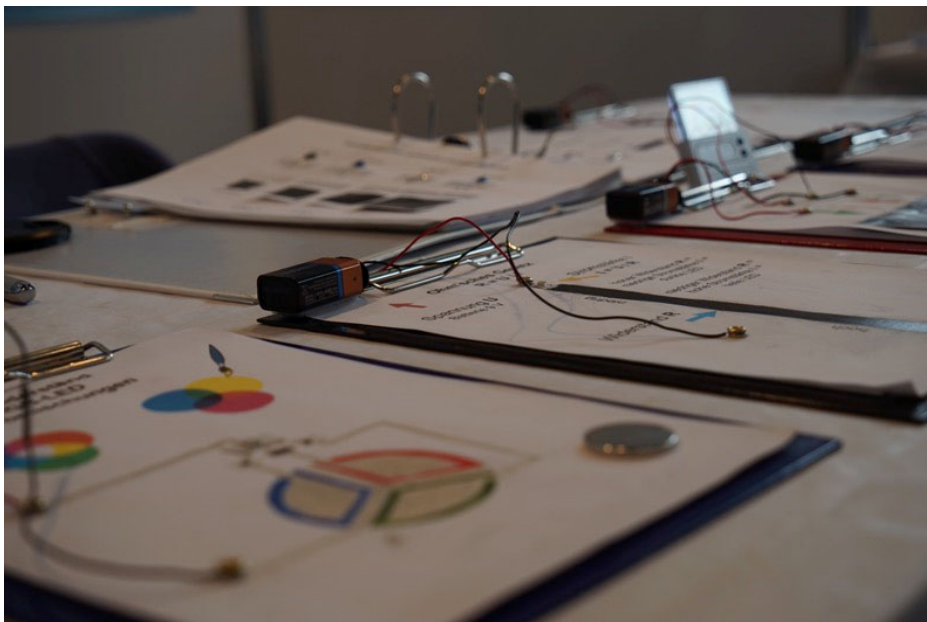


# Paperlectrics

Fundamentals of electronics with paper circuits

**FESTO**

**Workbook**



Revision level: 09/2016  
Author: Federico Burisch  
Editor: Reinhard Pittschellis  
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+49 711 3467-0



[www.festo-didactic.com](http://www.festo-didactic.com)



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# Contents

Contents	III
Preface	IV
Basic information	V
Basic equipment	VI
Parts list	IX
Experiment 1: Basic circuit on paper	1
Experiment 2: Control circuit	5
Experiment 3: Logic circuits	9
Experiment 4: Ohm's law and resistance	13
Experiment 5: Color mixing with RGB LEDs	17
Experiment 6: Measurements with a multimeter	21
Experiment 7: Capacitor	25
Experiment 8: Magnetic field of an energized coil	33
Experiment 9: Sound generation	35

## Preface

What would happen if you were to draw an electrical circuit into an exercise book, connect a lamp and a battery and switch it on? The exercise book would light up, of course. Impossible, you say? This workbook demonstrates how precisely this can be done with the help of a pencil, an LED and a battery. Furthermore, resistors and capacitors consisting of lines drawn with a pencil can be investigated as well. A sheet of paper can even be turned into a loudspeaker with silver-containing conductive varnish.

The worksheets support an introduction to the fundamentals of electronics because they make it possible for learners to conduct experiments themselves. The open layout promotes better understanding of the internal design and the functions of the individual components. The insulation found on conventional resistors and capacitors does not reveal the internal workings of these components. Touching the circuits is hazard-free thanks to the minimal battery voltage (9 V). In the truest sense of the word, this makes it possible to grasp scientific concepts. Independent experimentation and the subsequent sense of achievement are fun, and they foster the desire to carry on.

Experiments involving the use of lines drawn on paper with a pencil as electrical conductors are well-known. The electrical resistance of these lines is also a familiar effect. Nor are the use of graphite in capacitors and experiments involving spirals drawn on paper in combination with a magnet and an MP3 player in order to generate sound anything new. However, a comprehensive compilation and well-conceived further development permit active instruction in a simple manner.

Michael Faraday once said:

“The simplest experiment that one has devised oneself is better than the most elaborate experiment one merely watches.”

## Basic information

Graphite and diamonds both consist of carbon atoms (C) with 4 bonding options (4 free electrons). In the case of diamonds, all four of these options are made use of for bonding to the neighboring atoms. In the case of graphite, however, each carbon atom is bonded to only 3 other carbon atoms. This results in a two-dimensional layer consisting of hexagons. The 4<sup>th</sup> electron is left over and can move freely within this layer. Graphite is thus capable of conducting electricity parallel to the layers. Undamaged layers are referred to as graphs. This is the thinnest existing material, and it's pliable like a thin sheet of plastic and as hard as a diamond. It conducts electricity better than a copper cable.

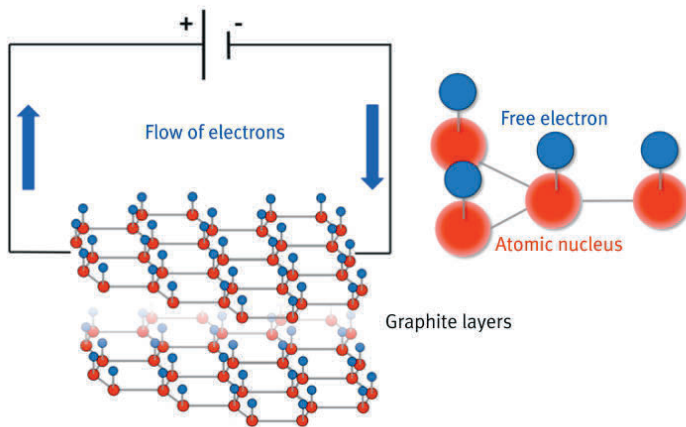


Figure 1: Graphite layers in a pencil line

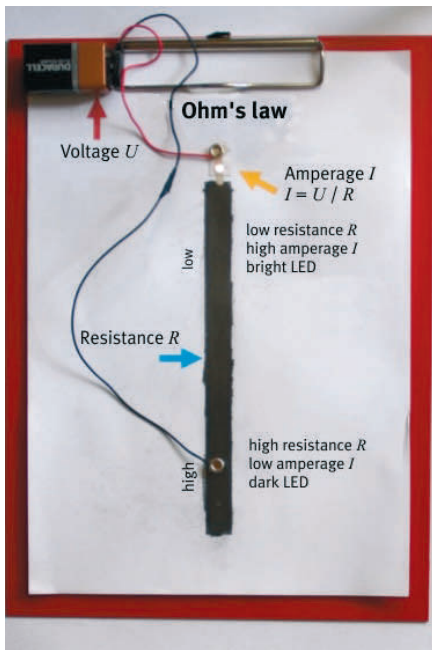
Graphite pencils consist of compressed powder in which the graphite structures have been destroyed to a given extent. The various layers are pressed together when the pencil leads are formed. If resistance is measured at the tip of an 8B pencil lead, the obtained value is 100 times less than the resistance of a line drawn with the same pencil lead. And thus a heavy line drawn with a bit of pressure also has a lower resistance value.

The resistance of a graphite line is unfortunately too high for some experiments. Silver-containing conductive varnish has to be used for the experiments involving light mixing with RGB LEDs for this reason. However, highly conductive graph pencils are used in the field of research.

## Basic equipment

Depending on previous knowledge, the individual experiments can be conducted separately. But due to the fact that they build upon one another, certain work steps are repeated in each experiment. Together with the basic equipment listed here, the most important recurrent work steps are summarized in this section:

- Edit and attach the template copy
- Connect LED
- Prepare connections
- Connect battery



Finished paper circuit

### ■ You'll need:

- 8B pencil
- DIN A4 clipboard
- DIN A4 iron foil
- For securing the paper: 4 disc magnets, 1S-06-02-N
- For electrical connections: 2 disc magnets, 1S-08-02-N
- 9 V battery
- Adhesive backed Velcro® strip for securing the battery
- 9 V battery connector
- Eyelets and a crimping tool for the ends of the wires from the battery connector
- LED from a 12 V LED strip
- Silver-containing conductive varnish
- Photocopying paper

## ■ Procedure

- Bond the iron foil to the base (clipboard).  
A thin piece of sheet iron can be used as an alternative.
- Secure the template copy with the 4 magnets.
- Draw a heavy pencil line onto the template copy over the light gray line with an 8B pencil.
- Cut an LED out of a white light strip and bond it into the top opening.

**Attention!** The LED has a “+” terminal and a “-” terminal.

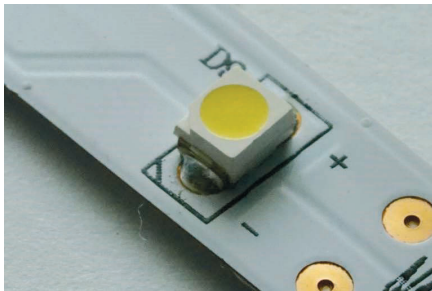


Figure 2: LED in light strip with +/- labelling

- Connect the LED's solder joints to the pencil lines with a brushstroke of silver-containing conductive varnish.

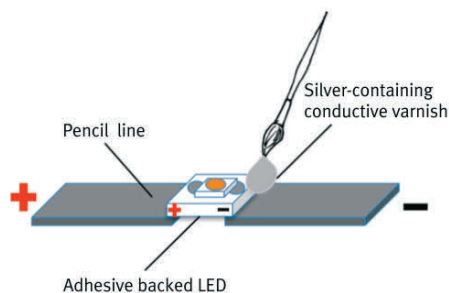


Figure 3: Connecting the LED to the pencil line with silver-containing conductive varnish

- Wind the stripped ends of the wires from the battery connector around the eyelets and crimp the eyelets with the crimping tool (see figure 4). Snap the battery connector onto the battery and secure it to the base with a Velcro® strip.

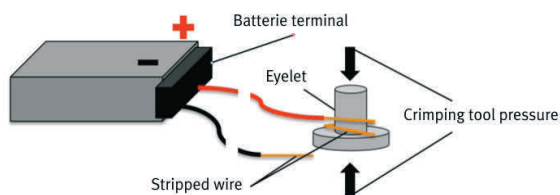


Figure 4: Winding the stripped ends of the battery connector wires around the eyelets and crimping

- Attach a magnet to the crimped eyelet and place it onto the template copy.  
**Attention!** The LED has a “+” terminal (red wire) and a “-” terminal (black wire).

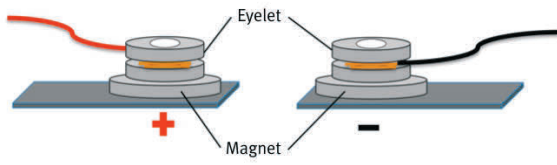


Figure 5: Attaching a magnet to the crimped eyelet and placing it onto the template copy



## Parts list

- 8B pencil
- DIN A4 clipboard
- DIN A4 iron foil, adhesive backed, e.g. [www.magnet-shop.biz](http://www.magnet-shop.biz)
- Disc magnets
  - For securing paper: 4 disc magnets, 1S-06-02-N, 6 mm dia., 2 mm thick, neodymium, N45, nickel plated, [www.supermagnete.de](http://www.supermagnete.de)
  - Electrical connection: 2 disc magnets, 1S-08-02-N, 8 mm dia., 2 mm thick, neodymium, N45, nickel plated, [www.supermagnete.de](http://www.supermagnete.de)
  - Slide switch: 2 disc magnets, 1S-08-05-N, 8 mm dia., 5 mm thick, neodymium, N45, nickel plated, [www.supermagnete.de](http://www.supermagnete.de)
  - Light mixing / sound: 1 – 2 disc magnets, 1S-30-03-N, 30 mm dia., 3 mm thick, neodymium, N45, nickel plated, [www.supermagnete.de](http://www.supermagnete.de)
- 9 V battery
- Adhesive backed Velcro® strip (hook and loop), 20 mm wide
- 9 V battery connector
- Eyelets and crimping tool, eyelet inside diameter: 5 mm
- LED, flexible 12 V DC LED strip
- RGB LED strip
- Silver-containing conductive varnish
- Photocopying paper

### Capacitor experiments

Various consuming devices with minimal operating voltage can be used to demonstrate the capacitor's ability to store a charge, for example:

SODIAL (R) digital LCD car dashboard clock, wires must be attached!

A multimeter is also required in order to measure the various capacitances.

### Magnetic field experiments

A compass is required in order to demonstrate the magnetic field which occurs around an energized conductor.

### Sound generation experiments

MP3 players and smartphones do not have enough power for the sound generation experiments. Output power has to be boosted with a small amplifier.

An audio connector cable (3.5 mm jack plug to 3.5 mm jack plug) is required in order to connect the smartphone.



## Experiment 1:

### Basic circuit on paper

#Circuit #Conductivity #Switch #LED

Click – the lamp lights up.

Have you ever thought about what happens when you turn on a light switch? This experiment will familiarize you with a simple electrical circuit with a switch, which you can draw and test yourself.

#### ■ You'll need:

- 8B pencil
- DIN A4 clipboard
- DIN A4 iron foil
- For securing the paper: 4 disc magnets, 1S-06-02-N
- For electrical connections: 2 disc magnets, 1S-08-02-N
- 9 V battery
- Adhesive backed Velcro® strip for securing the battery
- 9 V battery connector
- Eyelets and a crimping tool for the ends of the wires from the battery connector
- LED from a 12 V LED strip
- Silver-containing conductive varnish
- Photocopying paper

#### ■ Procedure

- Bond the iron foil to the base (clipboard).
- Secure the template copy with the 4 magnets.
- Draw a heavy line over the light gray line on the template copy (see figure 8) with an 8B pencil. Cut an LED out of a white light strip and bond it into the top opening.  
**Attention!** The LED has a “+” terminal and a “-” terminal.
- Connect the LED’s solder joints to the pencil lines with a brushstroke of silver-containing conductive varnish (see figure 3).
- Connect the battery (see figures 4 and 5) and secure it to the base with a Velcro® strip.  
**Attention!** The battery has a “+” terminal and a “-” terminal.

■ Try the following ...

- Cover the gap with your finger.
  - Cover the gap with a piece of aluminum foil.
  - Cover the gap with a piece of paper.
- What do you observe?

---

---

---

You have drawn a simple conductivity meter.

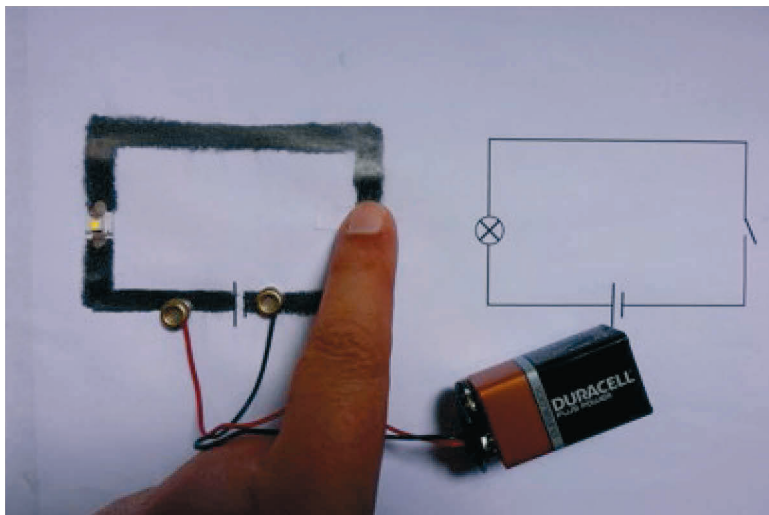


Figure 6: Simple electrical circuit

### ■ Improve your initial circuit

- Fully blacken one half of a piece of paper which entirely covers the gap with the 8B pencil and glue the other half onto the sheet so that graphite contacts graphite when the flap is lowered. Fold up the free end slightly (see figure 7).

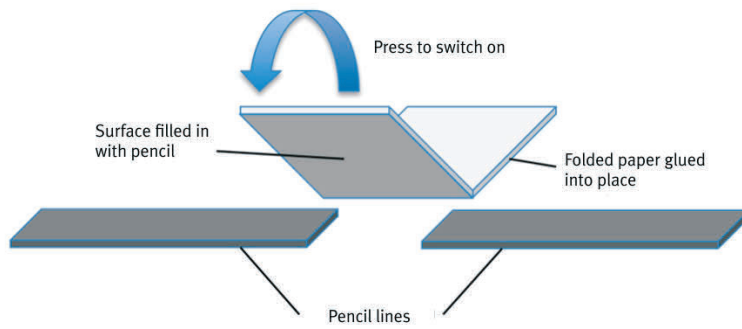


Figure 7: Simple paper switch

You have now created a light switch.

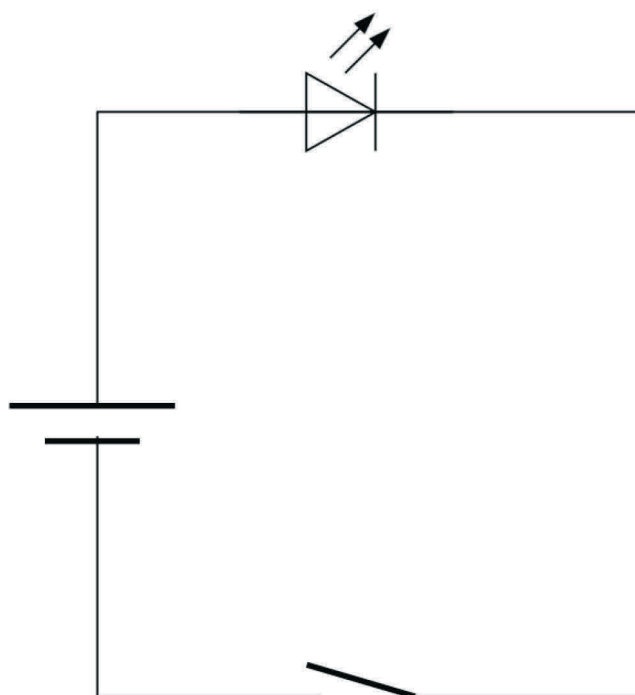
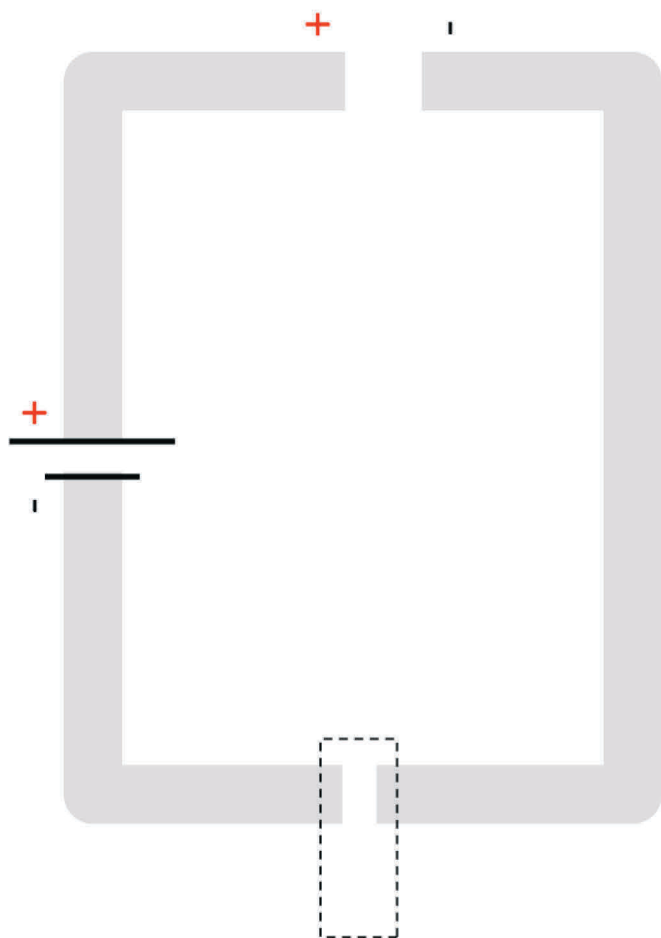


Figure 8: Template for “basic circuit on paper”

## Experiment 2:

### Control circuit

#### #Circuit #Changeover switch #LED

Up on and down off? In some stairwells, the same light bulb can be switched on and off with several switches. How does this work?

This experiment will familiarize you with an electrical circuit with several switches, which you can draw and test yourself.

#### ■ You'll need:

- 8B pencil
- DIN A4 clipboard
- DIN A4 iron foil
- For securing the paper: 4 disc magnets, 1S-06-02-N
- For electrical connections: 2 disc magnets, 1S-08-02-N
- For switching: 2 disc magnets, 1S-08-02-N
- 9 V battery
- Adhesive backed Velcro® strip for securing the battery
- 9 V battery connector
- Eyelets and a crimping tool for the ends of the wires from the battery connector
- LED from a 12 V LED strip
- Silver-containing conductive varnish
- Photocopying paper

#### ■ Procedure

- Bond the iron foil to the base (clipboard).
- Secure the template copy with the 4 magnets.
- Draw a heavy line over the light gray line on the template copy (see figure 9) with an 8B pencil.
- Cut an LED out of a white light strip and bond it into the top opening.  
**Attention!** The LED has a “+” terminal and a “-” terminal.
- Connect the LED’s solder joints to the pencil lines with a brushstroke of silver-containing conductive varnish (see figure 3).
- Connect the battery (see figures 4 and 5) and secure it to the base with a Velcro® strip.  
**Attention!** The battery has a “+” terminal and a “-” terminal.

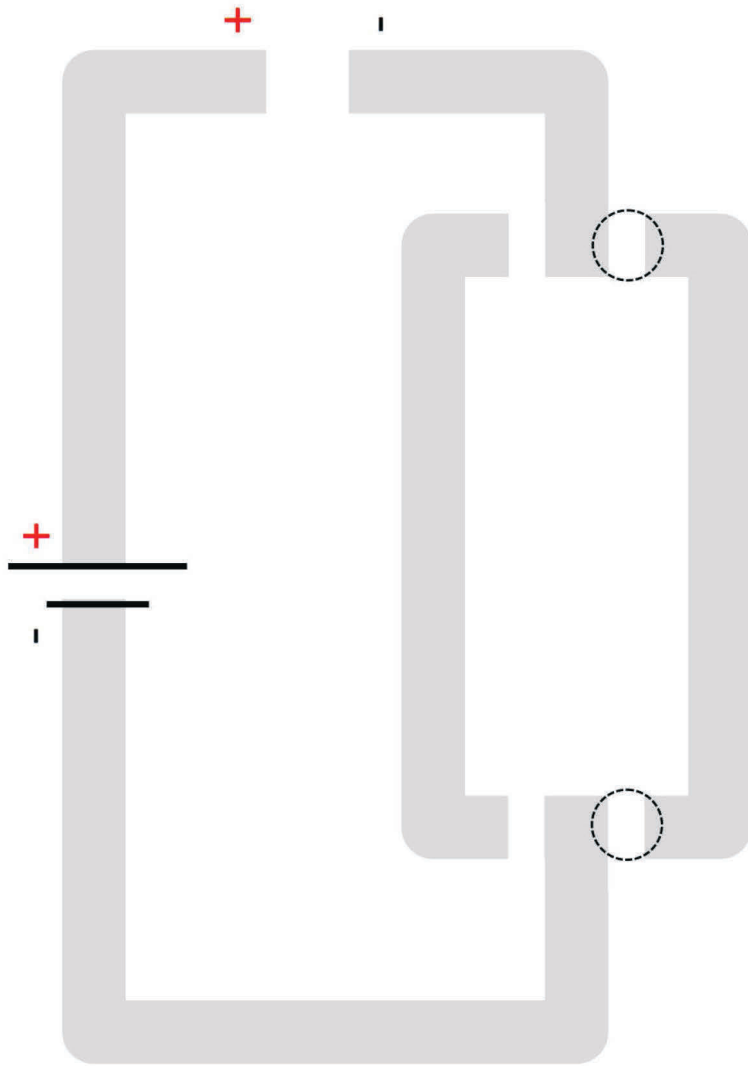


Figure 9: "Control circuit" template



**■ Try the following ...**

- Place two magnets onto one of the gaps at the top and one of the gaps at the bottom. What happens if the two magnets are placed onto the top and bottom gaps on the same side? What happens if the gaps are on opposite sides?
- 

This system consists of two parallel circuits, each with two interruptions. The LED only lights up when both of the interruptions on one of the circuit are closed.

Pushing the magnets back and forth results in a changeover switch which closes one circuit and interrupts the other, or vice versa. Two of these result in a stairwell circuit.



## Experiment 3:

### Logic circuits

#### #Logic circuit #AND circuit #OR circuit

Switches can be connected in series or parallel. Are you familiar with any examples of this? Sometimes it's necessary to switch both on, and sometimes it's only necessary to switch one or the other on. You can try out both types of circuit with this experiment.

Many dangerous machines, such as hedge trimmers used in the back yard and large presses in the automotive industry, are equipped with safety switches in order to prevent injuries to the hands. The machine only runs when both switches are activated at the same time with both hands.

In contrast to this, for example, only one of several switches has to be activated in order to trigger a fire alarm. As a logical consequence, this is known as an OR circuit.

Large numbers of both AND and OR circuits are used in computers.

#### ■ You'll need:

- 8B pencil
- DIN A4 clipboard
- DIN A4 iron foil
- For securing the paper: 4 disc magnets, 1S-06-02-N
- For electrical connections: 2 disc magnets, 1S-08-02-N
- For switching: 2 disc magnets, 1S-08-02-N
- 9 V battery
- Adhesive backed Velcro® strip for securing the battery
- 9 V battery connector
- Eyelets and a crimping tool for the ends of the wires from the battery connector
- LED from a 12 V LED strip
- Silver-containing conductive varnish
- Photocopying paper

### ■ Procedure

- Bond the iron foil to the base (clipboard).
- Secure the template copy with the 4 magnets.
- Draw a heavy line over the light gray line on the template copy (see figure 10) with an 8B pencil.
- Cut an LED out of a white light strip and bond it into the top opening.  
**Attention!** The LED has a “+” terminal and a “-” terminal.
- Connect the LED’s solder joints to the pencil lines with a brushstroke of silver-containing conductive varnish (see figure 3).
- Connect the battery (see figures 4 and 5) and secure it to the base with a Velcro® strip.  
**Attention!** The battery has a “+” terminal and a “-” terminal.

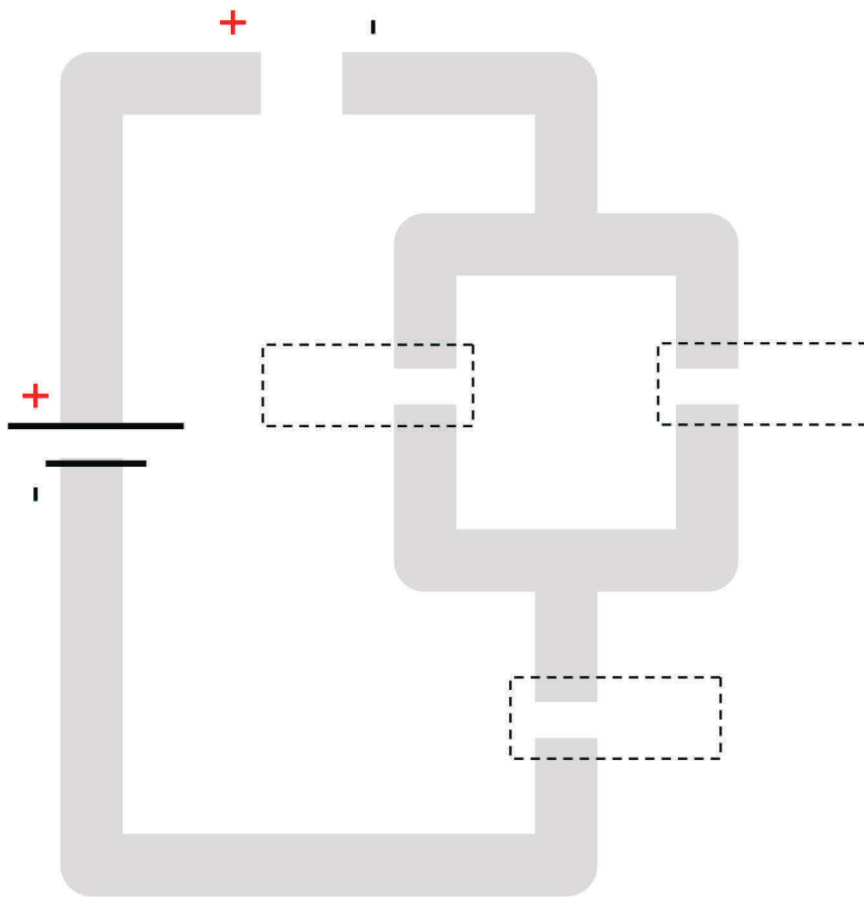


Figure 10: "Logic circuit" template



## Experiment 4:

### Ohm's law and resistance

#Ohm's law #Resistance #Amperage #Potentiometer

Did you try moving the battery connections closer to the LED during the other experiments? Try it now, without directly contacting the LED connectors (safety clearance: 1 cm). What do you notice? Can you explain it?

This experiment will familiarize you with electrical resistance, and you'll be able to draw and test several resistors yourself.

#### ■ You'll need:

- 8B pencil
- DIN A4 clipboard
- DIN A4 iron foil
- For securing the paper: 4 disc magnets, 1S-06-02-N
- For electrical connections: 2 disc magnets, 1S-08-02-N
- 9 V battery
- Adhesive backed Velcro® strip for securing the battery
- 9 V battery connector
- About 10 cm of wire (with black insulation)
- Eyelets and a crimping tool for the ends of the wires from the battery connector
- LED from a 12 V LED strip
- Silver-containing conductive varnish
- 2 cm of transparent adhesive tape
- Photocopying paper

#### ■ Procedure

- Bond the iron foil to the base (clipboard).
- Secure the template copy (see figure 11) with the 4 magnets.
- Draw a heavy line over the light gray line with an 8B pencil.
- Cut an LED out of a white light strip and bond it into the top opening.  
**Attention!** The LED has a "+" terminal and a "-" terminal.  
Bond the LED such that the "+" terminal is at the top.
- Connect the LED's solder joints to the pencil lines with a brushstroke of silver-containing conductive varnish.

- Connect the battery (see figures 4 and 5) and secure it to the base with a Velcro® strip.  
**Attention!** The battery has a “+” terminal and a “-” terminal. Connect the “+” terminal to the upper end (dashed circuit). Extend the “-” pole terminal with a piece of wire (with black insulation), so that it also reaches the bottom end of the drawing.
- Cover the bottom LED connection with a piece of transparent adhesive tape (insulation).

■ Try the following ...

- Connect the bottom end with the “-” terminal. How bright is the LED?

---

- Slowly slide the “-” terminal to the top without contacting the LED directly. What do you observe?

---

The shorter the pencil line the brighter the LED. The circuit's resistance  $R$  changes along with the length of the line, and thus amperage  $I$  as well, which causes the LED to light up. Resistance  $R$  slows down the flow of electrons and thus determines the number of electrons which pass through the conductor per second, which is designated amperage  $I$ . You may also have noticed that a fresh battery causes the LED to light up more brightly than an old, depleted battery. Battery voltage  $U$  (initially 9 V) drops as time goes by and the LED lights up less and less brightly. Georg Simon Ohm formulated an equation with these three quantities:

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

If you want to change the brightness of the LED, amperage  $I$  must be adjusted. The equation can be reformulated as follows:

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

Resistance  $R$  must be small in order for amperage  $I$  to be high. And thus the pencil line has to be short. Your drawn circuit with a variable resistor is known as a potentiometer. How can we make use of it? Have you ever thought about how dimmers at home and in your car work? Now you've drawn a dimmer switch yourself.



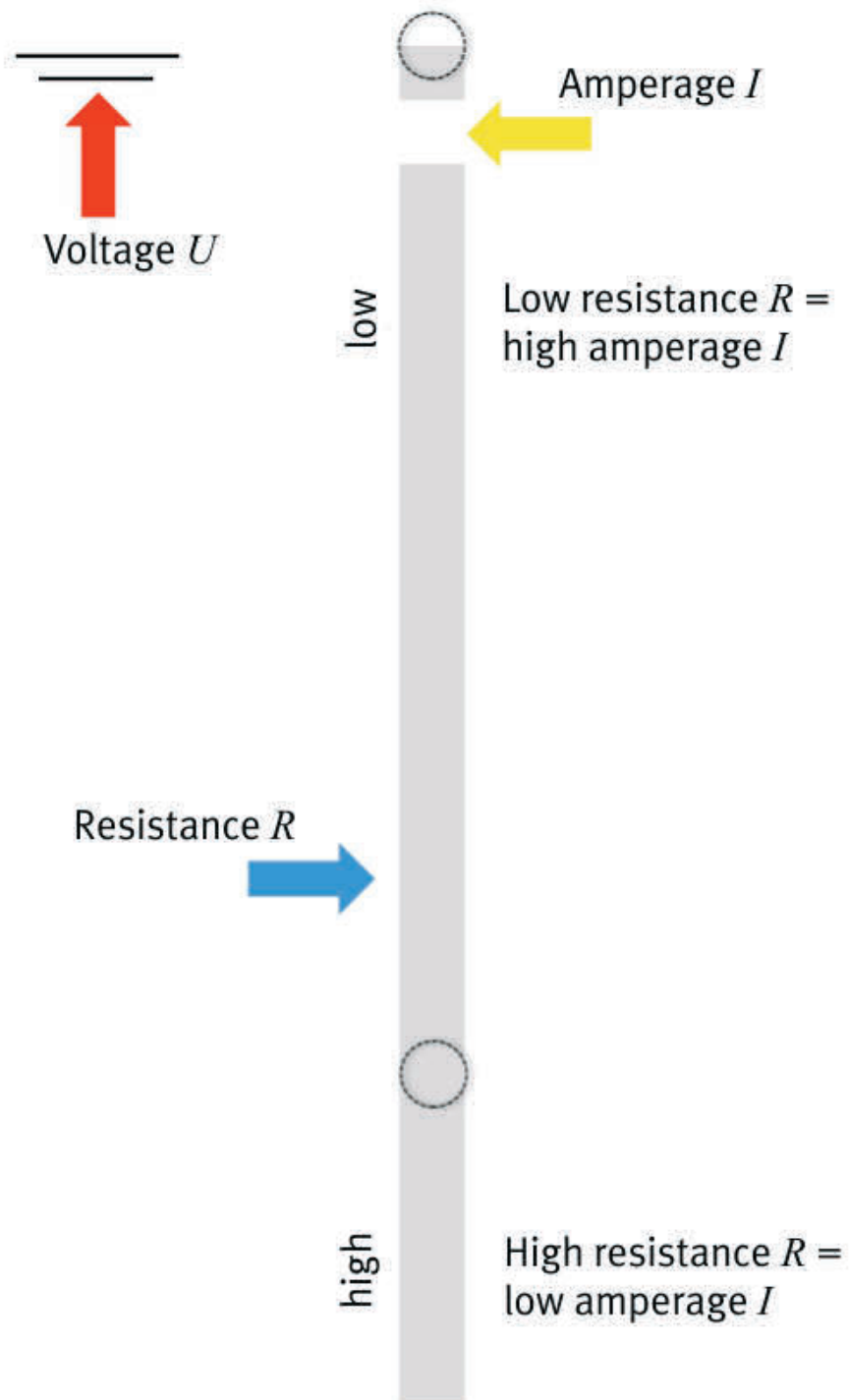


Figure 11: "Dimmer" template



## Experiment 5:

### Color mixing with RGB LEDs

#### #Resistor #Series resistor #RGB LED #Optical color mixing

Why do we need resistors and why do they have to have various resistance values? What happens if we leave them out?

If you have a white LED left over, you can try it out yourself. If you connect the battery directly to the solder joints on the LED, it lights up very brightly for a short time and then burns out. Too many electrons were flowing through the LED and amperage was too high. Amperage must therefore be limited upstream from the LED. Resistors are available to this end which are intended precisely for this task.

In addition to white LEDs, you may also have seen colored LEDs which can even change their color. How do you think it might work? RGB color LEDs consist of 3 small single color LEDs (red, green and blue), each of which is supplied with current individually. Each LED needs its own series resistor, which you can draw yourself with a 8B pencil.

This experiment will familiarize you with an electrical circuit with several series resistors and a color LED, which you can draw and test yourself.

#### ■ You'll need:

- 8B pencil
- DIN A4 clipboard
- DIN A4 iron foil
- For securing the paper: 4 disc magnets, 1S-06-02-N
- For electrical connections: 2 disc magnets, 1S-08-02-N
- For switching: 1 disc magnet, 1S-30-03-N
- 9 V battery
- Adhesive backed Velcro® strip for securing the battery
- 9 V battery connector
- Eyelets and a crimping tool for the ends of the wires from the battery connector
- RGB LED from 12 V color LED strip
- Silver-containing conductive varnish
- Photocopying paper

## ■ Procedure

- Bond the iron foil to the base (clipboard).
- Secure the template copy (see figure 16) with the 4 magnets.
- Brush over the light gray line with silver-containing conductive varnish.
- Cut an LED out of an RGB color light strip and bond it into the top opening (see figures 12 and 13).

**Attention!** The LED has 3 “+” and 3 “-” connections.



Figure 12: RGB LED with connections

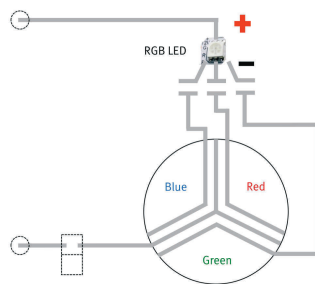


Figure 13: Inserting the RGB LED

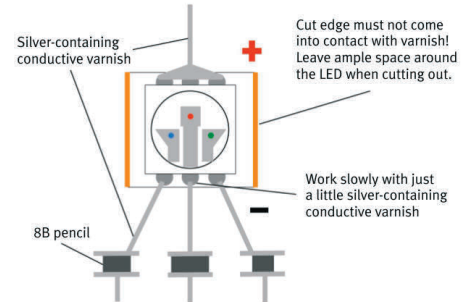


Figure 14: Instructions

- Connect the LED's solder joints to the pencil lines with silver-containing conductive varnish (see figure 14).
- Make a paper switch for turning the LED on and off, and glue it onto the base (see figure 7).
- Fully blacken one half of a piece of paper which entirely covers the gap with the 8B pencil and glue the other half onto the sheet so that graphite contacts graphite when the flap is lowered. Fold up the free end slightly (see figure 7).
- Connect the battery (see figures 4 and 5) and secure it to the base with a Velcro® strip.

**Attention!** The battery has a “+” terminal and a “-” terminal.

### ■ Try the following ...

- Place the large magnet onto the “RED” position (see figure) and turn the switch on.
- Fill out the empty field for connecting the color red bit by bit with an 8B pencil until it’s pleasantly bright. If it gets too bright, erase a portion of the field.
- Now place the large magnet onto the “BLUE” position (see figure) and turn the switch on. Blue LEDs require less current and thus a greater resistance value. The connecting line is thus thinner.
- Fill out the empty field for connecting the color blue bit by bit with an 8B pencil until it’s exactly as bright as the red LED.
- Now place the large magnet onto the “GREEN” position and proceed in the same way as you did for the other two colors.
- Finally, place the large magnet in the middle and turn the switch on. If you’ve adjusted the brightness of the LEDs with the pencil-drawn resistors correctly, the RGB LED now lights up white.
- Now try mixing the colors. What do we get if we mix red and green?
- Push the large magnet aside and use a finger as a jumper. The individual LEDs light up significantly weaker due to the high resistance of your finger, but you can observe the small spots of light much better as a result.

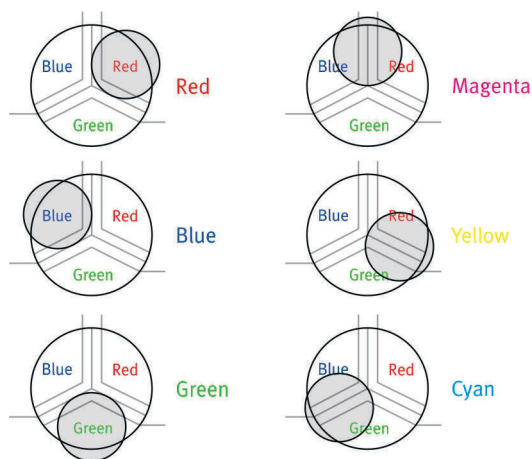


Figure 15: Color mixtures with RGB LED

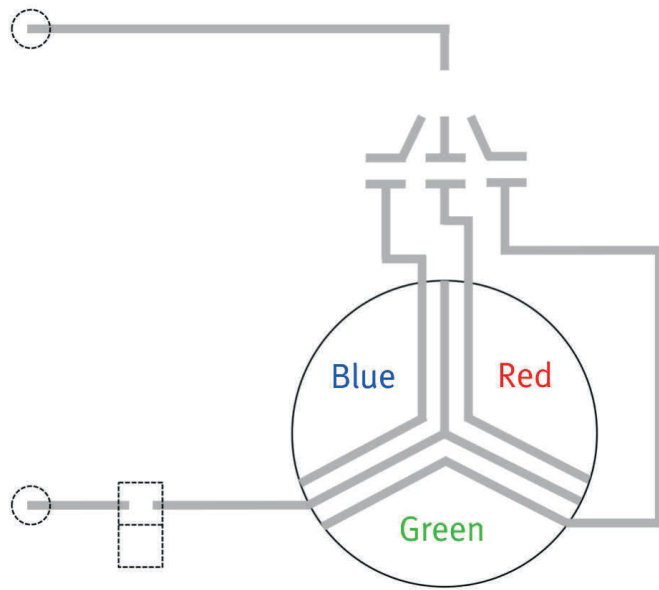


Figure 16: Template for “Color mixing with RGB LEDs”

## Experiment 6:

### Measurements with a multimeter

#### #Resistance measurement #Conductor cross-section #Specific resistance

During the previous experiments you examined the resistive effect of the pencil lines by means of trial and error. Is it possible to precisely determine the resistance of a pencil line, or even to calculate it in advance?

With the help of this experiment you'll learn how to change the resistance of a pencil line by making it longer or wider, and how to measure and calculate its resistance as well. The range of resistance values created with pencil lines can be greatly increased through the use of different pencils.

#### ■ You'll need:

- 8B pencil
- Photocopying paper
- Multimeter

#### ■ Procedure

- In order to determine the resistance of a pencil line relative to its length, carefully fill out the respective surface of the template (see figure 17) with an 8B pencil.
- Measure resistance with a multimeter. Contact the middle of the zero scale marking with one measuring probe and continuously move the other measuring probe to varying distances from the first. Take 5 measurements and calculate the mean value.
- Enter your measured values to a table.
- Enter the measured values relative to distance between the measuring probes to a graphic and connect the measuring points with a line.
- What does the resultant characteristic curve look like?
- In order to determine the resistance of a pencil line relative to its width, carefully fill out the respective surface of the template (see figure 17) with an 8B pencil.
- Measure resistance with a multimeter. Contact the middle of the red lines with both measuring probes. Measure each line width 5 times and calculate mean values. Divide the resultant values by 2 (line length: 2 cm).
- Enter your measured values to a table.
- Enter the measured values relative to width of the lines to a graphic and connect the measuring points with a line.
- What does the resultant characteristic curve look like?

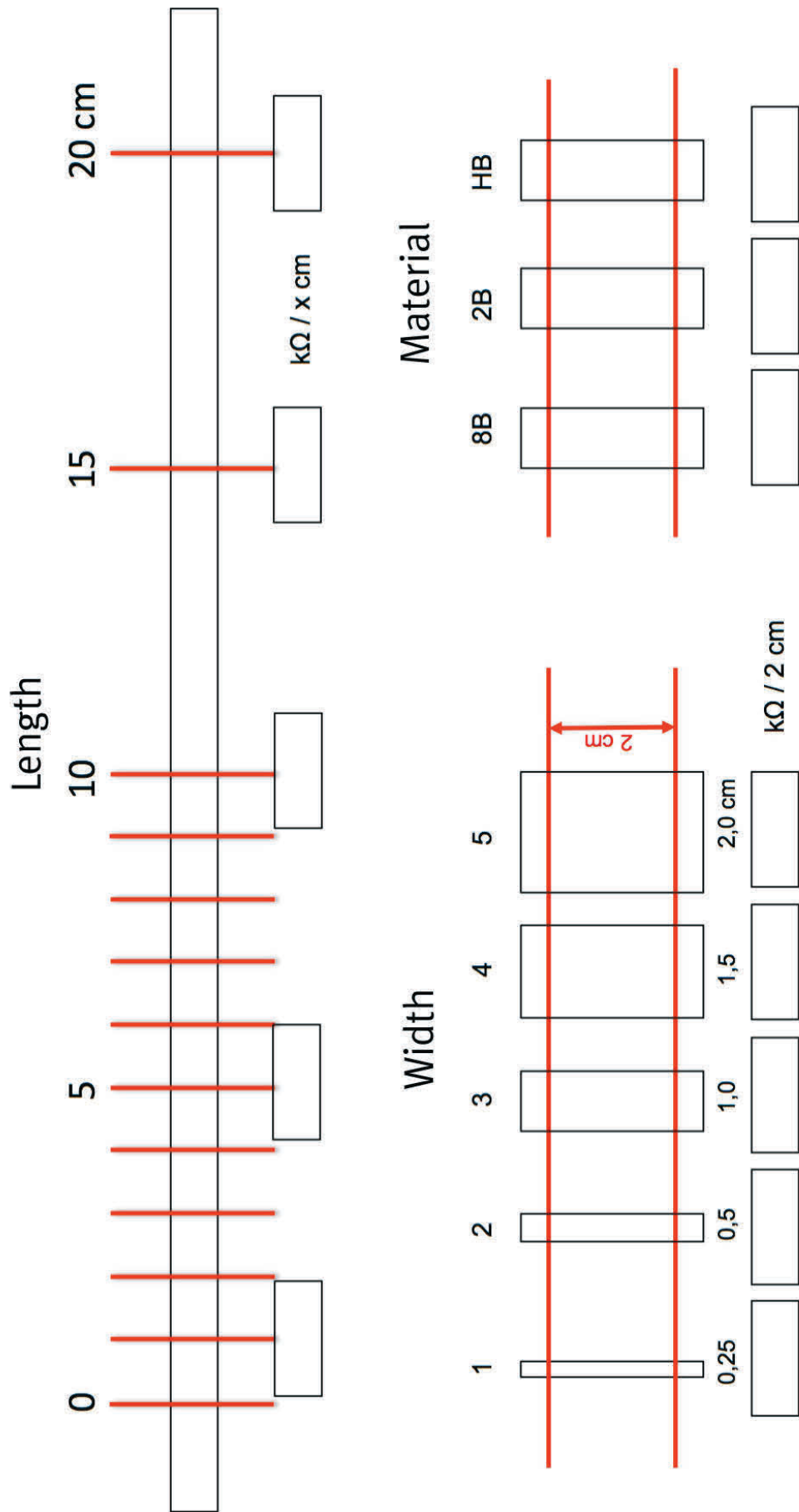


Figure 17: Template for “measurement with multimeter”



Resistance  $R$  increases in a linear relationship to line length  $l$ .

Resistance  $R$  drops in reverse proportion to line width  $b$ . Line cross-section  $A$  is determined by multiplying line width by constant line height.

And thus resistance  $R$  sinks in reverse proportion to line cross-section  $A$ .

This relationship is described in physics textbooks:

$$R = \rho \cdot \frac{l}{A}$$

Resistance ( $R$ ); specific resistance ( $\rho$ ); length ( $l$ ); surface area ( $A$ )

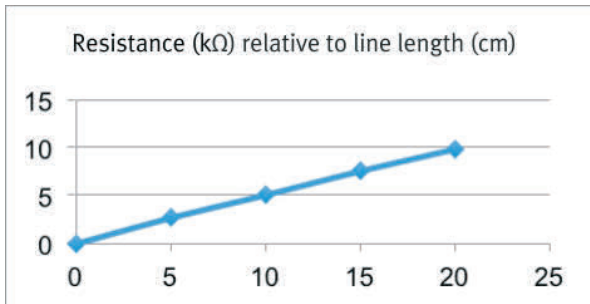


Figure 18: Characteristic resistance curve relative to line length

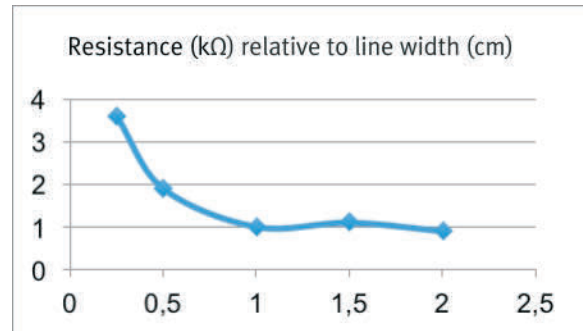


Figure 19: Characteristic resistance curve relative to line width or line cross-section

Varying degrees of pencil hardness result in different resistance values, because resistance depends on material characteristics. The softer the pencil the lower the resistance. The use of additional graphite results in a softer pencil. Clay is added to the graphite in order to make a pencil harder. That's why a pencil with hardness grade 8B is ideal for the experiments. Higher hardness grades increase resistance.

#### ■ Try the following ...

- Fill in the *Material* fields with different pencils (hardness grades 8B, 2B and HB) in the template (see figure 17). What are the resistance values now?
- Each material has a specific resistance ( $\rho$ ).



## Experiment 7:

### Capacitor

#### #Load separation #Capacitor #Capacitance #Energy storage

Have you ever touched a fleece blanket in the winter when the air is very dry, and gotten a small electric shock as a result? What caused this? Especially when the air is dry, electrical charges may be built up predominantly in one of two different bodies which rub against each other, resulting in load separation.

If differently charged bodies are then brought close to each other, charge equalization takes place as of a certain distance and a miniature bolt of lightning flashes over. The same phenomenon occurs with clouds. Charge equalization can take place either between two different clouds, or between one cloud and the ground.

Load separation is taken advantage of in electronic circuits in order to briefly store charges in a capacitor. In order to ensure that charge equalization doesn't take place immediately between the two bodies (electrodes), an insulator (dielectric) is inserted between them (see figure below). You can use paper as a dielectric for our experiment, and two surfaces (one on each side of the paper) filled in densely with pencil graphite will serve as electrodes. Try it!

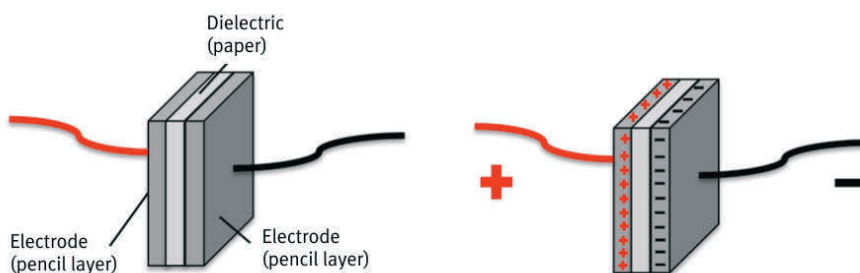


Figure 20: Layout of a capacitor

By conducting this experiment you'll learn how to draw a simple capacitor with paper and pencil, with which you'll even be able to briefly operate a liquid crystal display, for example on a clock.

■ **You'll need:**

- 8B pencil
- DIN A4 clipboard
- DIN A4 iron foil
- For securing the paper: 4 disc magnets, 1S-06-02-N
- For electrical connections: 2 disc magnets, 1S-08-02-N
- 9 V battery
- Adhesive backed Velcro® strip for securing the battery
- 9 V battery connector
- In order to connect the liquid crystal display: 2 disc magnets, 1S-08-02-N
- Eyelets and a crimping tool for the ends of the wires from the battery connector
- Silver-containing conductive varnish
- Photocopying paper

■ **Procedure**

- Bond the iron foil to the base (clipboard).
- Secure the template copy (see figure 26) with the 4 magnets.
- Brush over the light gray lines with silver-containing conductive varnish.



Figure 21: Brushing over the light gray lines with conductive varnish

- Prepare the battery connections (see figures 4 and 5) and secure the battery to the base with a Velcro® strip.  
**Attention!** The battery has a “+” terminal and a “-” terminal.
- Prepare the liquid crystal display connections (analogous to battery connection, see figures 4 and 5).  
**Attention!** The liquid crystal display has a “+” terminal and a “-” terminal.

- Using the 8B pencil, fill out both sides of the template (see figure 27) with identically positioned squares (light gray surface surrounded by an uninterrupted line) and then cut the square out along the dotted line.

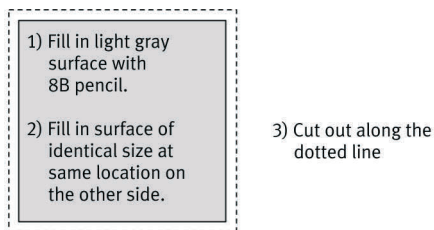


Figure 22: Paper square filled out on both sides with 8B pencil

- Glue the cut out square into the square with the dotted line in the first template (see figure 26). Just before joining the two sheets, generously fill out the circle surrounded by the dotted line on the first template with silver-containing conductive varnish (electrical contact between the two sheets) (see figure 23).

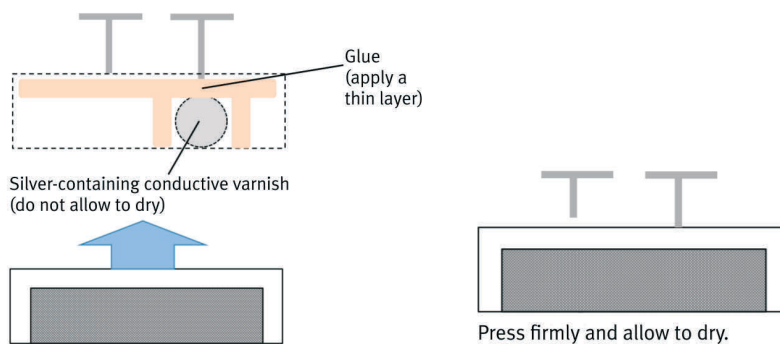


Figure 23: Gluing the paper square onto the template (figure x1)

- Press firmly and allow the glue to dry.
- Finally, connect the left-hand terminal with the help of silver-containing conductive varnish (see figure 24).

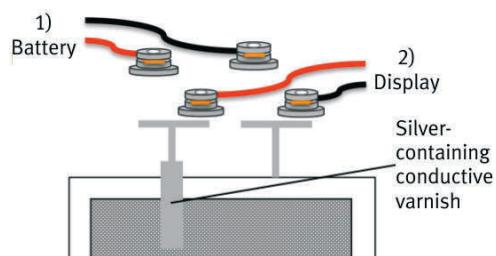


Figure 24: Establishing contact between the top of the filled in square and the terminal on the template with silver-containing conductive varnish

- The capacitor should now look like this.

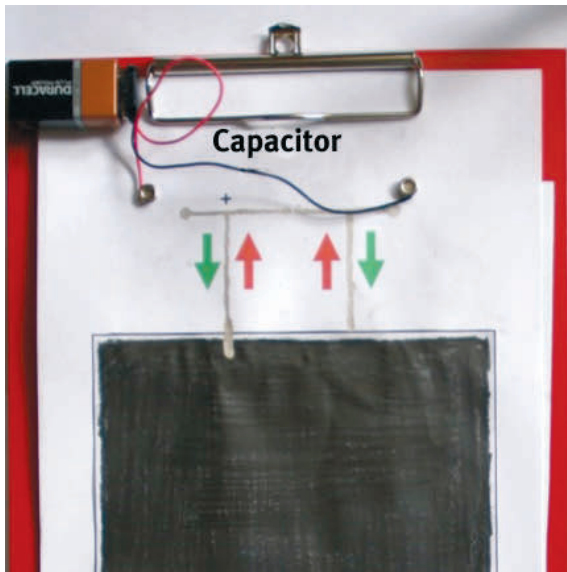


Figure 25: Finished paper capacitor

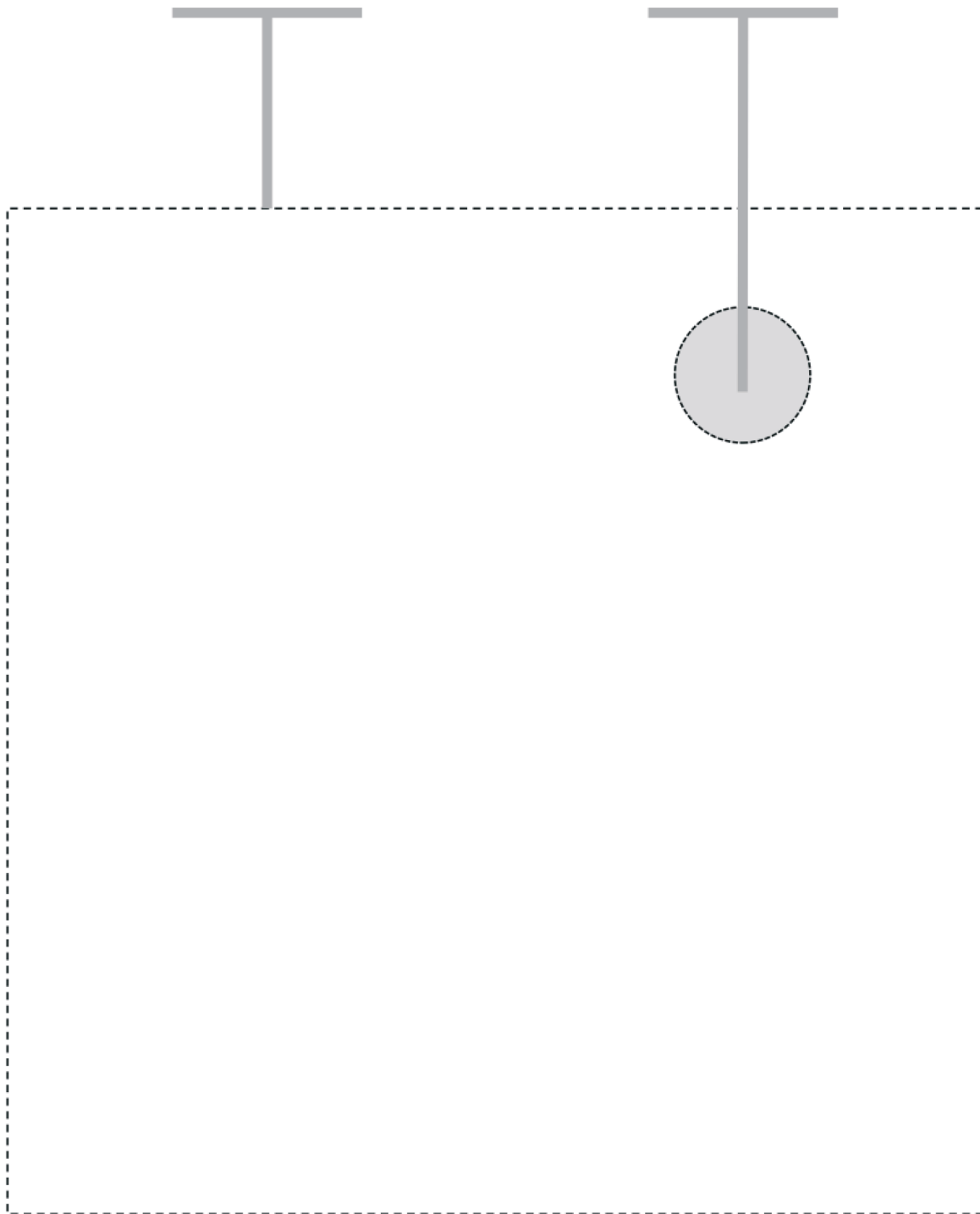


Figure 26: Template 1, "capacitor"

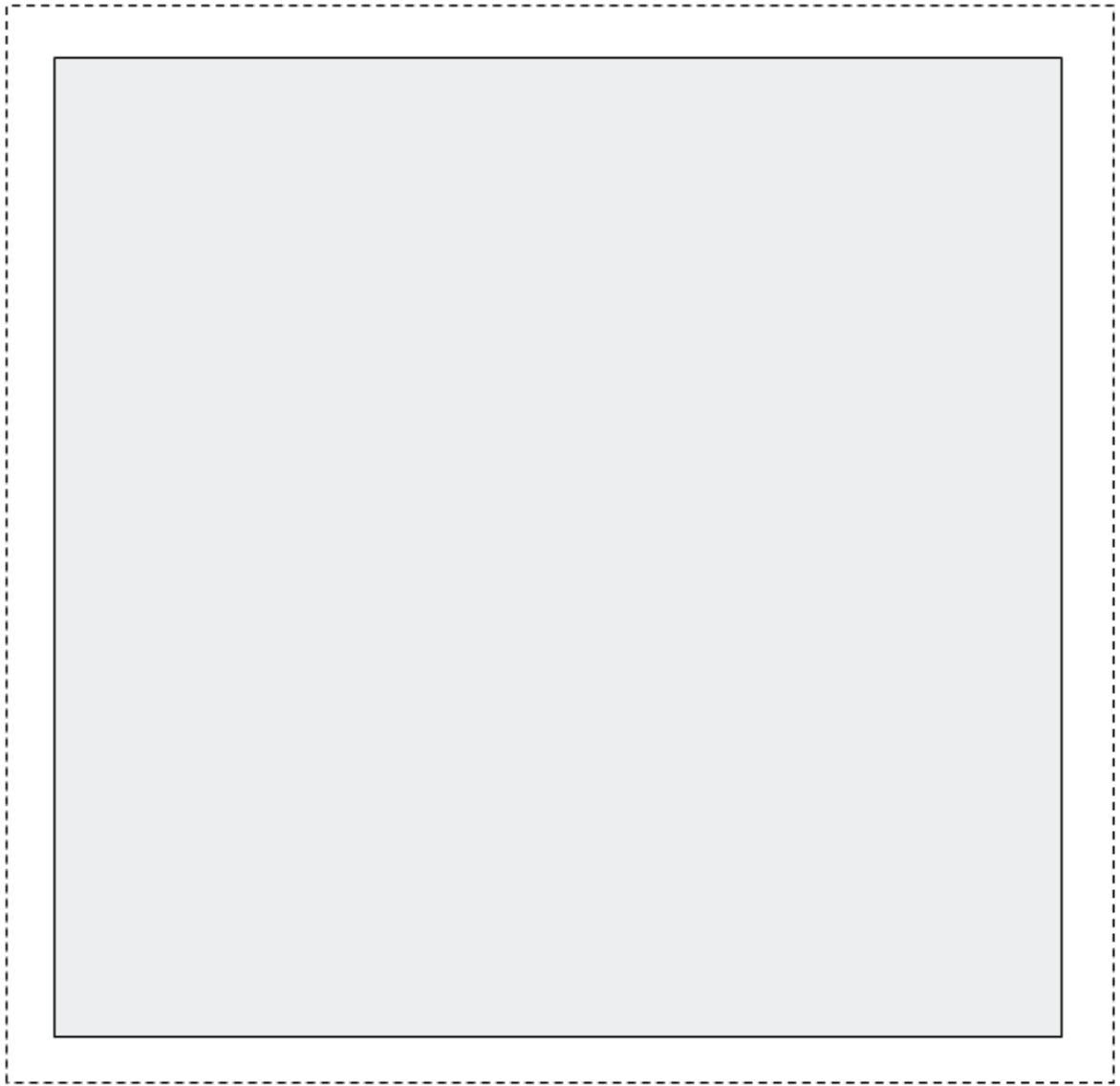


Figure 27: Template 2, "capacitor"

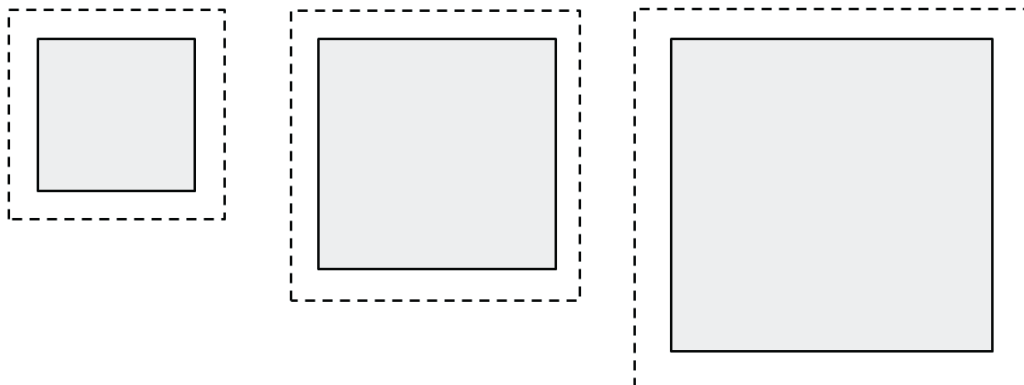


Figure 28: Template 3, "capacitor"



### ■ Try the following ...

- Charge the paper capacitor for about 5 minutes by connecting the battery.
- Disconnect the battery.
- Connect the liquid crystal display.
- Display illumination time can be varied by charging the battery for different amounts of time.
- Which charging time would you recommend?

### ■ How much energy can a capacitor store?

How big a charge can this sort of capacitor accumulate? How large is its capacitance? The unit of measures for electrical capacitance is the Farad. It was named after Michael Faraday. A capacitor with a capacitance of one Farad (F) can store a charge of one Coulomb (C) by charging it to a voltage of one Volt (V).

1 Coulomb is equivalent to 6,241,509,629,152,650,000 elementary charges.

But capacitors drawn with a pencil are much smaller – a capacitance of roughly 1 nF ( $10^{-9}$  F) is achieved in this case.

Filling in the required surface with pencil can be strenuous. How does the capacitance of a capacitor change relative to surface area?

### ■ Try the following ...

- Fill in variously sized squares (see template) on both sides with an 8B pencil.
  - Set the multimeter to the “Nano-Farad” measurement.
  - Contact both sides of the paper capacitor with the test probes.
  - Enter the measured value to a table (capacitance and capacitor surface area).
  - Connect the measuring points.
- What does the resultant characteristic curve look like?

The graphic might look like this.

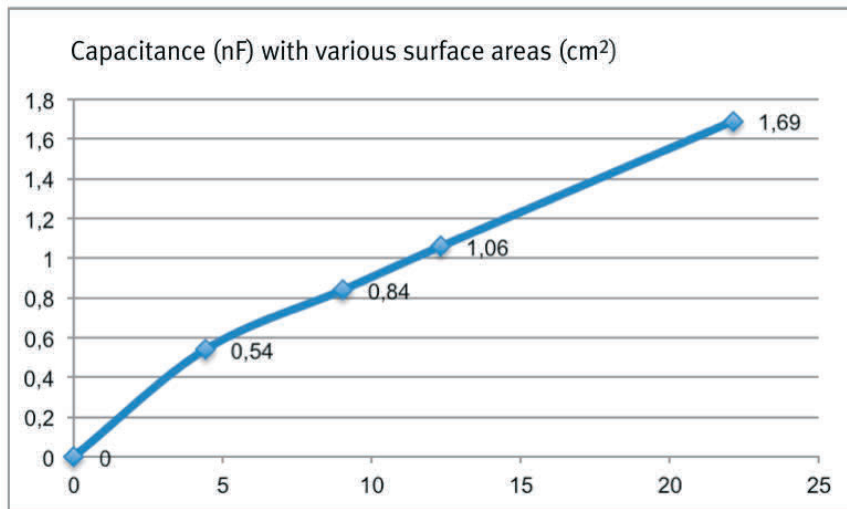


Figure 29: Change in capacitor capacitance relative to surface area

Within the selected measuring range, capacitance  $C$  changes in linear relation to the increase in surface area. There's a physical law for this phenomenon as well. The following applies to capacitance  $C$  of a plate capacitor with surface area  $A$  (graphite square), distance between plates  $d$  (paper thickness) and filling with a material with dielectric constant  $\epsilon_r$  (paper):

$$C = \epsilon_r * \epsilon_0 * A / d \quad \epsilon_0 = \text{dielectric constant, vacuum}$$

## Experiment 8:

### Magnetic field of an energized coil

#Electrical conductor #Magnetic field #Electromagnet

During your experiments using silver-containing conductive varnish as an electrical conductor have you ever coincidentally had a compass close by? If not, try it now! Make sure that there aren't any magnets close by.

By conducting this experiment you'll learn how to draw a simple electromagnet with paper and silver-containing conductive varnish, and how to operate it.

#### ■ You'll need:

- Silver-containing conductive varnish
- 9 V battery
- Adhesive backed Velcro® strip for securing the battery
- 9 V battery connector
- Eyelets and a crimping tool for the ends of the wires from the battery connector
- Compass
- Photocopying paper

#### ■ Procedure

- Paint a thin line (roughly 15 cm long and 3 mm wide) onto a sheet of photocopying paper with silver-containing conductive varnish.
- Prepare the battery connections (see figures 4 and 5) and secure the battery to the base with a Velcro® strip.

■ **Try the following ...**

- Position the compass next to the painted line and press the two wire ends against the ends of the painted line. What do you observe?
  - Reverse the cable ends and press them against the opposite ends of the painted line. What do you observe now?
- 

In 1820 during the course of a similar experiment, Ørsted observed deflection of the compass needle due to an energized wire and discovered the magnetic effect of electrical current. With the help of further experiments, he discovered the paths of the field lines of this magnetic field and where magnetic north and south are located.

## Experiment 9:

### Sound generation

**#Magnetic field #Electromagnet #Permanent magnet #Oscillation**

Do you enjoy listening to music with your MP3 player? Do you know how the little loudspeakers in your headset transform electrical signals back into sound?

By conducting this experiment you'll learn how to draw a loudspeaker with paper, silver-containing conductive varnish and a magnet, and how to use it.

#### ■ You'll need:

- DIN A4 clipboard
- DIN A4 iron foil
- For securing the paper: 4 disc magnets, 1S-06-02-N
- Silver-containing conductive varnish
- 2 disc magnets for connecting the amplifier outputs: 1S-08-02-N
- Eyelets and a crimping tool for the ends of the wires from the amplifier terminals
- 1 – 2 disc magnets, 1S-30-03-N
- An MP3 player or a smartphone
- MP3 players and smartphones do not have enough power for the sound generation experiments. Output power has to be boosted with a small, inexpensive amplifier (see parts list).
- A connector cable is required in order to connect the MP3 player to the amplifier (audio cable with 3.5 mm jack plugs).
- Photocopying paper

### ■ Procedure

- Brush over the light gray line in the template (figure 32) with silver-containing conductive varnish.
- Prepare the connections for the amplifier outputs (analogous to battery connection shown in figures 4 and 5).
- Plug the output cables and the MP3 connector cable into the amplifier (see figure 30) and connect the power cable.

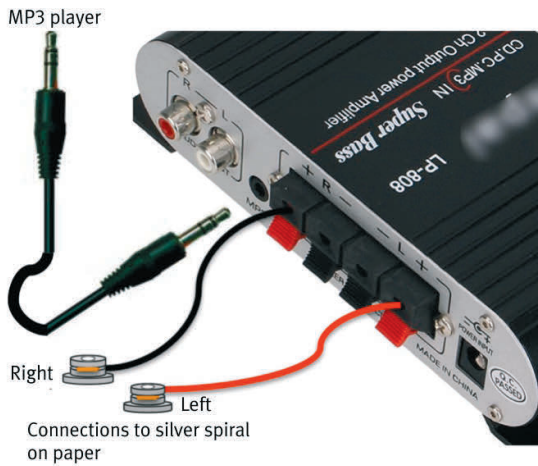


Figure 30: Amplifier cable connections

### ■ Try the following ...

- Set the large magnet (3 cm diameter) onto the iron foil and then secure the painted template on top of it. Make sure that the painted circle is directly on top of the magnet.
- Push the paper together slightly so that it bulges, thus resulting in a small space (1 or 2 mm) between the magnet and the paper at the painted circle (see figure 31).
- Connect the amplifier terminals to the painted leads.

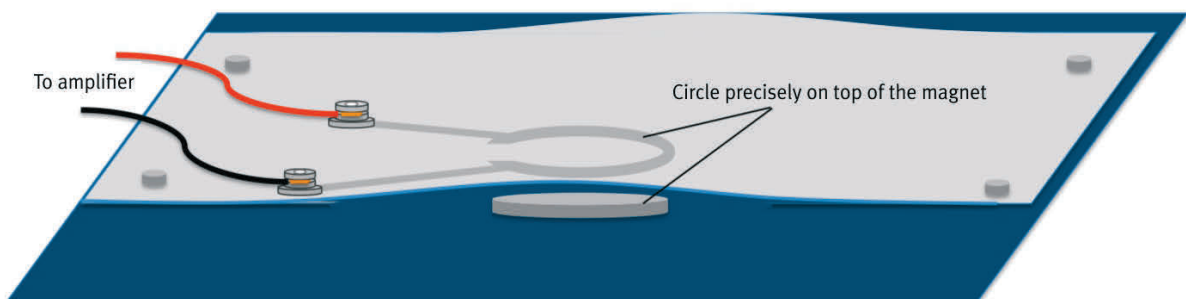


Figure 31: Layout and connection of the paper loudspeaker

- Pick a song with lots of bass and switch on the MP3 player and the amplifier. Set both to “loud”.

The MP3 player generates a fluctuating flow of current which is boosted by the amplifier. When this current flows through the silver coil it generates a magnetic field with an intensity which fluctuates relative to the music. The coil’s “oscillating” magnetic field interacts with the permanent magnet’s constant magnetic field. The paper is variously tensioned as a result and it begins to oscillate. This oscillation is transferred to the air and you hear music.

#### ■ Try the following ...

- If you lay two large magnets on top of each other the sound becomes more intensive.
- You can try out various ideas with regard to the design of the coil. View the following website for further inspiration:

<http://highlowtech.org/?p=1372>

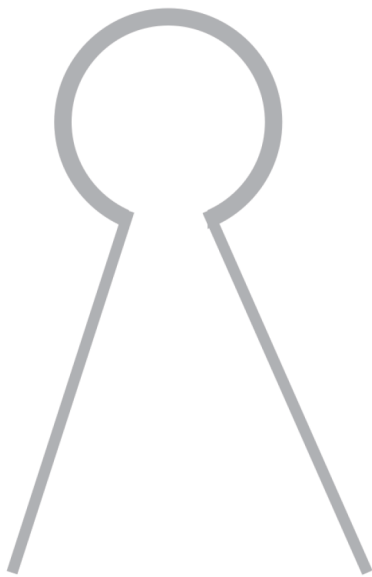


Figure 32: “Sound generation” template

**Festo Didactic SE**

Rechbergstr. 3  
73770 Denkendorf  
Germany



+49 711 3467-0



+49 711 34754-88500



[www.festo-didactic.com](http://www.festo-didactic.com)



[did@festo.com](mailto:did@festo.com)