Hands-on-Remote

Teaching Module

Sensors and Measurements

All materials and contact details can be found on the project websites as well as in the Erasmus+ project profile:
https://sites.google.com/campus.ul.pt/hands-on-remote-language/home
https://erasmus-plus.ec.europa.eu/projects/search/details/2020-1-DE02-KA226-VET-008295

Core development team

- Marion Pellowski and Lorenz Kampschulte, Deutsches Museum, Munich, Germany
- Pedro Reis, Mónica Baptista, Luís Alexandre da Fonseca Tinoca, Lisbon University, Institute of Education, Lisbon, Portugal
- Wojciech Karcz, Adam Zahler, Anna Strzeszewska-Potyrała, Karolina Klimaszewska, Copernicus Science Center, Warsaw, Poland
- Miriam Voss, Mike Kramler, Marion Pellowski, Technical University Munich, Munich, Germany

Disclaimer

The European Commission's support for the production of this publication does not constitute an endorsement of the contents, which reflect the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Co-funded by the Erasmus+ Programme of the European Union

Imprint

Authors: Karolina Klimaszewska, Adam Zahler, Wojciech Karcz
Copernicus Science Centre, Warsaw, Poland

Deutsches Museum, Munich, Germany
Layout & Design: Michał Romański
Print: February 2023

Index

1 Introduction

Teaching module
Sensors and Measurements

Students perform different experiments involving making DIY sensors. They investigate basic physics phenomena like elasticity, acceleration and electromagnetism. Students can work individually, or as a team. Remote collaboration is also possible.

Optional unit

Unit 1
Measurement error
Aim: Learning about measurement errors
Task: Measuring diagonal of a sheet of paper and calculating coarse/systematic errors

Teachers can change the sequence of the modules or use only one as an independent unit

Main teaching module

Unit 2a
Slingshot
Aim: Investigation of the distance of a fired object – stretched rubber band
Task: Building a simple slingshot model to make some experiments

Unit 2b
Rubber band drive
Aim: Using the potential energy of elasticity to design a simple drive
Task: Building a car model with rubber band drive

Unit 2c
Experiment results analysis
Aim: Presenting to the group the analysis of the collected measurement data and comparing the results with other students
Task: Presentation of collected data by student groups

Unit 3a
Building the pendulum
Aim: Using the pendulum to make some measurements e.g. oscillation period
Task: Building a model of mathematical pendulum using simple tools and materials

Unit 3b
Making a measuring tool
Aim: Making a remote sensor to collect data from the pendulum
Task: Using Arduino Science Journal or NodeMCU to make simple sensor and collect data

Unit 3c
Comparison of results
Aim: Presenting to the group the analysis of the collected measurement data and comparing the results with other students
Task: Presentation of collected data by student groups

Unit 4a
Building an electromagnet
Aim: Building a simple electromagnet model to investigate electromagnetism phenomenon
Task: Measuring strength of an electromagnet using a compass and board with scale

Unit 4b
Building the sensor
Aim: Finding the way of measuring electromagnetic field strength
Task: Measuring electromagnetic field strength using a smartphone or DIY sensor (NodeMCU + Hall sensor)

Unit 4c
Sorting device
Aim: Using newly acquired knowledge to design simple coin sorting device
Task: Building sorting device using an electromagnet

1.1 General aims

The main goal of this module is to show students how to conduct measurements and make measuring devices from very simple instruments to electronic sensors. In each unit, students build a set for experimentation (e.g. a model of a mathematical pendulum or a car driven by a rubber band). They use very simple materials and tools that everyone should have access to. Then, using the built equipment, experiments are performed. Various sensors may be used to record the measurements, from ordinary observations , using built-in sensors in the phone, to DIY sensors built from scratch. Depending on the technical level of the group, the teacher can only use simple observations and record the results manually, or construct his own sensor together with the students. Regardless of the chosen route, the most important element of each scenario is the final discussion of the results with students and drawing conclusions from the performed experiments.

1.2 Didactic rationale

Each lesson unit in this module is structured according to a similar scheme, which consists of a brief introduction to the topic through a simple demonstration of the phenomenon, discussion with students, design of the experiment, collection of measurements and observations, analysis of the results through discussion with students. The main idea of the entire module is to emphasize the involvement of students in actively analyzing the results of observations and trying to experiment on their own. In this process, the teacher plays the role of a facilitator who supports students in the process of arriving at conclusions, designing the experiment and carrying out the entire process in accordance with the research method.

An important aspect is the emphasis placed on hands-on activities undertaken by students. Unfortunately, today many young people have less opportunities to do DIY type of activities. More processes related to learning are moving to the online world, especially in the situation of the COVID-19 pandemic, which has caused even greater deepening of all forms of remote education, often detached from the practical, tangible aspect. Therefore, in the proposed module, all lesson units are strongly focused on practical activities through, for example, the construction of a measuring instrument or apparatus for experimentation. Also, the topics have been designed to use very simple and accessible materials and tools to build research equipment, which minimizes the entry threshold even for people without any DIY experience (whether they are teachers or students).

The main axis of each lesson unit is to conduct an experiment and construct a research device by yourself. The teacher has the choice of the technique to be used for observations and measurements. It all depends on the level of advancement of the students and it is the teacher who knows best what his students are capable of. Therefore, you can use an ordinary notebook and pen, a mobile phone, or program the DIY sensor yourself. Also when it comes to the construction of the measurement system, stl files have been made available in some lessons, for self-printing on a 3D printer, which can be included in the process of constructing the elements of the experiment. If there is no access to 3D printing, it's okay, because any experiment can be built using simple materials.

The final element of each lesson is the analysis of the results and discussion with students to draw conclusions. As mentioned above, completely analog techniques (such as hand-drawn graphs) can be used for data analysis, or software such as MS Excel or Google Sheets can be used. An important aspect worth paying attention to when using this module is the connection between the physical world (experiment, observations) and the digital world (measurements, data analysis). Thanks to this form of lessons, students have a chance to develop their digital competences and see the connection between a real phenomenon and data in digital form obtained by measuring this phenomenon.

1.3 Community feeling and digital collaboration

The module can be used both stationary in the classroom and fully remotely. The proposed methods of recording measurements (smartphone application and DIY sensor) store data in digital form by default. This allows you to share your results very quickly and easily, e.g. using any cloud service like Google Sheets.

Also one of the variants that the teacher can use is assigning a task - creating a sensor (based on NodeMCU), which automatically collects data and sends them to a shared database. Thanks to this, it is possible to gather data from dispersed measuring stations in one place. You can also reverse this approach and create a physical set for experimenting in one physical place with a sensor (for example at school) that sends data to a common cloud and everyone can analyze the results of the experiment remotely without being physically present, e.g. in a school classroom.

Structure of units

The module is divided into 2 main parts. The first (Unit 1) concerns measurement errors and the basics of the analysis of experimental results. This is not a mandatory part and each teacher can use it at their discretion. In the second part there are three bigger themes (Units 2-4). Each topic forms a separate whole and does not have to be implemented in order. In these topics we cover issues related to acceleration, elasticity and electromagnetism. They can easily be adapted to the implemented core curriculum. It is up to the teacher which module or its elements in the lesson he/she wants to use with his students.

2 Curriculum fits

The module was created based on consultations with teachers working in Polish vocational and technical schools. All activities have been matched to the core curriculum applicable in this case in physics and mathematics lessons. Teachers strongly emphasized the value of combining technical skills with other standard school subjects. The activities included in the teaching module cover the following topics:

Unit 1 - Measurement errors
Unit 2 - Kinetic energy of elasticity
Unit 3 - Mathematical pendulum
Unit 4 - Electromagnetism

At the beginning of each activity, all topics and subtopics related to the main theme are listed. Thanks to this, each teacher, regardless of the country, will be able to adjust individual elements of the activity or the entire activity to their core curriculum.

3 Overview of the module sequence for the teaching module "Sensors and measurements"

Unit 1. Measurement error Learning about measurement errors
Unit 2. In motion
Unit 2.a Slingshot Investigation of the distance of a fired object - stretched rubber band
Unit 2.b Rubber band drive Using the potential energy of elasticity to design a simple drive
Unit 2.c Experiment results analysis Presenting to the group the analysis of the collected measurement data and comparing the results with other students
Unit 3. Pendulum
Unit 3.a Building the pendulum Using the pendulum to make some measurements e.g. oscillation period
Unit 3.b Making a measuring tool Making a remote sensor to collect data from the pendulum
Unit 3.c Comparison of results Presenting to the group the analysis of the collected measurement data and comparing the results with other students
Unit 4. Electromagnet
Unit 4.a Building an electromagnet Building a simple electromagnet model to investigate electromagnetism phenomenon
Unit 4.b Building the sensor Finding the way of measuring electromagnetic field strength
Unit 4.c Sorting device Using newly acquired knowledge to design simple coin sorting device

4 Content: Learning sequence for the teaching module "Sensors and measurements”

4.1 Unit 1. Measurement errors

Brief Description
In this experiment we will learn about measurement errors that are part of a research paper.

Topics covered
Metrology (making measurements), measurement errors and uncertainties, accuracy of measuring tools, statistics of measurements, distribution of quantities.

Time
1 lesson + independent work of students at home

Lesson 1

Form

In class or online meeting with students
Can be combined with Unit 3, which explores the mathematical pendulum.

Objective

To study the motion of a mathematical pendulum, build it and calculate its period of oscillation and determine the value of the Earth's acceleration.

Materials needed for the teacher

- online program to present students' measurements collectively (if working remotely)
- a whiteboard for noting down the measurements (if working in class)

Materials needed for the student

- a metal cap larger than M8 or a similar metal weight
- non-stretchable thread about 1 m long
- sticky tape
- a stiff rod to hang the thread from
- sturdy construction for attaching the rod at a suitable height, so that the thread and the cap do not move the hanging point
- white A3 technical sheet
- protractor
- pencil
- various instruments for measuring length (school rulers of different lengths, folding rule, carpenter's tape measure, tailor's tape measure)
- stopwatch (e.g. in a phone)
- student worksheet - Lesson 1

Task 1: Measuring the diagonal length

Teacher's demonstration

1. Ask each student to measure the diagonal of the A3 sheet with their own measuring tape (if possible a different one).
2. One by one, note down the values obtained by the students in the spreadsheet (remote work) or on the board.
3. Present the results to the students.
4. Together with the students, we eliminate the measurements that have a "fat error" (strongly deviate from the rest) and calculate the arithmetic mean of all the remaining measurements.
5. We compare the result with the value calculated from the standard A3 sheet dimensions.

Questions to ask students after the demonstration

- Were there discrepancies in the results?
- Were there discrepancies in the results using the same measuring tool?
- How much was the smallest pitch in the measure we used?
- How are the values distributed on the bar graph?
- Does the diagonal value calculated from the arithmetic mean of the measurements obtained differ from that calculated from the standard A3 sheet dimensions?

Discussion

The aim of the discussion is to draw students' attention to the fact that various errors can occur during measurements:

- coarse errors - resulting from inattention, lack of focus (e.g. incorrect reading, moving the ruler on the measured surface, using the scale in inches instead of the scale in cm, etc.); results with such errors are rejected - we do not take them into account.

- systematic errors - resulting from the construction of the tool or the adopted measurement technique (e.g. too strong stretching of the measuring tape).
- accidental errors - caused by external factors (e.g. the influence of temperature on the length of the tape measure) or situational (e.g. parallax – incorrect reading of the result due to an incorrect alignment of the eye in relation to the scale on the ruler).

It is important for students to realize that mistakes will always occur, but it is important to identify them and eliminate them if possible. The discussion can be concluded with an experiment where students identify errors that might have occurred during the first measurement and try to eliminate them in the next one, i.e. repeat the measurement of the diagonal length of A3 sheet. We collect their results, present them in a graphical form (bar chart), calculate the average of the measured values, and compare with the results obtained from the first measurement.

Task 2: Pendulum

Each student conducts experiments independently on a stable surface.

Making a pendulum

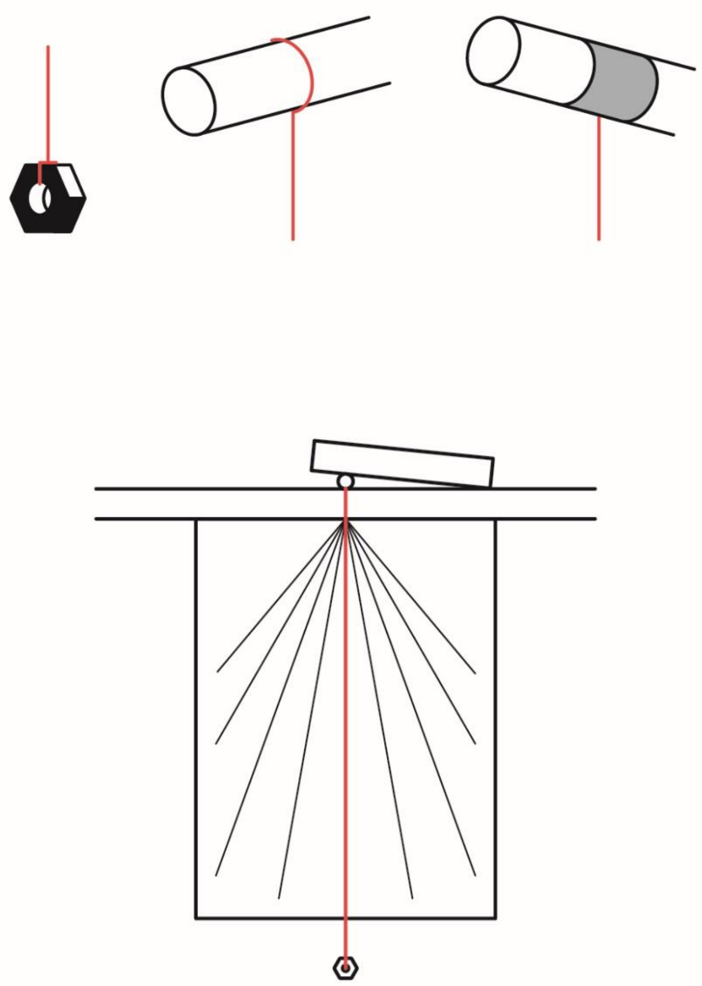
1. Fix a cap to the thread.
2. Attach the other end of the thread to a rod.
3. Fix the rod to a stable structure so that the pendulum cap does not move the fixing point.
4. Draw an angle scale on an A3 sheet (as shown).
5. Place the sheet behind the thread so that the centre point of the scale is level with the point where the thread hangs on the rod.

STUDY QUESTION 1

What is the period of oscillation of the pendulum you built?

Part 1 Measurement tool - a man with a stopwatch

1. Swing the pendulum about 10 degrees. Release the pendulum while turning on the stopwatch.
2. Count the number of oscillations, stop the stopwatch at five, record the result.
3. Calculate the period of the pendulum's oscillations by dividing the result by 5.
4. Repeat the measurement several times. Place the results on the bar graph.



STUDY QUESTION 2
What is the value of the acceleration of gravity?

- Make the pendulum swing by 10 degrees. Release the pendulum and at the same time start the stopwatch.
- Count the number of oscillations, stop the stopwatch at the fifth, record the result.
- Calculate the period of the pendulum, dividing the result by 5.
- After each measurement of the period of oscillation, measure the length of the thread (from the point of suspension to the center of gravity of the cap).
- Using the transformed formula for the period of oscillation of a pendulum, calculate the value of gravitational acceleration: $g=4L\pi 2/T2$
- Repeat the measurement several times. Plot the results on a histogram.

What can go wrong and how to deal with it

The suspension point moves as the pendulum moves.

- Immobilize the suspension point with, for example, plasticine or hot glue.

Summary of the experiment

Supporting questions:

- How can you measure a value more accurately?
- Is the measured value of the diagonal of an A3 sheet of paper its actual size?
- How will the value of the period of oscillation and the determined value of acceleration change if we change the angle of swing of the pendulum?

According to theory, for an infinitely large number of measurements, if there are only random errors, then the average value should correspond to the true value (also called the true value).

The true value of the measurand is usually not known before the measurement (at least in scientific measurements), so the elimination of statistical error, or its identification, can be difficult. Therefore, an important part of the development of science is the conduct and repetition of measurements by different teams - which in our case is accomplished by the work of many (independent) students.

Coarse errors, on the other hand, are relatively easy to eliminate. In our case, such an error could arise, for example, from using a tape measure scaled in inches and reading them as centimeters. Another common case of coarse errors in length measurement is shifting the initial "0" in relation to the measured object during the measurement. Colloquial care in making measurements is therefore crucial.

When measuring the period of oscillation in the pendulum in Part 1, the main source of error was the reflex of the person holding the stopwatch, their reaction time. When we eliminated the human factor by using a measuring tool the results obtained are less scattered. In practice, the diagram for the obtained pendulum periods (for e.g. 100 measurements) should be more "steep" than for manual measurements - i.e. the errors are smaller and the obtained ranges of measurement uncertainty are also smaller.

Evaluation of uncertainty and error in measurement - additional information

As stated above, the following types of errors may occur in different measurements:

- coarse errors
- systematic errors
- accidental errors

When determining the acceleration of gravity, try to carry out a full error calculation with your students, taking into account the uncertainties of measurement, the accuracy of the measuring instruments, and the rules resulting from a limited number of measurements (Student's t-ratios). In this case, is it possible to compare with the "true" value (as for the diagonal of a piece of paper)?

4.2 Unit 2. In motion

Brief Description

In this experiment we will get acquainted with the potential energy of elasticity, we will investigate what the distance depends on that an object moved when a rubber band with this energy is stretched. At the end of the experiment we will use the knowledge we gained to build a vehicle propelled by the energy stored in the rubber band and analyze its motion.

Topics covered

Kinematics, acceleration, elastic potential energy, data analysis, vehicle construction, acceleration sensor

Time

2 lessons + independent work of students at home

4.3 Unit 2.a Introduction to understanding the phenomenon (Lesson 1)

Form

In class or online meeting with students

Objective

To introduce the topic of the potential energy of elasticity and to investigate what the distance of a fired object depends on with a stretched rubber band (deformation of elastic material).

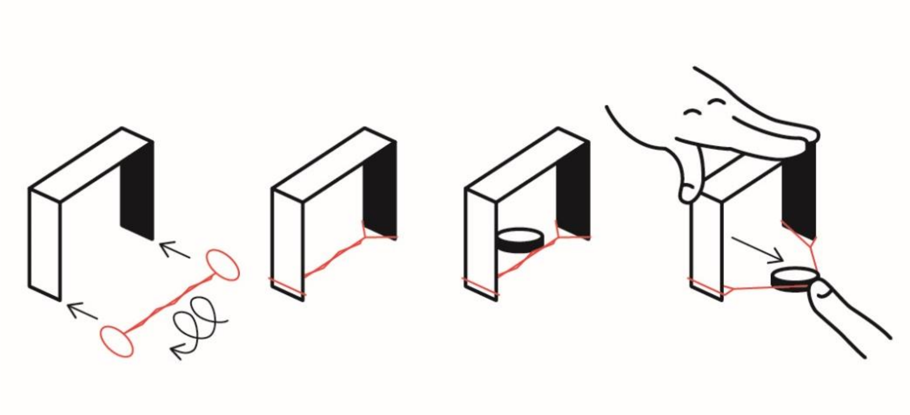
Materials needed for the teacher

- rubber band (min. diameter of the stretched rubber band 100 mm, cross-section e.g. 2x3 or 2x4 mm)
- bottle cap (preferably a wide milk bottle cap)
- a sturdy U-shaped frame, the span of whose arms must accommodate the flying cap

Materials needed for the student

- rubber band (min. diameter of an unfolded rubber band 100 mm, cross-section e.g. 2x3 or 2x4 mm)
- bottle cap (preferably a wide milk bottle cap)
- stable "U"-shaped frame, the distance between its arms must accommodate the flying cap
- plasticine
- weight
- an A5-size sheet of paper
- pencil
- ruler
- measuring tape
- student's worksheet - Lesson 1

Teacher's demonstration



1. Grasp the elastic in two fingers and stretch.
2. Twist the stretched rubber band so that it forms a single line.
3. Attach the ends of the twisted elastic to the ends of the frame arms. The rubber band should be taut.
4. Stand the frame up on its ends. The rubber band should be parallel to the ground.
5. Put the cap in front of the rubber band. The rubber band should be about halfway up the cap.
6. Press the frame down. Use one finger to press the cap onto the floor. Stretch it slightly and then release the rubber band.
7. Use the same method to pop the cap again. Tighten the rubber band more this time.

Questions to ask the students after the demonstration

- What happened to the cap shot out of the slingshot?
- In which trial did the cap fly further?
- How was the first trial different from the second trial?
- Where did the energy come from that set the cap in motion?

Discussion

Students think about what else, besides the force of the rubber band, affects the distance the cap will fly. The discussion should inspire further research questions.

Main research question

What does the distance at which the cap will be shot depend on?

The discussion should be steered in such a way that the students themselves come up with answers to the main research problem. Use guiding questions to moderate the discussion.

- What forces act on the cap at each moment of its motion?
- What kind of energy does a stretched rubber band have?
- What kind of energy does the cap have immediately after it is fired from the slingshot?

The discussion is meant to inspire further, detailed research questions and the design of new experiments.

Suggestion for working with students

To shorten the time we can divide the students into 2 teams, each team does task 1 and one of the three experiments. After the experiments, they share their results in class.

Student tasks and experiments

Each student conducts experiments independently on a flat, stable surface.

<u>Task 1: Making a slingshot</u>

1. Grasp the rubber band in two fingers and stretch it.
2. Twist the stretched rubber band so that it forms a single line.
3. Attach the ends of the twisted elastic to the ends of the frame arms. The rubber band should be taut (see Fig. 1).
4. Draw a millimeter scale from 0 - 10 cm on an A5 sheet of paper (see Figure 2).

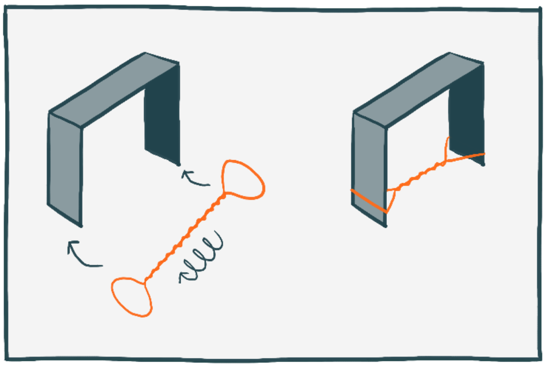


Fig. 1

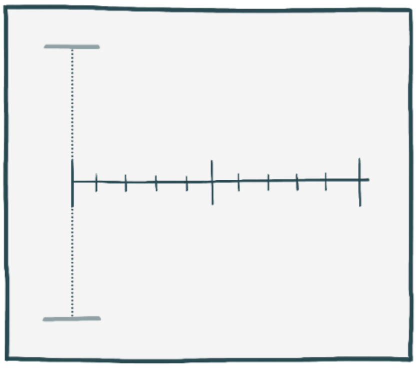


Fig. 2

STUDY QUESTION 1

How does the tension of the rubber band affect the distance the shot cap travels?

1. Weigh the cap, record the mass in the table.
2. Place a sheet of paper with a scale drawn on it. On the sheet, position the slingshot so that the taut rubber band is above the "0" line (see figure 3).
3. Place the cap in front of the stretched rubber band. 4.
4. Press the frame down. Press the cap to the floor with one finger. Tighten the rubber band to 0.5 cm (0.5 in.), then release the rubber band (see figure 3).

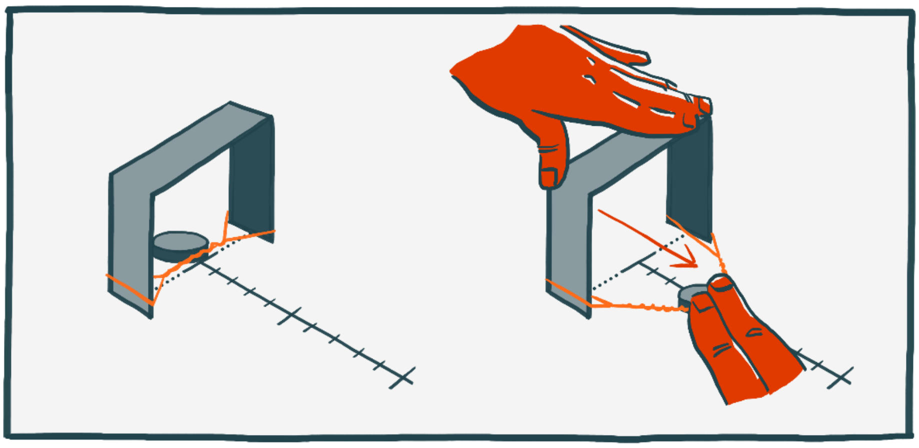


Fig. 3

1. Repeat the measurement of the distance covered by the cap s five times. With each repetition, stretch the rubber band to the same distance of 0.5 cm (use the scale drawn on the card). Determine the average of the results. 2.

2. Repeat the measurement for 1, 1.5, 2, 3, and 4 cm respectively.
3. Enter the results into a table or Excel/Calc and use them to create a graph of the distance covered by the cap and the tension of the rubber band for an empty cap.

Cap mass = ………………………….g

Cap material - ……………………. / Substrate material - ……………………………..

Rubber band tension d [cm]	0	0,5	1	1,5	2	3	4
The average distance a cap has traveled s [cm]	0						

Study question 2

How does the mass of the cap you shoot affect the distance it travels?

1. Repeat the measurements, this time shooting the cap by stretching the rubber band always the same (d = const) but increasing its mass each time by adding a piece of plasticine. Each time weigh the cap and enter its mass in the table before proceeding with the measurements. 2.
2. Enter the results into a table or excel/calc and use them to construct a graph of the distance covered by the cap and the mass of the cap.

Tension of the rubber band d = ...cm

Cap material - .... / substrate material - ....

Cap weight m [g]							
The average distance a cap has traveled s [cm]							

STUDY QUESTION 3

Does the material of the cap fired and the substrate affect the distance it travels?

1. Repeat the measurements, this time shooting a cap of constant mass m and stretching the rubber band always the same (d = const) but changing the material of the cap and the substrate. Enter the results into a table or Excel/Calc and use them to plot the distance covered by the cap against the tension of the rubber band for the cap with the tape.
2. Write your results in a table and compare them. Try to find the coefficient of friction of the materials you tested on the Internet and plot the distance travelled by the cap against the coefficient of friction.

Tension of rubber band d = ...cm

Mass of the cap = ...g

Cap material/substrate material	................../	................../	................../	................../ ....
Coefficient of friction f	....	....	....	....
The average distance a cap has traveled s [cm]				

What can go wrong and how to deal with it

After firing, the cap "pops".

- Keep pressing the cap down until the gun is fired.
- Stress the cap with plasticine. Remember to spread the Plasticine evenly over the entire surface of the cap.
- Check that the rubber band is halfway up the cap.

Rubbers stretch, they do not return to their original length.

- When shooting, do not stretch the rubber band too much.

The graduation card and the frame on which it rests move during shooting.

- Fix the scorecard with double-sided tape, for example. Press the frame firmly all the time.

How can I change the material of the cap without changing its mass?

- Use a cap with a certain amount of Plasticine. If you stick some other material on the surface of the cap (e.g., painter's tape or a piece of paper), weigh the cap and subtract enough plasticine to make the cap live up to its original weight.

Summary of Experiments

Guiding questions:

- Are the resulting relationships uniform, quadratic, or something else?
- Which parameter has the greatest influence on the distance the cap was shot?
- Did all students come up with the same relationships? What could be the reasons for any differences?

The potential energy of elasticity can be used to do a specific job, i.e., moving the cap a certain distance. The greater the tension of the rubber band (deviation from 0), the greater the work done (distance traveled) by the moving cap. The relationship between the distance traveled by the cap and the tension of the rubber band is quadratic. Increasing the reach of the cap requires increasing the tension of the rubber band, i.e., a greater expenditure of energy. Increasing the mass of the cap is simultaneously increasing its weight, which affects the frictional force that acts opposite to the movement of the cap. Thus, the greater the mass of the cap, the greater the frictional force acting on the moving cap, resulting in a shorter distance the cap will travel. Changing the material of the cap or the substrate also affects the frictional force and we observe different distances over which the cap will travel.

Explanation of the phenomenon

The potential energy of elasticity is the energy stored in an elastic body (e.g., a spring, rubber band, bowstring, etc.). If the body is perfectly elastic, that is, Hooke's law is satisfied, then the force required to stretch the elastic body a length from its equilibrium position is:

$$F = kx$$

where:

k - elasticity constant.

The potential energy Es of elasticity stored in a stretched rubber band is then equal to:

$$E_s = \frac{kx^2}{2}$$

Put differently, the energy increases in proportion to the square of the elongation of the elastic body. In the experiment, the elastic body (rubber band) is elongated when it is stretched before firing. When the stretched rubber band is released (let go), the stored elastic potential energy is transferred to the cap, which uses it to do specific work, i.e. to move a certain distance. With some simplifications (e.g., all of the energy stored in the rubber band is transferred to the cap without any loss), it can be assumed that:

$$E_s = W$$

where:

W - work done by the cap against the forces resisting motion over the distance traveled . When air resistance forces are neglected, it will be the frictional force . Which can be expressed by the formula:

$$W = Ts$$

A moving cap is subjected to a frictional force opposite to the velocity vector of the cap. The formula for the frictional force is:

$$T = fN$$

where:

f - coefficient of friction;

N - the pressing force (in this case, the force of gravity).

It can therefore be written:

$$T = fmg$$

where:

m - mass of the cap;

g - the intensity of the gravitational field at the Earth's surface (commonly called Earth acceleration).

The conversion of the elastic potential energy of the rubber band into work done by the cap against the frictional force acting on the cap moving on it is expressed by the formula

$$E_s = W \Rightarrow \frac{kx^2}{2} = Ts \Rightarrow \frac{kx^2}{2} = fmgs$$

from which the path s traveled by the cap can be determined:

$s = \frac{kx^2}{2fmg}$

For a fixed measurement system (same rubber band, same cap and substrate) then the only value that can be varied to send the cap different distances is the tension of the rubber band.

As the students built different measurement systems with different parameters, the results obtained varied. If the rubber band was twisted a bit more in one setup (a few more twists) than in the other, the results were different. A more twisted rubber band will have a different elasticity constant . Different results will also appear in experiments where one measurement system is set up on a carpeted floor and the other on a school bench - the coefficients of friction will be different in each system.

The relationships described here have been used for centuries in the construction of projectile weapons: bows, crossbows, and catapults. The formula for the mechanical energy of a projectile weapon includes the coefficient of elasticity (an elastomeric rubber band has a different coefficient than a steel crossbow arm or a composite Mongolian bow made of wood and animal sinew). The knowledge of this coefficient enabled the construction of more and more perfect types of projectile weapons.

Interesting fact

Twisted rubber bands are often used in modeling as a propulsion system for miniature model airplanes. The main advantages of this solution are relatively simple construction, low weight and low cost. Another example of the use of resilient structures are leaf or coil springs. The energy generated when driving over bumps is converted into spring energy by deforming the spring elements.

4.4 Unit 2.b Rubber band drive (Lesson 2)

Form

In class or online meeting with students

Objective

To introduce the rubber drive (related to the deformation of elastic material) and show students how it works. To show students the science journal app and test it.

Materials needed for the teacher

- a built car
- smartphone with the Arduino Science Journal app

Materials needed for the student

- smartphone
- Arduino Science Journal app user manual

Teacher's demonstration

1. We show students how a vehicle is built that is powered by a rubber band and which components are key.
2. Demonstrate to students the capabilities of such a vehicle by screwing on the rubber band and letting the vehicle go.

Questions to ask after the demonstration

- What happens to the rubber band before and during the movement of the car?
- How does the rubber band powered vehicle move?
- How is the rubber band stretched?
- How far does such a vehicle move?

Discussion

The discussion should clarify for the students and give them a better understanding of the laws of physics that account for the movement of the rubber band vehicle and reinforce the knowledge gained in the previous lesson.

Main investigation problem

What is the motion of a rubber band powered vehicle?

- Supporting questions can be used to moderate the discussion.
- What kind of energy does a stretched rubber band have?
- How does the rubber band propel the vehicle?
- What forces cause the vehicle to stop after a period of time?
- What kind of motion is the vehicle moving and how can we test it?
- What sensor can we use to test the motion of the vehicle?
- Is there such a sensor in your smartphones?

Measurement tool

With the Arduino Science Journal app, we will be able to better analyze the movement of a rubber band vehicle. The application uses the sensors built into our smartphones. In our case, we will need an acceleration sensor otherwise an accelerometer.

1. We ask students to install the Arduino Science Journal app.
2. We show how to set up the acceleration measurement and how to start it and ask students to do the same on their smartphones.
3. We ask students to move their phones in different directions and observe what happens on the phone screen depending on the direction of acceleration selected (there are three to choose from: along the x, y and z axis).
4. Then ask them to record several measurements of acceleration along one of the selected axes while moving their phones in different directions and then analyze the resulting graphs.

Questions and tasks for students to answer independently:

- What do we see on the phone screens?
- What data does the acceleration sensor record?
- What is the difference between the acceleration measurements signed as x, y, z in the app?

- Move the phone only toward its long edge on a flat surface and see along which axis the acceleration changes.

A video showing how to use the app and how you can use it for different measurements:

https://youtu.be/p2w2y6noE34

Summary

Using the smartphone, we can discover what motion the rubber band powered vehicle moves. We ask students to do the next step HOMEWORK independently at home. Supporting questions:

- In what direction do we mount the smartphone on the vehicle to correctly measure its acceleration over time?
- Which acceleration values will we record in the app: x, y, or z?

HOMEWORK - Vehicle construction and testing

Form

Independent work of students at home or in small groups at school.

Objective

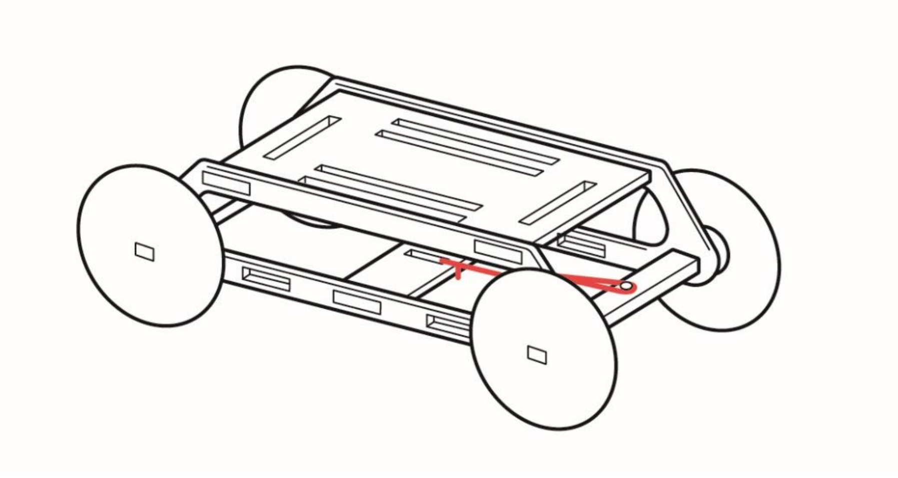
To have students build a vehicle and use it to take measurements of acceleration and the distance the vehicle will travel depending on the tension of the rubber band that drives it.

Materials needed for the student

- parts for building a vehicle (printed on a 3D printer or cut from hard material - plywood, rigid cardboard)
- construction instructions
- smartphone
- Arduino Science Journal application user manual
- rubber bands (4 for the wheels of the car and 1-3 for the drive)
- tape measure
- student worksheet – homework

Task 1: Making the vehicle

- Print or cut out the parts needed (to print; to cut out)
- Assemble the vehicle according to the instructions



RESEARCH QUESTION 1

What kind of motion does a vehicle propelled by a rubber band move?

Part 1: Acceleration tests

1. Run the pre-installed Arduino Science Journal app on your smartphone.
2. Attach the smartphone to the vehicle using the rubber bands.
3. In the application, select the measurement of accelerometer (acceleration sensor) along the appropriate axis.
4. Place the vehicle on the ground and stretch the rubber band by turning the rear wheels 4 times.
5. At the same time, start recording the acceleration measurement on your phone and let go of the vehicle.
6. When the vehicle stops, stop measuring and measure the distance the vehicle has moved using the tape measure.
7. Repeat the measurement several times, but for different rubber band tensions.
8. Transfer your measurements to Excel or Calc and use them to plot acceleration versus time for different elongations of the rubber band.

Questions for students to answer independently:

- What is displayed in the application?
- Has an acceleration measurement been recorded?
- In what file extension are the measurement results saved?
- Does the program (Excel or Calc) correctly read the measured data?
- What shape does the graph of acceleration vs. time have?
- At what point did the vehicle start moving?
- What is the motion of the vehicle?

Part 2: Data Analysis

1. Analyze the graphs of acceleration versus time for the different stretches of the rubber band.
2. Using the measured acceleration data, try to calculate/draw using the integral the values of velocity versus time and distance versus time.
3. Analyze the graphs and try to determine what motion the car was moving.

Questions and tasks for students to answer independently:

- How does acceleration change as the vehicle moves?
- How does the speed change as the vehicle moves?
- What motion is the vehicle moving in? Try to list the parts on the graph where the vehicle is moving in uniform motion, uniformly accelerated motion, non-uniformly accelerated motion, decelerated motion, etc.
- How far did the vehicle travel when the rubber band was stretched with a 4-fold rotation of the wheel, and how did it travel for larger and smaller stretches?
- Compare the resulting values for the distances the vehicle moved from the graph with those measured with the tape measure. Where might any differences come from?
- What can be changed in the design to make the vehicle travel longer distances with the same tension of the rubber band?
- Implement your proposed modifications and check whether the vehicle does indeed move greater distances.

What can go wrong and how to deal with it

The vehicle does not move.

- The rubber band power may be too weak, then twist the rubber band more or combine 2-3 rubber bands into one.
- There may be too much friction between the car's axle and its side frame, in which case use a small file and lightly sand the contact surfaces of the two.

The car does not move in a straight line.

- If the connection between the wheels and the shaft is too loose, try to take up the slack with pieces of paper, for example. You can also stiffen the structure with glue suitable for plastic, but then it will not be possible to remove it for any modification.

The wheels slip at the beginning (they box).

- Add rubber pads to the wheels or place the vehicle on carpeting, for example, to increase wheel/floor friction.

The movement lasts too short to be registered by a smartphone.

- The rubber band should be stretched tighter, or if this is not possible, a larger and thicker rubber band should be used.

The data in Excel/Calc is not displayed correctly.

- Before you open a *.csv file in Excel or Calc, open it in Notepad and check how the data is written. If individual columns are separated by "," replace it with ";". In addition, floating point data may be written with a period, in order for Excel/Calc to read it correctly "." needs to be replaced with ",".

It is hard to turn on the measurement and let go at the same time.

- This is a natural thing to do. It is important to start the measurement before you let go of the vehicle. The graph will show the moment when the movement started (acceleration starts increasing from 0). The data in the spreadsheet can already be processed properly and cut out the part before the moment the movement starts, remembering to change the time values accordingly.

4.5 Unit 2.c Comparison of results (Lesson 3)

Form

In class or online meeting with students.

Objective

To present to the group the analysis of the collected measurement data and to compare the results with other students.

Required materials for the student

- filled in worksheets
- results of tasks and experiments (tables, diagrams)

SUMMARY

Analysis of the acceleration diagram:

- Ask one of the students to show/share the acceleration-time diagram for the rubber band vehicle that he has created based on his measurements.
- We discuss together the different stages of motion of the vehicle.
- Ask if anyone has received a different graph and ask them to show us theirs.
- We discuss the differences together and wonder where they come from.

Supporting questions:

- At what point on the graph does the vehicle have the greatest acceleration?
- What was the maximum acceleration of the vehicle for the rubber band tension when the wheel was turned 2 times?
- Did all vehicles achieve similar acceleration for the same rubber band tension?
- How did the designs differ and how did this affect the results?
- What can we change in the design to make the vehicle travel longer distances?

4.6 Unit 3. Pendulum

Brief description

In this experiment we will learn how a mathematical pendulum works. We will construct a tool to measure the period of the pendulum and investigate which parameters it depends on. Finally, we will use this knowledge to experimentally determine the Earth's acceleration.

Topics covered

Mathematical pendulum, vibration theory, harmonic motion, amplitude, period of vibration, earth acceleration, data analysis, measurement tool design.

Time

3 lessons + independent student work at home

4.7 Unit 3.a Introduction to understanding the phenomenon part 1 (Lesson 1)

Form

In class or online meeting with students.

Objective

Analyze the motion of a mathematical pendulum, build it, and calculate its period of oscillation.

Materials needed for the teacher

- DIY model of a mathematical pendulum
- Stopwatch

Materials needed for the student

- metal cap M8 or similar (diameter about 1.5 cm; weight about 4.5 g)
- non-stretchable thread approx. 1 m long
- adhesive tape
- rigid rod for hanging the thread
- stable construction for attaching the rod at a suitable height so that the thread and cap hang freely (laboratory stand, table or desk)
- white technical sheet of paper A4 or A3
- protractor
- pencil
- long ruler or tape measure (minimum 50 cm)
- stopwatch (e.g. a smartphone)
- student worksheet - Lesson 1

Teacher's demonstration

1. Swing the pendulum out and release it, setting it in motion. Together with your students, observe the movement of the pendulum.
2. Together with students, using a stopwatch, measure the times it takes the pendulum weight to travel back and forth for several consecutive swings.
3. Note the individual swing times and compare them to each other.

Questions we can ask students after the show

- How does a weight suspended from the end of a pendulum move?
- What was the time difference between each fluctuation?
- Is this difference decreasing? Or is it growing?
- What do we call the difference in time measured between each swing of the pendulum?

Discussion

The purpose of this discussion is for students to realize that the time difference they note between each swing is the period of oscillation of the pendulum.

The main research problem

What is the period of oscillation of the pendulum?

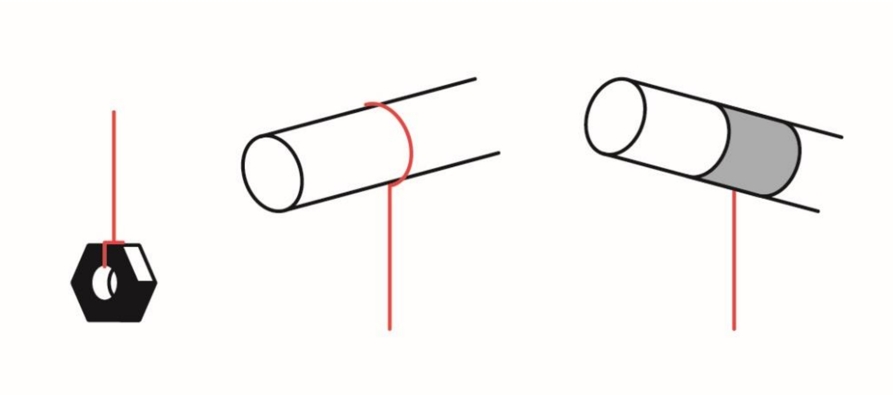
Guide the discussion so that students build their own pendulums and measure their period of oscillation.

Student Activities and Experiments

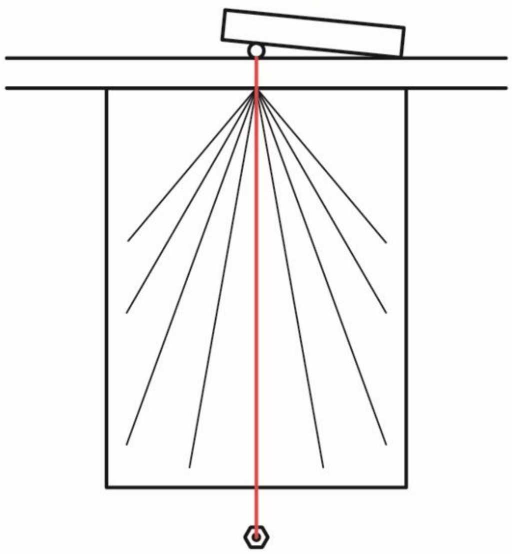
Each student conducts experiments independently on a stable surface.

Task 1: building a pendulum

1. Attach the cap to the thread.
2. Attach the other end of the thread to the rod, fix the hanging point with adhesive tape.



3. Secure the rod to a stable structure so that the cap hangs freely on the thread.
4. On an A4 or A3 sheet of paper, draw an angle scale (as shown in the illustrations).
5. Place the sheet behind the thread so that the center point of the scale is level with the point where the thread hangs on the rod.



Study question 1

What is the period of oscillation of the constructed pendulum?

1. Swing the pendulum **10 degrees**. Release the pendulum while **turning on the stopwatch**.
2. Count the swings, at the fifth stop the stopwatch, record the result.
3. Calculate the period of oscillation of the pendulum by dividing the result by 5.
4. Repeat the measurement several times and average the values obtained. The result obtained is the value of the period of oscillation for the constructed pendulum.

What can go wrong and how to deal with it

During the pendulum movement, the time differences between each swing are too large.

- Make sure that the suspension point of the pendulum is stationary.
- Time should be measured by several people. Inviting several students to participate in the show will eliminate big errors.
- Use a stopwatch with a measuring function. Using this feature will help you avoid measurement errors - you can focus on the pendulum movement and pressing the appropriate button will automatically record the results.
- The swing angle of the pendulum should be small, preferably about 10 degrees.

In repeated measurements with constant parameters, large differences in pendulum period values can appear.

- You can increase the number of swings counted, which will minimize errors due to reaction time when counting time values of consecutive swings.
- Do not include extreme values that strongly deviate from the rest of the results (coarse errors) in the calculated average.

The suspension point moves with the motion of the pendulum.

- Immobilize the suspension point, use plasticine or hot glue, for example.

Summary of the experiment

Supporting questions:

- What vibration period values did you get?
- Did everyone come up with the same values and where could any differences come from?
- How were your pendulums different?

A pendulum (a weight suspended from a thread) moves in an arc, back and forth. This one full swing is the distance the pendulum travels from the time it starts moving until it returns to its starting point. The time it takes the pendulum to complete one full swing is constant. This time is the **period of oscillation of the pendulum**, whose value depends on the design of the pendulum.

The values of the periods of oscillation determined experimentally for different pendulums will vary. This is natural because each student built his or her pendulum differently. In the next lesson we will try to find out which parameters influence the period of a pendulum.
Differences in values for the same pendulum design are due to human error. The human eye and reaction time can affect how fast the stopwatch stops or stops at the wrong time. To avoid such errors, you can use a measuring tool that will automatically measure the time of each pendulum by itself.
A homework assignment for students is to make such a measuring tool/device.

Homework 1 - Measurement tool

Form

Independent work by students at home or in small groups at school.

Objective

Have students design and build a measuring tool that will indirectly or directly measure the period of oscillation of a pendulum they have built.

Materials needed for the teacher

- none

Materials needed for the student

- smartphone with the light sensor or a microcontroller with the light sensor
- construction elements
- built pendulum for testing

Tips for students when creating a measurement tool:

Sensor Selection:

- The sensor should allow you to record changes in the movement of the cap.
- The sensor should not react noticeably to changes in the environment.

Sensor Mounting

- The design and the sensor itself should not block or interfere with the movement of the pendulum-cap (e.g., if the sensor were to be mounted on the end of a thread instead of a cap, remember that it must have a power supply, the weight of which or the stiffness of the power cable may interfere with the movement of the pendulum, so with this solution, these problems should be eliminated).
- The sensor should be mounted stably so that e.g. vibrations, movements do not influence the measurement results.

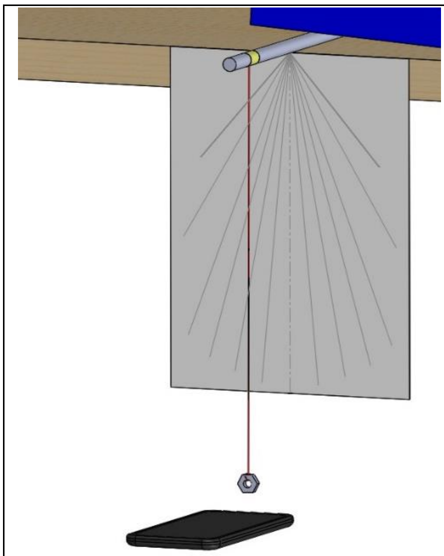
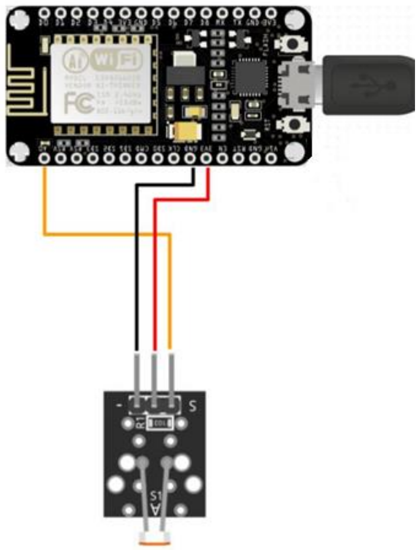
Tool testing

- After the device is built and possibly programmed, test it on the constructed pendulum.

- We check what data we obtain and whether we are able to read from it directly or indirectly the period of oscillation of the pendulum.
- We verify that the data obtained is correct, e.g. when collecting data at the same time we measure the period of oscillation of the pendulum with a stopwatch and compare it with the times read from the data collected with the measuring tool (small deviations are normal).
- We improve the program or design if necessary.
- If we are unable to read the vibration period from the data and the corrections made have not improved this, we should consider creating a new tool with a different sensor.

Examples of solutions:

USING THE LIGHT SENSOR

	
The phone is placed in such a way that the front camera, which is the light sensor, is placed over a freely hanging cap. When the pendulum moves, the cap will cover the light sensor at the moment of movement through point 0. Thanks to the Arduino Science Journal application we will be able to record the moments when the cap covers the sensor and later read the value of the pendulum's oscillation period from this data.	Using a nodeMCU microcontroller and a light sensor in the form of a photoresistor connected to it. We place the photoresistor like a phone camera under a free hanging cap. The microcontroller is programmed to send the recorded data from the sensor via wifi to the computer. From the data on the computer we read/calculate the period of the pendulum.

4.8 Unit 3.b Introduction to understanding the phenomenon part 2 (Lesson 2)

Form

In class or online meeting with students.

Objective

Analyze the motion of a pendulum and investigate on which parameters of a pendulum its period of oscillation depends.

Materials needed for the student

- constructed pendulum
- gauge
- scale with 0.1g accuracy
- student work sheet - lesson 2

Homework summary - Presentation of the created measurement tools

- We ask one of the students to present the measurement tool they have created.
- We ask if anyone has built another one and if so, please present it too.
- We discuss the differences in construction.
- If there are any problems we try to solve them together.

Discussion

The purpose of this discussion is to review what we learned in the previous lesson, namely, how we determine the period of a pendulum experimentally and that we determined different periods of oscillation for different pendulum designs.

The main research problem

What parameters of a pendulum affect its period of oscillation?

You should guide the discussion so that students themselves come up with parameters on which the period of a pendulum can depend, and you encourage them to use their own measuring devices to find out how and whether the period changes when a given parameter is changed. Sample research questions are provided below in the "Student Experiments" section, but each student may propose their own.

Proposal for working with students

We can divide students into teams and assign each team one parameter/one research question to investigate. Finally, all teams share their findings with the whole class.

Student experiments

Each student conducts experiments independently on a stable surface.

STUDY QUESTION 1

How does changing the angle of initial excursion affect the value of the period of oscillation?

Measure the period of oscillation of the pendulum with the measuring instrument for different values of the initial angle of the pendulum (the length and mass of the pendulum remain unchanged). Record the data obtained in a table or transfer it to a spreadsheet and create a graph based on the data.

Initial swing angle α [°]	5	10	15	20	30	40	50
Vibration period T [s]							

STUDY QUESTION 2

How does changing the mass of a pendulum affect the value of the period of oscillation?

Repeat the measurements for different pendulum masses. The mass of the pendulum can be changed by adding more caps as weights or pieces of plasticine previously weighed (the length of the pendulum and the angle of initial swing of the pendulum remain unchanged). Record the data obtained in a table or transfer it to a spreadsheet and create a graph based on the data.

Pendulum mass m [g].							
Vibration period T [s].							

STUDY QUESTION 3

How does changing the length of the pendulum affect the value of the period of oscillation?

Repeat the measurements for different lengths of the pendulum. You can vary the length of the pendulum by gradually shortening the thread. (The mass and the angle of the initial swing of the pendulum remain unchanged). Record the resulting data in a table or transfer to a spreadsheet and create a graph based on the data.

Pendulum length l [cm]	100	80	60	40	30	20	10
Vibration period T [s]							

What can go wrong and how to deal with it

The suspension point moves with the motion of the pendulum.

- Immobilize the suspension point, use plasticine or hot glue, for example.

The measuring device does not record measurements.

- We try to repair the device. If it fails we continue measuring with the stopwatch.

The type of relationship is not visible on the graph or is hard to recognize.

- Extend the measurement data, make some additional measurements for parameter values outside the one we made.

Summary of the experiment

Supporting questions:

- On what parameters does the period of oscillation of a pendulum depend?
- By what angle did we deflect the pendulum before letting go?

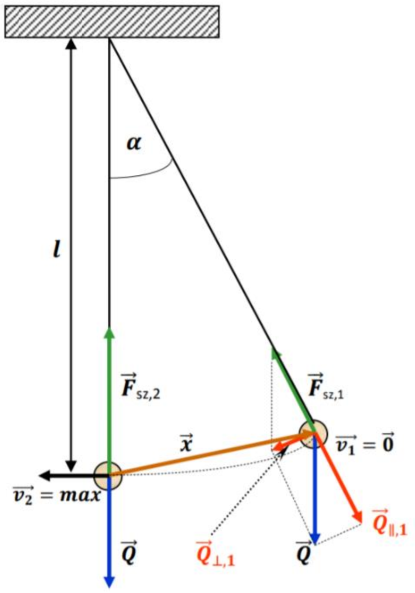
The value of the **Period of Vibration of a pendulum** depends only on the length of the pendulum and on a certain constant, which is the gravitational field strength at the Earth's surface. This constant is commonly called the acceleration of gravity.

The above conclusions from the experiments are true **only for small initial swing angles**. The function describing the dependence of the pendulum's oscillation period on its length is increasing - as the length of the pendulum increases, its oscillation period also increases in the root function.

The period of oscillation of a pendulum, assuming that we deflect it by a small angle, does not depend on its mass and the angle of initial deflection.

Explanation of the phenomenon - the theory of the mathematical pendulum

A mathematical pendulum is called a point mass suspended from an inextensible and weightless thread. A good example of such a pendulum is a small ball suspended from a long thread, where the thread is many times longer than the radius of the ball, and the mass of the thread is negligibly small compared to the mass of the ball.



Designations adopted in the figure:

l - The length of the pendulum (the distance from the ball's center of gravity to the axis of rotation);

m - The mass of the pendulum (the mass of the ball);

$\vec{Q}$ - ball weight ($Q = const = m \cdot g$);

$\vec{Q}_{\perp}$ - The component of the ball weight in the direction perpendicular to the thread;

$\vec{Q}_{\parallel}$ - The component of the ball's weight in the direction determined by the thread;

$\vec{F}_{sz}$ - thread tension force;

$\vec{F}_{w}$ - The resultant force vector;

$\vec{x}$ - The vector of deflection from the equilibrium position;

1 - The ball is tilted out of equilibrium as far as possible;

2 - ball as it passes through the equilibrium position;

A - Vibration amplitude (maximum excursion from the equilibrium position).

$$|\vec{x}_1| = max = A \qquad |\vec{x}_2| = 0$$

After the pendulum is released from the point with initial swing angle α the pendulum will start to make periodic motion with the amplitude equal to the initial swing. With little resistance of the medium (air) and in a short time interval this amplitude can be considered constant. Two forces influence the motion of the pendulum: the gravity force $\vec{Q}$ and the thread reaction force $\vec{F}_{sz}$. This can be expressed as follows:

$$\vec{F}_w = \vec{Q} + \vec{F}_{sz}$$

Ball weight $\vec{Q}$ can be decomposed into two components: $\vec{Q}_{\perp}$ i $\vec{Q}_{\parallel}$, and the relationship must hold:

$$\vec{Q}_{\perp} + \vec{Q}_{\parallel} = \vec{Q} \qquad \Rightarrow \qquad \vec{F}_w = \vec{Q}_{\perp} + \vec{Q}_{\parallel} + \vec{F}_{sz}$$

The ball does not move in the direction determined by the thread, which means that the forces in that direction balance each other, which can be written:

$$\vec{Q}_{\parallel} + \vec{F}_{sz} = 0 \qquad \Rightarrow \qquad \vec{F}_w = \vec{Q}_{\perp}$$

At the angle of inclination from the equilibrium position α the value of the component of the force of gravity perpendicular to the thread is expressed by the relation for a right triangle defined by the vector of the force of gravity and its components (see figure). Thus:

$$Q_{\perp} = Q \cdot \sin\alpha = m \cdot g \cdot \sin\alpha \qquad \Rightarrow \qquad F_w = m \cdot g \cdot \sin\alpha$$

For a sufficiently long pendulum and a small swing angle from the equilibrium position ($\alpha < 10°$) the triangle defined by the pendulum in equilibrium, the pendulum at maximum swing, and the swing-out vector $\vec{x}$ can be regarded (approximately) as a right triangle. For such a triangle, it can then be written that:

$$\sin\alpha \approx \frac{x}{l} \qquad \Rightarrow \qquad F_w = -\frac{m \cdot g}{l} \cdot x \qquad \Rightarrow \qquad F_w \sim -x$$

It follows that **the value of the resultant force is directly proportional to the swing of the pendulum from its equilibrium position.**

This relation is true only for small angles, not greater than 10 degrees, because that was the assumption made in deriving it. Moreover, vectors $\vec{F}_w$ i $\vec{x}$ have (approximately) the same directions but opposite returns, hence the "-" sign in the formulas presented above. Thus:

$$\vec{F}_w \sim -k \cdot \vec{x}$$

In physics, such an equation is called the harmonic oscillator equation.
It means that **a mathematical pendulum performs harmonic motion**. In such a motion there is a relationship:

$$k = m \cdot \omega^2 \qquad gdzie \quad \omega = \frac{2 \cdot \pi}{T}$$

where T is the period of vibration in harmonic motion.

Because:

$$F_w = -\frac{m \cdot g}{l} \cdot x \qquad \Rightarrow \qquad k = \frac{m \cdot g}{l} \qquad \Rightarrow \qquad m \cdot \omega^2 = \frac{m \cdot g}{l} \qquad \Rightarrow \qquad \omega^2 = \frac{g}{l} \qquad \Rightarrow \qquad \omega = \sqrt{\frac{g}{l}} \qquad \Rightarrow \qquad \frac{2 \cdot \pi}{T} = \sqrt{\frac{g}{l}}$$

Therefore (after a simple transformation) **the period of oscillation of a mathematical pendulum** T expresses the relation:

$$T = 2 \cdot \pi \cdot \sqrt{\frac{l}{g}}$$

To summarize:

- for small angles of deflection from the equilibrium position the period of oscillation of a mathematical pendulum **does not depend on the mass of the pendulum (the mass of the ball);**
- for small angles of swing from the equilibrium position the period of oscillation of a mathematical pendulum **does not depend on the value of the angle of swing from the equilibrium position** (so-called isochronism of a pendulum);
- for small angles of deflection from the equilibrium position the period of oscillation of a mathematical pendulum **is directly proportional to the square root of the pendulum length**. This means that if the length of the pendulum increases nine times, for example, the period of the pendulum will increase three times.

In the experiments, the results were similar, precisely because the measurements were made for angles less than 10 degrees.

Knowing the formula for the period of oscillation of a mathematical pendulum, we can experimentally determine the value of the Earth's acceleration. **This can be very interesting homework for students.**

Homework 2 - Earth acceleration

Form

Independent work by students at home or in small groups at school.

Objective

Design an experiment using a constructed pendulum and measuring tool to experimentally determine the value of the Earth's acceleration.

Materials needed for the student

- constructed pendulum
- gauge
- scale with 0.1g accuracy
- measure/ruler
- student worksheet - homework 2

STUDY QUESTION 1

What is the acceleration of the earth?

- Taking the necessary measurements.
- Calculate the value of the acceleration of the Earth from the data obtained.
- Comparing the obtained value of the acceleration due to gravity with the value given in physics classes.

Questions for students to answer independently:

- Approximately how much is the acceleration of the earth?
- Does the acceleration of the earth have the same value at every location on the globe?
- What is the formula for the period of oscillation of a mathematical pendulum?
- What values do I need to measure to calculate the value of the Earth's acceleration using the formula above?

What can go wrong and how to deal with it

The resulting value of the acceleration of gravity strongly deviates from the value given in physics class.

- Repeat the measurements even several times, discard extreme values (subject to coarse error) and draw an average.
- We check the measuring system: the construction of the pendulum and the measuring tool to make sure that they are not the source of coarse errors.

4.9 Unit 3.c Comparison of results (Lesson 3)

Form

In class or online meeting with students.

Objective

Present to the group the analysis of the collected measurement data and compare the results obtained with other students. Summary and conclusions.

Materials needed for the teacher

- none

Materials needed for the student

- completed worksheets
- results of tasks and experiments (tables, diagrams)

Presentation of the results obtained

1. We ask students to present the results of their experiments, i.e., the value of the acceleration of the Earth determined from the data collected while conducting the experiment.
2. We discuss the differences in the values obtained.
3. We ask students to describe their method of measurement, the measurement tool they used.

Discussion

The purpose of the discussion is to encourage students to learn more about the theory associated with measurement errors, the topic of which is covered in one of our experiences.

It should be strongly emphasized that using different tools, making measurements under different conditions, by different people, we can get different results and in the world of scientific research this is a natural thing.

When we answer the question of what and how our measurements were affected, we will learn how to measure the object under study more accurately, avoiding or minimizing possible errors. Will we thus determine, for example, the actual acceleration of the Earth? Not really. We will only give its approximate, maximally probable value.

Summary of all lessons

- Supporting questions:
- How does a pendulum move when let loose?
- What do we call the time between fluctuations (back and forth movement)?
- On what parameters does the period of oscillation of a pendulum depend?
- What is the formula for the period of oscillation of a mathematical pendulum and under what assumption is it true?
- What is the acceleration of the earth?

4.10 Unit 4. Electromagnet

Brief description

In this experiment we will learn how electromagnets work. We will build a tool to measure the strength of the magnetic field and investigate which parameters determine the strength of the magnetic field produced by an electromagnet. Finally, we will use the knowledge we gained to create a coin sorter.

Topics covered

Electromagnet, current, magnetic field lines, magnetic field strength, magnetic induction vector, data analysis, measurement tool design, magnetic sensor.

Time

3 lessons + independent student work at home

4.11 Unit 4.a Building an electromagnet (Lesson 1)

Form

In class or online meeting with students.

Objective

Building an electromagnet.

Materials needed for the teacher

- DIY electromagnet (not connected to battery)
- AA or AAA battery
- insulating tape
- scissors
- bar magnet
- compass

Materials needed for the student

- lacquered or insulated copper wire approx. 1 m long
- sandpaper
- duct tape
- cylinder (thick marker, plastic tube) on which the wire can be wound
- AA or AAA battery
- compass
- A4 sheet of paper
- pencil
- ruler
- scissors
- student worksheet - Lesson 1

Teacher's demonstration

SHOWCASE

- Connect the solenoid to the battery with insulating tape.
- Position the electromagnet in relation to the compass needle so that they are perpendicular to each other (Fig. 1) and spaced by e.g. 20 cm.
- Slowly bring the electromagnet closer to the compass and observe with your students what happens.
- Disconnect the solenoid from the battery so it doesn't heat up.
- Next, position the bar magnet in place of the electromagnet and slowly move it closer to the compass while watching what happens to the compass needle.

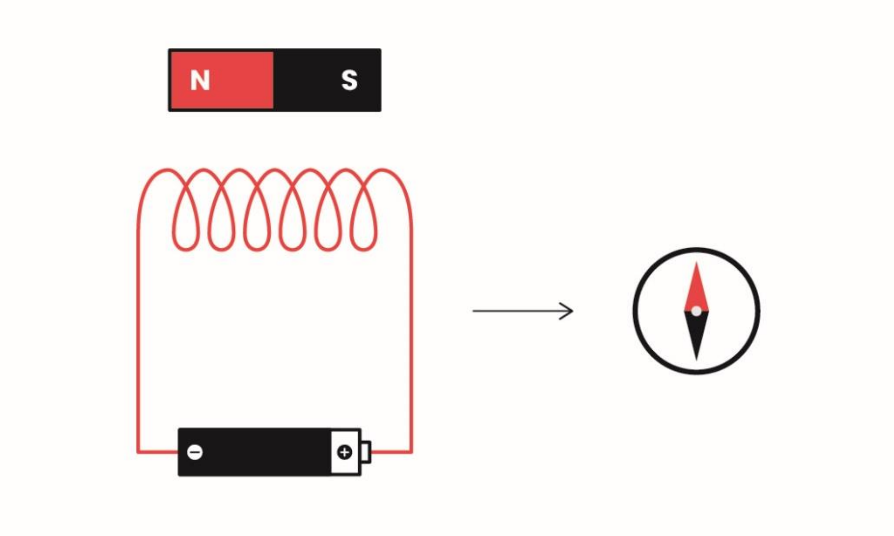


Fig. 1. Alignment of the electromagnet and bar magnet relative to the compass during the demonstration.

Questions we can ask students after the show

- Did the needle react the same way to the electromagnet and the bar magnet?
- In which case did the needle respond faster?
- What components does an electromagnet consist of?
- From which side of the electromagnet is the south pole "formed" and from which side is the north pole formed?

Discussion

The purpose of the discussion is to get students interested in the phenomenon of electromagnetism and to inspire them to investigate what can affect the strength of electromagnets.

Main research question

What affects the strength of an electromagnet?

Direct the discussion so that the students themselves suggest which factors might affect the strength of the electromagnet. The discussion should inspire them to investigate these factors using self-made electromagnets. Supporting questions can be used to moderate the discussion.

- What can we do to increase the strength of the electromagnet?
- How do you compare the performance of different self-built electromagnets?

A proposal on how to work in teams

Each student builds their own electromagnet and tests its strength. Ideally, each student should have the same compass.

Student Activities and Experiments

Each student builds their own electromagnet and tests it.

Task 1: Making the electromagnet and the board for measurements

1. Remove the insulation at the ends of the wire (about 1 cm at each end). If the wire is varnished, remove the insulation with sandpaper. If the insulation is rubber, use scissors.
2. Wrap some of the wire tightly around a small cylinder. Leave three to four centimeters of uncoiled wire at each end. Finally, remove the cylinder from the center.
3. Connect one end of the wire to the "-" of the battery. Use insulating tape. Leave the other end unattached for now.

4. Draw a straight line through the center of an A4 sheet of paper along the long edge and mark a centimeter scale from 0 to 20 cm on it.

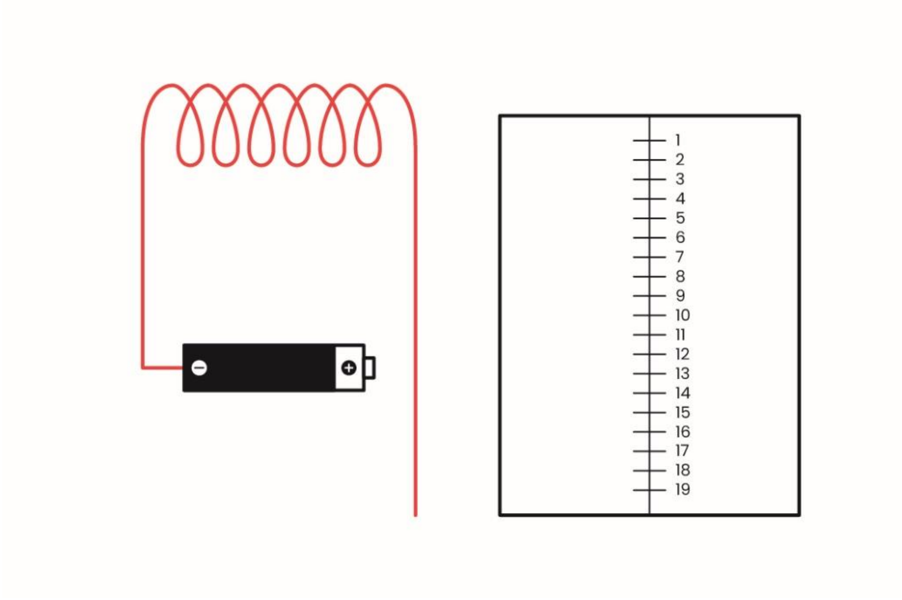


Figure 2: Example electromagnet and scale board.

Study question 1

How strong is the electromagnet we made?

1. Place the compass on the board at the point 0. Position the sheet of paper with the compass so that the needle lines up with the shorter edge of the board.
2. Position the electromagnet on the board as shown in Figure 3 and connect the free end of the wire to the "+" of the battery with insulating tape.
3. Slowly move the electromagnet toward the compass and observe the needle.
4. As soon as you notice that the compass needle has moved, stop the electromagnet and note the distance on the scale.
5. Disconnect the wire from the "+" battery so that the solenoid does not heat up unnecessarily.
6. Repeat the measurements several times.

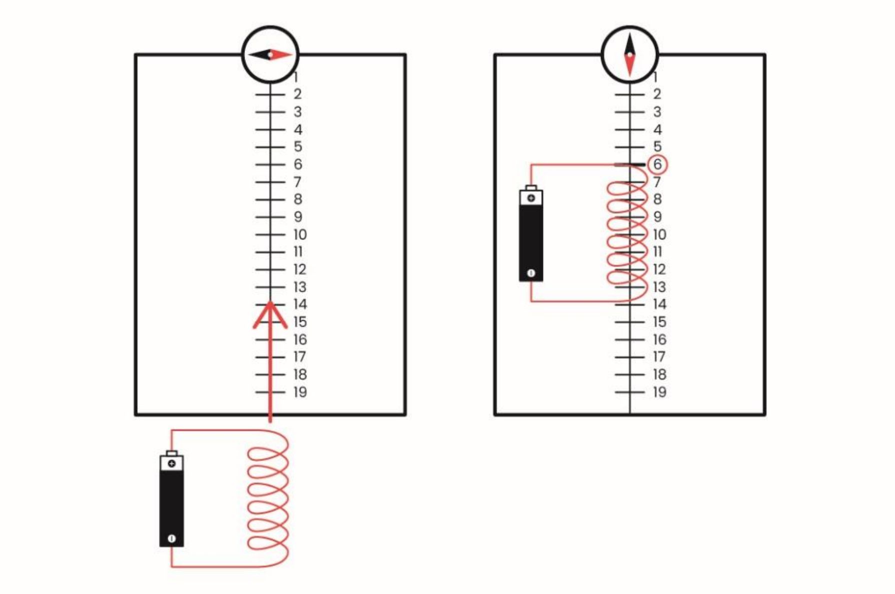


Fig. 3 The course of the experiment

What can go wrong and how to deal with it

The solenoid does not work on the needle.

- Check that the battery you are using is not discharged and that the wires are making proper contact with the battery.
- Check if the needle is stuck, test it by using a bar magnet. However, if the needle works, it means you need to construct a new electromagnet with more coils or a larger wire gauge.

The electromagnet heats up until it steams.

- Wearing gloves, connect the wire to the battery for shorter periods of time, waiting a moment before each connection.

Summary of the experiment

Supporting questions:

- At what distance from the compass did your electromagnet swing the compass needle?
- Did the same values come out for everyone?
- Where might any differences come from?
- How were your electromagnets different?

A conductor (in our case a copper wire) through which a current flows and which is wrapped in a spiral generates a magnetic field around itself. The shape of this field is similar to the shape of the field generated around a bar magnet (Figure 4).

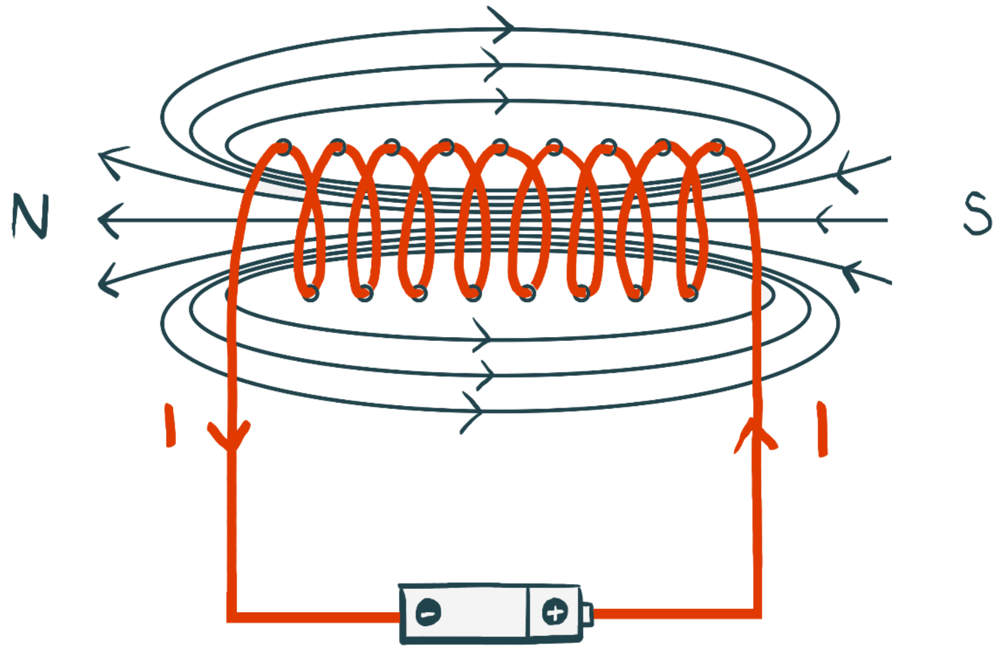


Figure 4: Layout of magnetic field lines around a coil (coiled wire) connected to a battery.

We tested the strength of the magnetic field of our electromagnets using a centimeter scale and a compass. The stronger the electromagnet was the greater the distance it swung the compass needle. The values of these distances for different electromagnets will vary. This is natural because each student built their electromagnet a little differently. In the next lesson we will try to discover which elements of the electromagnet's construction, its parameters, affect the strength of its magnetic field.

Our method of measurement is only able to determine whether a given electromagnet is stronger or weaker than another. To be able to check exactly how the strength of an electromagnet's magnetic field changes with a change of some specific element of its structure we need a measuring tool which will measure this field (e.g. its intensity).

A homework assignment for students is to make such a measuring tool/device.

Homework 1 - Measurement tool

Form

Independent work by students at home or in small groups at school.

Objective

Have students design and build a measuring tool that will indirectly or directly measure the force of the electromagnet they build.

Materials needed for the student

- a smartphone with the proper sensor or a microcontroller with the proper sensor
- construction elements
- DIY electromagnet for testing

Tips for students when creating a measurement tool:

Sensor Selection

- The sensor should allow recording of changes in the magnetic field strength produced by the electromagnet.
- The sensor should not react noticeably to changes in the environment.

Sensor Mounting

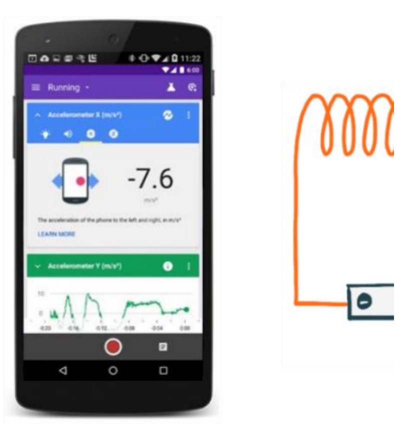
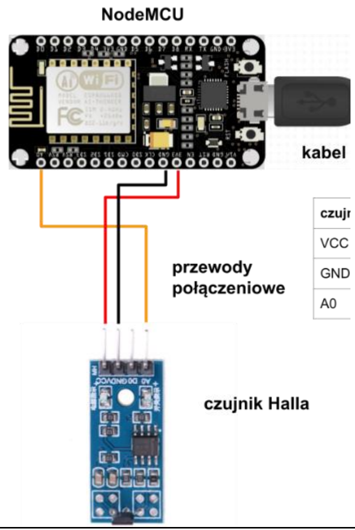
- The sensor should be mounted steadily so that e.g. its vibrations or movements do not influence the measurement results.
- The sensor should always be at the same distance from the electromagnet. If we change this distance during the measurements we can distort the results. That is why you can think about fixing the electromagnet and the sensor so that the distance between them is the same for every measurement.

Tool testing

- Once the device is built and possibly programmed, test it on the built electromagnet.
- We check what data we get and whether we can read from it directly or indirectly the magnetic field strength, the magnetic field strength, or any other parameter that allows us to determine the strength of the magnetic field.
- We verify whether the obtained data are correct, e.g. when the electromagnet is brought closer to the tool the values of the magnetic field strength should increase.
- We improve the program or design if necessary.
- If we are unable to read the magnetic field strength, strength, or any other parameter from the data that would allow us to determine this, and the corrections made have not corrected it, we should consider creating a new tool with a different sensor.

Examples of solutions:

USING A HALL SENSOR (MAGNETOMETER)

	
We run the Arduino Science Journal application on a phone placed a short distance from the electromagnet and read the magnetic field strength using a magnetometer. Not every phone has such a sensor built in, so before choosing this option you should make sure that it is available in your phone model. The values are not stable, i.e. there are some fluctuations, so you should wait a while and more or less read the average of the values that the sensor shows. Apart from that the sensor shows non-zero intensity at the very beginning because there may be magnets in the environment and also the sensor registers the magnetic field of the earth.	Using a nodeMCU microcontroller and a Hall sensor connected to it. We place the sensor like a phone in a small distance from the electromagnet. The microcontroller is programmed to send the recorded data from the sensor via wifi to the computer. From the data on the computer we read/calculate the magnetic field strength.

4.12 Unit 4.b Building the sensor (Lesson 2)

Form

In class or online meeting with students.

Objective

Investigate what parameters the strength of an electromagnet's magnetic field depends on.

Materials needed for the student

- lacquered or insulated copper wires approx. 2 m long with various cross-sections
- sandpaper
- duct tape
- cylinder of different diameters (thick marker, plastic tube, pencil) on which you can wind a wire
- AA or AAA batteries
- ruler
- scissors
- gauge
- multimeter (optional)
- student worksheet - lesson 2

Homework summary

Presentation of the created measurement tools

1. We ask one of the students to present the measurement tool they have created.
2. We ask if anyone has built another one and if so, please present it too.
3. We discuss the differences in construction.
4. If there are any problems we try to solve them together.

Discussion

The purpose of this discussion is to repeat the knowledge from the previous lesson, namely, how the strength of an electromagnet's magnetic field can be measured and that for different electromagnet designs we have observed different strengths of their magnetic fields.

Main study problem

What parameters of an electromagnet affect the strength of its magnetic field?

Direct the discussion so that the students themselves propose the parameters on which the strength of the magnetic field of the electromagnet depends, and encourage them to use their instruments to investigate how and whether the strength of the magnetic field changes when a given parameter is changed. Below in the "Student Experiments" section you will find sample research questions, but each student may propose their own.

Proposal for working with students

We can divide students into teams and assign each team one parameter/one research question to investigate. Finally, all teams share their findings with the whole class.

Student experiments

Each student conducts experiments independently.

STUDY QUESTION 1

How does the number of turns of an electromagnet affect the strength of its magnetic field?

Measure the strength of the magnetic field with the measuring tool for electromagnets with different number of turns (make sure that the ambient conditions as well as other parameters do not change during the measurements). Record the obtained data in a table or spreadsheet and create a graph based on the data.

- We use the same winding cylinder, same battery, same wire, length of coil also try to make it the same.
- It is best to start with the largest number of coils, mark the beginning and the end of the coil on the cylinder. When decreasing the number of coils, make sure that the beginning and the end are always in the places marked on the cylinder.
- Also remember to take the measurement as quickly as possible and afterwards immediately disconnect the solenoid from the battery. This will prevent the electromagnet from heating up.

Number of coils						
Magnetic field strength H [μT]						

STUDY QUESTION 2

How does the cross-sectional diameter of the wire from which an electromagnet is made affect the strength of its magnetic field?

Measure the strength of the magnetic field with the measuring tool for electromagnets made of copper wires of different cross-sectional diameters (make sure that the ambient conditions as well as other parameters do not change during subsequent measurements). Record the obtained data in a table or spreadsheet and create a graph based on the data (if you have only 2-3 wires of different thickness, do not make a graph, just compare the results).

- We use the same winding cylinder, one battery, the same number of coils, the length of the coil should also be the same.
- The best way is to mark the beginning and the end of the coil on the cylinder and then wind a wire with the smallest cross-sectional diameter on it. Then remove the cylinder and do the same for other wire thicknesses you have available.

- Also remember to take the measurement as quickly as possible and afterwards immediately disconnect the solenoid from the battery. This will prevent the electromagnet from heating up.

Wire section diameter [mm]						
Magnetic field strength H [μT]						

STUDY QUESTION 3

How does the diameter of the coil itself (the cylinder on which the wire is wound) of an electromagnet affect the strength of its magnetic field?

Measure the strength of the magnetic field with the measuring tool for electromagnets made up of rolls of different diameters on which a copper wire is wound (make sure that the ambient conditions as well as other parameters do not change during subsequent measurements). The obtained data are recorded in a table or spreadsheet and on its basis we create a graph (if you have only 2-3 rolls of different thickness, do not make a graph, just compare the results).

- We use the same winding wire, one battery, a fixed number of coils, the length of the coil should also be the same.
- The best way is to mark the same length of each roll (the beginning and the end of the coil) and then wind a wire on the largest roll, remembering the number of coils you have wound. Then take the measurement and disassemble the electromagnet. Then build up the electromagnets one by one using smaller and smaller coils and remembering that the number of coils and the length of the coil does not change.
- Also remember to take the measurement as quickly as possible and afterwards immediately disconnect the solenoid from the battery. This will prevent the electromagnet from heating up.

Cross-section diameter of the coil (cylinder) [mm]						
Magnetic field strength H [μT]						

STUDY QUESTION 4

How does the length of the coil itself (the distance from the first coil to the last coil) of an electromagnet affect the strength of its magnetic field?

Measure the magnetic field strength with the measuring tool for electromagnets of different coil lengths (make sure that the ambient conditions as well as other parameters do not change during the measurements). Record the obtained data in a table or a spreadsheet and create a graph based on the data.

- We use the same wire for winding, the same roller, one battery, fixed number of coils.
- It is best to mark on the cylinder the "beginning" of the coil (the place of the first coil) and at various distances some of its "ends" (the place of the last coil). Starting from the largest segment we wind the wire remembering the number of coils we have wound. We measure the electromagnet and then dismantle it to create another one with a different coil length, remembering to keep the number of coils.
- Also remember to take the measurement as quickly as possible and afterwards immediately disconnect the solenoid from the battery. This will prevent the electromagnet from heating up.

Coil length [cm]						
Magnetic field strength H [μT]						

What can go wrong and how to deal with it

The electromagnet does not act on the measuring device.

- Check that the battery you are using is not discharged and that the wires are making proper contact with the battery.
- Check that the measuring tool is working properly, e.g. test it using a simple magnet.

The electromagnet heats up until it steams.

- Wearing gloves, wire to the battery for a shorter time, always wait a moment before connecting again.

There is no difference in the performance of the electromagnet in the following parts of the experiment.

- Use larger differences in the tested parameters (e.g. do not compare the performance of a solenoid with 10 and 12 coils but e.g. 10 and 20 or even 30).
- If you are using several different batteries, check to see if they give different voltages (doesn't the action of the wire change when plugged into another battery, we don't want the battery to be the variable factor in the experiments).
- If you have a current meter, use it during the measurements to make sure that the current flowing through the electromagnet is constant or changes only slightly. The exception to this is experiment #2, in which the current will vary depending on the wire thickness used.

Summary of the experiments and explanation of the phenomenon

Supporting questions:

- On what parameters does the strength of the magnetic field produced by an electromagnet depend?
- Have we examined all possible parameters/factors that affect the magnetic field strength of an electromagnet?

Homework 2 - Sorting Device

Form

Independent work by students at home or in small groups at school.

Objective

Design and construction of a device which will pick up from the coins scattered on the floor only those of 1 and 2 groszy.

Materials needed for the student

- components for building an electromagnet
- measuring tool to measure magnetic field strength
- construction elements (e.g. plywood, hard cardboard, LEGO bricks)
- 0.1g accuracy scale (optional)
- coins of various denominations

Task 1: Construction of the sorting device

1. Weigh coins of different denominations.
2. Build an electromagnet and modify it to attract only selected coins.

Questions for students to answer independently

- What forces act on the coins lifted by the electromagnet?
- What parameters of an electromagnet can we change to alter its force on attracted coins?
- What values do I need to measure in order to select parameters of the electromagnet so that it lifts only 1 and 2 „grosz" coins?

4.13 Unit 4.c Sorting device demonstration (Lesson 3)

Form

In class or online meeting with students.

Objective

Present to the group the operation of the constructed sorting device and compare its construction and operation with others. Summary and conclusions.

Materials needed for the student

- completed worksheets
- devices built
- coins of various denominations

1. Homework summary

Presentation of the results obtained

- We ask students to present their coin sorting devices.
- We discuss the differences in construction and operation of various coin sorting devices.
- We ask students to describe their method of sorting, the tool/mechanism they used.

Discussion

The purpose of the discussion is to encourage students to share the difficulties they encountered while making the device and how they dealt with them. If something went wrong then discuss why it happened and how we can fix it.

2. Summary of all lessons

Supporting questions:

- How is an electromagnet built?
- Does an electromagnet work the same as a regular magnet?
- On what parameters does the "strength" of an electromagnet depend?
- What is the formula for the magnetic field strength produced by an electromagnet?

5 Appendix – How to use the sensors with Arduino Journal App

Arduino Science Journal

A video showing how to operate the app and how it can be used for various measurements:

https://youtu.be/p2w2y6noE34

LAUNCHING THE APPLICATION

After launching the application, we see a window with the experiments/projects performed. At the first launch, we see only the block "Welcome to Science Journal" where we can find information about the application.

To start a new experience, click on the button in the lower right corner with a "+" sign. An experiment window will appear, in which our observations will be saved.

EXPERIMENT WINDOW

In the experiment window, we can change the experiment title by clicking on the pen icon in the upper right corner.

A window will appear to update the experiment

We can then change its title and paste the photo/motif of the experiment.

After making changes, click "v" in the upper right corner to commit the changes

At the bottom of the experiment window, there are icons that allow us to enter observations into our experiment:

Text - in the form of a text note

Sensors - in the form of measurements from the sensors built into our phone.

Camera - in the form of a picture that we take

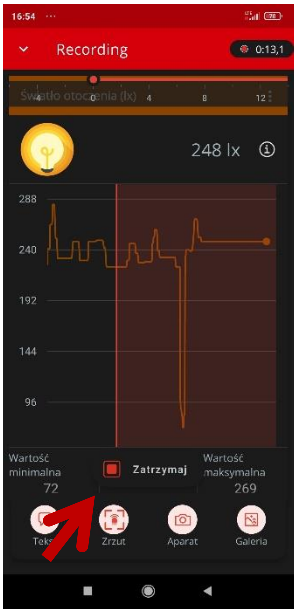
Gallery - in the form of a photo/illustration selected from the photo gallery on our phone.

MEASUREMENTS BY SENSORS

When you click the sensors icon in the experiment window, the measurement data logging window appears.

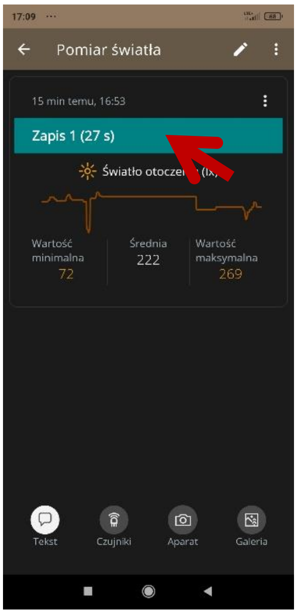
In the top menu, we have a choice of different sensors.

We can observe/record data from several sensors at once. To do this, we add them using the "Add Sensor" button which is located in the lower left corner..



After selecting the sensor we want to observe, the measurement data appears on the screen as a graph in real time.
To save the measurement data we have to start recording with the red dot at the bottom of the graph.

To stop data logging and save the measurements, click the red square at the bottom of the graph.
The measurement data has been saved and will be available in the experiment window.



To see a saved measurement, find it in the experiment window and click on its frame

We can name our measurement, to do this we click the pen icon in the upper right corner.
In the new window, type the title of the recorded data.
To save the data in *.csv file format, click the three dots in the upper right corner and select Download from the list (when downloading, select the Relative time option).

We can also view the measurement data on a graph in the application. For this purpose, we can move the slider on the timeline and read individual measurement points on the graph.
We can also add notes to the measurements in the form of text or photo using the icons located at the bottom.

CAR PRINT

Printable parts:

3 x axle_car.stl

1 x car_axle.stl

1 x sub-set_phone.stl

2 x side frame.stl

4 x wheel.stl

1 x hitch_rubber.stl

Print parameters:

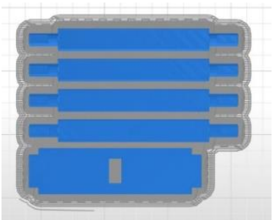
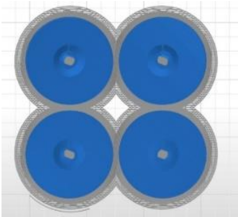
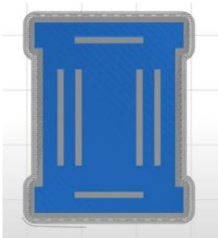
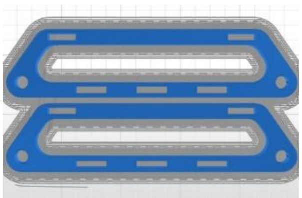
Material: any

Raft: not needed

Support: not needed

Infill/Fill: 20 - 40 %

Layer thickness/layer thickness: 0.19 - 0.29

			
REPORT Estimated print time: **3h 3m** Material usage: **14.54m (35g)** Printer: **Zortrax M200** Profile: **Last settings** Support type: **Automatic** Support: **20°** Material: **Z-ULTRAT** Nozzle diameter: **0.4 mm** Layer: **0.19 mm** Quality: **Normal** Infill: **40%**	**REPORT** Estimated print time: **3h 57m** Material usage: **22.48m (53g)** Printer: **Zortrax M200** Profile: **Last settings** Support type: **Automatic** Support: **20°** Material: **Z-ULTRAT** Nozzle diameter: **0.4 mm** Layer: **0.29 mm** Quality: **Normal** Infill: **20%**	**REPORT** Estimated print time: **3h 35m** Material usage: **20.91m (50g)** Printer: **Zortrax M200** Profile: **Last settings** Support type: **Automatic** Support: **20°** Material: **Z-ULTRAT** Nozzle diameter: **0.4 mm** Layer: **0.29 mm** Quality: **Normal** Infill: **30%**	**REPORT** Estimated print time: **3h 27m** Material usage: **18.43m (44g)** Printer: **Zortrax M200** Profile: **Last settings** Support type: **Automatic** Support: **20°** Material: **Z-ULTRAT** Nozzle diameter: **0.4 mm** Layer: **0.29 mm** Quality: **Normal** Infill: **30%**

Deutsches Museum

INSTITUTO DE EDUCAÇÃO ULISBOA

CENTRUM NAUKI KOPERNIK

TUM
Technische Universität München

All materials are available at

https://erasmus-plus.ec.europa.eu/projects/search/details/2020-1-DE02-KA226-VET-008295

The Hand-on Remote project was funded in the Erasmus+ KA226 Partnerships for Digital Education Readiness program (2020-1-DE02-KA226-VET-008295)

Co-funded by the Erasmus+ Programme of the European Union

Hands-on-Remote