languages. You'll find further training materials in our catalogue and on the Internet.

Learning objectives – Fundamentals of direct current technology

■ Resistor and capacitor components

- You will be familiar with the relationship between the resistance value and conductance of a resistor.
- You will be familiar with the characteristic features and main designs of resistors.
- You will be able to use the IEC series of standards for identifying resistors.
- You will be familiar with the circuit symbols and mode of operation of the non-linear resistors NTC, PTC, VDR and LDR.
- You will be able to trace and interpret the characteristics of non-linear resistors.
- You will be able to select and use non-linear resistors as appropriate to the technical requirements.
- You will be familiar with the structure, application and characteristics of a capacitor.
- You will be able to measure and evaluate the charging and discharging process of a capacitor in a DC circuit.

■ Basic circuits and sample circuits

- You will be able to interpret the basic electrical variables of voltage, current and resistance and perform calculations using them.
- You will be familiar with Ohm's law and be able to determine the relationship by measurement and represent it graphically.
- You will be able to trace basic electrical variables by measurement and evaluate them.
- You will be able to use suitable measuring equipment to perform measurements.
- You will be able to apply the basic electrical variables of energy and power.
- You will be able to investigate basic electrical circuits by measurement and extrapolate laws from the measurement variables determined.
- You will be able to size and calculate basic electrical circuits such as series circuits.
- You will be able to test the function of electrical circuits and equipment.
- You will be able to size and calculate basic electrical circuits such as parallel circuits.
- You will be able to size and calculate hybrid circuits.
- You will be able to use suitable measuring circuits to perform measurements.
- You will be familiar with voltage dividers as an application of hybrid circuits.
- You will be able to calculate the output voltage for an unloaded and a loaded voltage divider.
- You will be able to size a loaded voltage divider.

■ Voltage sources

- You will be able to calculate and apply the characteristics of a voltage source.
- You will be able to trace and interpret the working characteristic of a voltage source.
- You will be familiar with the applications of power adaptation and voltage adaptation for a voltage source.

Allocation of learning objectives and exercises – Fundamentals of DC technology

Exercise	1	2	3	4	5	6	7	8	9	10
Learning objective										
You will be able to interpret the basic electrical variables of voltage, current and resistance and perform calculations using them	•									
You will be familiar with Ohm's law and be able to determine the relationship by measurement and represent it graphically	•									
You will be able to trace basic electrical variables by measurement and evaluate them	•									
You will be able to use suitable measuring equipment to perform measurements	•									
You will be familiar with the relationship between the resistance value and conductance of a resistor		•								
You will be familiar with the characteristic features and main designs of resistors		•								
You will be able to use the IEC series of standards for identifying resistors.		•								
You will be able to apply the basic electrical variables of energy and power			•	•	•					
You will be able to investigate basic electrical circuits by measurement and extrapolate laws from the measurement variables determined			•	•						
You will be able to size and calculate basic electrical circuits such as series circuits			•							
You will be able to test the function of electrical circuits and equipment			•							
You will be able to size and calculate basic electrical circuits such as parallel circuits				•						
You will be able to size and calculate hybrid circuits					•					
You will be able to use suitable measuring circuits to perform measurements						•				

Exercise	1	2	3	4	5	6	7	8	9	10
Learning objective										
You will be familiar with voltage dividers as an application of hybrid circuits							•			
You will be able to calculate the output voltage for an unloaded and a loaded voltage divider							•			
You will be able to size a loaded voltage divider							•			
You will be familiar with the circuit symbols and mode of operation of the non-linear resistors NTC, PTC, VDR, LDR								•		
You will be able to trace and interpret the characteristics of non-linear resistors								•		
You will be able to select and use non-linear resistors as appropriate to the technical requirements								•		
You will be able to calculate and apply the characteristics of a voltage source									•	
You will be able to trace and interpret the working characteristic of a voltage source									•	
You will be familiar with the applications of power adaptation and voltage adaptation for a voltage source									•	
You will be familiar with the structure, application and characteristics of a capacitor										•
You will be able to measure and evaluate the charging and discharging process of a capacitor in a DC circuit										•

Equipment set

The workbook Fundamentals of direct current technology covers the structure and function of resistors and capacitors as well as the behaviour of these components in basic circuits and simple application circuits.

The equipment set Fundamentals of electrical engineering/electronics TP 1011 contains all the components required to achieve the specified learning objectives. Two digital multimeters and safety laboratory cables are also for building and evaluating functioning circuits.

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










Component	Order no.	Quantity
Basic power supply unit EduTrainer®	567321	1
Universal patch panel EduTrainer®	567322	1
Component set for electrical engineering/electronics	567306	1
Jumper plug set, 19 mm, grey-black	571809	1










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

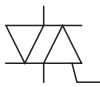


Component	Quantity
Resistor, 10 Ω /2 W	1
Resistor, 22 Ω /2 W	2
Resistor, 33 Ω /2 W	1
Resistor, 100 Ω /2 W	2
Resistor, 220 Ω /2 W	1
Resistor, 330 Ω /2 W	1
Resistor, 470 Ω /2 W	2
Resistor, 680 Ω /2 W	1
Resistor, 1 k Ω /2 W	3
Resistor, 2.2 k Ω /2 W	2
Resistor, 4.7 k Ω /2 W	2
Resistor, 10 k Ω /2 W	3
Resistor, 22 k Ω /2 W	3
Resistor, 47 k Ω /2 W	2
Resistor, 100 k Ω /2 W	2
Resistor, 1 M Ω /2 W	1


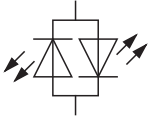
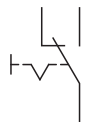
Component	Quantity
Potentiometer, 1 k Ω /0.5 W	1
Potentiometer, 10 k Ω /0.5 W	1
Resistor, temperature-dependent (NTC), 4.7 k Ω /0.45 W	1
Resistor, light-dependent (LDR), 100 V/0.2 W	1
Resistor, voltage-dependent (VDR), 14 V/0.05 W	1
Capacitor, 100 pF/100 V	1
Capacitor, 10 nF/100 V	2
Capacitor, 47 nF/100 V	1
Capacitor, 0.1 μ F/100 V	2
Capacitor, 0.22 μ F/100 V	1
Capacitor, 0.47 μ F/100 V	2
Capacitor, 1.0 μ F/100 V	2
Capacitor, 10 μ F/250 V, polarised	2
Capacitor, 100 μ F/63 V, polarised	1
Capacitor, 470 μ F/50 V, polarised	1
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
UNIUNCTION 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
Transformer iron core with holder	1
Indicator light, 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

Graphical symbols for the equipment set

Component	Graphical symbol
Resistor	
Potentiometer	
Resistor, temperature-dependent (NTC)	
Resistor, light-dependent (LDR)	
Resistor, voltage-dependent (VDR)	
Capacitor	
Capacitor, polarised	
Coil	
Diode	

Component	Graphical symbol
Zener diode	
DIAC	
NPN transistor	
PNP transistor	
P-channel JFET transistor	
N-channel JFET transistor	
UNIJUNCTION transistor	
P-channel MOSFET transistor	
Thyristor	

Component	Graphical symbol
TRIAC	
Transformer coil	
Indicator light	

Component	Graphical symbol
Blue LED	
Red or green LED	
Changeover switch	

Allocation of components and exercises – Fundamentals of direct current technology

Component	Exercise										
	1	2	3	4	5	6	7	8	9	10	
Resistor, 10 Ω /2 W		1									
Resistor, 22 Ω /2 W		1				1					
Resistor, 33 Ω /2 W		1							1		
Resistor, 100 Ω /2 W	1	1	1	1	1		1		1		
Resistor, 220 Ω /2 W	1	1		1	1						
Resistor, 330 Ω /2 W	1	1	1	1	1		1				
Resistor, 470 Ω /2 W	1	1	1	1					1		
Resistor, 680 Ω /2 W	1	1									
Resistor, 1 k Ω /2 W	1	1					1	1	3		
Resistor, 2.2 k Ω /2 W		1									
Resistor, 4.7 k Ω /2 W		1							1		
Resistor, 10 k Ω /2 W		1				1	1			1	
Resistor, 22 k Ω /2 W		1									
Resistor, 47 k Ω /2 W		1									
Resistor, 100 k Ω /2 W		1								1	
Resistor, 1 M Ω /2 W		1								1	
Potentiometer, 1 k Ω /0.5 W		1					1				
Potentiometer, 10 k Ω /0.5 W		1									
Resistor, temperature-dependent (NTC), 4.7 k Ω /0.45 W		1						1			
Resistor, light-dependent (LDR), 100 V/0.2 W		1						1			
Resistor, voltage-dependent (VDR), 14 V/0.05 W		1						1			
Capacitor, 100 pF/100 V										1	
Capacitor, 10 nF/100 V										1	
Capacitor, 47 nF/100 V										1	
Capacitor, 0.1 μ F/100 V										1	
Capacitor, 0.22 μ F/100 V										1	
Capacitor, 0.47 μ F/100 V										1	
Capacitor, 1.0 μ F/100 V										1	
Capacitor, 10 μ F/250 V, polarised										1	
Capacitor, 100 μ F/63 V, polarised										1	
Capacitor, 470 μ F/50 V, polarised										1	

Component	Exercise									
	1	2	3	4	5	6	7	8	9	10
Indicator light, 12 V/62 mA				1				1		
Light emitting diode (LED), 20 mA, blue			1							
Changeover switch										1
Digital multimeter	2	1	1	1	1	2	2	2	2	1
Basic power supply unit EduTrainer®	1		1	1	1	1	1	1	1	1

Notes for the teacher/trainer

Learning objectives

The main objective of this workbook is to explain how to analyse and evaluate simple DC circuits with a resistor and capacitor. It does this through a combination of theoretical questions and practical exercises where the students are required to build the circuits and measure electrical variables. The combination of both theory and practice ensures faster progress and longer-lasting learning. The more specific learning objectives are documented in the matrix. Concrete, individual learning objectives are assigned to each exercise.

Required time

The time required for working through the exercises depends on the student's previous knowledge of the subject matter. Each exercise should take approx. 1 to 1.5 hours.

Equipment set components

The workbook, set of exercises and equipment match each other. All 10 exercises can be completed using components from one equipment set TP 1011.

Standards

The following standards are applied in this workbook:

EN 60617-2 to EN 60617-8	Graphical symbols for circuit diagrams
EN 81346-2	Industrial systems, installations and equipment and industrial products; structuring principles and reference designations
IEC 60364-1	Low-voltage electrical installations – Fundamental principles, assessment of general characteristics, definitions
IEC 60364-4-41	Low-voltage electrical installations – Protective measures – Protection against electric shock

Classifications in the workbook

Solutions and supplements in graphics or diagrams are in red.

Exception: information and evaluations relating to current are always in red, information and evaluations relating to voltage are always in blue.

Classifications in the set of exercises

Texts which require completion are identified with a grid or grey table cells.

Graphics which require completion include a grid.

Notes for the lesson

These provide additional information about the training approach, method or about the components. These notes are not included in the set of exercises.

Solutions

The solutions specified in this workbook are the results of test measurements. The results of your measurements can deviate from these data.

Learning topics

The training subject "Fundamentals of direct current technology" is part of the learning topics in technical colleges for electronic engineering.

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 each worksheet in the set of exercises.

Component designations

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

Resistors: R, R1, R2, etc.

Capacitors: C, C1, C2, etc.

Signalling devices: P, P1, P2, etc.

Note

If resistance and capacitance are being interpreted as physical variables, the letter identifying them is shown in italics (symbols). If numbers are required for numbering, these are treated like indices and subscript is used.

CD-ROM contents

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
- Images
- Product information

Operating instructions

Contains operating instructions for various components in the training package. These instructions are helpful when using and commissioning the components.

Images

Contains photos and graphics of components and industrial applications. These can be used to illustrate individual tasks or to supplement project presentations.

Product information

Contains the manufacturer's product information for selected components. The representations and descriptions of the components in this format are intended to demonstrate how they are presented in an industrial catalogue. Additional information regarding the components is also included.

Exercise 1:

Analysing electrical circuits and establishing laws

■ Learning objectives

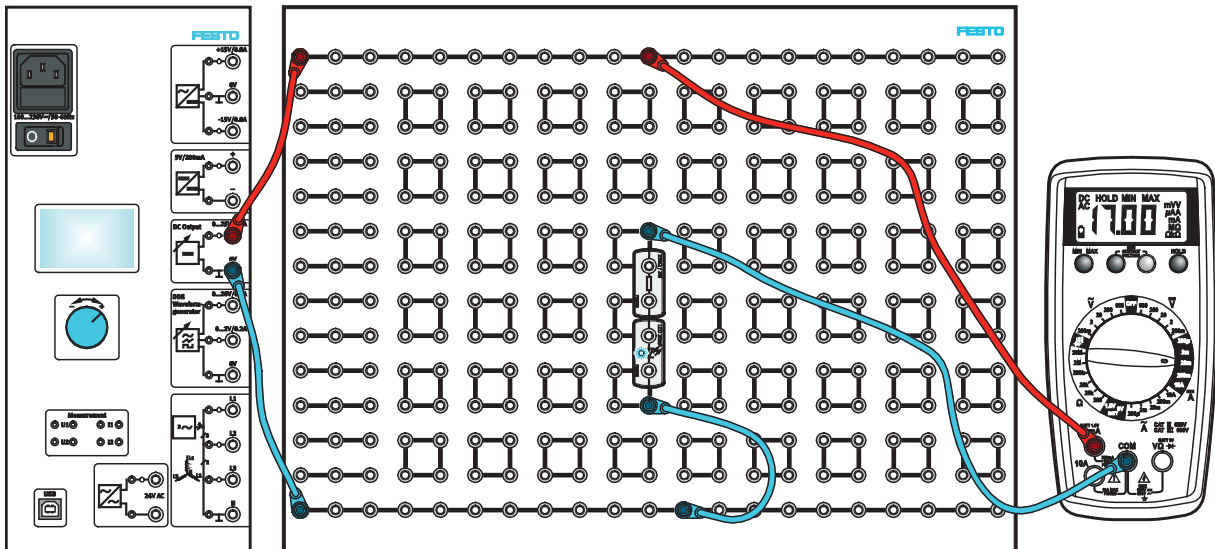
After completing this exercise:

- You will be able to interpret the basic electrical variables of voltage, current and resistance and perform calculations using them.
- You will be familiar with Ohm's law and be able to determine and represent the relationship by measurement.
- You will be able to trace electrical variables by measurement and evaluate them.
- You will be able to use suitable measuring equipment to perform measurements.

■ Problem description

You are about to start work on the planning and implementation of lighting systems. You therefore need to learn about the laws governing simple electrical circuits and the associated measurement technology. Find the information you need for the exercise in textbooks, books of tables and on the Internet.

■ Circuit



Laboratory workstation

■ **Project assignments**

1. Work out the electrotechnical relationships established when operating a lamp. Use the prepared worksheets for this.
2. Find out about digital and analogue multimeters and answer the questions.
3. Select a suitable measuring device for measuring current, voltage and resistance in DC circuits.
4. Find out how to measure voltage, current and resistance and answer the questions.
5. Take the measurements for Ohm's law in a simple electrical circuit.

■ **Work aids**

- Textbooks, books of tables
- Data sheets
- WBT Electrical engineering 1
- Internet

Note

Do not switch on the electrical power supply until you have made and checked all the connections. Once you have completed the exercise, switch off the power supply again before dismantling the components.

■ Describing the relationships in an electrical circuit

Work out the laws that apply when operating a lamp. With this information you can size simple circuits.

Components of an electrical circuit

- Describe the main components of a simple electrical circuit.

Each electrical circuit essentially consists of

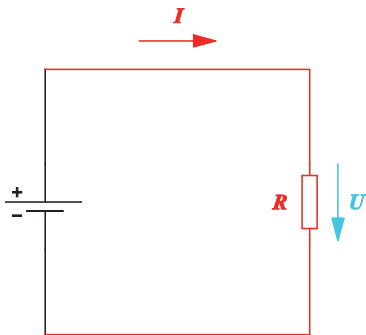
- a voltage source,
- connecting cables and
- a consuming device.

The voltage source, for example a battery or plug socket, provides electrical energy in the form of a separate charge.

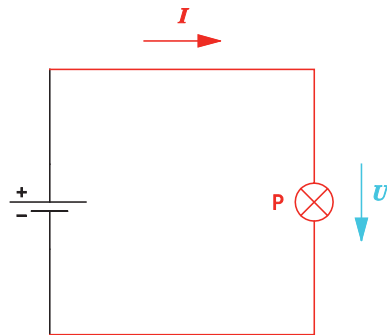
The circuit serves as a pathway for the electrical energy that flows between the voltage source and the consuming device as electrical current.

The energy generated by the voltage source is converted into another form of energy such as heat, light energy or movement in the consuming device.

- Complete the electrical circuit to produce a simple, closed electrical circuit.
- Enter the electrical variables as arrows with designation in the circuit.



Electrical circuit with resistor as consuming device

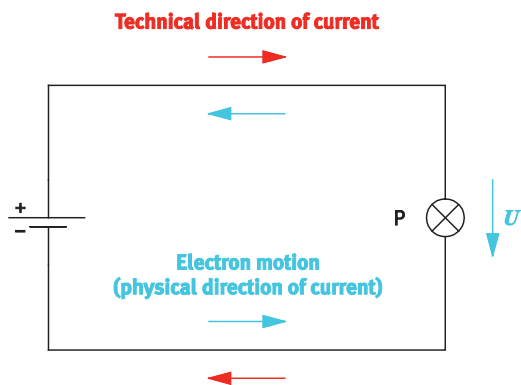


Electrical circuit with lamp as consuming device

Direction of current

Electrical voltage is produced by separating positive and negative charges.

- Negative charge: too many electrons
 - Positive charge: too few electrons
- Describe what is meant by the technical direction of current and what is meant by the physical direction of current.
- Enter the technical and physical directions of current in the illustrated circuit diagram.



Direction of current in the circuit

Physical direction of current

The physical direction of current describes the direction of current of the negative charge carriers (electrons) in metals from the negative terminal to the positive terminal.

Technical direction of current

The technical direction of current is historically determined and is based on a current of charges assumed to be positive. The technical direction of current is therefore agreed as the direction from the positive terminal to the negative terminal.

The technical direction of current has been retained for practical reasons. That is why the direction of current within a circuit is still defined as from positive to negative to this day.

Basic electrical variables

- Complete the table of basic electrical variables. Enter a brief description, the symbol and the physical unit.

Electrical variable	Description	Symbol	Unit of measurement
Electrical current	Electrical current is a measure of the number of free electrical charge carriers flowing in one direction in the circuit.	I	Ampere [A]
Electrical voltage	Electrical voltage specifies the difference between the charge at both terminals. Voltage sources always have two terminals with different voltages.	U	Volt [V]
Electrical resistance	Electrical resistance is a measure of a material's ability to impede the flow of current in an electrical circuit.	R	Ohm [Ω]

Basic electrical variables

Ohm's law

- Describe the relationship between current, voltage and resistance. It is formulated in Ohm's law.

Information

Ohm's law only applies to ohmic resistances. Ohmic resistances are linear resistances.

If the applied voltage in a simple electrical circuit with a constant resistance is increased, the current flowing in the circuit also increases. The current intensity I is proportional to the applied voltage U , i.e.

- If the voltage U rises, the current intensity I rises too.
- If the voltage U falls, the current intensity I falls too.

$$U = R \cdot I$$

or formula solved for I or R :

$$I = \frac{U}{R} \qquad R = \frac{U}{I}$$

- Describe what ohmic resistance is.

Ohmic resistance is a special electrical resistance whose resistance value is not dependent on current, intensity or frequency.

- Calculate the resistance value of the lamp if a current of 0.062 A is flowing when a voltage of 12 V is applied.

Information

Bulbs behave like ohmic resistors after they are switched on.

Given

Voltage $U = 12 \text{ V}$

Current intensity $I = 62 \text{ mA}$

To be found

Resistance R in Ω

Calculation

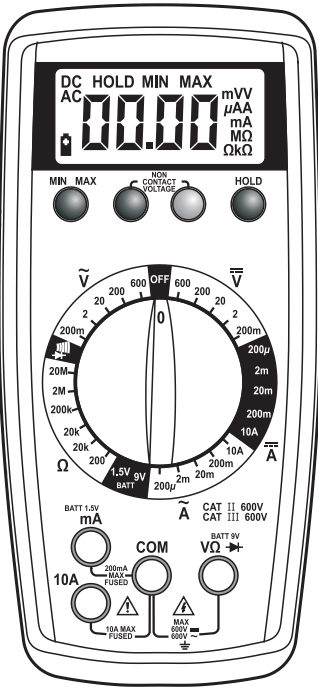
$$R = \frac{U}{I} = \frac{12 \text{ V}}{62 \text{ mA}} = \frac{12 \text{ V}}{0.062 \text{ A}} = 193.5 \Omega$$

■ Describing the features and symbols of measuring devices

You will be taking different measurements in electrical circuits. You will need to use suitable measuring devices for this.

Two types of measuring devices are generally used to measure DC voltage and direct current in electrical circuits:

- Analogue multimeters
- Digital multimeters

Digital multimeter	Extract from the technical data
	<p>Display LCD 3 3/4 digits (3999 count) and analogue bar chart with 41 segments</p> <p>DC voltage Measuring range: 400 mV, 4 V, 40 V, 400 V, 1000 V Resolution: 100 μV Accuracy: \pm (0.7% of display + 1 digit) Input resistance: 10 MΩ</p> <p>AC voltage (45 Hz – 500 Hz) Measuring range: 400 mV, 4 V, 40 V, 400 V, 750 V Resolution: 100 μV Accuracy: \pm (1.5% of display + 4 digits) For 4 V range: \pm (2.0% of display + 4 digits) Input resistance: 10 MΩ</p> <p>Direct current Measuring range: 400 μA, 4 mA, 40 mA, 300 mA, 10 A Resolution: 0.1 μA Accuracy: \pm (1.0% of display + 1 digit)</p> <p>Alternating current (45 Hz – 500 Hz) Measuring range: 400 μA, 4 mA, 40 mA, 300 mA, 10 A Resolution: 0.1 μA Accuracy: \pm (1.5% of display + 4 digits) For 10 A range: \pm (2.5% of display + 4 digits)</p>

Example of a digital multimeter

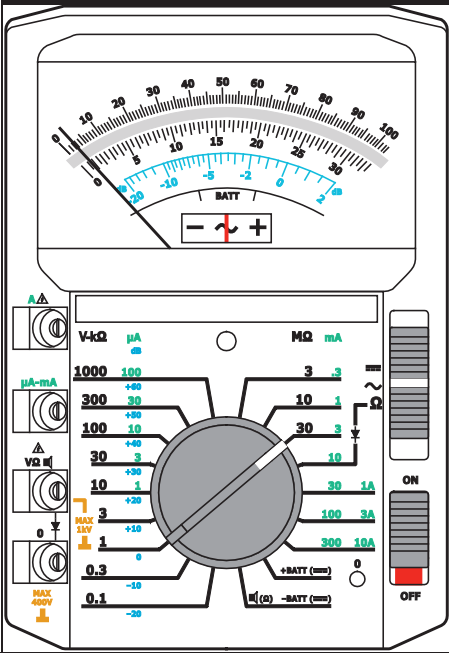
- Describe what the specification 3 3/4 digits means.

The measuring instrument's display has four places.

The numbers 0 to 9 can appear in the last three places. Only the numbers 0 to 3 can be displayed in the left-most decimal place.







Example:

In the 400 V range, the highest possible display with a resolution of 0.1 V is 399.9 V.

Analogue multimeter	Extract from the technical data
 <p>The diagram shows an analogue multimeter with a semi-circular scale. The top scale is for voltage and resistance, ranging from 0 to 100. The bottom scale is for current, ranging from 0 to 30. A battery symbol is shown below the scales. The front panel features a rotary selector knob with various settings: V-kΩ, μA, MΩ, mA, 1000, 300, 100, 30, 10, 3, 1, 0.3, 0.1, 3, 10, 30, 100, 300, 1A, 3A, 10A, +BATT, -BATT, Ω, ON, and OFF. There are also terminals for μA-mA, VΩ, and MAX 400V.</p>	<p>Measuring range for voltage measurement: 0.1 V, 0.3 V, 1 V, 3 V, 10 V, 30 V, 100 V, 300 V, 1000 V =/~</p> <p>Input resistance: 10 MΩ</p> <p>Measuring range for current measurement: 1 μA, 3 μA, 10 μA, 30 μA, 100 μA, 300 μA, 1 mA, 3 mA, 10 mA, 30 mA, 100 mA, 1 A, 3 A, 10 A =/~</p> <p>Accuracy: 1.5 =, 2.5 ~</p>

Example of an analogue multimeter

- Explain the meaning of the symbols shown.

Symbol	Description
	Moving coil meter with rectifier
	Use in horizontal position
	Alternating current only
	Direct current only
	See manual
	Dangerous electrical voltage
CAT II 1000 V CAT III 600 V	Safety marking to EN 61010-1 or IEC 61010-1: indicates the overvoltage category and the permissible test voltage

■ Selecting a measuring device

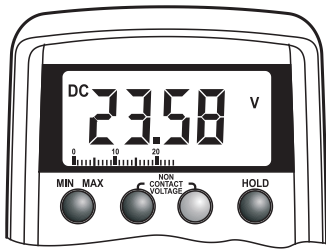
You need to take measurements in DC circuits. Digital and analogue multimeters are available. The measuring accuracy should be the determining factor in your decision about which measuring device to use.

The **accuracy of a multimeter** specifies the maximum measurement error that can occur under certain ambient conditions.

Measurement errors with digital multimeters

With digital multimeters, the accuracy is specified as a percentage in relation to the current measured value. When using a digital multimeter, a constant error resulting from the conversion of analogue to digital must additionally be added. This value affects the right-most decimal place.

A measurement using a digital multimeter produces the value shown below.



Value measured by a digital multimeter

- Specify the measured value.

The measurement reading is **23.58 V**.

- Determine the absolute measurement error for the measured value shown. The accuracy for the set measuring range is:
± (0.7% of display + 1 digit)

$$\pm \left(\frac{0.7}{100} \cdot 23.58 \text{ V} + 1 \cdot 0.01 \text{ V} \right) = \pm 0.175 \text{ V}$$

The true value is therefore between **23.405 V** (23.58 V - 0.175 V) and **23.755 V** (23.58 V + 0.175 V).

- Determine the relative measurement error.

$$\frac{0.175 \text{ V}}{23.58 \text{ V}} \cdot 100 = 0.74 \%$$

Measurement errors with analogue multimeters

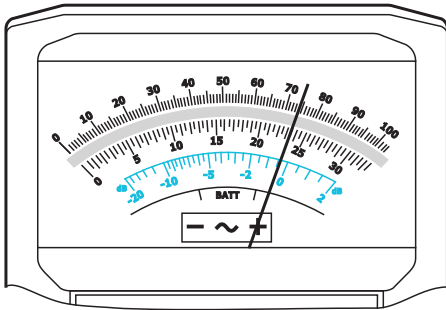
With analogue multimeters, the accuracy is always based on the measuring range's final value. The multimeters are divided into accuracy classes. This means that the same error must always be added regardless of the measurement reading. The percentage error therefore drops the closer the measured value comes to the end of the measuring range. When using analogue multimeters, the measurement should always be taken in the top third of the scale.

Example of an accuracy class

An accuracy class of 2.5 means that the error is $\pm 2.5\%$ of the measuring range in relation to the measuring range's final value.

If, for example, the measuring range final value is 70, the maximum error is $\pm 2.5\%$ of 70, or ± 3.571 .

A measurement using an analogue multimeter produces the value shown below. 30 V is set as the measuring range.



Value measured by an analogue multimeter

- Specify the measured value.

The measurement reading is **23.5 V**.

- Determine the absolute measurement error.

The accuracy class of the analogue multimeter used is 1.5 for this measuring range.

$$\pm \left(\frac{1.5}{100} \cdot 30 \text{ V} \right) = \pm 0.45 \text{ V}$$

The true value is therefore between **23.05 V** ($23.5 \text{ V} - 0.45 \text{ V}$) and **23.95 V** ($23.5 \text{ V} + 0.45 \text{ V}$).

- Determine the relative measurement error.

$$\frac{0.45 \text{ V}}{23.5 \text{ V}} \cdot 100 = 1.91 \%$$

Selecting a measuring device

- Select a measuring device for measurements in a DC circuit and explain the reason for your choice.

The digital multimeter is used for measurements in a DC circuit.

The advantages of a digital multimeter are:

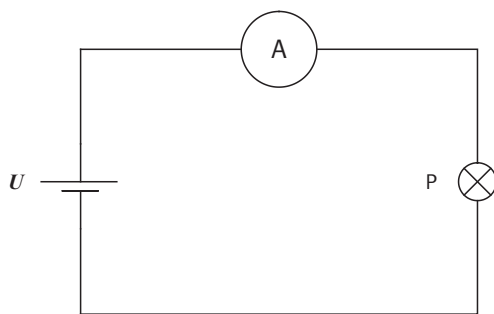
- Greater accuracy and resolution
- Low probability of reading errors
- More robust

■ Measuring current intensity, voltage and resistance

Using a measuring instrument will always change measured values in an existing circuit. It is therefore important to be able to identify and assess the possible influences.

Current measurement

- When measuring current, always connect the **measuring device** to the consuming device **in series**. The full consuming device current flows through the measuring device.
- The internal resistance of the measuring device should be as **low impedance** as possible to minimise the influence on the circuit to be measured.



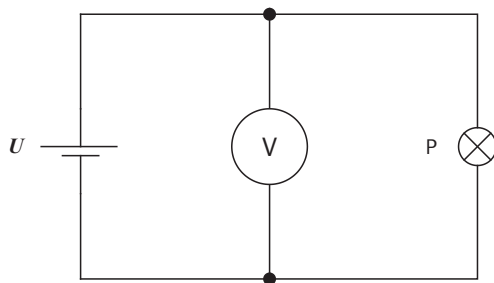
Current measurement

- Describe what effect the internal resistance of the measuring device has on the measurement process.

Each current measuring device (ammeter) has its own internal resistance. This additional resistance reduces the current flow. To keep the measurement error as low as possible, an ammeter may only exhibit a very small internal resistance.

Voltage measurement

- When measuring voltage, always connect the **measuring device** to the consuming device **in parallel**. The voltage drop across the consuming device corresponds to the voltage drop across the measuring device.
- The internal resistance of the measuring device should be as **high impedance** as possible to minimise the influence on the circuit to be measured.



Voltage measurement

- Describe what effect the internal resistance of the measuring device has on the measurement process.

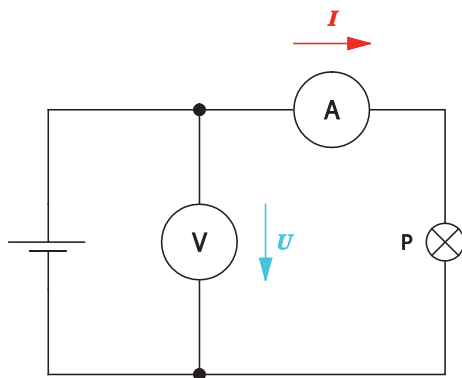
Each voltage measurement device (voltmeter) has its own internal resistance. The current flowing through the meter should be very small to minimise the distortion of the measurement result. This means that the internal resistance of the voltmeter must be as big as possible.

Resistance measurement

The resistance of a consuming device in a DC circuit can either be measured indirectly or directly.

Indirect measurement

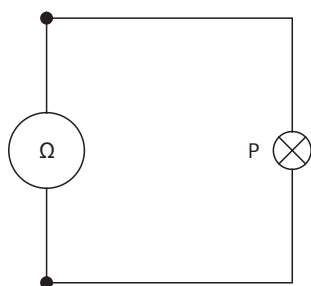
- Indirect measurements involve measuring the current through the consuming device and the voltage drop across the consuming device.
- The two measurements can either be performed one after the other or at the same time.
- The resistance is then calculated using Ohm's law.



Indirect resistance measurement

Direct measurement

- Disconnect the consuming device from the rest of the electrical circuit.
- The consuming device must not be connected to a voltage source during measurement.
- Set the operating mode and measuring range on the measuring device.
- Connect the consuming device to the measuring device and read off the resistance value.



Direct resistance measurement

- Explain why the consuming device must not be connected to a voltage source when measuring resistance directly.

The consuming device must not be connected to a voltage source when measuring resistance directly because the measuring device determines the resistance value via an internally specified voltage or current.

Procedure for measurements in an electrical circuit

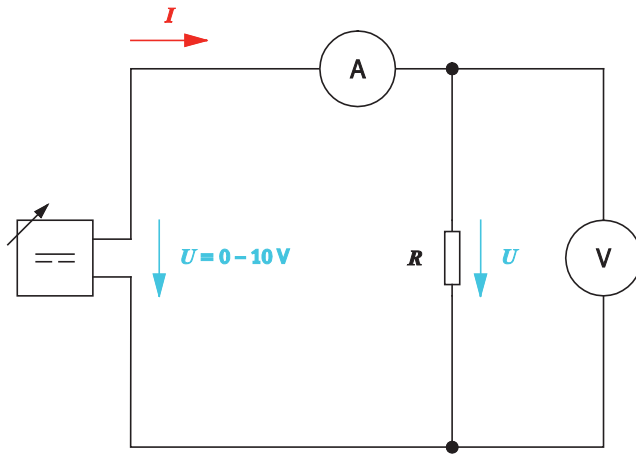
- Disconnect the supply voltage to the electrical circuit.
- Set the required operating mode as well as current or voltage measurement on the multimeter.
- With pointer instruments, check that the pointer is at zero and adjust if necessary.
- Select the widest measuring range so that the pointer's deflection does not go beyond the scale on the analogue measuring device.
- Connect the measuring device with the correct polarity when measuring DC voltage and direct current.
- Switch on the power supply to the electrical circuit.
- Observe the pointer deflection or the display and gradually switch over to a narrower measuring range.
- Read off the display at the greatest possible pointer deflection (narrowest possible measuring range).
- When using pointer instruments, always read the display by looking down onto it to avoid reading errors.

■ **Performing measurements relating to Ohm's law**

Prove the relationships that define Ohm's law by means of suitable experiments. To do this, trace the characteristics $I = f(U)$ at constant resistance and $I = f(R)$ at constant voltage.

Voltage/current characteristic of an ohmic resistor

- Select a resistor $R = 330 \Omega$.
- Check the selected resistance R with a direct resistance measurement in de-energised condition.
- Build the circuit with the resistance R .



Measuring circuit with $R = 330 \Omega$

Identifier	Designation	Values
R	Resistor	$330 \Omega / 2 \text{ W}$
-	Digital multimeter	-
-	Basic power supply unit EduTrainer®	-

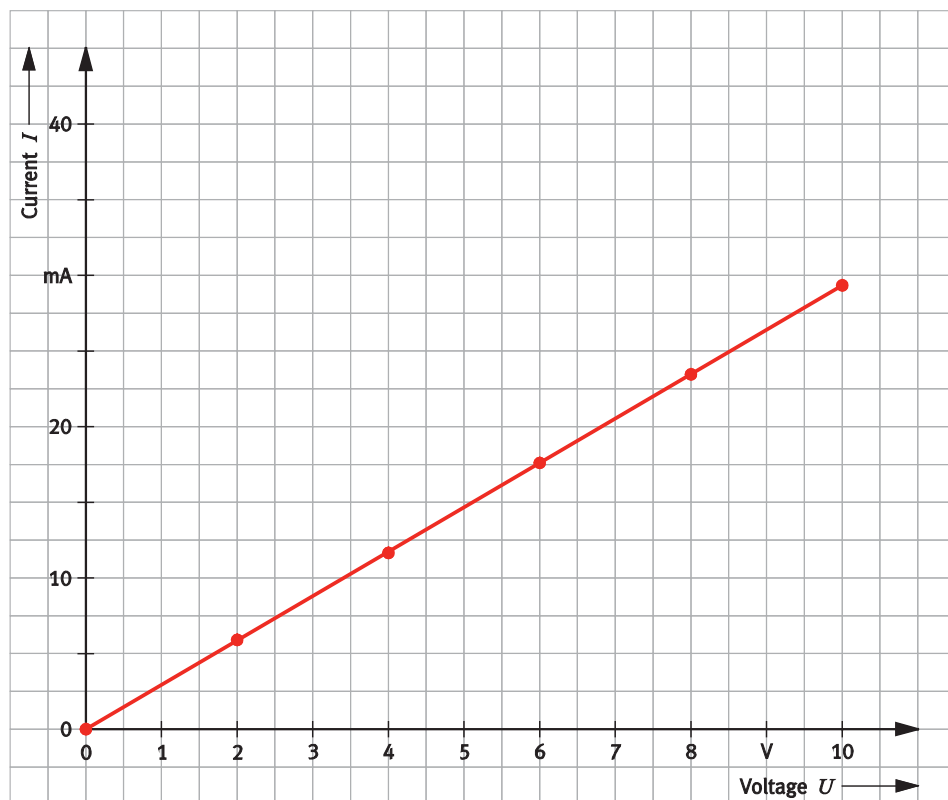
Equipment list

- Increase the voltage from $U = 0 \text{ V}$ to $U = 10 \text{ V}$ in 2 V increments and measure the current intensity I after each increase.
Enter the measurement results in the measurement log.

Voltage U (V)	Current I (mA)
0	0
2	5.9
4	11.65
6	17.6
8	23.45
10	29.33

Measurement log: $I = f(U)$, $R = 330 \Omega$

- Illustrate the measurement results graphically. To do this, transfer the values from the measurement log to the graph.



Voltage/current characteristic, $R = 330 \Omega$

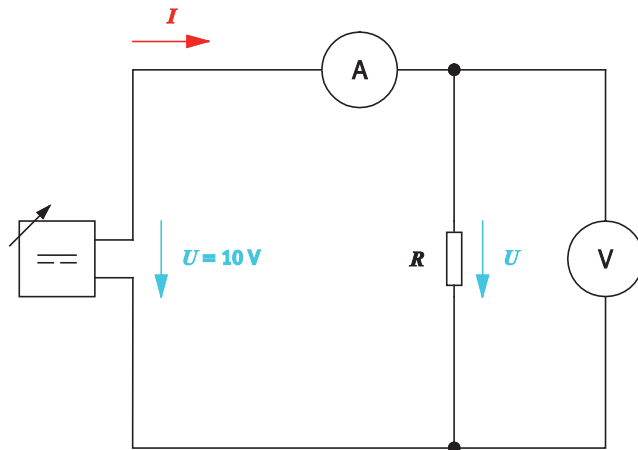
- Describe the dependence of the current I on the voltage U at constant resistance R .

The voltage/current characteristic is a straight line. This means:
 If the voltage is increased, the current intensity increases to the same extent. The current is proportional to the voltage.

$$I \sim U$$

Resistance/current characteristic of an ohmic resistorTrace the characteristic $I = f(R)$ at constant voltage.

- Build the circuit.



Measuring circuit with different resistors

Identifier	Designation	Values
R	Resistor	$100\ \Omega/2\ \text{W}$
R	Resistor	$220\ \Omega/2\ \text{W}$
R	Resistor	$330\ \Omega/2\ \text{W}$
R	Resistor	$470\ \Omega/2\ \text{W}$
R	Resistor	$680\ \Omega/2\ \text{W}$
R	Resistor	$1\ \text{k}\Omega/2\ \text{W}$
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

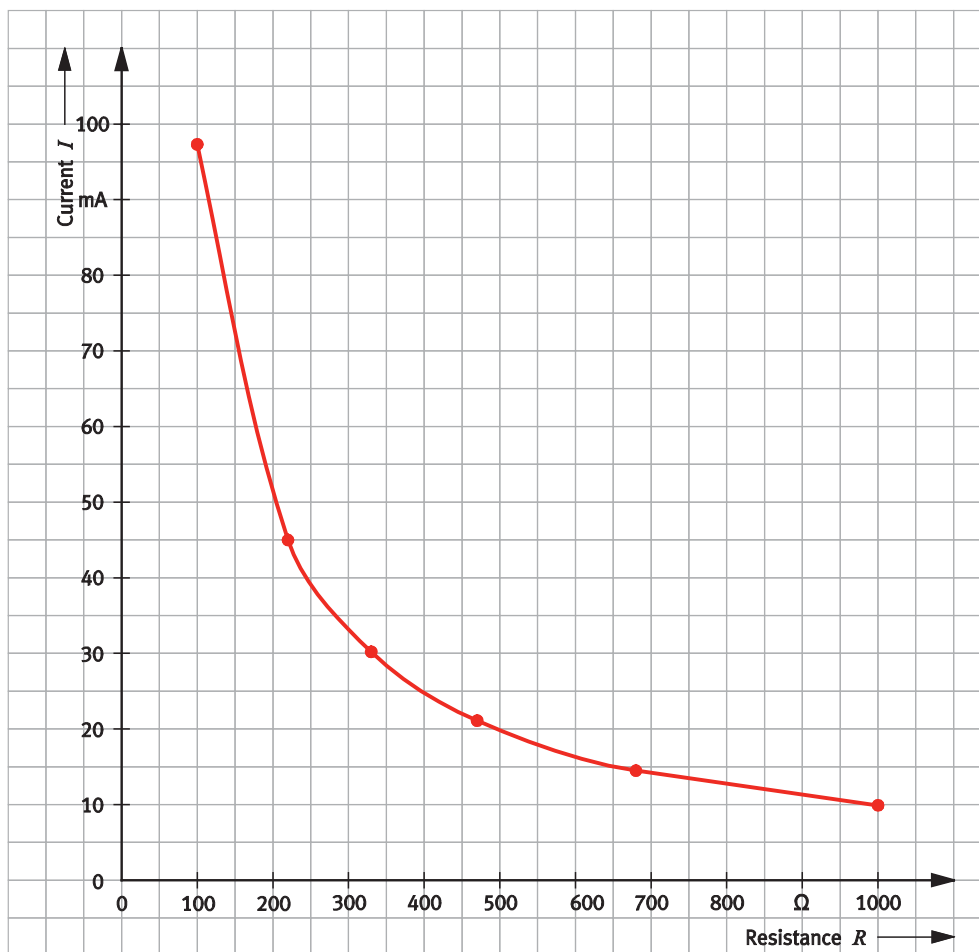
Equipment list

- Apply a constant voltage of $U = 10\text{ V}$ to the circuit.
- Connect 6 to 8 different resistors between $100\ \Omega$ and $1\ \text{k}\Omega$ to the electrical circuit and measure the current intensity I after each one is connected.
Enter the measurement results in the measurement log.
- Add the resistors used to the equipment list.

Resistance R (Ω)	Current I (mA)
100	97.3
220	45.0
330	30.2
470	21.1
680	14.5
1000	9.9

Measurement log: $I = f(R)$, $U = 10\text{ V}$

- Illustrate the measurement results graphically. To do this, transfer the values from the measurement log to the graph.



Resistance/current characteristic, $U = 10\text{ V}$

- Describe the dependence of the current intensity I on the resistance R at constant voltage U .

The current decreases as the resistance increases. The current is inversely proportional to the resistance.

$$I \sim \frac{1}{R}$$

Exercise 2:

Analysing resistors

■ Learning objectives

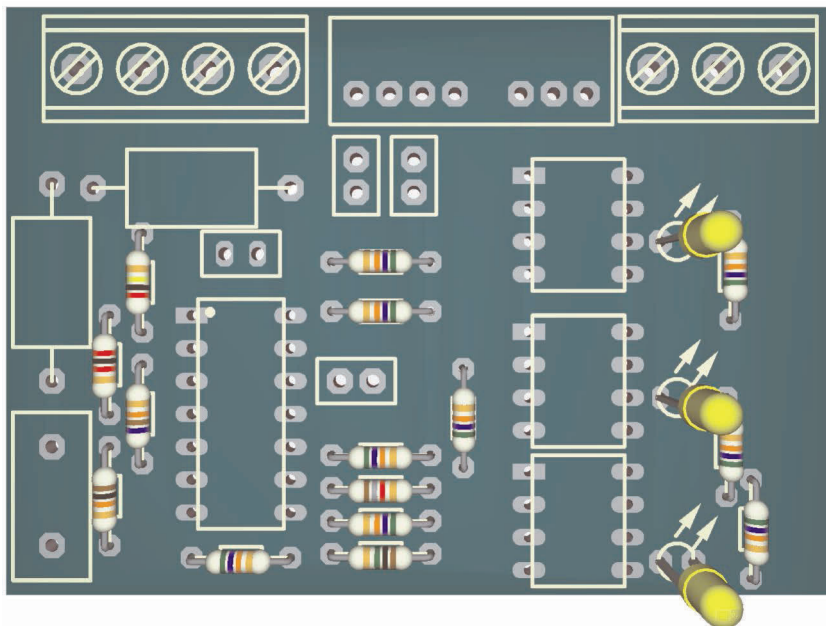
After completing this exercise:

- You will be familiar with the relationship between the resistance value and conductance of a resistor.
- You will be familiar with the characteristic features and main designs of resistors.
- You will be able to apply the IEC series of standards for identifying resistors.

■ Problem description

You are working in the development department of a company that manufactures electronic circuits. You will be building prototypes for amplifier circuits and therefore need to learn about the resistors used in the circuits in question.

■ Circuit



Detail of a circuit on a printed circuit board

■ **Project assignments**

1. Describe the key features of a resistor.
2. Find out more about the design of the resistors you are using.
3. Check whether the resistor $R = 330 \Omega$ can be used in a circuit with an operating voltage of 24 V.
4. Using the colour codes, determine the resistance value of two resistors that are to be replaced.

■ **Work aids**

- Textbooks, books of tables
- Data sheets
- WBT Electrical engineering 1
- Internet

Note

Do not switch on the electrical power supply until you have made and checked all the connections. Once you have completed the exercise, switch off the power supply again before dismantling the components.

■ Describing the features of electrical resistors

The electrical resistor limits the flow of current. It is mainly used for adjusting and dividing current and voltage.

- Name some characteristic features of a resistor.

Features of an electrical resistor

- Resistance value
- Load capacity/power loss
- Temperature behaviour
- Frequency dependence
- Fixed resistance – variable resistance
- Tolerance

There are linear and non-linear resistors.

- Describe when a resistor is called a **linear resistor**.

A resistor is called linear if the current flowing through it changes in proportion with the applied voltage. The current/voltage characteristic is then a straight line.

The electrical resistance of a component or electrical consuming device is the quotient of its voltage and current:

$$R = \frac{U}{I}$$

where R is electrical resistance in Ω

U is electrical voltage in V

I electrical current in A

- Describe how the electrical conductance of a resistor is defined. To do this, completed the prepared table.

Physical variable	Description	Symbol	Formula	Unit of measurement
Electrical conductance	Electrical conductance is the reciprocal value of electrical resistance. If a consuming device is a good conductor of electrical current, then it has high conductance and low resistance.	G	$G = \frac{1}{R}$	Siemens [S]

- An electrical resistor has a resistance of $R = 10 \Omega$. Specify the associated conductance G of the resistor.

The conductance for a resistor with $R = 10 \Omega$ is 0.1 S .

■ Determining fixed resistors and variable resistors at a laboratory workstation

Resistors are divided into fixed resistors and variable resistors.

- Specify the two main designs of fixed resistors.

The two main designs of fixed resistors are

- Wire resistors
- Film resistors

- Find out which resistors are available to you for DC circuits. Enter the resistors in the corresponding table and complete the associated fields.

Fixed resistors	Design
Ohmic resistors with different resistance values	Metal film resistor

Fixed resistors in the equipment set

Variable resistors	Mechanically variable resistor	Physically variable resistor, change in resistance due to
Rotary encoder	x	-
NTC resistor	-	Temperature
VDR resistor	-	Voltage
LDR resistor	-	Light

Variable resistors in the equipment set

■ Calculating and evaluating the load carrying capacity of the resistor $R = 330 \Omega$

In a resistor, electrical energy is converted into heat. This thermal energy is called **power loss**. The thermal energy heats up the resistor. The maximum temperature of a resistor is limited. The resistor is damaged if this temperature is exceeded.

Check whether the resistor $R = 330 \Omega$ can be used in a circuit with an operating voltage of 24 V.

- Specify the formula for calculating the power loss of a resistor.

The power loss of a resistor is calculated in accordance with the following formula:

$$P = U \cdot I$$

- For the resistor $R = 330 \Omega$, calculate the voltage at which the maximum power loss $P = 2 \text{ W}$ occurs.

Given

Resistor	$R = 330 \Omega$
Power loss	$P = 2 \text{ W}$

To be found

Maximum voltage U in V

Calculation

The power P is calculated as follows:

$$P = U \cdot I$$

The current I is calculated as follows in accordance with Ohm's law:

$$I = \frac{U}{R}$$

Used in P :

$$P = U \cdot \frac{U}{R} = \frac{U^2}{R}$$

Solved for U :

$$U = \sqrt{P \cdot R} = \sqrt{2 \cdot 330} \text{ V} = \sqrt{660} \text{ V} = 25.69 \text{ V}$$

- Can the resistor $R = 330 \Omega$ be used in a circuit with 24 V DC?

The resistor $R = 330 \Omega$ can be used in a circuit with 24 V. Its maximum power loss is not achieved until a voltage of 25.69 V is reached.

■ **Determining the resistance value from the colour code and checking it through measurement**

Two resistors are to be replaced in one circuit. Determine the resistance value from the colour code of the resistors in question.

The resistance values of the fixed resistors are defined by the IEC series. The numerical series specify the resistance values for a decade. The standard values for the resistors are calculated in such a way that the tolerance produces slight overlaps. This means that there are no gaps between two adjacent standard series.



- Specify the three most important IEC series with the number of resistance values and the tolerance.

The three most important IEC series are:

- Series E6: 6 values with 20% tolerance
- Series E12: 12 values with 10% tolerance
- Series E24: 24 values with 5% tolerance

The resistance value is generally identified by means of coloured rings or dots.

- Determine the resistance value of the two resistors shown based on the colour code.

Resistor	Resistance value																
	<p>Numerical sequence in the direction of reading</p> <table> <tr> <td>1</td> <td>2</td> <td>3</td> <td>4</td> </tr> <tr> <td>RD</td> <td>RD</td> <td>OG</td> <td>GD</td> </tr> <tr> <td>=</td> <td>=</td> <td>=</td> <td>=</td> </tr> <tr> <td>2</td> <td>2</td> <td>10^3</td> <td>± 5</td> </tr> </table> <p>$\rightarrow 22 \cdot 10^3 \Omega \pm 5\% = 22000 \Omega \pm 5\%$ $= 22 \text{ k}\Omega \pm 5\%$</p>	1	2	3	4	RD	RD	OG	GD	=	=	=	=	2	2	10^3	± 5
1	2	3	4														
RD	RD	OG	GD														
=	=	=	=														
2	2	10^3	± 5														
	<p>Numerical sequence in the direction of reading</p> <table> <tr> <td>1</td> <td>2</td> <td>3</td> <td>4</td> </tr> <tr> <td>BR</td> <td>BK</td> <td>BR</td> <td>GD</td> </tr> <tr> <td>=</td> <td>=</td> <td>=</td> <td>=</td> </tr> <tr> <td>1</td> <td>0</td> <td>10^1</td> <td>± 5</td> </tr> </table> <p>$\rightarrow 10 \cdot 10^1 \Omega \pm 5\% = 100 \Omega \pm 5\%$</p>	1	2	3	4	BR	BK	BR	GD	=	=	=	=	1	0	10^1	± 5
1	2	3	4														
BR	BK	BR	GD														
=	=	=	=														
1	0	10^1	± 5														

- Determine the value of the two resistors by measurement and enter the values in the measurement log.

Identifier	Designation	Values
R	Resistor	22 k Ω /2 W
R	Resistor	100 Ω /2 W
–	Digital multimeter	–

Equipment list

- Add the missing entries in the measurement log.
- For both resistors, check whether their resistance values are within the specified tolerance.

Nominal value	Tolerance	Tolerance range with largest and smallest resistance value	Measured value	Measured value in tolerance range?
22 k Ω	5%	20.9–23.1 k Ω	21.83 k Ω	Yes
100 Ω	5%	95–105 Ω	99.7 Ω	Yes

Measurement log

Exercise 3:

Determining the series resistance for a light emitting diode

■ Learning objectives

After completing this exercise:

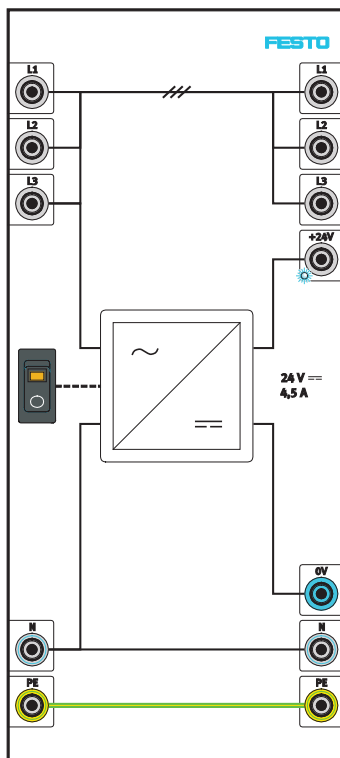
- You will be able to apply the basic electrical variables of energy and power.
- You will be able to investigate basic electrical circuits by measurement and extrapolate laws from the measurement variables determined.
- You will be able to size and calculate basic electrical circuits such as series circuits.
- You will be able to test the function of electrical circuits and equipment.

■ Problem description

A light emitting diode is used to indicate the output voltage at a power supply unit. The light emitting diode in the power supply unit is defective and needs to be replaced.

Select a suitable series resistor for the new light emitting diode.

■ Positional sketch



Power supply unit with output voltage indication by means of an LED

■ Project assignments

1. Describe what the series resistor does in the circuit with the light emitting diode.
2. Find out about the laws governing series connection and summarise your findings.
3. Learn about series connection by conducting some experiments on series connection of ohmic resistors.
4. Calculate the necessary series resistance for the light emitting diode. Select a suitable resistor.

■ Work aids

- Textbooks, books of tables
- Data sheets
- WBT Electrical engineering 1
- Internet

Note for the lesson

There are two ways of completing the exercise:

- First, research the electrotechnical relationships,
- then check the results through experiment

or vice versa.

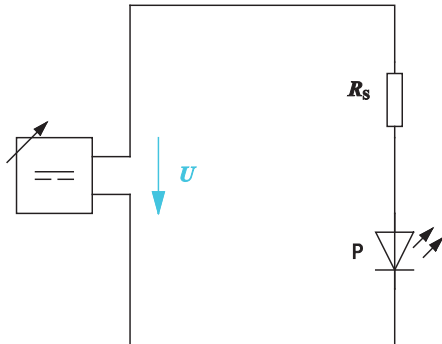
If the decision about the order is left to the student, he can take his individual needs into consideration.

Note

Do not switch on the electrical power supply until you have made and checked all the connections. Once you have completed the exercise, switch off the power supply again before dismantling the components.

■ Describing what a series resistor does

- Describe what the series resistor R_S does in the circuit with the light emitting diode.



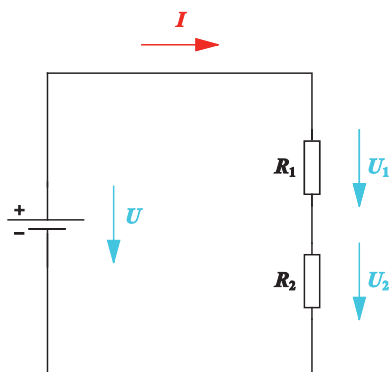
Circuit with light emitting diode and series resistor

The operating voltage of the circuit in which the light emitting diode is operated is higher than the nominal voltage of the light emitting diode. The light emitting diode would be damaged beyond repair if a series resistor were not used.

The series resistor limits the voltage and current in the circuit so that the light emitting diode is not damaged.

■ Describing the laws governing series connection of ohmic resistors

Series connection refers to the connection of two or more consuming devices in series in one current path.



Series circuit with two resistors

- Find out about the laws governing series connection of ohmic resistors.
- Using the example of a series circuit with two resistors, describe how the electrical variables current, voltage and resistance behave in a series circuit.

The following applies to the electrical variables in a series circuit:

Current

The same current I flows through all the resistors.

Voltage

Kirchhoff's second law applies to the voltages dropping at the individual resistors: the total voltage is equal to the sum of the component voltages.

$$U = U_1 + U_2$$

Resistance

The same current I flows through all the resistors in a series circuit. According to Ohm's law, the following holds for the voltages

$$U_1 = R_1 \cdot I$$

$$U_2 = R_2 \cdot I$$

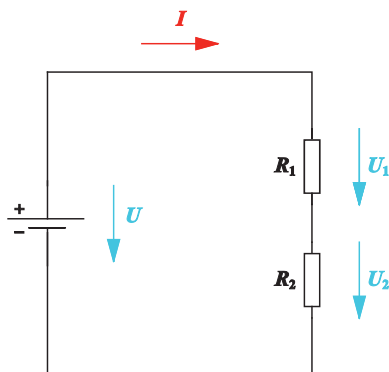
The following therefore applies to the resistance R

$$R = \frac{U}{I} = \frac{U_1 + U_2}{I} = \frac{U_1}{I} + \frac{U_2}{I} = \frac{R_1 \cdot I}{I} + \frac{R_2 \cdot I}{I} = R_1 + R_2$$

The total resistance of the series circuit is the sum of all the individual resistances.

Example

Apply the laws governing series connection to a series circuit with two resistors $R_1 = 220 \Omega$ and $R_2 = 470 \Omega$.



Series circuit with $R_1 = 220 \Omega$, $R_2 = 470 \Omega$, $U = 24 \text{ V}$

- Calculate the current, component voltages and total resistance for the series circuit.

Given

Operating voltage	$U = 24 \text{ V}$
Resistance	$R_1 = 220 \Omega$
Resistance	$R_2 = 470 \Omega$

To be found

Current intensity	I in A
Component voltage at R_1	U_1 in V
Component voltage at R_2	U_2 in V
Total resistance	R_{total} in Ω

Calculation

$$R_{\text{total}} = R_1 + R_2 = 220 \Omega + 470 \Omega = 690 \Omega$$

$$I = \frac{U}{R_{\text{total}}} = \frac{24 \text{ V}}{690 \Omega} = 0.03478 \text{ A} = 34.78 \text{ mA}$$

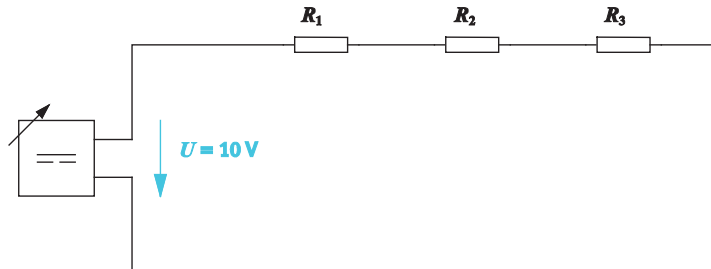
$$U_1 = R_1 \cdot I = 220 \Omega \cdot 0.03478 \text{ A} = 7.65 \text{ V}$$

$$U_2 = R_2 \cdot I = 470 \Omega \cdot 0.03478 \text{ A} = 16.35 \text{ V}$$

$$U = U_1 + U_2 = 7.65 \text{ V} + 16.35 \text{ V} = 24 \text{ V}$$

■ Performing measurements relating to series connection of resistors

Verify the laws governing series connection by means of experiments. To do this, use a series circuit with three different resistors.

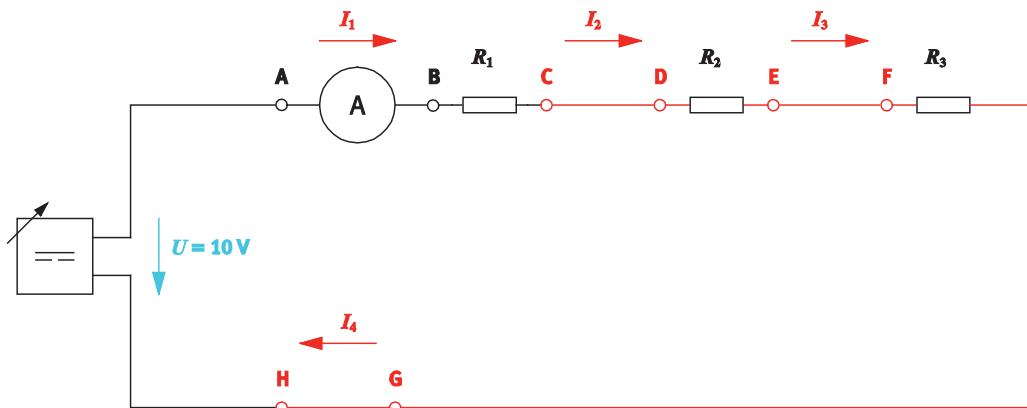


Series circuit with three resistors

Measuring the currents

Prepare the series circuit for measuring the currents. To do this, disconnect the line wherever you want to successively measure the currents using a digital multimeter.

- Enter the line disconnections in the measuring circuit and label the measuring points.
- Identify the measuring points with current arrows.
- Complete the measuring circuit.
- Build the measuring circuit and perform the measurements.
- Enter the measured values in the measurement log.
- Evaluate the measurement results.
- Verify the measured value for the current intensity by means of calculation.



Measuring circuit with $U = 10 \text{ V}$, $R_1 = 100 \Omega$, $R_2 = 330 \Omega$, $R_3 = 470 \Omega$

Identifier	Designation	Values
R_1	Resistor	100 Ω /2 W
R_2	Resistor	330 Ω /2 W
R_3	Resistor	470 Ω /2 W
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

Equipment list

I_1 (mA) Measuring points A-B	I_2 (mA) Measuring points C-D	I_3 (mA) Measuring points E-F	I_4 (mA) Measuring points G-H
11.0	11.0	11.0	11.0

Measurement log: Current intensities

Evaluating the current

The current is the same at every resistor.

$$I_1 = I_2 = I_3 = I = 11.0 \text{ mA}$$

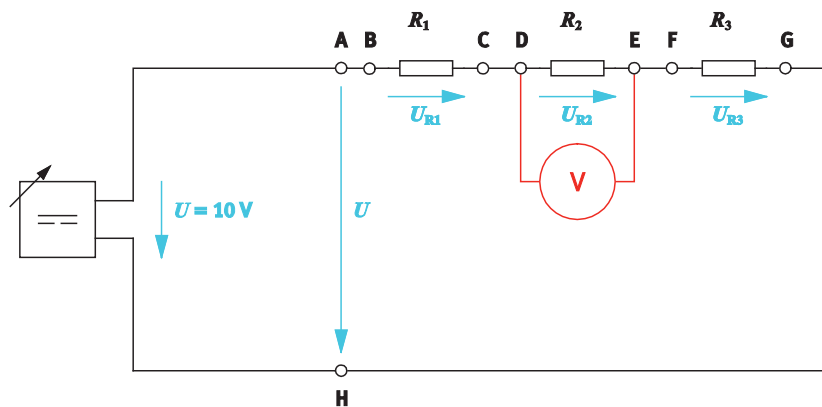
Verification of the current intensity I by calculation:

$$I = \frac{U}{R_{\text{total}}} = \frac{U}{R_1 + R_2 + R_3} = \frac{10 \text{ V}}{900 \Omega} = 11.1 \text{ mA}$$

Slight deviations between the measured values and the calculated values are due to measuring errors and component tolerances.

Measuring the voltages

- Enter voltage arrows between the measuring points where you measure the voltage drop.
- Sketch the digital multimeter in the circuit as an example for one voltage measurement.
- Build the measuring circuit and perform the individual voltage measurements one after the other.
- Enter the measured values in the measurement log.
- Evaluate the measurement results.



Measuring circuit with $U = 10 \text{ V}$, $R_1 = 100 \Omega$, $R_2 = 330 \Omega$, $R_3 = 470 \Omega$

$U_{R1} \text{ (V)}$ Measuring points B-C	$U_{R2} \text{ (V)}$ Measuring points D-E	$U_{R3} \text{ (V)}$ Measuring points F-G	$U \text{ (V)}$ Measuring points A-H
1.11	3.66	5.23	10.0

Measurement log: Voltages

Evaluating the voltage

The sum of the individual voltages is equal to the total voltage.

$$U = U_{R1} + U_{R2} + U_{R3} = 1.11 \text{ V} + 3.66 \text{ V} + 5.23 \text{ V} = 10.0 \text{ V}$$

Slight deviations are due to measurement errors and component tolerances.

- Describe how the component voltages behave relative to the associated resistance value.
- To do this, complete and then evaluate the table.

Evaluation of the measurement log			
Component voltages	1.11 V	3.66 V	5.23 V
Associated resistance value	100 Ω	330 Ω	470 Ω

In the series circuit, the individual component voltages behave like the associated resistance values. The biggest component voltage is applied to the biggest resistor.

This can also be illustrated mathematically.

The following formula applies:

$$I = I_1 = I_2 = I_3$$

Applying Ohm's law to the current intensity gives:

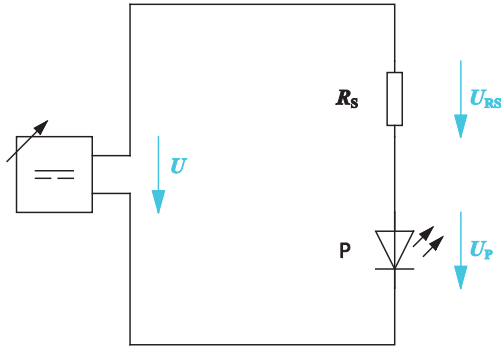
$$I = \frac{U_{R1}}{R_1} = \frac{U_{R2}}{R_2} = \frac{U_{R3}}{R_3}$$

This gives the following formula for the component voltages U_{R1} and U_{R2} as well as the individual resistances R_1 and R_2 :

$$\frac{U_{R1}}{U_{R2}} = \frac{R_1}{R_2}$$

■ **Determining the series resistance for the light emitting diode**

Determine the series resistance for the light emitting diode and select a suitable resistor from the IEC series E12 on the basis of your calculations.



Operating voltage: $U = 10\text{ V}$
 Operating data for light emitting diode: $U_P = 4\text{ V}$ $I_P = 20\text{ mA}$

Circuit with light emitting diode

Identifier	Designation	Values
R_s	Resistor	330 Ω /2 W
P	Light emitting diode	20 mA, blue
–	Basic power supply unit EduTrainer®	–

Equipment list

The series resistor and light emitting diode form a series circuit. The operating voltage is split at the series resistor and light emitting diode.

- Calculate the series resistance for the light emitting diode.

Given

Operating voltage $U = 10\text{ V}$
 Voltage of light emitting diode $U_P = 4\text{ V}$
 Current intensity of light emitting diode $I_P = I = 20\text{ mA}$

To be found

Series resistance R_s in Ω

Calculation

$$U_{RS} = R_S \cdot I$$

Solved for R_S :

$$R_S = \frac{U_{RS}}{I}$$

The following applies to U_{RS} :

$$U = U_{RS} + U_P$$

Solved for U_{RS} :

$$U_{RS} = U - U_P$$

This gives the following for R_S :

$$R_S = \frac{U_{RS}}{I} = \frac{U - U_P}{I} = \frac{10 \text{ V} - 4 \text{ V}}{20 \text{ mA}} = \frac{6 \text{ V}}{0.020 \text{ A}} = 300 \cdot \frac{\text{V}}{\text{A}} = 300 \Omega$$

- Select the appropriate resistor from the IEC series E12.

The E12 resistor series doesn't include the resistance value 300 Ω . The next biggest resistance value is therefore used. A series resistor with 330 Ω is chosen.

Power loss

Series resistors are generally only used with low currents in the mA range because the power loss at the series resistor is very high.

Check whether the maximum power of the selected series resistor R is sufficient for the light emitting diode circuit.

- Find out how the electrical power P is defined.
- Complete the table for electrical power. Enter the calculation formula and the physical unit.

	Symbol	Calculation formula	Physical unit
Electrical power	P	$P = U \cdot I$ where U is voltage in V I is current intensity in A	Watt [W]

Note

The power P_{RS} of the series resistor is calculated using the voltage at the series resistor and the current flowing through it.

- Calculate the power loss P_{RS} at the series resistor R_S .
- Compare the power loss of the series resistor R_S with the power data for the selected series resistor.

Given

Operating voltage $U = 10 \text{ V}$
Voltage of light emitting diode $U_P = 4 \text{ V}$

To be found

Power loss P_{RS} in mW

Calculation

$$P_{RS} = U_{RS} \cdot I$$

$$U_{RS} = U - U_P = 10 \text{ V} - 4 \text{ V} = 6 \text{ V}$$

$$I = \frac{U_{RS}}{R_S} = \frac{6 \text{ V}}{330 \Omega} = 0.0182 \text{ A} = 18.2 \text{ mA}$$

This gives the following for P_{RS} :

$$P_{RS} = U_{RS} \cdot I = 6 \text{ V} \cdot 18.2 \text{ mA} = 109.2 \text{ mW}$$

Result:

The selected series resistor R_S with 330Ω and 2 W is more than sufficient to accommodate the power P_{RS} of 110 mW that is produced.

- Add the necessary series resistor for the circuit to the equipment list.
- Build the circuit and make sure it operates correctly.

Exercise 4:

Adding an electrical consuming device to a circuit

■ Learning objectives

After completing this exercise:

- You will be able to apply the basic electrical variables of work and power.
- You will be able to investigate basic electrical circuits by measurement and extrapolate laws from the measurement variables determined.
- You will be able to size and calculate basic electrical circuits such as parallel circuits.

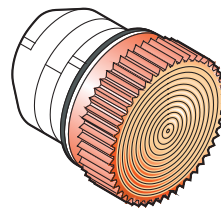
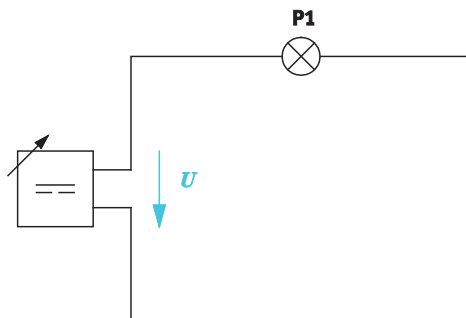
■ Problem description

The control console for a machine has one control lamp connected. Add a further control lamp to the control console. The second control lamp should illuminate as brightly as the one that is already installed. Both control lamps therefore have the same nominal data.

Information

Control lamps behave like ohmic resistors after they are switched on.

■ Circuit



Nominal voltage of P1: $U = 12\text{ V}$

Nominal current of P1: $I = 62\text{ mA}$

Electrical circuit for a control lamp

■ Project assignments

1. Find out more about the possible basic electrical circuits for realising the circuit for the control lamps. Describe the laws governing parallel connection in this context.
2. Verify the laws governing parallel connection by means of experiments.
3. Calculate the electrical power for the control lamps when they are connected in series and in parallel.
4. Design the electrical circuit for the control lamps.

■ Work aids

- Textbooks, books of tables
- Data sheets
- WBT Electrical engineering 1
- Internet

Notes for the lesson

There are two ways of completing the exercise:

- First, find out about electrotechnical relationships,
- then check the results through experiment

or vice versa.

If the decision about the order is left to the student, he can his individual needs take into consideration.

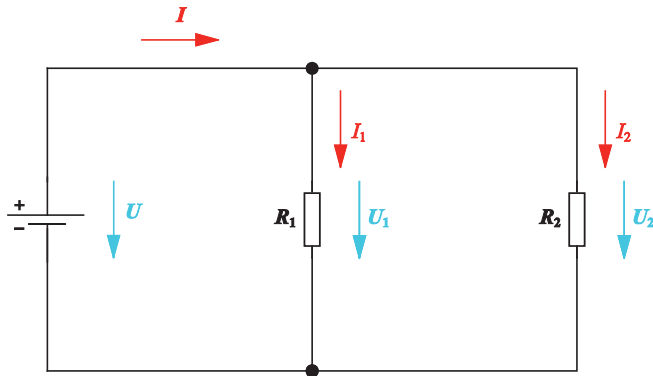
Note

Do not switch on the electrical power supply until you have made and checked all the connections. Once you have completed the exercise, switch off the power supply again before dismantling the components.

■ Describing the laws governing parallel connection of ohmic resistors

Basic electrical circuits include series and parallel circuits.

Parallel connection refers to the connection of several consuming devices one beside the other in parallel in a branched current path.



Parallel circuit with two resistors

- Using the example of a parallel circuit with two resistors, describe how the electrical variables current, voltage and resistance behave in a parallel circuit.

Current

Kirchhoff's first law applies to the currents:
the total current is equal to the sum of the individual currents.

$$I = I_1 + I_2$$

Voltage

The voltage U is the same at all resistors.

$$U = U_1 = U_2$$

Resistance

The total resistance is always smaller than the smallest individual resistance.

Using Ohm's law for the currents

$$I_1 = \frac{U}{R_1} \quad I_2 = \frac{U}{R_2}$$

gives the following for the total resistance:

$$R = \frac{U}{I} = \frac{U}{I_1 + I_2} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

The total resistance is also called **equivalent resistance**.

- Describe the composition of the electrical power in the parallel circuit with two resistors.

P_{R1} Power consumption at the resistor R_1

P_{R2} Power consumption at the resistor R_2

The total power P is calculated as follows:

$$P = P_{R1} + P_{R2}$$

The total power is made up of the powers of the individual resistors.

- Specify the formula for calculating the powers P_{R1} and P_{R2} .

Power P_{R1} :

$$P_{R1} = U \cdot I_1$$

Power P_{R2} :

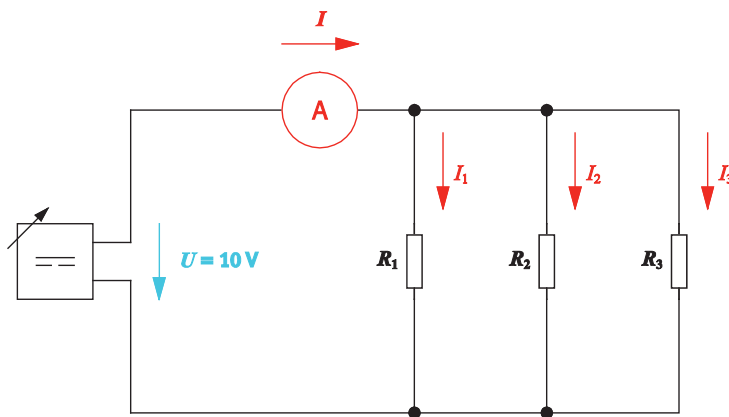
$$P_{R2} = U \cdot I_2$$

■ **Performing measurements relating to parallel connection of resistors**

Check the laws governing parallel connection by means of experiments. To do this, use a parallel circuit with three different resistors.

Measuring the currents

- Add current arrows to the parallel circuit wherever you want to measure the currents.
- Sketch the digital multimeter as an example for one current measurement.
- Build the measuring circuit and perform the measurements.
- Enter the measured values in the measurement log.
- Evaluate the measurement results.



Parallel circuit with $U = 10\text{ V}$, $R_1 = 100\ \Omega$, $R_2 = 330\ \Omega$, $R_3 = 470\ \Omega$

Identifier	Designation	Values
R_1	Resistor	100 Ω /2 W
R_2	Resistor	330 Ω /2 W
R_3	Resistor	470 Ω /2 W
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

Equipment list

Component current I_1 (mA)	Component current I_2 (mA)	Component current I_3 (mA)	Total current I (mA)
97.4	30.1	21.1	145.6

Measurement log: Currents

Evaluating the current

The total current is equal to the sum of the component currents.

Slight deviations are due to measurement errors and component tolerances.

$$I = I_1 + I_2 + I_3 = 97.4 \text{ mA} + 30.1 \text{ mA} + 21.1 \text{ mA} = 148.6 \text{ mA}$$

- Verify the measurement results by calculation.

Current intensities calculated using Ohm's law:

$$I_1 = \frac{U}{R_1} = \frac{10 \text{ V}}{100 \Omega} = 100 \text{ mA}$$

$$I_2 = \frac{U}{R_2} = \frac{10 \text{ V}}{330 \Omega} = 30 \text{ mA}$$

$$I_3 = \frac{U}{R_3} = \frac{10 \text{ V}}{470 \Omega} = 21 \text{ mA}$$

$$I = I_1 + I_2 + I_3 = 100 \text{ mA} + 30 \text{ mA} + 21 \text{ mA} = 151 \text{ mA}$$

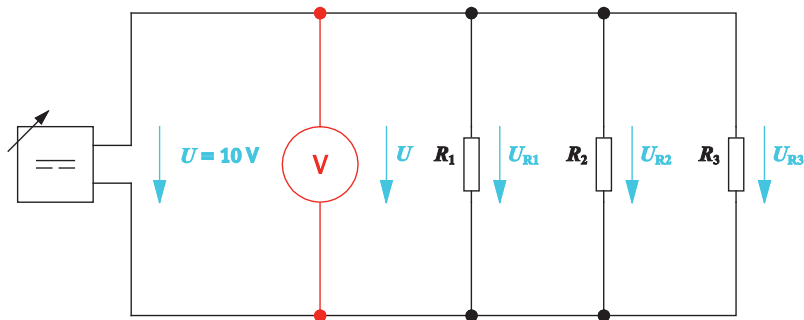
- Describe how the component currents behave relative to the associated resistance value. To do this, complete and evaluate the table.

Evaluation			
Component currents	100 mA	30 mA	21 mA
Associated resistance value	100 Ω	330 Ω	470 Ω

The component currents are inversely proportional to the respective resistance. This means that the higher the resistance value, the lower the associated component current.

Measuring the voltages

- Add appropriate voltage arrows to the parallel circuit wherever you want to measure component voltages.
- Sketch the digital multimeter as an example for one voltage measurement.
- Build the measuring circuit and perform the voltage measurements one after the other.
- Enter the measured values in the measurement log.
- Evaluate the measurement results.



Measuring circuit with $U = 10 \text{ V}$, $R_1 = 100 \Omega$, $R_2 = 330 \Omega$, $R_3 = 470 \Omega$

$U \text{ (V)}$	$U_{R1} \text{ (V)}$	$U_{R2} \text{ (V)}$	$U_{R3} \text{ (V)}$
10.0	10.0	10.0	10.0

Measurement log: Voltages

Evaluating the voltage

The voltage is the same at all resistors.

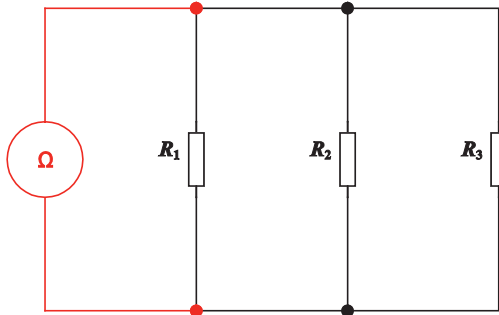
Slight deviations in the measured values are due to measurement errors and component tolerances.

$$U = U_{R1} = U_{R2} = U_{R3} = 10 \text{ V}$$

Determining the equivalent resistance

Determine the equivalent resistance of the parallel circuit by measuring the resistance directly. Verify the measured value subsequently by calculation.

- Add the device for measuring resistance to the circuit.
- Build the circuit.
- Measure the equivalent resistance.
- Verify the equivalent resistance by calculation. To do this, use the nominal values for the resistances.



Direct measurement of the equivalent resistance of the circuit with $R_1 = 100 \Omega$, $R_2 = 330 \Omega$, $R_3 = 470 \Omega$

Component resistance $R_1 (\Omega)$	Component resistance $R_2 (\Omega)$	Component resistance $R_3 (\Omega)$	Equivalent resistance $R_A (\Omega)$
100	330	470	65.9

Measurement log: Resistances

Verify the equivalent resistance by calculation:

The equivalent resistance R_A is calculated as follows:

$$\frac{1}{R_A} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{100 \Omega} + \frac{1}{330 \Omega} + \frac{1}{470 \Omega} = 0.01 \frac{1}{\Omega} + 0.003 \frac{1}{\Omega} + 0.002 \frac{1}{\Omega} = 0.015 \frac{1}{\Omega}$$

$$R_A = \frac{1}{0.015} \Omega = 66 \Omega$$

Slight deviations between the measured value and the calculated value are due to measuring errors and component tolerances.

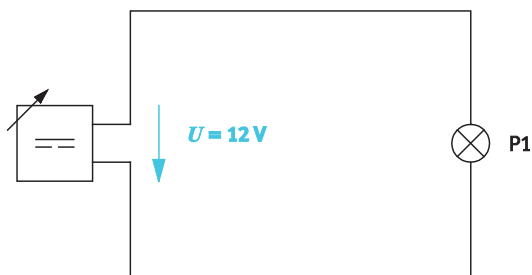
■ Calculating the electrical power in a series and parallel circuit

Add another control lamp to the circuit for the control lamp. In the new circuit, the second control lamp is to illuminate with the same power as the first control lamp.

To decide which circuit is suitable, calculate the power consumed by the control lamps for both circuits.

Electrical variables in the lamp circuit

- Start by calculating the missing electrical variables for the control lamp circuit.



Circuit with control lamp P1, nominal data of P1: 12 V/62 mA

Given

Voltage	$U = 12 \text{ V}$
Current	$I = 62 \text{ mA}$

To be found

- Resistance R of the lamp P1 in Ω
- Power P of the lamp P1 in mW

Calculation

Ohm's law gives the following for the resistance R of the lamp P1:

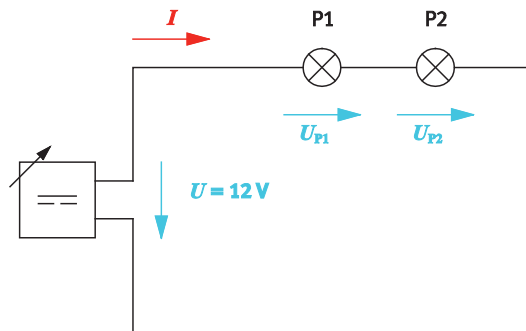
$$R = \frac{U}{I} = \frac{12 \text{ V}}{62 \text{ mA}} = 193.5 \Omega$$

The power P is calculated as:

$$P = U \cdot I = 12 \text{ V} \cdot 62 \text{ mA} = 744 \text{ mW}$$

Electrical power in the series circuit

- To make it easier to perform calculations for the circuit, add the appropriate current arrows to the circuit.
- Calculate the consumed electrical power for the lamps P1 and P2 for the series circuit.



Series circuit with two control lamps

Given

Voltage $U = 12\text{ V}$
 Lamp resistance $R_{P1} = 193.5\ \Omega$

To be found

Power P_{P1} of lamp P1 in mW
 Power P_{P2} of lamp P2 in mW

Calculation

The power is calculated as follows:

$$P_{P1} = U_{P1} \cdot I \quad P_{P2} = U_{P2} \cdot I$$

The following applies to the voltages in the series circuit:

$$U = U_{P1} + U_{P2}$$

$$\frac{U_{P1}}{U_{P2}} = \frac{R_{P1}}{R_{P2}}$$

Since $R_{P1} = R_{P2}$, it follows that $U_{P1} = U_{P2}$

This gives the following for the **component voltages**:

$$U_{R1} = 6\text{ V} \quad U_{P2} = 6\text{ V}$$

The following applies to the **resistances** in the series circuit:

$$R = R_{p1} + R_{p2} = 2 \cdot 193.5 \, \Omega = 387 \, \Omega$$

The following applies to the **current** in the series circuit:

$$I = \frac{U}{R} = \frac{12 \, \text{V}}{387 \, \Omega} = 31 \, \text{mA}$$

This gives the following for the **power** of lamp P1 and lamp P2:

$$P_{p1} = U_{p1} \cdot I = 6 \, \text{V} \cdot 31 \, \text{mA} = 186 \, \text{mW}$$

$$P_{p2} = U_{p2} \cdot I = 6 \, \text{V} \cdot 31 \, \text{mA} = 186 \, \text{mW}$$

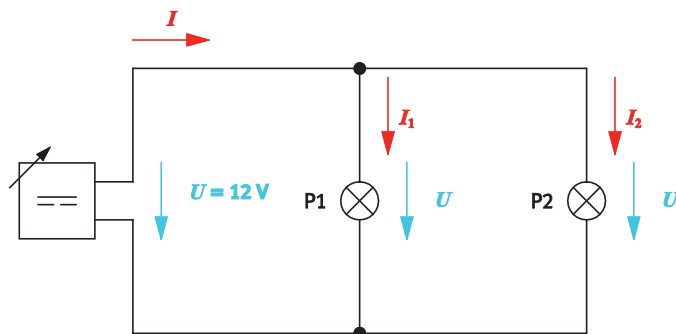
Note for the lesson

The power P can of course also be calculated using one of the formulae

$$P = \frac{U^2}{R} \quad \text{or} \quad P = I^2 \cdot R$$

Electrical power in the parallel circuit

- To make it easier to perform calculations for the circuit, add the appropriate current arrows to the circuit.
- Calculate the consumed electrical power for the lamps for the parallel circuit.



Parallel connection of two control lamps

Given

$$\begin{array}{ll} \text{Voltage} & U = 12 \text{ V} \\ \text{Lamp resistance} & R_{P1} = 193.5 \ \Omega \end{array}$$

To be found

$$\begin{array}{l} \text{Power } P_{P1} \text{ of lamp P1 in mW} \\ \text{Power } P_{P2} \text{ of lamp P2 in mW} \end{array}$$

Calculation

The **power** is calculated as follows:

$$P_{P1} = U \cdot I_1 \qquad P_{P2} = U \cdot I_2$$

The following applies to the **currents** in the parallel circuit:

$$I = I_1 + I_2$$

$$I_1 = \frac{U}{R_{P1}} \qquad I_2 = \frac{U}{R_{P2}}$$

$$\text{Since } R_{P1} = R_{P2}, \text{ it follows that } I_1 = I_2 = \frac{U}{R_{P1}} = \frac{12 \text{ V}}{193.5 \ \Omega} = 62 \text{ mA}$$

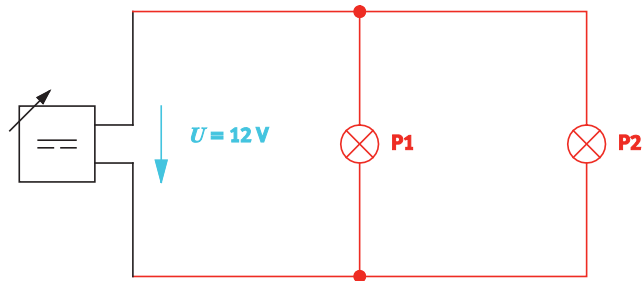
This gives the following for the **power** of the lamps P1 and P2:

$$P_{P1} = U \cdot I_1 = 12 \text{ V} \cdot 62 \text{ mA} = 744 \text{ mW}$$

$$P_{P2} = U \cdot I_2 = 12 \text{ V} \cdot 62 \text{ mA} = 744 \text{ mW}$$

■ Extending the circuit for the control lamps

- Extend the circuit for the control lamps and explain the reason for your choice of circuit.



Circuit for two control lamps P1 and P2 with the nominal data 12 V/62 mA

Identifier	Designation	Values
P1	Indicator light	12 V/62 mA
<i>R</i>	Resistor	220 Ω/2 W
–	Basic power supply unit EduTrainer®	–

Equipment list

The two lamps must be connected in parallel so that they can consume their maximum electrical power and release it again as light energy.

- Build the selected circuit and make sure it operates correctly.
- Complete the equipment list for the circuit.

Note

If you do not have two lamps, you can substitute a suitable ohmic resistor for one of the lamps.

Exercise 5:

Determining the electrical power for two circuit variants

■ Learning objectives

After completing this exercise:

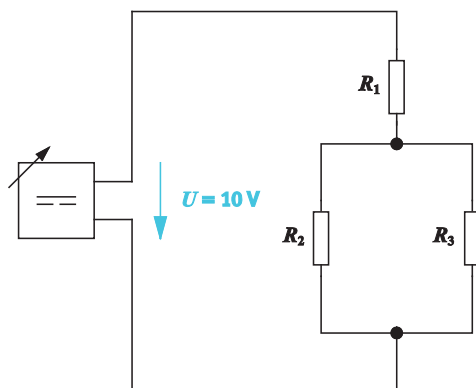
- You will be able to apply the basic electrical variables of energy and power.
- You will be able to size and calculate hybrid circuits.

■ Problem description

In electric cooking rings, different electrical powers are achieved with the help of differently connected resistors. Series circuits provide the least power, while parallel circuits provide the most power. The resistors are connected together in groups to achieve gradations in the power values or the generated thermal energy.

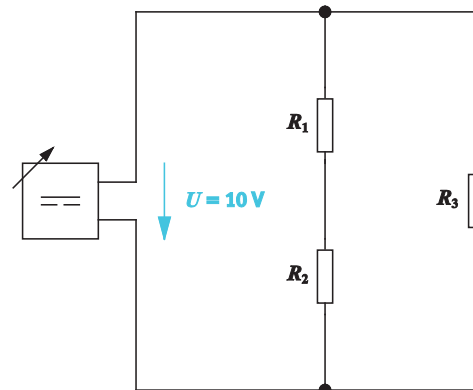
Determine the group circuit that provides the higher electrical power.

■ Circuit



Circuit 1

$R_1 = 100 \Omega$, $R_2 = 330 \Omega$, $R_3 = 220 \Omega$, $U = 10 \text{ V}$



Circuit 2

$R_1 = 100 \Omega$, $R_2 = 330 \Omega$, $R_3 = 220 \Omega$, $U = 10 \text{ V}$

■ **Project assignments**

1. Determine the electrical power for both circuits by measurement.
2. Calculate the total resistance for both circuits.
3. Calculate the electrical power for both circuits and select the circuit with the higher power.
4. Calculate the costs associated with operating a hotplate.

■ **Work aids**

- Textbooks, books of tables
- Data sheets
- Internet

Note

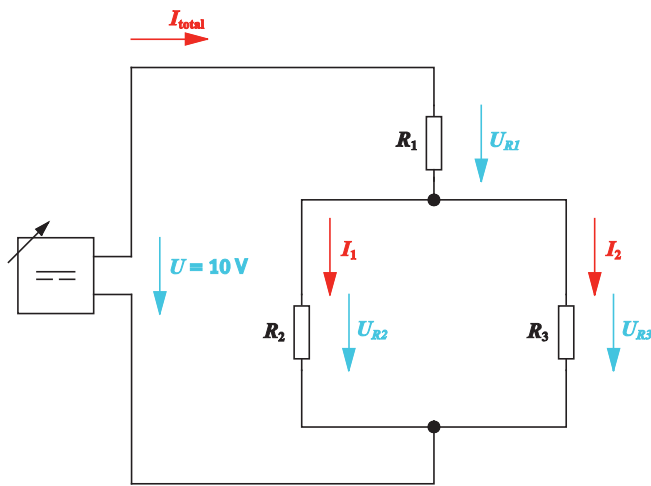
Do not switch on the electrical power supply until you have made and checked all the connections. Once you have completed the exercise, switch off the power supply again before dismantling the components.

■ Determining the electrical power by measurement

Determine the total resistance and electrical power of the two circuits by measuring current and voltage.

Electrical power of circuit 1

- Enter current and voltage arrows in the circuit wherever you measure current and voltage.
- Build the circuit.
- Measure the component currents and component voltages.
- Enter the measured values in the tables.



Measuring circuit 1 with $U = 10 \text{ V}$, $R_1 = 100 \Omega$, $R_2 = 330 \Omega$, $R_3 = 220 \Omega$

Identifier	Designation	Values
R_1	Resistor	$100 \Omega / 2 \text{ W}$
R_2	Resistor	$330 \Omega / 2 \text{ W}$
R_3	Resistor	$220 \Omega / 2 \text{ W}$
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

Equipment list

Component current I_1 (mA)	Component current I_2 (mA)	Total current I_{total} (mA)
17.2	25.7	42.7

Measurement log: Currents

Component voltage U_{R1} (V)	Component voltage U_{R2} (V)	Component voltage U_{R3} (V)
4.31	5.67	5.67

Measurement log: Voltages

- Calculate the total resistance using the measured values.

$$R = \frac{U}{I_{\text{total}}} = \frac{10 \text{ V}}{42.7 \text{ mA}} = 234 \Omega$$

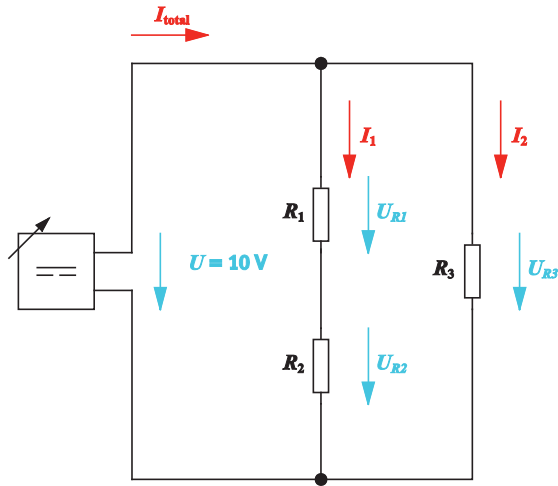
- Calculate the electrical power of the circuit from the measured values.

Electrical power of measuring circuit 1:

$$P = U \cdot I_{\text{total}} = 10 \text{ V} \cdot 42.7 \text{ mA} = 10 \text{ V} \cdot 0.0427 \text{ A} = 0.427 \text{ W}$$

Electrical power of circuit 2

- Enter current and voltage arrows in the circuit wherever you measure current and voltage.
- Build the circuit.
- Measure the component currents and component voltages.
- Enter the measured values in the tables.



Measuring circuit 2 with $U = 10 \text{ V}$, $R_1 = 100 \Omega$, $R_2 = 330 \Omega$, $R_3 = 220 \Omega$

Component current I_1 (mA)	Component current I_2 (mA)	Total current I_{total} (mA)
22.66	45.0	67.7

Measurement log: Currents

Component voltage U_{R1} (V)	Component voltage U_{R2} (V)	Component voltage U_{R3} (V)
2.33	7.66	10.0

Measurement log: Voltages

- Calculate the total resistance from the measured values.

$$R = \frac{U}{I_{total}} = \frac{10 \text{ V}}{67.7 \text{ mA}} = 147.7 \Omega = 148 \Omega$$

- Calculate the electrical power of the circuit from the measured values.

Electrical power of measuring circuit 2:

$$P = U \cdot I_{\text{total}} = 10 \text{ V} \cdot 67.7 \text{ mA} = 10 \text{ V} \cdot 0.0677 \text{ A} = 0.677 \text{ W}$$

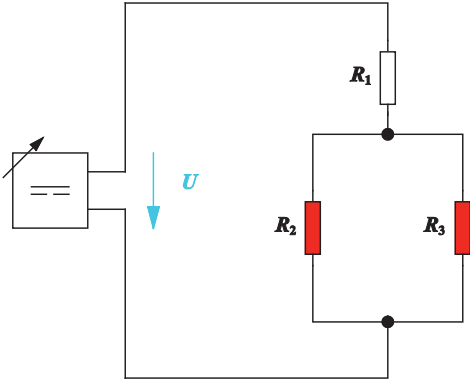
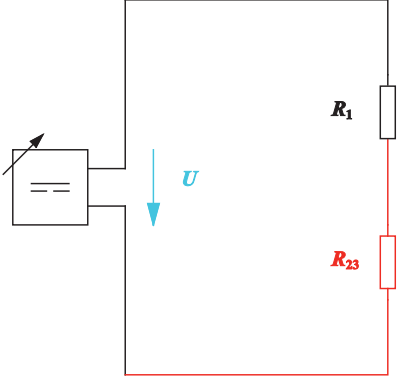
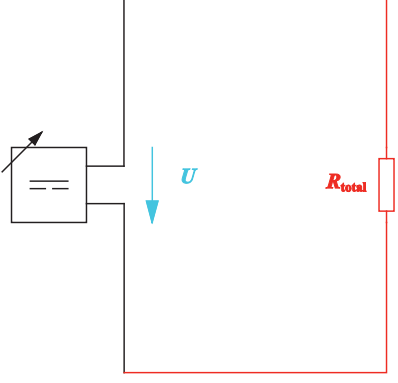
■ Determining the total resistance

Hybrid circuits are combinations of series and parallel circuits.

You break down the hybrid circuit by first calculating the equivalent resistances of parts of a circuit of this type and then calculating the total resistance of the complete circuit.

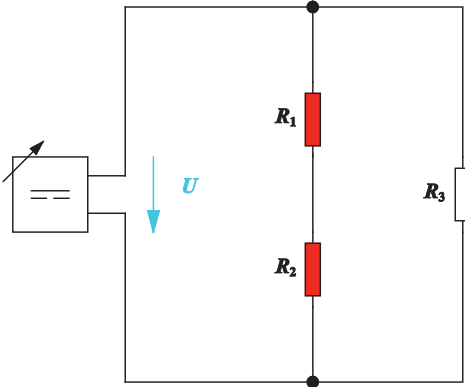
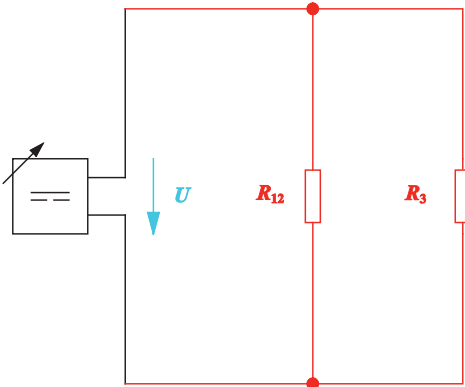
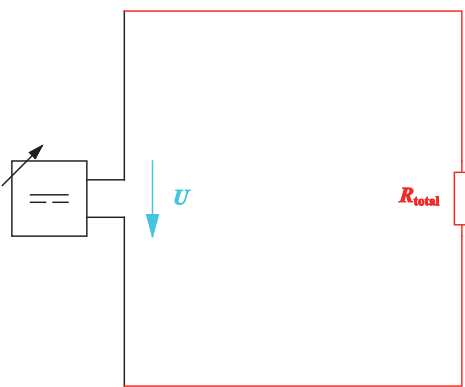
Total resistance for hybrid circuit 1

- Combine the resistances of the parallel circuit into one resistance.
- Sketch the equivalent resistance of the parallel circuit in the simplified circuit and specify the formula for calculating the equivalent resistance.
- Then determine the total resistance of the series circuit produced in this way.

Circuit	Resistance value
	<p>Individual resistances in the circuit</p> $R_1 = 100 \Omega, R_2 = 330 \Omega, R_3 = 220 \Omega$
	$R_{23} = \frac{R_2 \cdot R_3}{R_2 + R_3} = \frac{220 \Omega \cdot 330 \Omega}{220 \Omega + 330 \Omega} = 132 \Omega$
	$R_{\text{total}} = R_1 + R_{23} = 100 \Omega + 132 \Omega = 232 \Omega$

Total resistance for hybrid circuit 2

- Combine suitable resistances into one resistance.
- Draw the simplified circuit and specify the formula for calculating the equivalent resistance.
- Repeat the two steps until the entire circuit is represented by one resistance.

Circuit	Resistance value
	<p>Individual resistances in the circuit $R_1 = 100 \Omega$, $R_2 = 330 \Omega$, $R_3 = 220 \Omega$</p>
	$R_{12} = R_1 + R_2 = 100 \Omega + 330 \Omega = 430 \Omega$
	$R_{\text{total}} = \frac{R_{12} \cdot R_3}{R_{12} + R_3} = \frac{430 \Omega \cdot 220 \Omega}{430 \Omega + 220 \Omega} = 146 \Omega$

■ Selecting the circuit with the higher power

Formulae for calculating the electrical power

Use the following formula so that you do not have to rely on measured values when calculating the electrical power of a circuit:

$$P = \frac{U^2}{R}$$

- Using Ohm's law and the formula for power $P = U \cdot I$, explain why the two formulae are valid:

$$P = \frac{U^2}{R} \qquad P = I^2 \cdot R$$

The voltage is calculated as follows in accordance with Ohm's law:

$$U = R \cdot I$$

Inserted in the formula for the power P:

$$P = U \cdot I = (R \cdot I) \cdot I = R \cdot I^2$$

The current intensity is calculated as follows in accordance with Ohm's law:

$$I = \frac{U}{R}$$

Inserted in the formula for the power P:

$$P = U \cdot \frac{U}{R} = \frac{U^2}{R}$$

- Describe how the electrical power P changes if the voltage U is doubled.

If the voltage U is doubled, then the associated electrical power P is quadrupled.

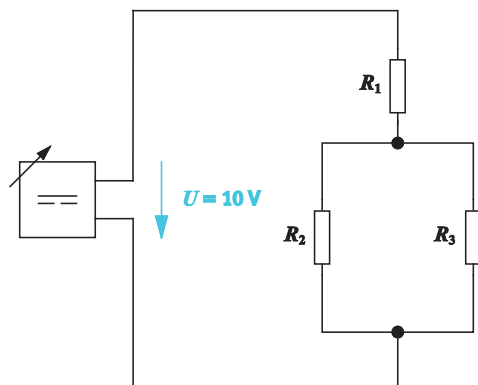
The power P is calculated as follows: $P = \frac{U^2}{R}$

The power P at twice the voltage U is calculated as follows:

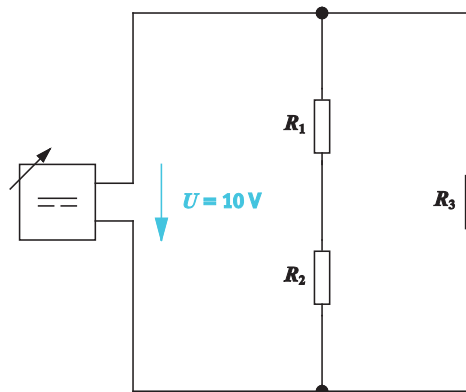
$$P = \frac{(2U)^2}{R} = \frac{2^2 \cdot U^2}{R} = 4 \cdot \frac{U^2}{R}$$

Calculating the electrical power for circuit variants 1 and 2

- Calculate the electrical power for the two hybrid circuits.
Use the calculated total resistance for the calculation.



Circuit 1: $R_1 = 100\ \Omega$, $R_2 = 330\ \Omega$, $R_3 = 220\ \Omega$
 $U = 10\ \text{V}$



Circuit 2: $R_1 = 100\ \Omega$, $R_2 = 330\ \Omega$, $R_3 = 220\ \Omega$
 $U = 10\ \text{V}$

Electrical power of circuit 1:

$$P = \frac{U^2}{R} = \frac{(10\ \text{V})^2}{232\ \Omega} = 0.43\ \text{W}$$

Electrical power of circuit 2:

$$P = \frac{U^2}{R} = \frac{(10\ \text{V})^2}{146\ \Omega} = 0.68\ \text{W}$$

Selecting the circuit with the higher power

- Compare the electrical power of circuit 1 and 2 and select the circuit with the higher power.

Circuit 2 provides the higher electrical power. If the resistances are combined, then the basic circuit is a parallel circuit.

■ Calculating the electricity costs for electrical work

Find out how electrical work is defined. Then calculate the costs for operating a hotplate.

- Specify the unit of measurement and the formula for calculating the electrical work.

$$W = U \cdot I \cdot t$$

here W is electrical work in $\text{Ws} = \text{J}$

U is electrical voltage in V

I is electrical current in A

t is time in s

Other formulae for calculating the electrical power:

Using $Q = I \cdot t$ gives $W = U \cdot Q$

Using $P = U \cdot I$ gives $W = P \cdot t$

- Calculate the annual cost of operating a hotplate that is used for an average of one hour per day. The hotplate's electrical power consumption is 1,200 W. 1 kWh costs 20 cent.

Given

Power $P = 1,200 \text{ W}$

Operating time $t = 365 \text{ h}$

Rate 20 cent/kWh

To be found

Costs in €

Calculation

Electrical work:

$$W = P \cdot t = 1200 \text{ W} \cdot 365 \text{ h} = 438000 \text{ Wh} = 438 \text{ kWh}$$

Costs for the electrical work:

$$0.20 \frac{\text{€}}{\text{kWh}} \cdot 438 \text{ kWh} = 87.60 \text{ €}$$

The annual cost of operating the hotplate is €87.60.

Exercise 6:

Selecting measuring circuits

■ Learning objectives

After completing this exercise:

- You will be able to use suitable measuring circuits to perform measurements.
- You will be able to test the function of electric circuits.

■ Problem description

In a circuit, a resistance value is determined indirectly by means of a voltage/current measurement.

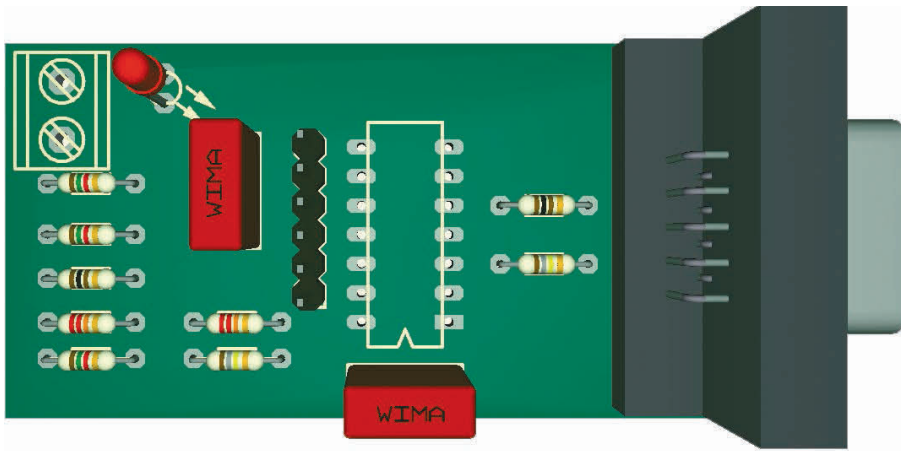
The resistance value is $27\ \Omega$. The control measurement using the digital multimeter gives a value of $22\ \Omega$.

What is the reason for this big deviation?

The voltage error circuit was used as the measuring circuit for the indirect resistance measurement. Current and voltage were measured at the same time.

Check whether the indirect resistance measurement was performed correctly.

■ Circuit



PCB with circuit

■ **Project assignments**

1. Build the voltage error circuit and check the measured values.
2. Find out other measuring circuits for indirect resistance measurement.
3. To gain a better understanding of the measuring circuits, describe Kirchhoff's first (nodal) and second (mesh) laws.
4. Supported by measurement experiments, decide when the voltage error circuit and when the current error circuit should be used for indirect measurement of a resistance.

■ **Work aids**

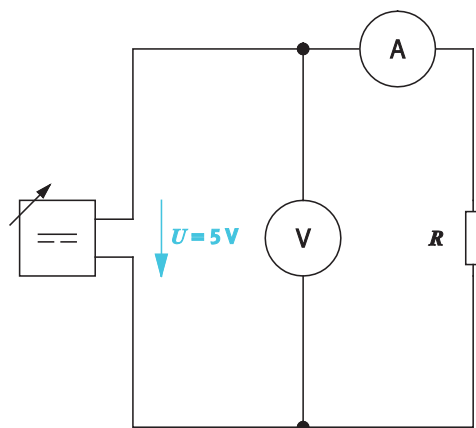
- Textbooks, books of tables
- Data sheets
- Internet

Note

Do not switch on the electrical power supply until you have made and checked all the connections. Once you have completed the exercise, switch off the power supply again before dismantling the components.

■ Checking the indirect resistance measurement with voltage error circuit

- Use the prescribed resistance of $22\ \Omega$ for the measurement.
- Determine the exact resistance values according to the direct measuring method using the digital multimeter. Enter the values in the measurement log.
- Build the voltage error circuit.
- Measure voltage and current at the same time for the selected resistance.
- Enter the measured values as well as the calculated resistance value and the formula for calculating the resistance value in the table.
- Evaluate the measurement results.



Voltage error circuit

Identifier	Designation	Values
R	Resistor	$22\ \Omega/2\ \text{W}$
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

Equipment list

The resistance R is calculated in accordance with the formula:

$$R = \frac{U}{I}$$

$R (\Omega)$ measured using multimeter	I (mA) measured	U (V) measured	$R (\Omega)$ calculated from measured values
22.1	182	4.99	27.4

Measurement log: Voltage error circuit

Evaluation

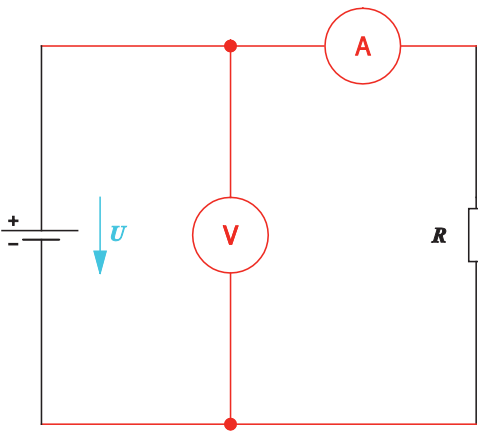
The voltage error circuit for determining the resistance value gives too high a value.

■ **Compiling the possible measuring circuits for indirect resistance measurement**

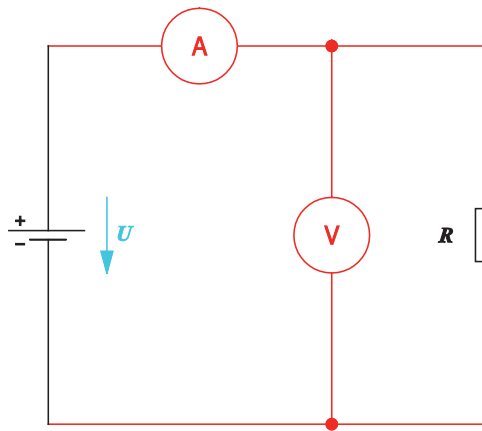
When measuring resistance indirectly, you calculate the value of the unknown resistance from the measured values for current and voltage.

The internal resistance of the ammeter and voltmeter influences the measurement result. Depending on the magnitude of the unknown resistance, that is why different measuring circuits are used.

- Research the types of measuring circuits available.
- Complete the measuring circuits and also write down the name of the measuring circuit.



Voltage error circuit



Current error circuit

■ Describing Kirchhoff's first and second laws

The laws governing series and parallel connection play a role when evaluating measuring circuits. The laws are generally formulated as Kirchhoff's first and second laws.

Kirchhoff's first law

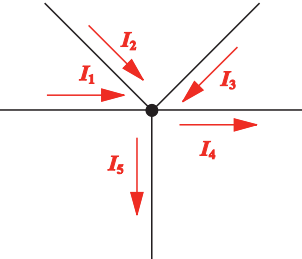
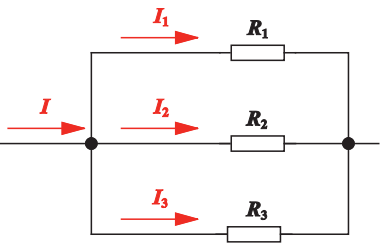
Parallel connection of resistors results in branching points (so-called nodes) in the electrical current.

- Formulate Kirchhoff's first law.

Kirchhoff's first law

In each node, the sum of the currents flowing into the node is equal to the sum of the currents flowing out of it or the sum of all currents is zero.

- Enter the formula that applies to the currents for the circuits.

Sample circuit	Formula for calculating the currents
	$I_1 + I_2 + I_3 = I_4 + I_5$
	$I = I_1 + I_2 + I_3$

Sample circuits for Kirchhoff's first law

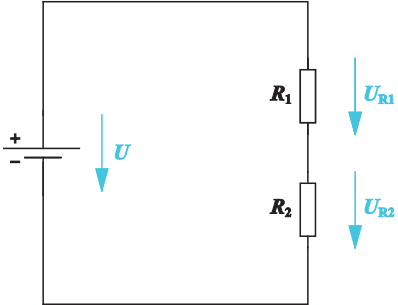
Kirchhoff's second law

A certain voltage distribution takes place in a closed electrical circuit (also called a mesh).

- Formulate Kirchhoff's second law.
- Enter the formula that applies to the voltages for the sample circuit.

Kirchhoff's second law

The sum of all component voltages is zero in any closed electrical circuit.

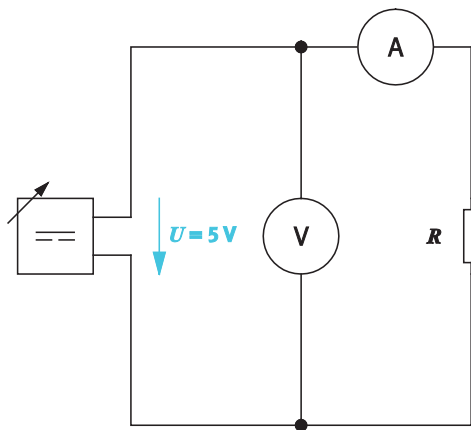
Sample circuit	Formula for calculating the voltage
	$U = U_{R1} + U_{R2}$

Sample circuit for Kirchhoff's second law

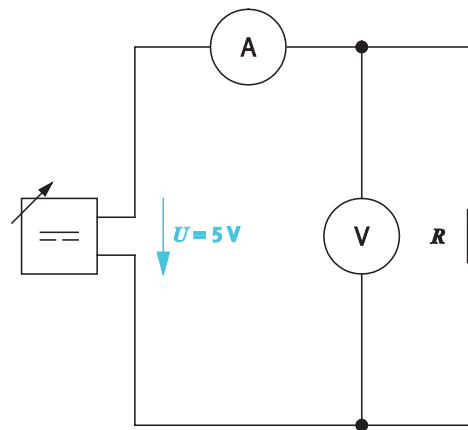
■ Evaluating the current and voltage error circuit

To be able to assess the use of the different measuring circuits, perform measurement experiments using a high-impedance and a low-impedance resistor.

- Use both measuring circuits for a high-impedance resistor as well as the prescribed low-impedance resistor. To do this, select a suitable high-impedance resistor. Also enter the resistor in the equipment list.
- Determine the exact resistance value for the two resistors according to the direct measuring method using the digital multimeter. Enter the values in the measurement log.
- Build the two measuring circuits for the two resistors one after the other and perform the necessary current and voltage measurements.
- Enter the measured values as well as the calculated resistance value in the corresponding measurement log.



Voltage error circuit



Current error circuit

Identifier	Designation	Values
R	Resistor	$22\ \Omega/2\ \text{W}$
R	Resistor	$10\ \text{k}\Omega/2\ \text{W}$
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

Equipment list

R (Ω) measured	I (mA) measured	U (V) measured	R (Ω) calculated
9.94 k Ω	0.5	5.0	10 k Ω
22.1 Ω	182	4.99	27.42 Ω

Measurement log: Voltage error circuit

R (Ω) measured	I (mA) measured	U (V) measured	R (Ω) calculated
9.94 k Ω	0.5	4.99	9.98 k Ω
22.1 Ω	182.2	3.96	21.73 Ω

Measurement log: Current error circuit

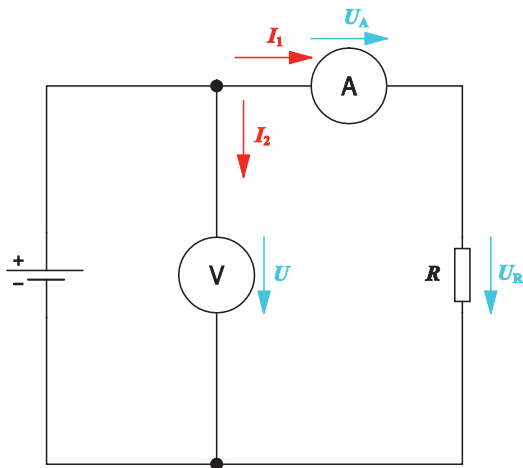
- Evaluate the measurements. Decide which measuring circuit provides the more accurate results for low impedance and high-impedance consuming devices.

The voltage error circuit is suitable for high-impedance consuming devices.

The current error circuit is suitable for low-impedance consuming devices.

One variable is measured incorrectly in both measuring circuits.

- Sketch the component voltages and component currents as well as the total voltage and total current in both measuring circuits.
- For each measuring circuit, name the electrical variable that is calculated incorrectly.
- Explain why this variable is calculated incorrectly.



Voltage error circuit

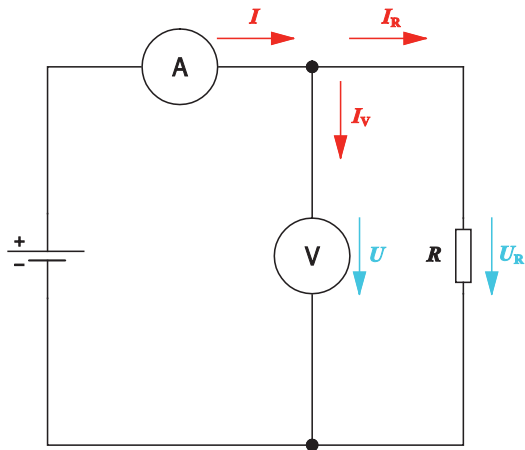
Voltage error circuit

In the voltage error circuit, it is the total voltage U that is measured and not the voltage U_R applied to the resistor R .

U is calculated as follows: $U = U_A + U_R$ (Kirchhoff's second law)

The total voltage is therefore higher than the voltage applied to the resistor R . That is why this circuit is called a voltage error circuit.

In high-impedance consuming devices, the internal resistance of the ammeter is small compared with the resistance to be measured. The internal resistance and therefore the ammeter's voltage drop exert very little influence on the measurement result.



Current error circuit

Current error circuit

In the current error circuit, it is the total current intensity I that is measured and not the current intensity I_R flowing through the resistor R .

I is calculated as follows: $I = I_R + I_V$ (Kirchhoff's first law)

The total current intensity I used is greater than the current intensity I_R flowing through the resistor. The circuit is therefore called a current error circuit.

The current error circuit is better with low-impedance consuming devices. Here, the low current flow through the high-impedance voltmeter only has a minimal effect on the measurement result compared with the current flow through the low-impedance consuming device.

Exercise 7:

Designing a circuit for a voltage divider

■ Learning objectives

After completing this exercise:

- You will be familiar with loaded voltage dividers as an application of hybrid circuits.
- You will be able to calculate the output voltage for an unloaded and a loaded voltage divider.
- You will be able to size a loaded voltage divider.

■ Problem description

A voltage divider is to be installed in the circuit of the battery charger for the mobile Robotino[®] robot.

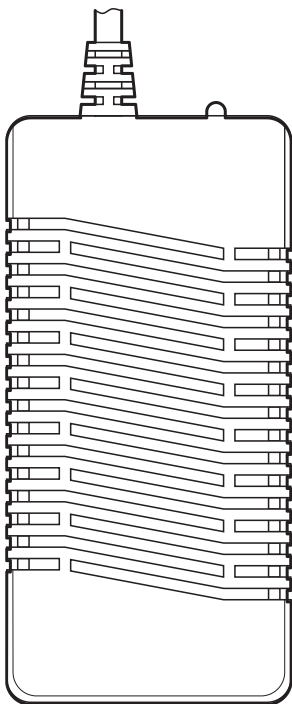
The voltage divider's function is to generate an output voltage of $U = 2\text{ V}$ from a total voltage of $U = 12\text{ V}$.

The load current through the consuming device is 10 mA .

In order for the output voltage to remain relatively constant even when the load fluctuates, the transverse current through the voltage divider should be five times greater than the load current.

Design and size the circuit for the voltage divider.

■ Circuit



Battery charger for Robotino[®]

■ **Project assignments**

1. Calculate the output voltage at the unloaded voltage divider.
2. Measure the output voltage at the unloaded voltage divider.
3. Specify the formula for calculating the output voltage at the loaded voltage divider.
4. Measure the output voltage at the loaded voltage divider.
5. Design and size the circuit for the battery charger's voltage divider.

■ **Work aids**

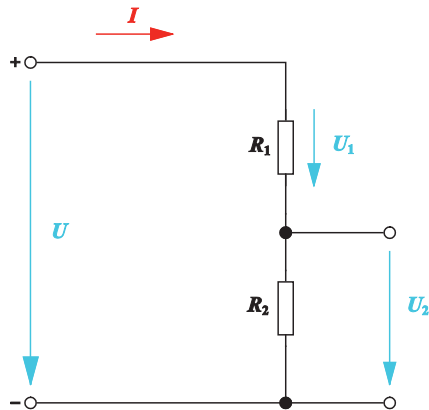
- Textbooks, books of tables
- Data sheets
- WBT Electrical engineering 1
- Internet

Note

Do not switch on the electrical power supply until you have made and checked all the connections. Once you have completed the exercise, switch off the power supply again before dismantling the components.

■ Calculating the output voltage at the unloaded voltage divider

Voltage dividers are used if available voltages are too high and therefore need to be divided.



Fixed unloaded voltage divider

The voltage divider consists of two resistors R_1 and R_2 connected in series. There is no consuming device connected to the unloaded voltage divider.

The component voltage U_2 is also called the **output voltage** of the voltage divider.

The output voltage of the unloaded voltage divider is the voltage drop across the resistor R_2 .

- Specify the formula for calculating the output voltage U_2 .

In the series circuit, the component voltages behave like the associated resistances.

$$\frac{U}{U_2} = \frac{R}{R_2} = \frac{R_1 + R_2}{R_2}$$

This gives the following for the output voltage U_2 :

$$U_2 = U \cdot \frac{R_2}{R_1 + R_2}$$

- Calculate the output voltage U_2 for the unloaded voltage divider. The voltage divider is constructed with the resistors $R_1 = 680 \Omega$ and $R_2 = 330 \Omega$. The total voltage U is 10 V.

Given

Resistance	$R_1 = 680 \Omega$
Resistance	$R_2 = 330 \Omega$
Voltage	$U = 10 \text{ V}$

To be found

Output voltage U_2 in V

Calculation

$$\frac{U}{U_2} = \frac{R_1 + R_2}{R_2}$$

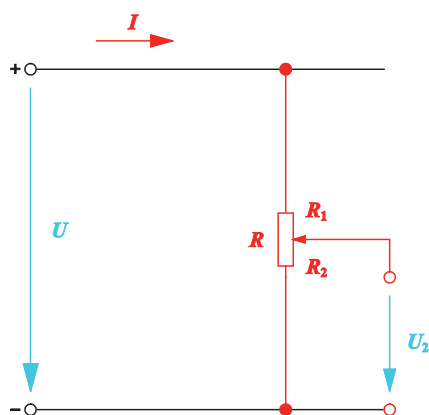
This gives the following for the output voltage U_2 :

$$U_2 = U \cdot \frac{R_2}{R_1 + R_2} = 10 \text{ V} \cdot \frac{330 \Omega}{680 \text{ k}\Omega + 330 \text{ k}\Omega} = 10 \text{ V} \cdot \frac{330 \Omega}{1010 \Omega} = 3.27 \text{ V}$$

Voltage divider with potentiometer

In order to be able to adjust the voltage U_2 , one potentiometer is connected to the electrical circuit instead of the two fixed resistors. The adjustable pick-off divides the total resistance R into R_1 and R_2 .

- Complete the circuit so that you end up with an adjustable unloaded voltage divider.



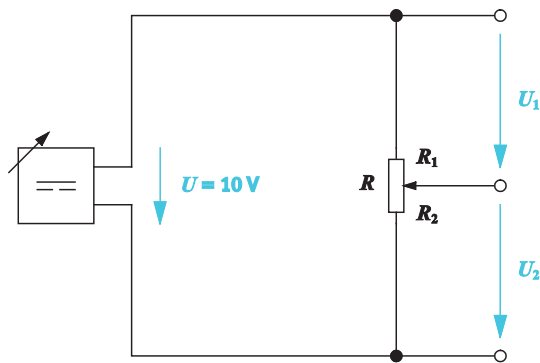
Adjustable unloaded voltage divider

■ **Measuring the voltages at the unloaded voltage divider**

Create the characteristic for an unloaded voltage divider. The characteristic shows the dependence of the output voltage U_2 on the set resistance R_2 .

Construct the voltage divider using a potentiometer so that you can adjust its resistance R_2 .

- Build the circuit with the variable voltage divider.



Adjustable unloaded voltage divider with $R = 1\text{ k}\Omega$, $U = 10\text{ V}$

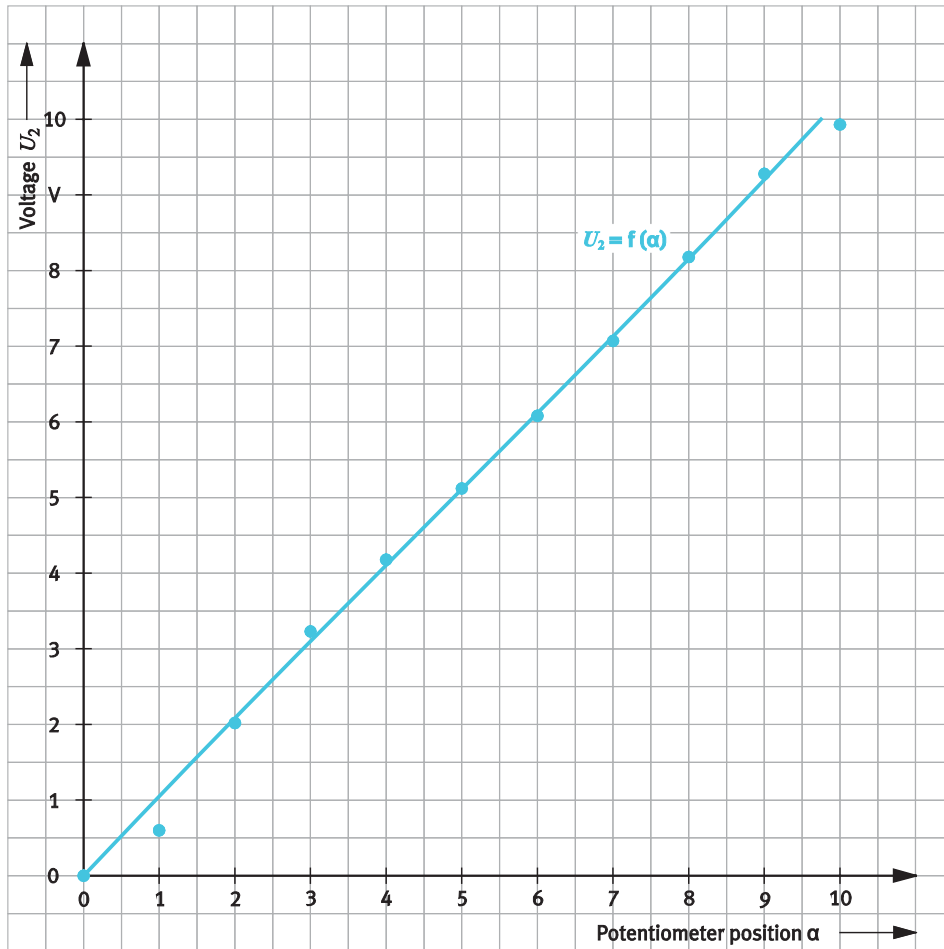
Identifier	Designation	Values
R	Potentiometer	1 k Ω /0.5 W
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

Equipment list

- Apply a DC voltage of 10 V to the circuit.
- Measure the voltages U_1 and U_2 at the specified potentiometer positions.
- Enter the measured values in the table.

Measurement log: Output voltage											
Potentiometer position	0	1	2	3	4	5	6	7	8	9	10
U_1 (V)	9.94	9.29	7.91	6.70	5.77	4.79	3.88	2.86	1.76	0.66	0.01
U_2 (V)	0	0.6	2.02	3.23	4.18	5.12	6.08	7.07	8.18	9.28	9.93

- Draw the characteristic of the output voltage U_2 as a function of the potentiometer setting. To do this, transfer the measured values for U_2 to the graph.



Characteristic $U_2 = f(\alpha)$.

α is the rotation angle of the potentiometer and specifies the potentiometer position

- Describe the waveform of the characteristic.

The characteristic of the potentiometer $U_2 = f(\alpha)$ is a straight line.

- Describe the relationship between the component voltages U_1 and U_2 .

When the component voltages U_1 and U_2 are added, this results in the applied voltage U regardless of the potentiometer position.

$$U = U_1 + U_2$$

- Calculate the component resistance R_2 for the potentiometer position 4. The component voltage U_2 is picked off for this resistance R_2 .

Given

Component voltage $U_2 = 4.18 \text{ V}$

To be found

Component resistance R_2 in Ω

Calculation

$$\frac{U}{U_2} = \frac{R_1 + R_2}{R_2}$$

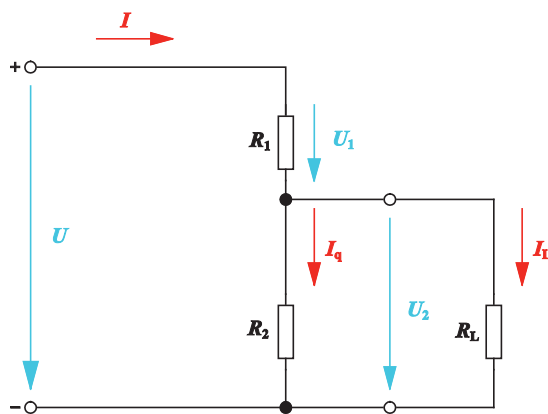
Solved for R_2 :

$$R_2 = \frac{U_2}{U} \cdot (R_1 + R_2) = \frac{4.18 \text{ V}}{10 \text{ V}} \cdot 1 \text{ k}\Omega = 0.418 \cdot 1000 \Omega = 418 \Omega$$

■ Formula for calculating the output voltage at the loaded voltage divider

The component voltage U_2 achieved by dividing the voltage is generally supplied to a consuming device R_L . In this case we talk about a loaded voltage divider.

The voltage drop at the parallel circuit is the output voltage of the loaded voltage divider.



Fixed loaded voltage divider with cross current I_q and load current I_L

The parallel connection of R_2 and R_L changes the voltage ratio of R_1 and R_2 compared with an unloaded voltage divider.

The voltages and resistances in a loaded voltage divider are calculated using a ratio equation. To do this, you need the equivalent resistance R_A of the parallel circuit containing R_2 and R_L .

- Specify the formula for calculating the equivalent resistance R_A .

$$R_A = \frac{R_2 \cdot R_L}{R_2 + R_L}$$

- Specify the formula for calculating the output voltage U_2 .

The following ratio equation applies to the series circuit consisting of the resistance R_1 and the equivalent resistance R_A :

$$\frac{U}{U_2} = \frac{R_1 + R_A}{R_A}$$

This gives the following for the output voltage U_2 :

$$U_2 = U \cdot \frac{R_A}{R_1 + R_A}$$

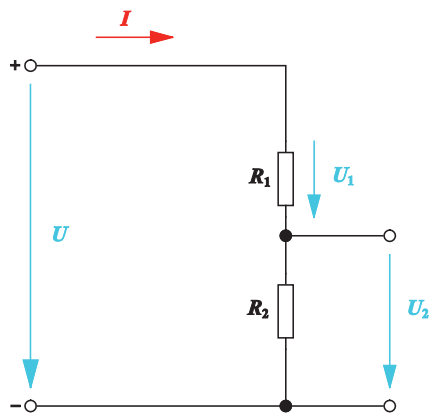
- Specify the formula for calculating the total current I .

$$I = I_q + I_L$$

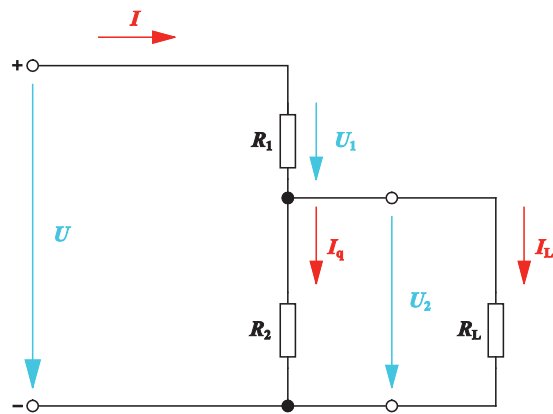
- Describe how the voltage ratios in the loaded voltage divider change compared with the unloaded voltage divider.

Information

If the transverse current I_q is a multiple of the load current I_L , then the output voltage U_2 is relative load-independent. Conversely, this means that the resistance R_1 should be a multiple of the resistance R_2 .



Unloaded voltage divider



Loaded voltage divider

In the **unloaded voltage divider**, the output voltage U_2 is determined by the resistance R_2 .

In the **loaded voltage divider**, the output voltage U_2 is determined by the equivalent resistance R_A . The following applies to the equivalent resistance R_A : it is always smaller than the smallest resistance in the parallel circuit. The equivalent resistance R_A is therefore always smaller than the resistance R_2 . The voltage U_2 therefore decreases.

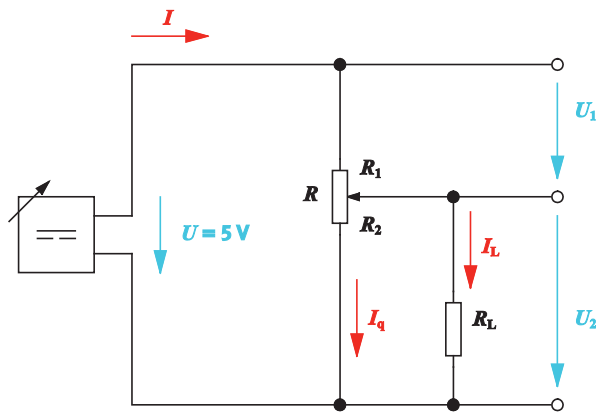
The total resistance of the circuit is reduced by the load resistance R_L . The current consumption I of the circuit therefore increases. The voltage U_1 at the resistance R_1 increases.

■ **Measuring the output voltage at the loaded voltage divider**

Determine the effect of a change in the load resistance on the output voltage U_2 by means of suitable measurements. Therefore select four different load resistances for the measurements.

In order to be able to adjust the voltage U_2 of the loaded voltage divider, use a potentiometer. Depending on the position of the wiper (rotation angle α of the potentiometer), a voltage from $0 - U_{\max}$ can now be set.

- Build the circuit with the adjustable voltage divider.



Adjustable loaded voltage divider with $R = 1 \text{ k}\Omega$
and different load resistances: $R_L = 100 \Omega$, $R_L = 330 \Omega$, $R_L = 1 \text{ k}\Omega$, $R_L = 10 \text{ k}\Omega$

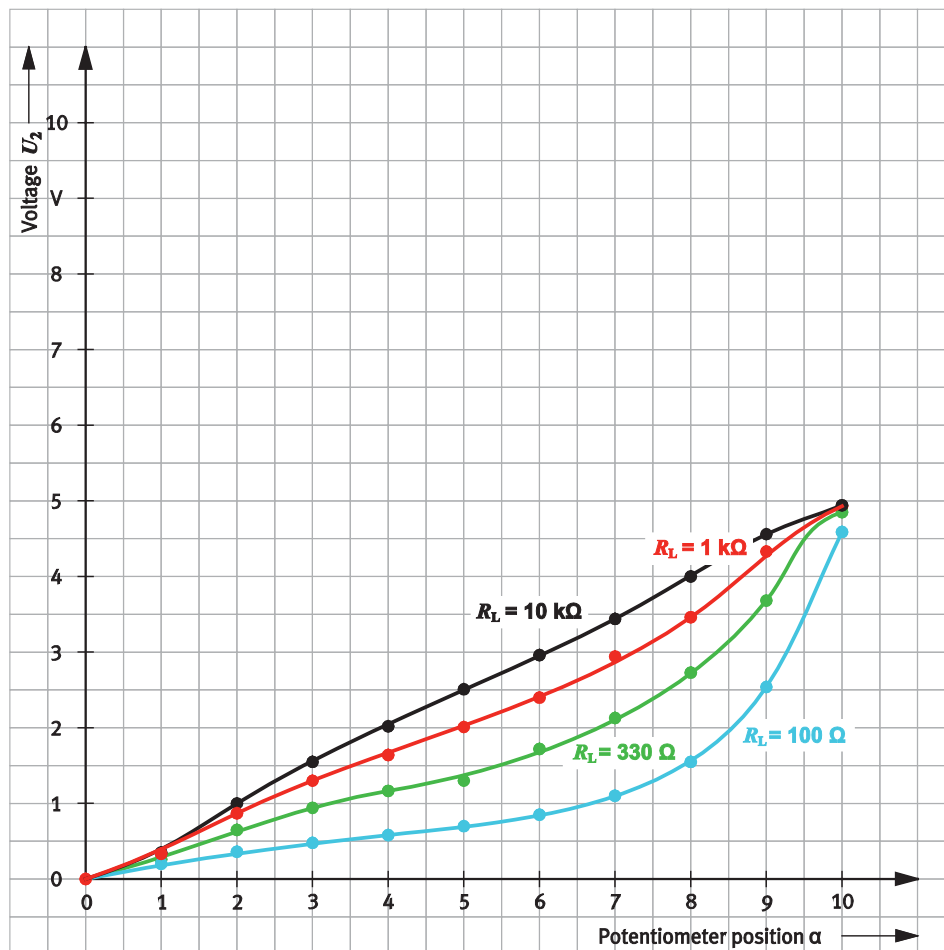
Identifier	Designation	Values
R	Potentiometer	1 kΩ/0.5 W
R_L	Resistor	100 Ω/2 W
R_L	Resistor	330 Ω/2 W
R_L	Resistor	1 kΩ/2 W
R_L	Resistor	10 kΩ/2 W
-	Digital multimeter	-
-	Basic power supply unit EduTrainer®	-

Equipment list

- Apply a DC voltage $U = 5 \text{ V}$ to the circuit.
- Measure the voltage U_2 at the specified potentiometer positions for each load resistance R_L .
- Enter the measured values in the table.

Measurement log: Output voltage											
Potentiometer position	0	1	2	3	4	5	6	7	8	9	10
U_2 (V) for $R_L = 10 \text{ k}\Omega$	0	0.31	1.00	1.55	2.02	2.51	2.96	3.44	4.00	4.56	4.94
U_2 (V) for $R_L = 1 \text{ k}\Omega$	0	0.3	0.87	1.30	1.64	2.01	2.40	2.94	3.46	4.33	4.93
U_2 (V) for $R_L = 330 \text{ k}\Omega$	0	0.26	0.65	0.94	1.17	1.30	1.72	2.13	2.73	3.68	4.85
U_2 (V) for $R_L = 100 \text{ k}\Omega$	0	0.20	0.36	0.48	0.58	0.70	0.85	1.10	1.55	2.54	4.59

- Draw the four characteristics for the output voltage U_2 as a function of the potentiometer position. To do this, transfer the measured values for U_2 to the graph.



Characteristics $U_2 = f(\alpha)$.

α is the rotation angle of the potentiometer and specifies the potentiometer position

- Describe the waveform of the characteristics.

The characteristics of the loaded voltage divider do not have a linear waveform. Depending on the extent of the load, the voltage change per unit is smaller in the bottom adjusting range than in the top adjusting range.

- Describe what effect the magnitude of the load resistance has on the output voltage U_2 of the voltage divider.

The smaller the load resistance R_L , the more curved the characteristic waveform.

With small values for R_L , precise voltage values U_2 are difficult to set. Load fluctuations then have a relatively strong effect on the output voltage U_2 .

- Calculate the output voltage U_2 of the voltage divider for all four load resistances for the potentiometer's mid-position.
- Enter the values to be found in the table.

Given

Resistance R_1 when the wiper is in the mid-position

$$R_1 = R_2 = 0,5 \cdot 1 \text{ k}\Omega = 500 \Omega$$

Voltage $U = 5 \text{ V}$

To be found

Output voltage U_2 for load resistance $R_L = 100 \Omega$, $R_L = 330 \Omega$, $R_L = 1 \text{ k}\Omega$, $R_L = 10 \text{ k}\Omega$

Calculation

$$\frac{U}{U_2} = \frac{R_1 + R_A}{R_A}$$

Solved for U_2 :

$$U_2 = U \cdot \frac{R_A}{R_1 + R_A}$$

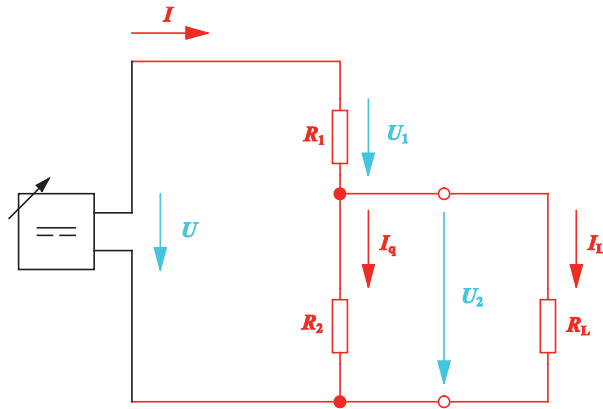
The equivalent resistance of the parallel circuit is calculated as follows:

$$R_A = \frac{R_2 \cdot R_L}{R_2 + R_L}$$

Load resistance	Equivalent resistance	Output voltage
$R_L = 100 \Omega$	$R_A = 83.33 \Omega$	$U_2 = 0.71 \text{ V}$
$R_L = 330 \Omega$	$R_A = 198.80 \Omega$	$U_2 = 1.42 \text{ V}$
$R_L = 1 \text{ k}\Omega$	$R_A = 333.33 \Omega$	$U_2 = 2.00 \text{ V}$
$R_L = 10 \text{ k}\Omega$	$R_A = 476.19 \Omega$	$U_2 = 2.44 \text{ V}$

■ Designing and sizing the circuit for the voltage divider

- Complete the circuit for the battery charger's voltage divider.
Use fixed resistors and enter a resistor as a replacement for the consuming device.



Circuit for the voltage divider

- Size the resistances R_1 and R_2 of the voltage divider.

Given

Total voltage	$U = 12 \text{ V}$
Output voltage	$U_2 = 2 \text{ V}$
Load current	$I_L = 10 \text{ mA}$
Transverse current	$\frac{I_q}{I_L} = 5$

To be found

Transverse current I_q in mA
 Voltage divider resistance R_1 in Ω
 Voltage divider resistance R_2 in Ω

Calculation

$$R_1 = \frac{U_1}{I} = \frac{U - U_2}{I}$$

I_q is calculated as follows:

$$I_q = 5 \cdot I_L = 5 \cdot 10 \text{ mA} = 50 \text{ mA}$$

I is calculated as follows:

$$I = I_q + I_L = 50 \text{ mA} + 10 \text{ mA} = 60 \text{ mA}$$

This gives the following for R_1 :

$$R_1 = \frac{U_1}{I} = \frac{U - U_2}{I} = \frac{12 \text{ V} - 2 \text{ V}}{60 \text{ mA}} = \frac{10 \text{ V}}{0.06 \text{ A}} = 167 \Omega$$

R_2 is calculated as follows:

$$R_2 = \frac{U_2}{I_q} = \frac{2 \text{ V}}{50 \text{ mA}} = \frac{2 \text{ V}}{0.05 \text{ A}} = 40 \Omega$$

Result:

The resistances of the voltage divider are: $R_1 = 167 \Omega$ and $R_2 = 40 \Omega$.

Exercise 8:

Designing safety circuits for a drill

■ Learning objectives

After completing this exercise:

- You will be familiar with the circuit symbols and mode of operation of the non-linear resistors NTC, PTC, VDR, LDR.
- You will be able to trace and interpret the characteristics of non-linear resistors.
- You will be able to select and use non-linear resistors as appropriate to the technical requirements.

■ Problem description

The safety circuits for an electric drill are still incomplete.

To make the drill more durable, it is equipped with thermal overload protection. The thermal overload protection is to be realised using a non-linear resistor.

A voltage-dependent resistor is to be used to prevent voltage surges in the drill's control electronics.

Select suitable resistors and safety circuits for the drill.

■ Positional sketch



Drill

■ Project assignments

1. Find out which non-linear resistors are available to you.
2. Describe the mode of operation of the temperature-dependent resistors NTC and PTC.
3. Trace the characteristic of the NTC resistor.
4. Sketch the behaviour of the PTC resistor.
5. Trace the characteristic of the VDR resistor.
6. Investigate the behaviour of the LDR resistor by means of measurement experiments.
7. Select a suitable non-linear resistor for limiting current in the drill.
8. Create the circuit for using the VDR resistor as overvoltage protection for the drill.

■ Work aids

- Textbooks, books of tables
- Data sheets
- WBT Electrical engineering 1
- Internet

Note

Do not switch on the electrical power supply until you have made and checked all the connections. Once you have completed the exercise, switch off the power supply again before dismantling the components.

■ Compiling the non-linear resistors

Resistors are components with a particular resistance behaviour. Based on their behaviour in the electrical circuit, a differentiation is made between

- linear resistors and
- non-linear resistors.

- Describe the key characteristic of linear resistors.

Linear resistors are resistors with a linear voltage/current characteristic. Ohm's law applies.




- Describe the key characteristic of non-linear resistors.

Non-linear resistors have a **non-linear** voltage/current characteristic.

The current/voltage characteristic is therefore **not** a straight line.

The resistance value changes as a function of one or even more than one physical variable such as voltage, temperature, pressure or light.

- Find out which non-linear resistors are available for DC circuits.
- Enter the resistors in the table and complete the associated fields.

Non-linear resistor	Change in resistance due to	Circuit symbol
NTC resistor	Temperature	
VDR resistor	Voltage	
LDR resistor	Light	



Non-linear resistors in the equipment set

■ **Describing the mode of operation of temperature-dependent resistors**

With temperature-dependent resistors, the resistance value changes as a function of temperature.

Two types of temperature-dependent resistors are differentiated:

- PTC resistors
 - NTC resistors
- Complete the table and describe which resistor conducts electrical current better in cold conditions and in hot conditions.

PTC resistors (Positive Temperature Coefficient)	NTC resistors (Negative Temperature Coefficient)
Positive temperature coefficient α	Negative temperature coefficient α
Temperature increases ↑ Resistance value increases ↑	Temperature increases ↑ Resistance value decreases ↓
	
The resistor conducts better in cold conditions → PTC thermistor	The resistor conducts better in hot conditions → NTC thermistor

Temperature-dependent resistors

Temperature-dependent resistors are characterised by their temperature coefficient α .

- Describe what is meant by the temperature coefficient α .

The temperature coefficient α specifies the percentage change in the resistance value when the temperature is increased by 1 K.

Temperature-dependent resistors can be heated up in different ways

- External heating
 - Self-heating
- Describe what is meant by **external heating** and **self-heating**.

External heating:

The resistor is heated up by the ambient temperature.

Self-heating:

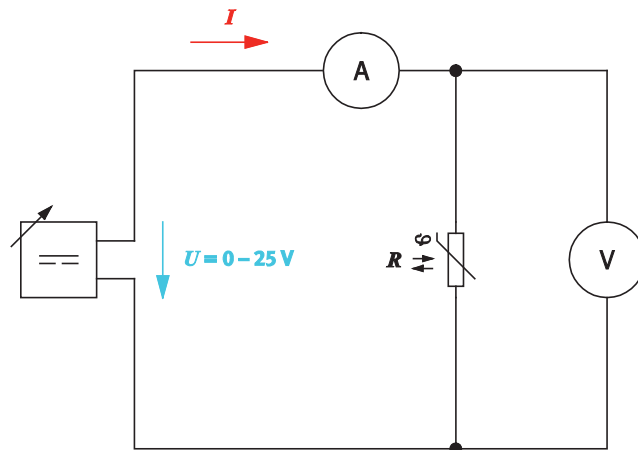
The resistor is heated up by the current flowing through it.

■ Determining the characteristics of the NTC resistor

Trace the characteristics of the NTC resistor.

To do this, start by performing the measurements for the voltage/current characteristic. Using the voltage/current characteristic, create the voltage/resistance characteristic.

The change in the resistance of the NTC resistor is temperature-dependent and is to be induced through self-heating of the NTC resistor. The self-heating is induced through the application of different electrical loads to the NTC resistor.



Measuring circuit with NTC resistor

Identifier	Designation	Values
R	NTC resistor	4.7 k Ω /0.45 W
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

Equipment list

- Investigate and explain whether precautions to limit current and voltage need to be made during the measurements.

If the voltage U is increased, the electrical load on the resistor increases. The associated increase in temperature reduces the resistance value. The current intensity rises disproportionately. The current in this circuit must be limited to ensure that the maximum power loss of the NTC resistor is not exceeded during the measurements.

- Calculate the maximum current intensity I that can flow through the NTC resistor at a voltage $U = 25 \text{ V}$.

The following formula applies:

$$P = U \cdot I$$

Solved for I :

$$I = \frac{P}{U} = \frac{0,45 \text{ W}}{25 \text{ V}} = 0.018 \text{ A}$$

At $U = 25 \text{ V}$, the current intensity must be limited to $I = 18 \text{ mA}$.

- Build the circuit.
- Measure the current through the NTC resistor at the voltages specified in the measurement log.
- Enter the measured values in the measurement log.

Note

After increasing the voltage, wait approx. 30 seconds before reading off the current. This delay is to enable the NTC resistor to achieve a thermally stable state after a change in resistance.

- Calculate the power converted in the NTC resistor as well as the resistance value for the measured values.

Note

Abandon the series of measurements if the calculated power P reaches a value of 0.45 W. The current through the NTC resistor must not exceeded 18 mA.

Measurement log: Voltage/current characteristic at 22°C room temperature							
Voltage U_{NTC} (V)	1	2	5	10	15	20	25
Current I (mA)	0.192	0.384	0.965	2.003	3.213	5.01	8.10
Power P_{NTC} (mW)	0.192	0.768	4.825	20.03	48.195	100.2	202.5
Resistance R_{NTC} (kΩ)	5.208	5.208	5.181	4.993	4.669	3.992	3.086

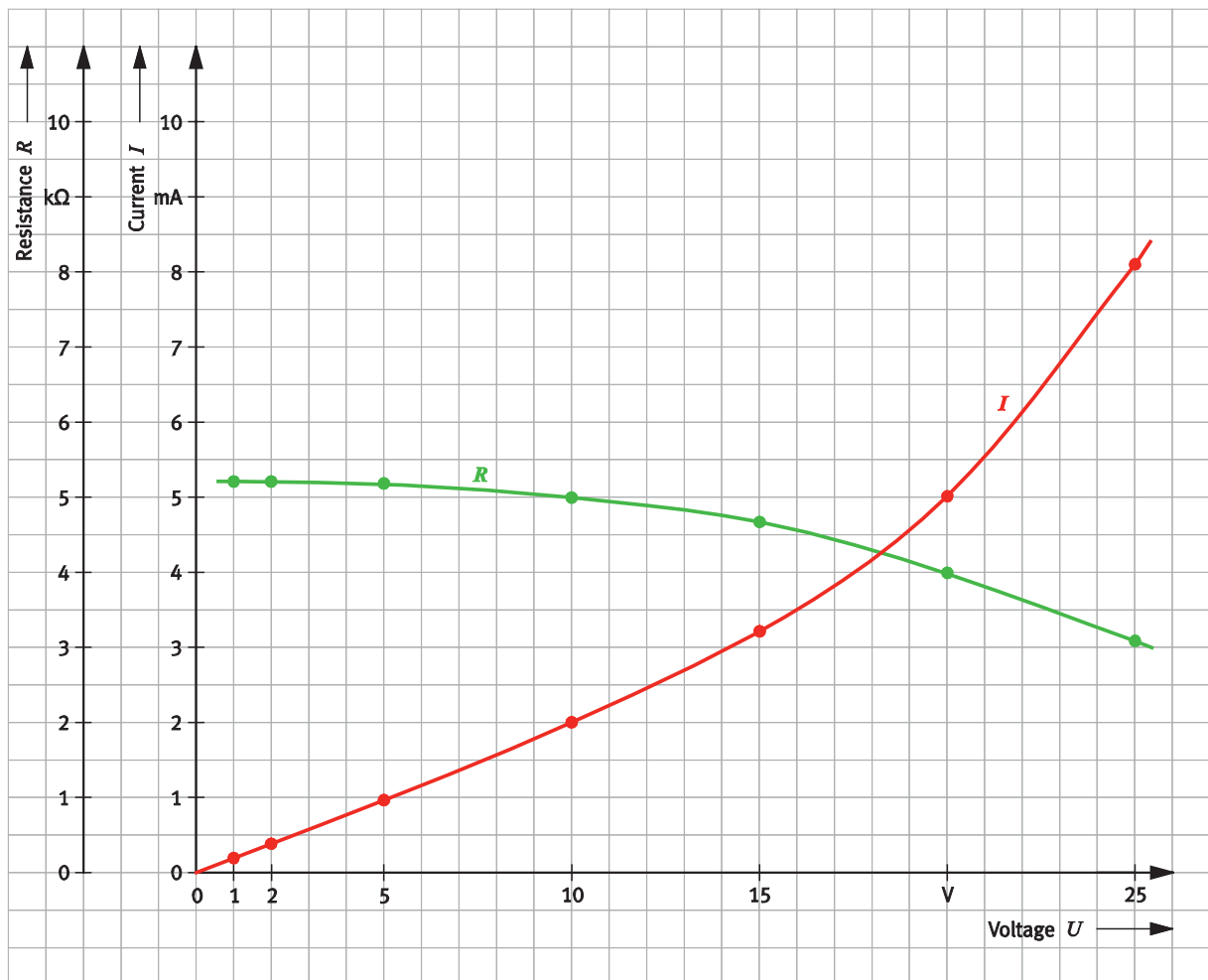
Note for the lesson

Other room temperatures may result in very different measured values.

- Draw the current as a function of voltage in the prepared graph.
- Describe which behaviour exhibited by the measured values points to self-heating of the NTC resistor.

Perceptible self-heating of the NTC resistor occurs during the series of measurements above a voltage of approx. 15 V. The self-heating leads to a gradual increase in the current at constant voltage.

- Indicate the range for self-heating and external heating in the graph.
- Draw the resistance as a function of voltage in the graph as well.



Voltage/current characteristic and voltage/resistance characteristic of the NTC resistor

- Describe the behaviour of the voltage/current characteristic of the NTC resistor.

If the voltage is slowly increased, the current intensity initially rises in a linear manner. Outside the range for self-heating, the current increases sharply.

- Explain the behaviour of the voltage/current characteristic.

In the flat part of the voltage/current characteristic, the supplied electrical power is so low that the NTC resistor barely heats up. Only the ambient temperature determines the resistance value of the NTC resistor. The resistance value is roughly constant. The current intensity rises linearly relative to the voltage.

Above a voltage of approx. 15 V, the supplied electrical power is so high that the NTC resistor heats up. The working range for self-heating is now active. The resistance value of the NTC resistor decreases, the current flowing through it is increased disproportionately.

- Name some sample applications of an NTC resistor.

The NTC resistor is used

- as a temperature sensor in the area of linear external heating,
- for limiting starting currents.

■ Describing the behaviour of a PTC resistor

- Find out about the typical behaviour of a PTC resistor.
- Sketch the basic waveform of the voltage/current characteristic of a PTC resistor in the prepared graph.
- Indicate the range for self-heating and external heating in the graph.



Voltage/current characteristic of a PTC resistor

- Describe the behaviour of the voltage/current characteristic of the PTC resistor.

The current through the PTC resistor initially rises linearly as voltage increases, but then drops suddenly as of a certain voltage.

- Explain the behaviour of the voltage/current characteristic.

In the ascending part of the voltage/current characteristic, the supplied electrical power is so low that the PTC resistor barely heats up. Only the ambient temperature determines the resistance value of the PTC resistor. The resistance value is roughly constant. The current intensity rises linearly relative to the voltage.

Outside the range for self-heating, the supplied electrical power is so high that the PTC resistor heats up. The resistance value of the PTC resistor increases sharply due to the increase in temperature; the current flowing through it is reduced accordingly.

■ **Determining the characteristics for the VDR resistor**



To learn about the behaviour of the voltage-dependent resistor, trace its characteristics.

To do this, start by performing the measurements for the voltage/current characteristic.

Using the voltage/current characteristic, create the voltage/resistance characteristic.

The voltage-dependent resistor is also called a VDR (voltage-dependent resistor) or varistor.

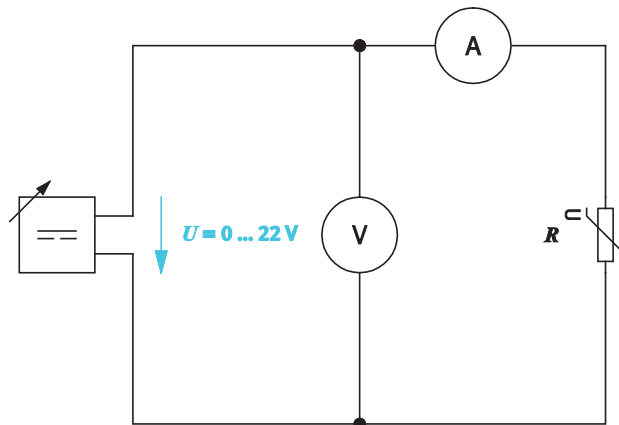
- Explain the meaning of the individual symbols. To do this, complete the prepared fields.

Circuit symbol	Meaning of the individual symbols	
		Non-linear, variable
	U	Dependent on the voltage

- Investigate whether the properties of the VDR resistor require precautions to be taken during the measurements.

With the VDR resistor, the resistance value decreases as the voltage increases. The falling resistance and the rising voltage cause the current to increase disproportionately. It must therefore be ensured that the power loss of the VDR resistor is not exceeded during the measurements.

- Build the circuit.



Measuring circuit with VDR resistor

Identifier	Designation	Values
R	VDR resistor	14 V/0.05 W
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

Equipment list

- Trace the series of measurements as specified in the measurement log.
- Enter the measured values in the measurement log.
- Calculate the power converted in the resistor as well as the resistance value for the measured values.

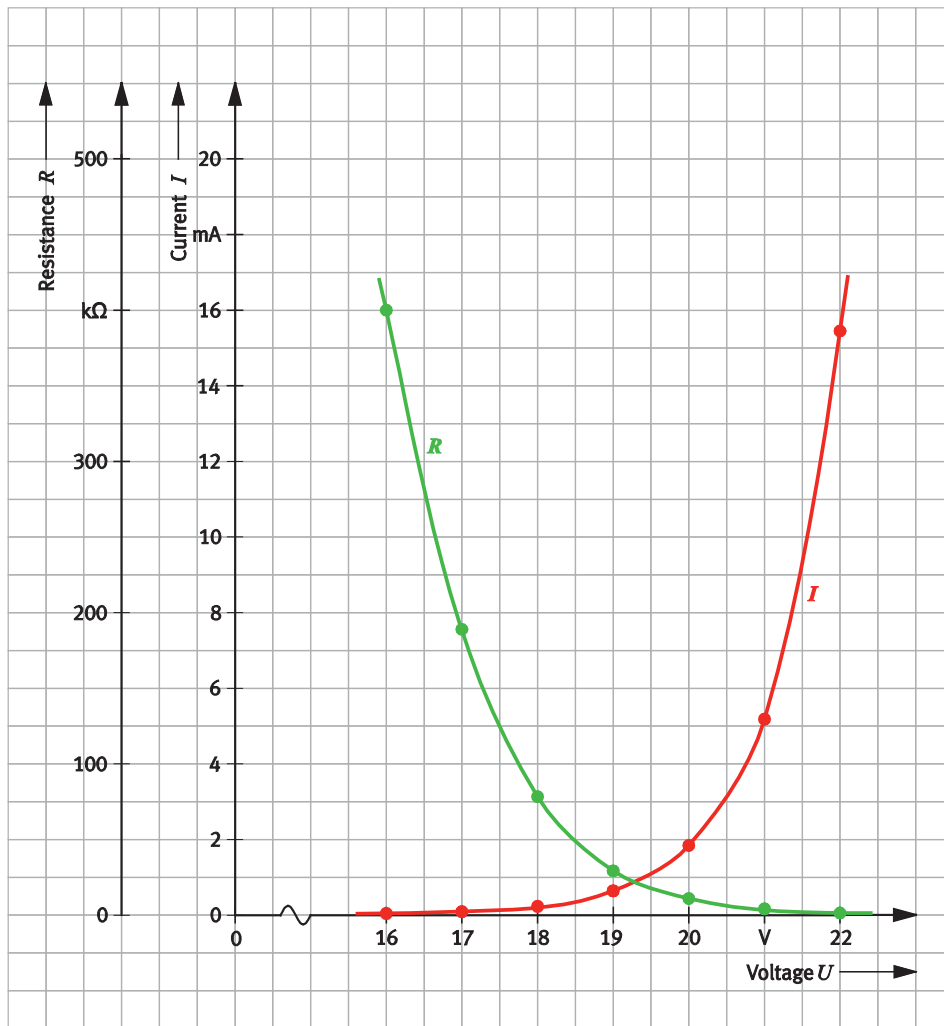
Note

Do not trace the measured values during continuous operation as the varistor as a voltage-limiting component is only designed for a certain power loss.

Abandon the series of measurements if the calculated power P reaches a value of 0.5 W.

Measurement log: Voltage/current characteristic at 22°C room temperature									
Voltage U (V)	14	15	16	17	18	19	20	21	22
Current I (mA)	0.01	0.02	0.04	0.09	0.23	0.65	1.84	5.18	15.45
Power P (mW)	0.14	0.3	0.64	1.53	4.14	12.35	36.8	108.78	339.9
Resistance R (k Ω)	1400	750	400	188.9	78.3	29.2	10.9	4.1	1.4

- Draw the current as a function of voltage in the prepared graph.
- Draw the resistance as a function of voltage in the graph as well.



Voltage/current characteristic and voltage/resistance characteristic of the VDR resistor

- Describe the behaviour of the voltage/resistance characteristic of the VDR resistor.

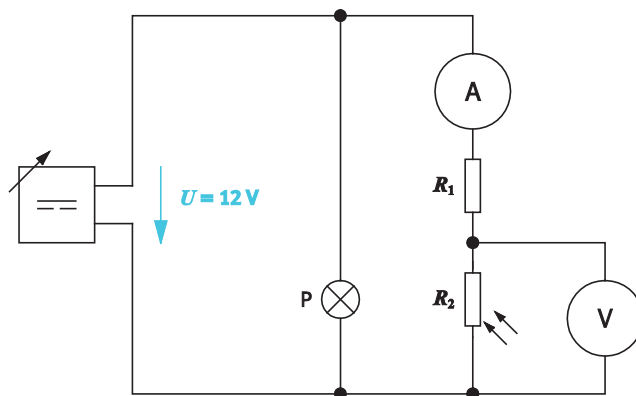
The VDR resistor drastically reduces its resistance value as the voltage increases.

■ Investigating the behaviour of the LDR resistor

To learn about the behaviour of light-dependent resistors, perform a number of qualitative measurements.

Light-dependent resistors are also called LDRs (light-dependent resistor) or photoresistors.

- Build the measuring circuit.
Connect the indicator light P using connecting cables so that you can hold the indicator light close to the LDR resistor.



Measuring circuit with LDR resistor R_2 , series resistor $R_1 = 1 \text{ k}\Omega$, $U = 12 \text{ V}$

Identifier	Designation	Values
R_1	Resistor	1 k Ω /2 W
R_2	LDR resistor	100 V/0.2 W
P	Indicator light	12 V/62 mA
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

Equipment list

- Commission the circuit with a supply voltage of 12 V.

- Perform the measurements specified in the measurement log and enter the results in the log.

	Current I_{LDR} (mA)	Voltage U_{LDR} (V)	Resistance R_{LDR} (k Ω)
LDR covered with a hand	0.34	11.67	34.324
LDR with normal room lighting	6.46	5.57	0.862
LDR with light source (indicator light P1) held as close as possible	10.17	1.86	0.183

Measurement log

- Describe how the resistance value of an LDR resistor changes as incidence of light increases.

The resistance value of an LDR resistor decreases as incidence of light increases.

■ Selecting a non-linear resistor as thermal overload protection for the drill

The drill features thermal overload protection.

The function of the overload protection is to limit the current through the machine if an increased current value is exceeded. Increased current values occur due to increased electrical load.

- Select a suitable non-linear resistor as overload protection and explain the reason for your choice.

Thermal overload protection for the drill is realised using a PTC thermistor (i.e. a PTC resistor). The PTC resistor is connected in series with the drill. As a result, the same operating current flows through the PTC resistor and the machine. If this current exceeds a critical value because the machine has changed its resistance value due to overloading, the PTC resistor is heated up by the increased current. The PTC resistor becomes high-impedance and limits the current to a harmless value.

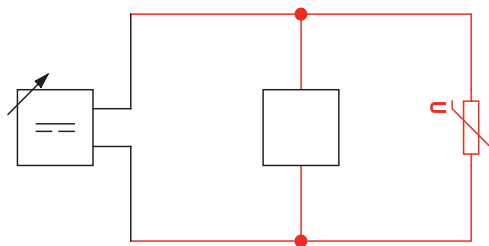
■ Designing the safety circuit with a VDR resistor for the drill

The VDR resistor is to be used to prevent voltage surges at a component in the drill's control electronics.

- Describe how a VDR resistor behaves during normal operation and in the event of voltage surges.

The resistance of a VDR is very high during normal operation. If voltage surges occur, the resistance becomes very low almost without delay and dissipates charge.

- Describe how the VDR resistor has to be connected to the component to prevent voltage surges at the component and explain why.
- Complete the VDR resistor in the circuit accordingly.



Circuit with VDR resistor as overvoltage protection

The VDR resistor is connected in parallel with the component to be protected.

If the voltage in the circuit increases, the resistance value of the VDR resistor changes. The resistance value decreases. For the parallel circuit, this means that the total resistance also decreases. This is because the total resistance is always smaller than the smallest individual resistance. The smaller total resistance also means a smaller voltage drop. This means that the voltage at the sensitive component cannot increase above a certain value (dependent on the VDR resistance).

Exercise 9:

Constructing a DC voltage source

■ Learning objectives

After completing this exercise:

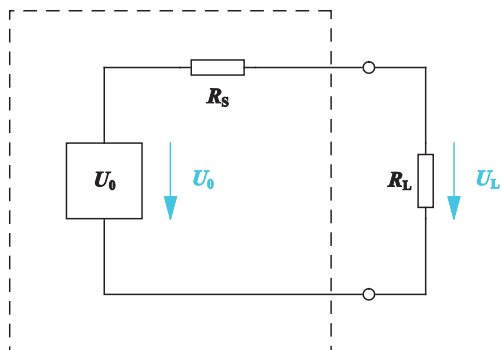
- You will be able to calculate and apply the characteristics of a voltage source.
- You will be able to trace and interpret the working characteristic of a voltage source.
- You will be familiar with the applications of power adaptation and voltage adaptation for a voltage source.

■ Problem description

A DC voltage is needed for actuating interfaces in a PC. The DC voltage source that is available supplies too high a voltage. A series resistor is to be installed to reduce the voltage to the required value.

Construct the voltage source. Document the behaviour of the voltage source by tracking the working characteristic and the power characteristic for the voltage source.

■ Circuit



Electromotive force source with constant voltage:	Electromotive force	$U_0 = 6 \text{ V}$
Consuming device at the voltage source:	Load resistance	$R_S = 100 \Omega$
	Voltage	$U_L = 1 \text{ V}$

Equivalent circuit diagram for the DC voltage source

■ Project assignments

1. Describe the structure of an equivalent voltage source.
2. Describe the three load cases for an equivalent voltage source.
3. Describe how the characteristics of a voltage source are determined by measurement.
4. Construct the DC voltage source and create the current/voltage working characteristic for the voltage source.
5. Test the use of the DC voltage source for a further consuming device.
6. Create the power characteristic of the DC voltage source.
7. Describe what applies to the resistances R_L and R_S in the event of voltage adaptation.

■ Work aids

- Textbooks, books of tables
- Data sheets
- Internet

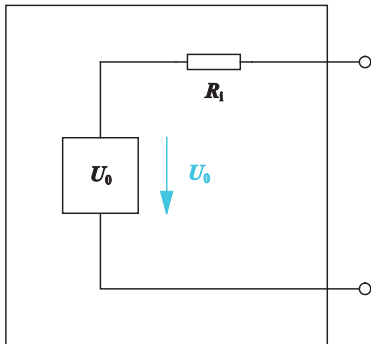
Note

Do not switch on the electrical power supply until you have made and checked all the connections. Once you have completed the exercise, switch off the power supply again before dismantling the components.

■ Describing the structure of the equivalent voltage source

Voltage sources have different structures. An equivalent circuit diagram for voltage sources exists to enable these sources to be compared despite their different structures. Each voltage source can be ascribed to this equivalent circuit diagram, regardless of its actual structure.

- Name and describe the main elements in the equivalent circuit diagram.



Equivalent circuit diagram for voltage sources

Designation	Description
U_0	Electromotive force that supplies a constant electromotive force U_0
R_i	Internal resistance of the voltage source
○ ○	Terminals for the consuming device

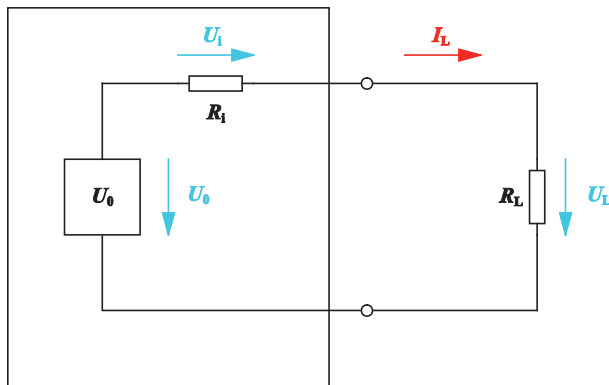
- Why is the equivalent voltage source represented using a closed rectangular line?

The equivalent voltage source constitutes a device and is therefore represented by a closed line.

■ Describing the load cases for an equivalent voltage source

The load current I_L flows when an electrical consuming device R_L is connected to the terminals of the voltage source. The voltage picked off at the terminals is also called terminal voltage U_L .

- Complete the missing voltage arrows in the circuit.



Circuit with equivalent voltage source and consuming device

- Specify the formula for calculating the terminal voltage U_L .

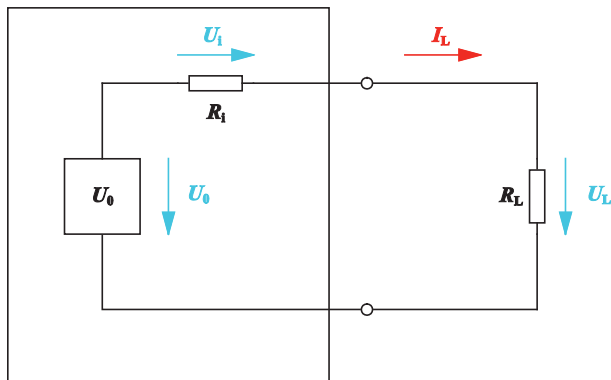
The circuit is a series circuit. The following therefore applies:

$$U_0 = U_i + U_L$$

Solved for the terminal voltage U_L :

$$U_L = U_0 - U_i = U_0 - R_i \cdot I_L$$

There are three load cases for a voltage source.



Circuit with equivalent voltage source and consuming device

- Complete the descriptions for the three load cases.
For each load case, specify the formula for calculating the terminal voltage and load current or short-circuit current.

No-load operation

The equivalent voltage source has no load during no-load operation. There is no consuming device connected.

The following applies to the load current I_L :

$$I_L = 0 \text{ A}$$

The following applies to the terminal voltage U_L :

$$U_L = U_0$$

Load operation

During load operation, an electrical consuming device is connected to the terminals of the voltage source. The load current I_L flows. The magnitude of the load current I_L depends on the resistance R_L of the consuming device.

The following applies to the terminal voltage U_L :

$$U_L = U_0 - R_i \cdot I_L$$

The following applies to the load current I_L :

$$I_L = \frac{U_0}{R_i + R_L}$$

Short-circuit operation

A short circuit occurs if there is a direct connection between the terminals of the voltage source. The load resistance is then zero.

The following applies to the terminal voltage U_L :

$$U_L = 0 \text{ V}$$

The short-circuit current I_{SC} flows:

$$I_{SC} = \frac{U_0}{R_i}$$

The short-circuit current is only limited by the internal resistance R_i of the voltage source.

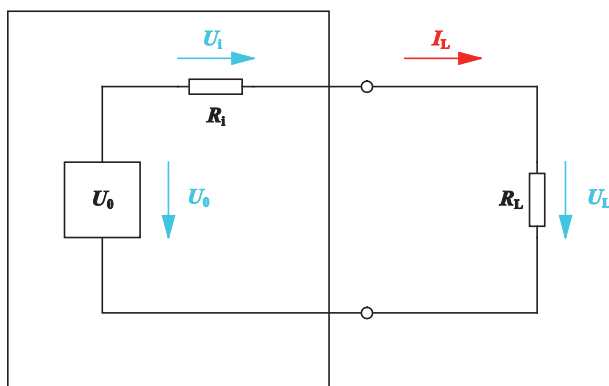
- Describe how the short-circuit current I_{SC} behaves if the internal resistance R_i decreases.

The smaller the internal resistance, the greater the short-circuit current.

■ Determining the characteristics of a voltage source by measurement

The characteristics of a voltage source are the electromotive force U_0 and the internal resistance R_i .

You can determine these two characteristics by measurement with the help of the load cases for a voltage source.



Circuit with equivalent voltage source and consuming device

- Describe how to determine the electromotive force U_0 by measurement.

The terminal voltage U_L is measured using the 'no load' load case.

The following applies for the 'no load' load case: Electromotive force $U_0 = U_L$

- Describe how to determine the internal voltage R_i by measurement.

The short-circuit current I_{SC} is measured using the 'short circuit' load case.

The internal resistance R_i can be calculated using the formula for the short-circuit current.

$$I_{SC} = \frac{U_0}{R_i}$$

Internal resistance: $R_i = \frac{U_0}{I_{SC}}$

■ Performing measurements relating to the working characteristic of the DC voltage source

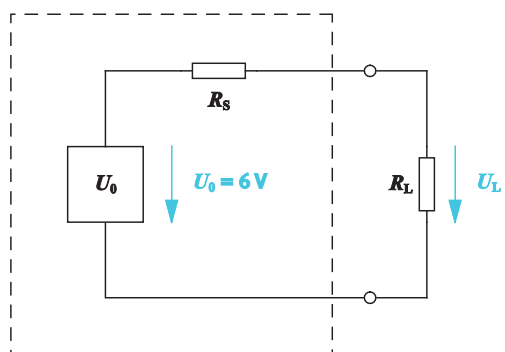
Next construct the voltage source for actuating a PC interface.

Specifications

- The consuming device has a resistance value $R_L = 100 \Omega$.
- The consuming device is supplied with a voltage $U = 1 \text{ V}$.
- The following applies to the electromotive force: $U_0 = 6 \text{ V}$.
- A series resistor R_S is to be used.

The series resistor represents the internal resistance of the voltage source.

As soon as the voltage source is constructed, create the associated working characteristic. The working characteristic shows the dependence of the terminal voltage U_L on the load current I_L .



Circuit for the loaded voltage source with $R_L = 100\ \Omega$

Identifier	Designation	Values
R_L	Resistor	100 Ω /2 W
R_s	Resistor	1 k Ω /2 W
R_s	Resistor	1 k Ω /2 W
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

Equipment list

- Calculate the series resistance R_s needed to produce a voltage $U = 1\text{ V}$ at the terminals of the new voltage source.

Given

Electromotive force $U_0 = 6\text{ V}$
 Load resistance $R_L = 100\ \Omega$
 Load voltage $U_L = 1\text{ V}$

To be found

Series resistance R_s in Ω

Calculation

The laws governing series connection apply to the circuit.

The load current I_L is calculated as follows:

$$I_L = \frac{U_L}{R_L} = \frac{1 \text{ V}}{100 \Omega} = 0.01 \text{ A} = 10 \text{ mA}$$

The series resistance R_S is calculated in accordance with the following formula:

$$R_S = \frac{U_S}{I_L}$$

U_S is calculated as follows:

$$U_S = U_0 - U_L = 6 \text{ V} - 1 \text{ V} = 5 \text{ V}$$

This gives the following for R_S :

$$R_S = \frac{U_S}{I_L} = \frac{5 \text{ V}}{0.01 \text{ A}} = 500 \Omega$$

- Select a suitable resistor or resistor combination from the available hardware. Specify the resistor combination.

The series resistance $R_S = 500 \Omega$ is produced by connecting two resistors $R = 1 \text{ k}\Omega$ in parallel.

- Add the series resistor to the equipment list.
- Build the circuit.
- Determine the missing variables in the measurement log.

Voltage U_0 (V)	Voltage U_L (V)	Voltage U_S (V)	Load current I_L (mA)
6	0.99	4.95	10.0

Measurement log

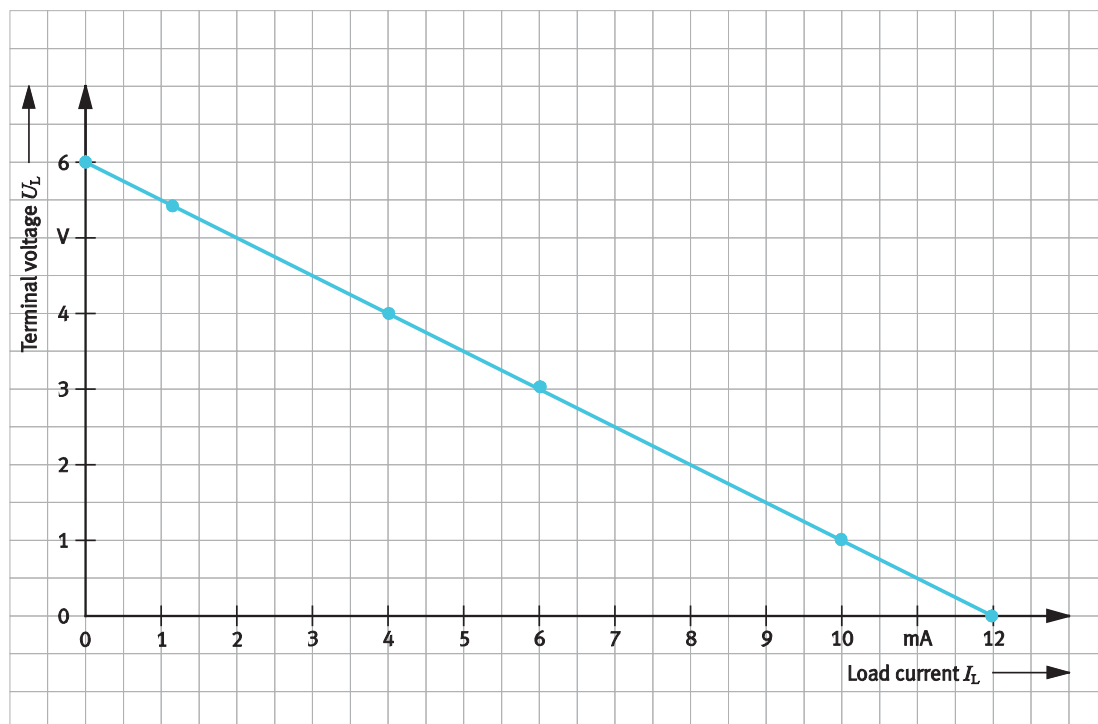
To create the working characteristic of the voltage source, you will need the associated current and voltage values for further load resistances R_L .

- Substitute the resistance values specified in the table for the load resistance $R_L = 100 \Omega$ and perform the necessary measurements.
- Enter the measured values in the measurement log.

Load resistance R_L (Ω)	Terminal voltage U_L (V)	Load current I_L (mA)	Load case
0	0	11.98	<< Short circuit
100	1.01	9.99	
500 (470+33)	3.03	6.01	
1,000	4.00	4.01	
4,700	5.42	1.15	
Infinite	6.00	0	<< No load

Measurement log for the voltage/current working characteristic

- Transfer the measured values to the voltage/current graph and draw the working characteristic $U(I)$ for the voltage source.



$U(I)$ working characteristic of the voltage source

- Describe how the terminal voltage U_L changes as a function of the load current I_L .

The higher the load current I_L of the consuming device, the lower the terminal voltage U_L .

- Specify the value for the short-circuit current I_{SC} .
To do this, evaluate the characteristic. Verify the determined value by calculation.

Short-circuit current I_{SC} measured:

$$I_{SC} = 11.98 \text{ mA}$$

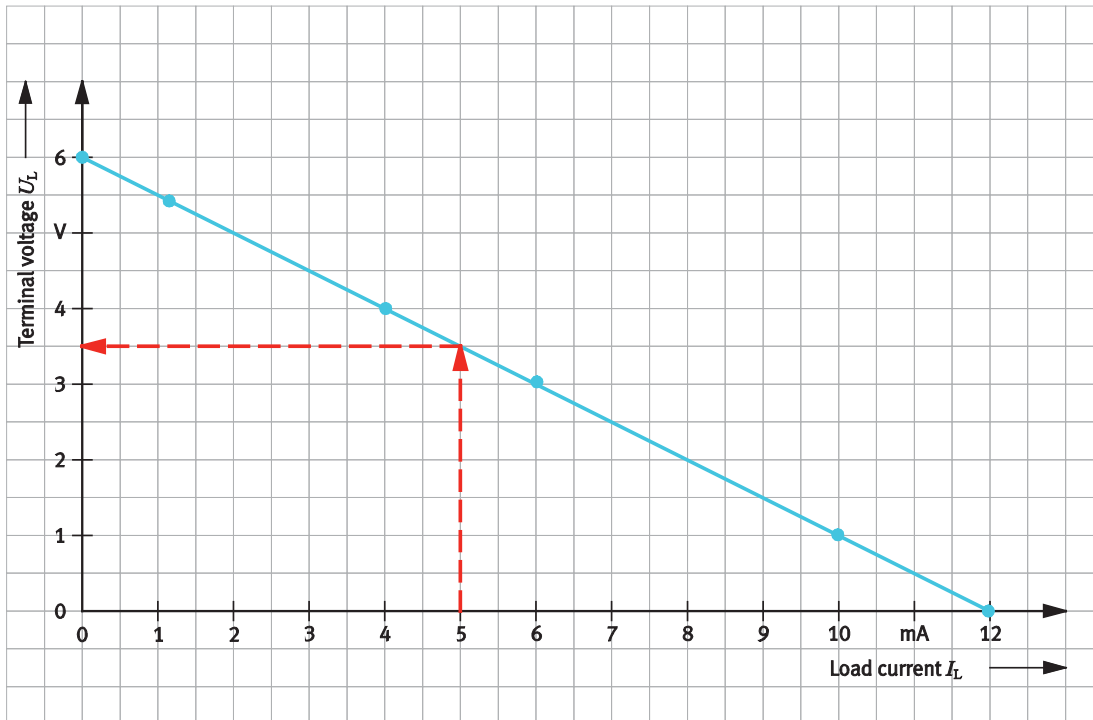
Short-circuit current I_{SC} calculated:

$$I_{SC} = \frac{U_0}{R_S} = \frac{6 \text{ V}}{500 \Omega} = 0.012 \text{ A} = 12 \text{ mA}$$

■ Applying the working characteristic of the voltage source to a consuming device

A consuming device needs a power supply of 4.5 V and a current of 5 mA.

- Using the working characteristic of the voltage source, check whether it can be used to generate power for the consuming device and explain your findings.



Working characteristic of the voltage source

The voltage source is not suitable for supplying power to the consuming device.
 With a current of 5 mA, the voltage source only supplies a voltage of 3.5 V at its terminals.
 The consuming device, however, needs a power supply of 4.5 V.

■ Creating the characteristic for power adaptation of the voltage source

The power that is taken from a voltage source depends on the load resistance associated with the terminals of the voltage source.

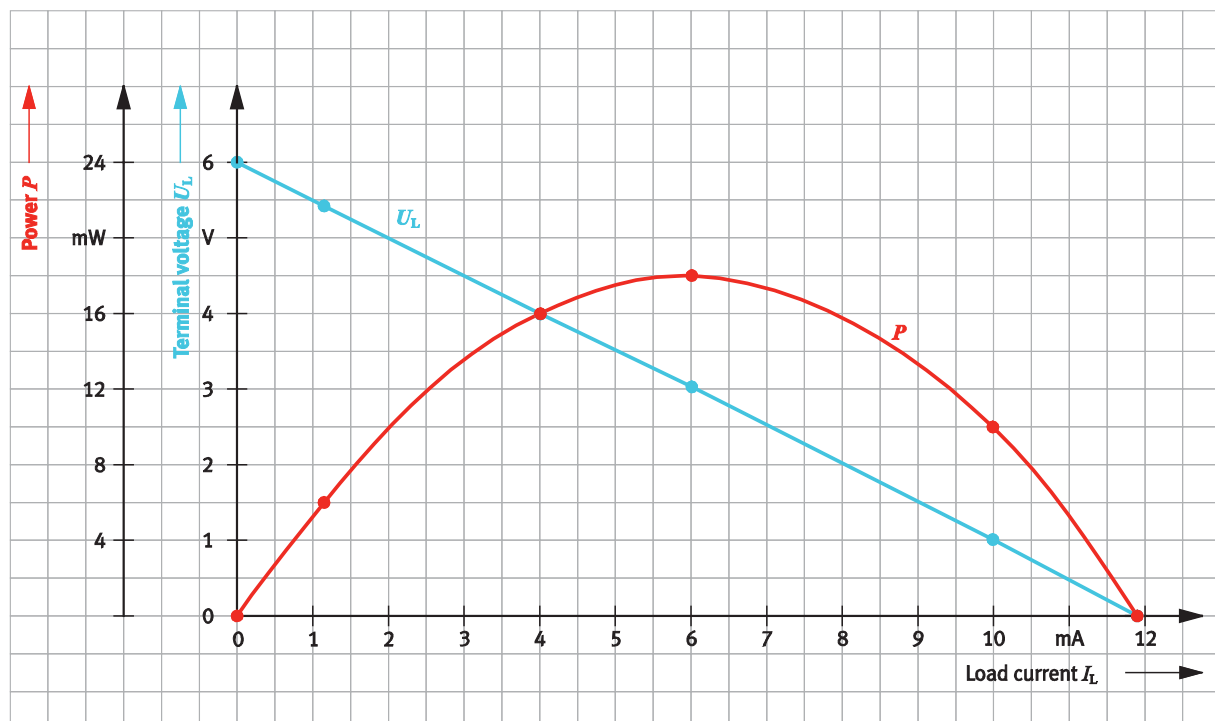
To create the power characteristic, the load current I_L and the terminal voltage U_L are therefore measured for different load resistances R_L . The power supplied can then be calculated from the measured values.

- Calculate the power P supplied to the load resistor from the values for current and voltage.

Load resistance R_L (Ω) set	Load voltage U_L (V) measured	Load current I_L (mA) measured	Power P (mW) calculated
0	0	11.98	0
100	1.01	9.99	10
500	3.03	6.01	18
1,000	4.00	4.01	16
4,700	5.42	1.15	6
Infinite	6.00	0	0

Evaluation of the measurement log

- Draw the power curve $P(I)$ in the prepared graph.



Working characteristic and power curve of the DC voltage source

- Describe the waveform of the power P supplied by the voltage source to the load resistor R_L .

The power curve is a parabola. The values rise to a maximum and then fall again.

- Read from the graph the terminal voltage U_L and load current I_L for which the maximum power P is supplied.

Information

Using a voltage source in such a way that it supplies maximum power to the consuming device is called **power adaptation**.

Power adaptation is frequently used with wind power plants and solar plants to maximise the energy yield. The internal resistance R_i is dynamically adapted to the load resistance R_L during this process.

The voltage source supplies the maximum power to the consuming device at

- $U_L = 3 \text{ V}$
- $I_L = 6 \text{ mA}$

In general:

The supplied power P is highest when the terminal voltage U_L is half as big as the electromotive force U_0 .

$$U_L = \frac{U_0}{2}$$

- Describe the relationship between load resistance R_L and internal resistance R_i or R_s if the voltage source is supplying the **maximum power** to the load resistor.
To do this, evaluate the measurement log and the technical data for the voltage source.

The voltage source supplies the **maximum power** to the consuming device when the load resistance and internal resistance are the same.

$$R_L = R_i$$

- Calculate the efficiency η of the power P .
To do this, use the formula for calculating the efficiency.

The following applies to the efficiency η of the electrical power:

$$\text{Efficiency } \eta = \frac{\text{Power out}}{\text{Power in}} = \frac{P_{\text{out}}}{P_{\text{in}}}$$

The circuit is a series circuit with the two resistors R_i and R_L .

With power adaptation, $R_i = R_L$. The voltage drop is the same at the two resistors.

The following therefore applies to the power supplied at the resistors: $P_i = P_L$.

This gives the following for the powers P_{out} and P_{in} :

$$P_{\text{out}} = P_L$$

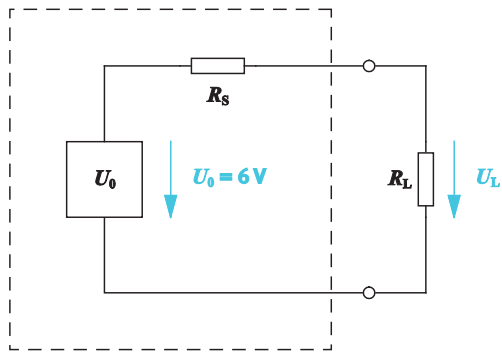
$$P_{\text{in}} = P_i + P_L = 2 \cdot P_L$$

The following therefore applies to the efficiency η :

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{P_L}{2 \cdot P_L} = 0.5 = 50 \%$$

■ Describing what is meant by voltage adaptation

Voltage sources are frequently used in sound engineering to supply the maximum voltage to the consuming device. We then talk about voltage adaptation.



Circuit for the loaded voltage source with $R_L = 100 \Omega$

- Describe the relationship between load resistance R_L and internal resistance R_i or R_s if the voltage source is to supply **maximum voltage** to the terminals.
To do this, evaluate the measurement log.

A voltage source supplies the **maximum voltage** when the load resistance R_L is very big compared with the internal resistance R_i .

$$R_L \gg R_i$$

The total electromotive force U_0 then drops almost entirely at the load resistor R_L .
The terminal voltage U_L only changes very little if the load resistance R_L changes.

Exercise 10:

Selecting a capacitor with a short charging time

■ Learning objectives

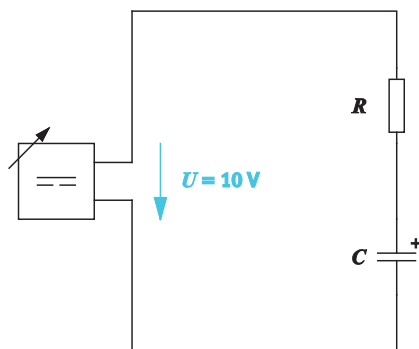
After completing this exercise:

- You will be familiar with the structure, application and characteristics of a capacitor.
- You will be able to measure and evaluate the charging and discharging process of a capacitor in a DC circuit.

■ Problem description

A capacitor is used in a circuit to store energy. Different resistors are available to build the capacitor circuit. Select the resistor that charges the capacitor in the shortest time.

■ Circuit



Capacitor circuit with $U = 10 \text{ V}$, $C = 100 \mu\text{F}$

■ **Project assignments**

1. Research how energy storage works in the capacitor and answer the questions.
2. Specify the formula for calculating the capacitance of a capacitor.
3. Describe the characteristics and designs of capacitors.
4. Select a suitable circuit for performing measurements at the capacitor.
5. Perform measurements for determining the charging and discharging time of the capacitor.
6. Select the capacitor circuit with the shortest time constant.

■ **Work aids**

- Textbooks, books of tables
- Data sheets
- WBT Electrical engineering 2
- Internet

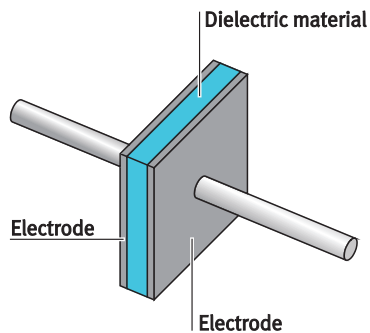
Note

Do not switch on the electrical power supply until you have made and checked all the connections. Once you have completed the exercise, switch off the power supply again before dismantling the components.

■ Describing the behaviour of a capacitor

A capacitor is a passive electrical component with the capability to store electric charge and thus stores electrical energy.

The capacitor consists at its most basic of two electrically conductive surfaces, the electrodes. The electrodes are kept apart by an insulating material, the so-called dielectric material. The two electrodes are so close together that the electrical forces can act through the insulating material.



Schematic diagram of a capacitor

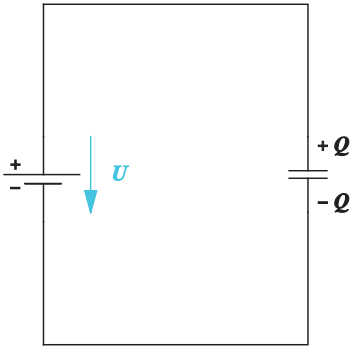
Note

In the simplest case, the electrodes consist of two conductive plates.

- Describe the behaviour of the capacitor when DC voltage is applied to its connections.

If a constant voltage is applied to the connections of an uncharged capacitor, an electrical current flows briefly and charges one electrode positively and the other one negatively. This electrical charge of the capacitor is maintained if it is disconnected from the voltage source. If a charge or a current is taken from the capacitor, its voltage falls again.

■ Calculating the capacitance of a capacitor



Capacitor in the DC current

The capacitance is a measure for the charge that the capacitor can store when a specific voltage is applied.

- Specify the formula for calculating the charge quantity Q .

$$Q = C \cdot U$$

where Q is the charge in As
 C is the capacitance in F (Farad)
 U is the voltage in V

The capacitance is determined by the structural size of the capacitor.

- Specify the formula for calculating the capacitance C for a plate capacitor.

$$C = \epsilon_0 \cdot \epsilon_r \cdot \frac{A}{d}$$

where C is the capacitance in F (Farad)
 ϵ_0 is the electrical field constant in $\frac{As}{Vm}$
 ϵ_r is the permittivity number
 A is the plate area in m^2
 d is the plate spacing in m

- Describe how the capacitance changes as a function of plate area and plate spacing.

The greater the area of a plate and the smaller the gap between the plates, the greater the capacitance.

The Farad unit of measurement for a capacitor is too big in most cases. The common smaller units are summarised in the table.

- Complete the prepared fields in the table.

Designation	Unit of measurement	Converted to Farad
1 millifarad	1 mF	10^{-3} F
1 microfarad	1 μ F	10^{-6} F
1 nanofarad	1 nF	10^{-9} F
1 picofarad	1 pF	10^{-12} F

■ Describing the characteristics and designs of capacitors

Capacitors come in different versions as fixed capacitors and as capacitors with variable capacitance.

- Name the key characteristics of a capacitor.

Capacitors have the following characteristics:

- Capacitance
- Dielectric strength
- Tolerance
- Insulation resistance
- Loss factor




Note for the lesson

The loss factor is significant when operating the capacitor with AC voltage.

- Describe what is meant by the dielectric strength of a capacitor.

The dielectric strength of a capacitor is dependent on the type of dielectric material. It determines the highest voltage that can be applied to the capacitor. If the voltage is exceeded, the dielectric material will no longer act as an insulator. Breakdown occurs through the dielectric material. A charge exchange takes place between the capacitor's two electrodes. The energy that is released can be very large. The charge exchange makes itself felt through a bang and an arc of light.

- Find out which capacitors are available to you in your equipment set for DC and AC circuits.
- Enter the capacitors in the table and complete the associated fields.

Design	Capacitance	Circuit symbol	Suitable for DC voltage	Suitable for AC voltage
Polypropylene film/film capacitors	100 pF, 10 nF		x	x
Metallised polyester capacitors	47 nF, 0,1 µF, 0,22 µF, 0,47 µF, 1 µF		x	x
Electrolytic capacitors	10 µF, 100 µF, 470 µF		x	-

- Describe why higher capacitances can be achieved with an electrolytic capacitor than a wound capacitor.

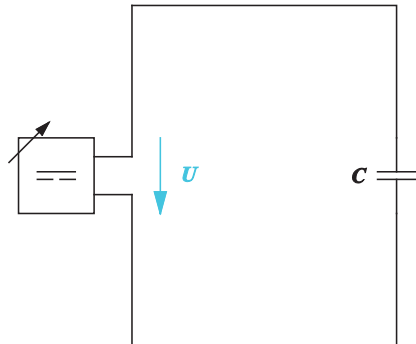
With electrolytic capacitors, the insulating layer is generated by a sheer oxide film between the plates. The oxide layer is much thinner than the thinnest film in a wound capacitor can be. The smaller the space between the plates, the greater the capacitance of the capacitor.

- Name an example of a capacitor with variable capacitance.

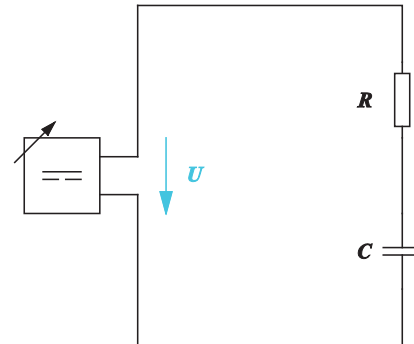
Variable capacitors are capacitors with variable capacitance.

■ Selecting a circuit for measurements at the capacitor

Two circuit variants are available for measuring the charging and discharging process at the capacitor.



Circuit without series resistor



Circuit with series resistor, also called an RC element

Note

Uncharged capacitors have no resistance value.

- Select a circuit for your measurements at the capacitor and explain the reasons for your choice.

A circuit with series resistor is used for the measurements in order to limit the current flow in the circuit.

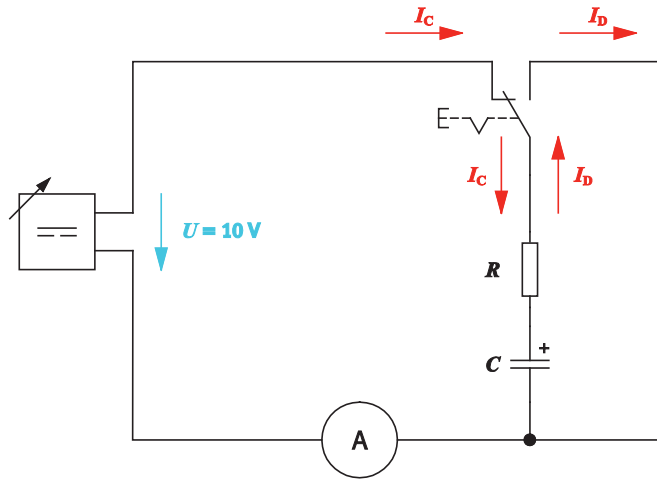
Uncharged capacitors have no resistance value. When a capacitor is connected directly to a voltage source, a short circuit occurs briefly. The current that flows during this process is only limited by the internal resistance of the voltage source and can damage the capacitor. That's why capacitors should always be charged and also discharged via a series resistor.

■ **Measuring the capacitor's charging and discharging process**

Investigate the capacitor's charging and discharging process by measurement. To do this, measure the voltage and current values during the charging and discharging process.

Time response of current during the charging and discharging process

- Add the current arrow for the charging process and the discharging process to the circuit.



Measuring circuit with RC element: $U = 10\text{ V}$, $C = 100\ \mu\text{F}$, $R = 100\ \text{k}\Omega$

Identifier	Designation	Values
R	Resistor	100 k Ω /2 W
C	Capacitor	100 μF /63 V
–	Digital multimeter	–
–	Basic power supply unit EduTrainer®	–

Equipment list

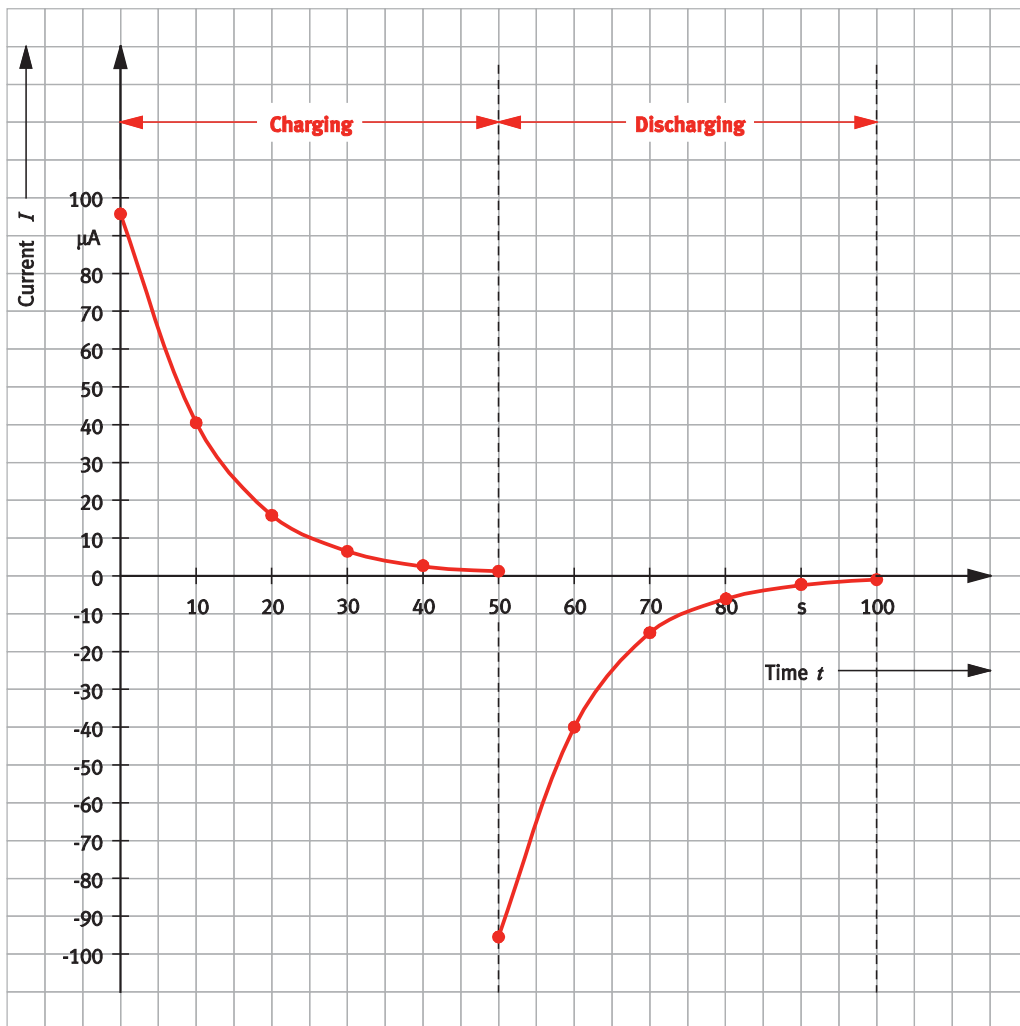
- Build the circuit with a series resistor $R = 100\ \text{k}\Omega$. Note the polarity of the capacitor when building the electrical circuit.
- Set a DC voltage of 10 V as the operating voltage.
- Measure the charging current as specified in the measurement log.
- Enter the measured values in the measurement log.

Measurement log: Time response of current during the charging process						
Charging time t (s)	0 (at the moment of switch-on)	10	20	30	40	50
Current I (μA)	95.7	40.5	15.9	6.5	2.7	1.3

- Measure the current when discharging the capacitor in the same way.
To do this, turn the switch in the circuit.
- Trace the current values as specified in the measurement log and write down the values.

Measurement log: Time response of current during the discharging process						
Discharging time t (s)	0 (at the moment of switch-on)	10	20	30	40	50
Current I (μA)	-95.5	-40.0	-15.1	-5.8	-2.2	-0.9

- Draw the current as a function of time in the prepared graph.
Sketch the charging curve in the range 0 – 50 seconds.
Sketch the discharging curve in the range 50 – 100 seconds.
- Indicate the range for charging and discharging in the graph.



Current waveform when charging and discharging a capacitor

- Describe the waveform of the current.
 - The current intensity initially falls swiftly during charging, and then increasingly slowly.
 - During discharging, the current flows in the opposite direction to during charging and initially falls swiftly and then more slowly.
 - The charging and discharging currents are the same.
 - The capacitor blocks the direct current after recharging. It has an almost infinite resistance when charged.

- Calculate the current intensity I_0 at the switch-on moment when charging starts and enter the value in the graph.

Given

Voltage	$U = 10 \text{ V}$
Resistance	$R = 100 \text{ k}\Omega$

To be found

Current intensity I_0 in mA

Calculation

U_c is as follows immediately after switch-on:

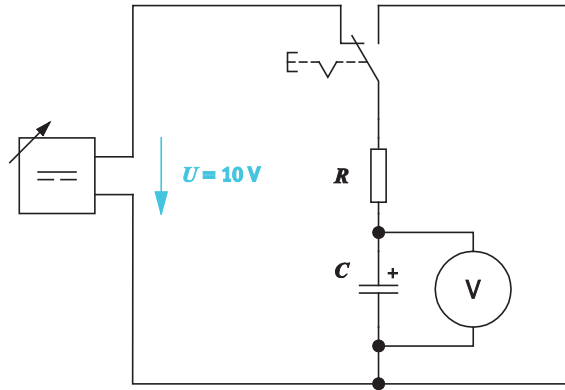
$$U_c = 0 \text{ V}$$

The initial current intensity I_0 is therefore:

$$I_0 = \frac{U}{R_{\text{total}}} = \frac{U}{R} = \frac{10 \text{ V}}{100 \text{ k}\Omega} = \frac{1 \text{ V}}{1000 \Omega} = 0.0001 \text{ A} = 0.1 \text{ mA} = 100 \mu\text{A}$$

Time response of voltage during the charging and discharging process

- Build the circuit with a series resistor $R = 100 \text{ k}\Omega$.



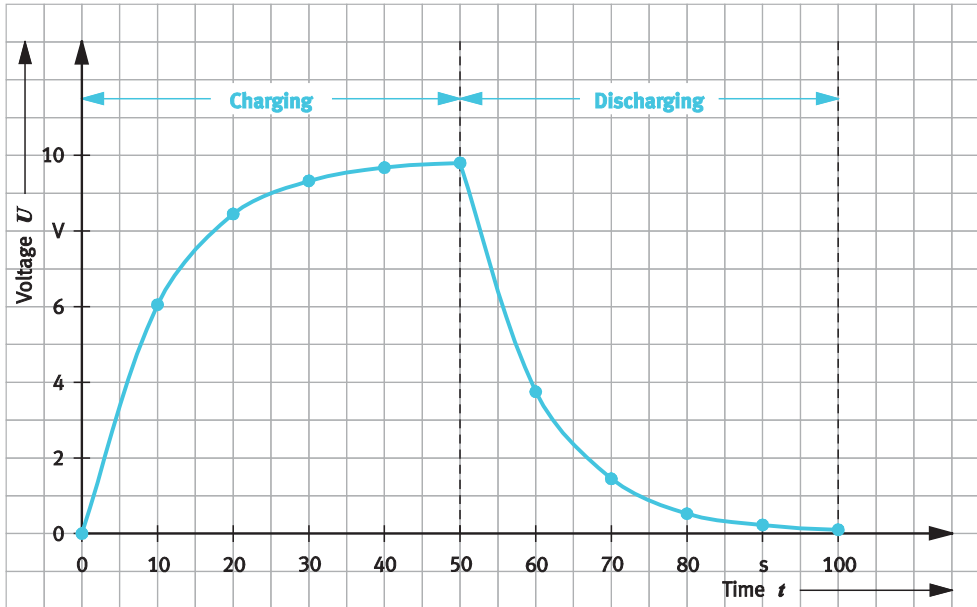
Measuring circuit with RC element: $U = 10 \text{ V}$, $C = 100 \text{ }\mu\text{F}$, $R = 100 \text{ k}\Omega$

- Set a DC voltage of 10 V as the operating voltage.
- Measure the charging voltage as specified in the measurement log.
- Enter the measured values in the measurement log.
- Measure the voltage when discharging the capacitor in the same way. To do this, turn the switch in the circuit appropriately.
- Trace the voltage values as specified in the measurement log and enter the measured values in the log.

Measurement log: Time response of voltage during the charging process						
Charging time t (s)	0 (at the moment of switch-on)	10	20	30	40	50
Voltage U (V)	0.07	6.05	8.46	9.33	9.68	9.81

Measurement log: Time response of voltage during the discharging process						
Discharging time t (s)	0 (at the moment of switch-on)	10	20	30	40	50
Voltage U (V)	9.82	3.76	1.44	0.53	0.22	0.09

- Draw the voltage as a function of time in the prepared graph.
Sketch the charging curve in the range 0 – 50 seconds.
Sketch the discharging curve in the range 50 – 100 seconds.
- Indicate the range for charging and discharging in the graph.



Voltage waveform when charging and discharging a capacitor

- Describe the waveform of the voltage.
 - The voltage at the capacitor initially rises swiftly during charging, and then increasingly slower.
 - The charging process continues until the capacitor voltage has increased to the terminal voltage U .
 - The voltage initially falls swiftly during discharging, and then increasingly slowly.

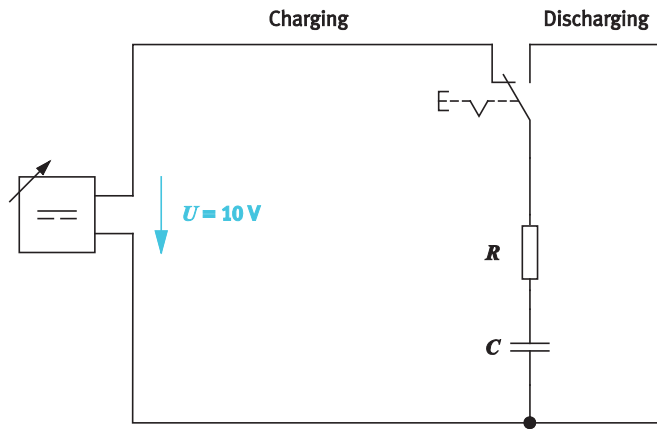
Note

Avoid discharging a capacitor too quickly, for example by means of a short circuit. The temporarily very high current can damage the capacitor beyond repair.

- Specify the duration of the capacitor's charging and discharging time. To do this, evaluate the current and voltage curves.

The capacitor's charging and discharging time is the same since the same series resistor is used for the charging and discharging operation. The time is approx. 50 seconds.

■ Evaluating the time constant of a capacitor



Circuit for charging and discharging a capacitor

A capacitor takes a certain amount of time to charge. The charge time of the capacitor in the RC element is measured using the time constant τ .

In theory, a capacitor needs an infinite amount of time to charge. In practice it is assumed that the capacitor will be fully charged or discharged after the time $t = 5 \cdot \tau$.

- Specify the formula for calculating the time constant τ .

$$\tau = R \cdot C$$

where τ is the time constant in s
 R is the resistance for limiting current in Ω
 C is the capacitance in F

The momentary values for voltage and current when charging and discharging a capacitor can be calculated using the following formulae:

When charging

$$i_c = I_0 \cdot e^{-\frac{t}{\tau}}$$

$$u_c = U_0(1 - e^{-\frac{t}{\tau}})$$

$$I_0 = \frac{U_0}{R}$$

When discharging

$$i_c = -I_0 \cdot e^{-\frac{t}{\tau}}$$

$$u_c = U_0 \cdot e^{-\frac{t}{\tau}}$$

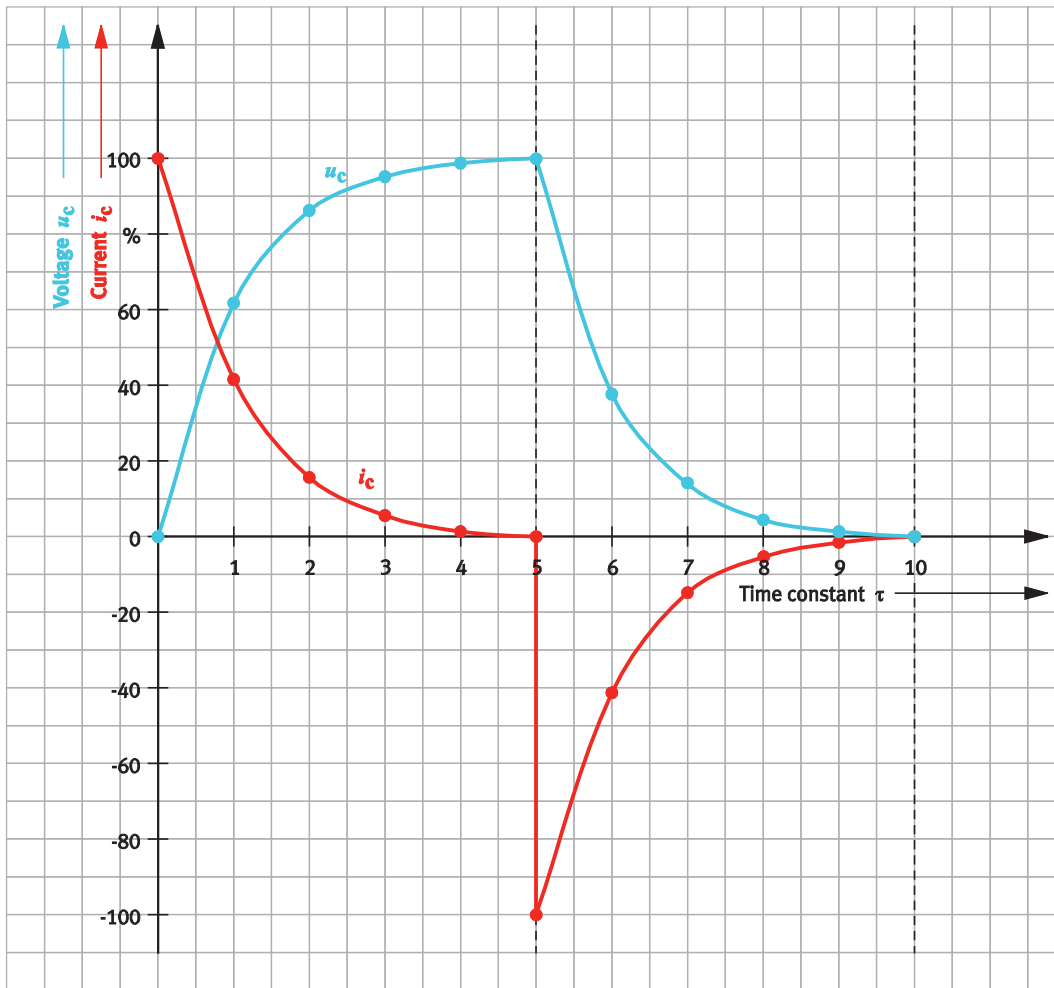
Where

U_0 is the charging voltage or voltage at the charged capacitor

R is the resistance for limiting current in Ω

e is the basic number 2.718

t is the charging time in s



Current and voltage waveform at the capacitor

63% of the applied voltage is reached after the time τ when charging the capacitor.

The capacitor is fully charged after approx. 5τ .

During discharge, approx. 37% of the original voltage remains after the time τ .

- Describe what percentage value of the switch-on current the current drops to during charging after the time τ .

When charging a capacitor, the current falls to 37% of the switch-on current after the time τ .

- Describe what effect the magnitude of the resistance has on the charging time of the capacitor.

The greater the resistance, the smaller the current intensity and the longer the charging time.

■ Selecting a capacitor with short charging time

The capacitor circuit should be designed for the shortest possible charging and discharging times.

The following specifications apply to the capacitor circuit:

- The capacitor circuit is operated with $U = 10 \text{ V}$ DC voltage.
- A capacitor with $C = 100 \text{ }\mu\text{F}$ is used.
- The following series resistors are available:
 - $R = 10 \text{ k}\Omega$
 - $R = 100 \text{ k}\Omega$
 - $R = 1 \text{ M}\Omega$

- Determine the charging times for the illustrated circuit variants by measurement or by calculation.
- Enter the charging times in the table.

	Circuit with series resistor $R = 10 \text{ k}\Omega$	Circuit with series resistor $R = 100 \text{ k}\Omega$	Circuit with series resistor $R = 1 \text{ M}\Omega$
Charging time $t = 5 \tau$	5 s	50 s	500 s

Charging times for capacitor circuits

- Select the circuit variant with the shortest charging time.

The smaller the capacitance C of the capacitor and the smaller the resistance R , the faster the capacitor charges.

Charging time:

$$t = 5 \cdot \tau = 5 \cdot R \cdot C$$

The capacitor circuit with the series resistor $R = 10 \text{ k}\Omega$ delivers the shortest charging time.

