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Contemporary Experiments and New Devices in Physics Classrooms

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Contemporary Experiments and New Devices in Physics Classrooms

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Abstract. Classroom demonstrations and experiments have played an important role in physics teaching for centuries. They are important for deepening student knowledge and helping students gain meaningful understanding of physical principles. In addition, experiments can motivate students and facilitate their active engagement with abstract concepts. In this paper, we present four novel physics experiments and demonstrations that address the pedagogical needs of the 21st century physics teaching. These experiments: (a) employ modern technologies that bring physical phenomena closer to the students; (b) showcase teaching methods that reduce barriers for the students with special needs; and (c) suggest an innovative thermodynamics demonstration related to environmental issues and green energy. The descriptions of the experiments, their applications to secondary school teaching as well as to college-level physics education are thoroughly discussed.

1. Introduction

Physics is an empirical science. Thus, experiments, have often took a center stage in of physics teaching [1-5]. Carefully designed experiments have the potential to help students experience and understand isolated physical phenomena within the classroom walls. Students can also perform quantitative experimental measurements and test them against the theoretical predictions to experience the very nature of scientific thinking and the applied methods. In addition to deepening students' knowledge, such activities can also significantly increase students' engagement and raise their interest towards natural sciences in general.

Although there exists ample literature on classroom experiments and demonstrations and their applications, trends of the 21st century call for further developments in this area [3-5]. First, the emerging technologies offer novel opportunities: (i) with the broadened possibilities of the new devices and techniques, several fascinating phenomena can be now brought into classrooms or demonstrated in a more convincing manner, (ii) modern tools, such as smartphones or microcontrollers, are easily accessible to the students, therefore, these tools can be very useful in a physics classroom. Secondly, the expectations of the modern society towards physics (and the sciences in general) teaching now also includes the requirement for critical and scientific thinking about the big challenges humanity faces due to rapid technological development and globalization, such as the climate change and environmental degradation. Thus, experiments addressing these issues must also be included in the physics curriculum in the secondary schools, as well as at the university. Last but not least, there is a growing effort of the teaching community to develop methodologies that provide all students, including the students with special needs, with the opportunity to engage with science in a meaningful way. For instance, the students with special needs should also be able to carry out lab experiments and analyze their results. Fortunately, novel technologies now offer a chance to reach this goal.

This paper presents four new experiments and corresponding experimental methods that address the goals described above. Firstly, in Section 2 proposes the usage of fast-speed cameras and slow motion videos in the physics classrooms. With this method, phenomena occurring on very short timescales (such as the shutter of a glass) can be visualized. This novel technology makes it possible to quantitatively investigate the physics behind these processes. Secondly, a thermoacoustic heat engine is presented in Section 3. On the one hand, it is capable of being operated as a heat engine as well as a heat pump, and on the other hand, it is extremely spectacular. It also provides the possibility for students to perform measurements with their own smartphones and tablets. It also gives the opportunity to introduce heat pumps, which might be used as an energy efficient (i.e., "green") heating application for homes. Thirdly, Section 4 introduces a modern set-up of the rotating balance designed by Loránd Eötvös in the 19th century that is capable of proving the rotation of the Earth. This version employs contemporary technology with Arduino controllers and is intended for more advanced secondary or undergraduate students or to be used during physics competitions. Finally, in Section 5, we discuss possibilities of using tablets in secondary schools to reduce the barriers that are faced by students with special needs during laboratory activities.

2. Seeing Fast and Slow: Engaging Students in Science through Slow Motion Videos

2.1. Introduction

Physics teachers often use experiments to increase student engagement [3, 4]. Yet, not every physics experiment has a positive effect on student learning and science attitudes [5, 6]. Pedagogically powerful experiments have to illustrate physics phenomena, allow students to see the sources of physical laws, and appreciate the process of science and not only its outcomes. This is relevant to both secondary or introductory physics courses and methods courses for future secondary physics teachers. And yet, pedagogically effective use of physics experiments in these courses is frequently lacking [5]. As a result, students often view physics as a collection of facts often described by complicated and incomprehensible formulae and sometimes accompanied by experiments that bear little connection to the discussed phenomena [7]. Not surprisingly, future physics teachers have very limited knowledge of how to design pedagogically effective physics experiments and classroom demonstrations for high school teaching.

Modern research-based computer simulations, such as PhET [8], have partially helped address this issue, but their effects are inconsistent and even in the best case scenario virtual simulations should not replace real life physics experiments [9]. One clear advantage of simulations is their ability to make the invisible phenomena visible, for example, making visible electric current in electric circuit simulations. This begs a question: How can modern technology help make the invisible phenomena visible in real life experiments performed in front of the students? How can we document and share these experiments with physics educators at secondary and post-secondary institutions? How can students collect and analyze real data from these experiments and demonstrations?

In our earlier studies, we found that engaging future physics teacher in creating educational videos of science experiments motivates them to use these experiments in their own classes during their school practicum [10]. This motivated us to consider how we can use modern technology, such as fast-speed camera, to introduce engaging physics experiments into introductory physics teaching and teacher education in order to make the invisible physics phenomena visible while engaging students in hands-on physics. In this paper, we briefly outline how we use slow motion videos in introductory physics courses and in physics teacher education to engage students in physics learning. A more detailed description can be found elsewhere [11]. The image below (Fig. 1) shows a series of screenshots of the shuttering glass experiments that were videotaped live during a large (250 students) university introductory physics class and analyzed with the students.

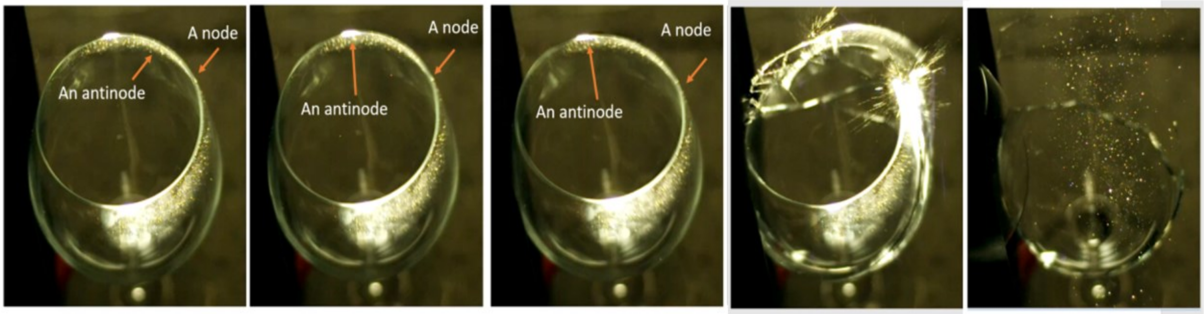

Figure 1. Consequent screenshots of a shuttering glass experiment performed live with a ~5000 frames per second fast-speed camera. The natural frequency of these wine glasses: ~400 Hz.

2.2. Slow-motion physics experiments: Making the invisible visible

We are currently working on designing slow motion video experiments of fast pace physics phenomena relevant to secondary school and introductory physics courses to be performed and analyzed during classes. We are also creating accompanying instructional videos, so we can share these experiments with other educators. Unlike many slow motion videos found on the internet, ours focus on the understanding and analysis of physics phenomena, as well as on the technical side of setting up slow motion videos in physics classrooms. While current smartphone slow motion features are yet insufficient for most of these experiments and fast speed cameras are still expensive, they are becoming more and more affordable. Slow motion videos will be the physics tools of the near future. We are convinced that very soon students will have in their hands powerful tools for science experiments that will make physics learning more engaging and meaningful. So far, we have piloted seven different experiments: resonance in a wine glass, standing waves on strings, interfering water waves, Chladni plates, free falling water stream, popping soap bubble, and resonating Chinese Spouting Bowl.

We have implemented these experiments in both introductory physics courses and in physics methods courses and have seen very positive student response. The effect of slow-motion video on student engagement was especially pronounced in physics methods courses. Many of the future physics teachers have never observed these phenomena in slow motion and especially have never seen how the experiments can be set up in front of the students. For example, we recorded in slow motion the oscillations of the C4 tuning fork (f = 256 Hz)) and were able to correspond the slow-motion video with the data recorded from the microphone using Logger Pro sensors [12]. Thus, future physics teachers were able to see live that in the time interval of 0.016 s the tuning fork will undergo about 4 oscillations:

$$T = \frac{1}{f} = \frac{1}{256\ \text{Hz}} = 0.0039\ \text{s} \Rightarrow 4T = 0.0156\ \text{s} \approx 16\ \text{ms} \qquad (1)$$

Making connections between different representations of physics phenomena (mathematical, visual, graphical, etc.) allowed students a rare opportunity to build authentic physics understanding and test it through additional physics experiments (Fig. 2).

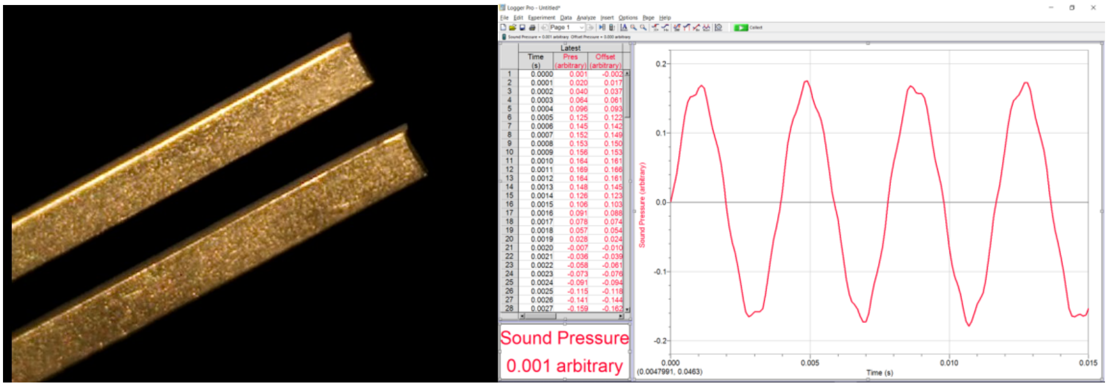

Figure 2. A C4 tuning fork and a Logger Pro graph depicting pressure oscillations corresponding to the sound wave generated by the fork.

There were two more unintended outcomes of performing slow-motion physics experiments in front of and with the students. First, since these experiments were more complicated than traditional low-tech demonstrations, the instructor was more likely to encounter technical difficulties and even make mistakes. As a result, the students were able to participate in joint authentic problem solving. Thus, they saw not only the result, but also the process of science. Secondly, having access to slow-motion experiments invited students to ask new questions. For example, in the case of the tuning fork experiment, the students asked questions about different modes of tuning fork's oscillations. While the fundamental mode is the mode most commonly associated with the tuning fork and is traditionally described in introductory physics textbooks, it is not the only possible mode of vibration for the tuning fork. There are many asymmetric oscillation modes that can be easily heard but can only be visible in slow motion experiments. Seeing the demonstration in slow motion, inspired students to ask many more "what-if" questions. For example, *What would happen if the mass of one of the prongs of the tuning fork were increased*? Such a question would have been likely overlooked in a traditional physics lesson, but we can examine it using modern technology.

2.3. Conclusions

In anonymous student course evaluations, slow motion physics experiments were listed as one of the most memorable and exciting parts of the course both in introductory physics courses and in physics methods courses for future physics teachers. We are working on developing more slow-motion experiments for fast-speed camera and for the smartphones. In addition, we are incorporating slow-motion videos conducted with the help of smartphones as part of the course assignments for future physics teachers. We are also working on designing meaningful measuring tools for collecting hard evidence for student learning outcomes in this experiment-based pedagogy. We hope to uncover a few promising opportunities on how modern technology can help us improve secondary and post-secondary physics learning and engage students in science through slow-motion video analysis.

3. Thermoacoustics as a Tool of Teaching Thermodynamics in Secondary Schools

3.1. The teaching unit

Thermodynamics is a difficult but an important topic in the physics curriculum. In order to raise students' interest and bring physics closer to them, both the discussions of the operation of practical everyday-life appliances, novel applications, as well as classroom experiments employing thermodynamics principles are useful. When thermodynamics is taught, important everyday applications, such as heat engines are often discussed, and yet less attention is payed to heat pumps. We take it for granted that we have refrigerators or freezers, and that during hot summer days air conditioners are turned on. Yet, in Hungary, very limited amount of time in secondary schools is dedicated to discussing heat pumps, especially the ones used for heating buildings. We often hear from the media that the emission of carbon dioxide should be reduced and that we should use more “green energy” like geothermal or solar energy. Therefore, it is vital to explain to the young generation both the advantages and the drawbacks of the devices concerning these issues. The heat pump is clearly one of these devices.

In two groups of secondary school students, a teaching unit was devoted to explain the theoretical background of reversed cyclic processes and the use of heat pumps in everyday life for space heating and cooling. As a demonstration for a cyclic thermodynamic process, which can be operated in clockwise (as a prime mover) or in a counter clockwise direction (as a heat pump) the test tube thermoacoustic heat engine and heat pump were shown and explained to the students. (In 2015, a similar teaching unit was designed and taught, but that unit didn’t include any experiments [13].)

3.2. Efficiency and Coefficient of Performance (COP)

In order to characterise how efficiently a heat engine or a heat pump works, we introduce two different concepts: efficiency and COP (coefficient of performance that is often referred to as energy efficiency ratio for cooling devices), respectively. In Hungarian secondary schools, usually only the first one (efficiency) is taught and little attention is paid to the COP. Furthermore, the second law of thermodynamics is often quoted as the efficiency of any heat engine should be strictly smaller than 1. Without a clear differentiation between these two different physics terms – the efficiency and COP, it can be confusing for the students to learn from the social media that the efficiency (actually it is COP) rating of standard heat pumps is usually greater than one, reaching the values of four, five or even higher. The problem is that in everyday life these two different terms are often confused.

With the following two simple diagrams (Figs. 3 and 4) and proper definitions, students can easily understand the difference between the efficiency and COP. So let us consider a heat engine and a heat pump, which are operated between two heat reservoirs (see Figs. 3 and 4).

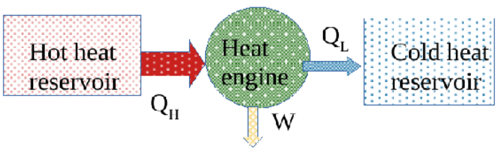

Figure 3. Schematic view of a heat engine

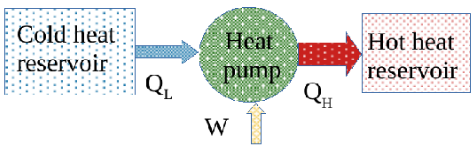

Figure 4. Schematic view of a heat pump

Figure 3 shows the schematic view of a heat engine. HeatQ_H is *absorbed from* the hot heat reservoir and the heat engine does work W and *delivers* heat Q_L *to* the low temperature (cold) heat reservoir. Thus the efficiency can be defined as:

$$\eta = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H} \tag{2}$$

In case of the heat pump (Fig. 4) two COP-s can be defined, one for a heat pump, which is used for heating, and another for a heat pump, which is used for cooling. In this case Q_H stands for the heat *delivered to* the hot heat reservoir, whilst Q_L is the heat *absorbed from* the low temperature heat reservoir, whilst W work is done by the environment:

- For heating: $$\mathrm{COP}_{\mathrm{heating}} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_L} \tag{3}$$
- For cooling: $$\mathrm{COP}_{\mathrm{cooling}} = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L} \tag{4}$$

From the three formulae discussed above (2-4), the students can easily understand that the COP value in case of heating is always greater than one, or that if the same heat pump can be operated under the same circumstances, then the COP value for heating is exactly one more than that of for cooling. So there is no contradiction with the second law of thermodynamics, just the COP introduced for rating heat pumps is not the same as the efficiency of heat engines.

3.3. Heat pumps in practice

It was Lord Kelvin, who in the 19th century proposed that it would be better to use heat pumps to heat buildings rather than just to burn fossil fuels [14], but it was not until the end of the 20th century that heat pumps were begun to be used as heating devices for homes. Many students realised that refrigerators and air conditioners are heat pumps and some students even knew that modern air conditioners can also be used for heating. With the Carnot cycle, an upper limit can be given for the COP value of a heat pump operated between two heat reservoirs. For heating, the COP value of a reversible Carnot heat pump operated between the two reservoirs of temperatures T_H (a high temperature heat reservoir) and T_L (a low temperature heat reservoir) is the following [15]:

$$\mathrm{COP}_{\mathrm{Rev,Carnot,heating}} \frac{T_H}{T_H - T_L} \tag{5}$$

From Eq. (5) it is easy to understand that the COP of the heat pump is smaller when the temperature difference between the heat reservoirs is greater. Therefore, it means the air conditioner works better in the spring and in the autumn, than during the cold winters.

Students were also interested in other types of heat pumps, such as ground or water-sourced pumps. The students were eager to find examples on the internet, and it also gave them an opportunity to examine the environmental issues. Possible discussion points can be: *What substance can serve as a refrigerant?*; *How "green" is a heat pump (the compressor of the pump is usually operated by an electric motor, so the pump needs electricity to work)?*; *Can the temperature of the heat reservoir change?*; or *What should be done if the ground gets too cold at the end of the winter?*

3.4. Thermoacoustics

The great majority of heat pumps are gas-compression pumps in which the refrigerant is usually a type of HFC (Hydrofluorocarbon) which is periodically compressed and allowed to expand. During these processes the refrigerant changes its phase from liquid to gas and back from gas to liquid. This is why the process is not simple. Also this pump cannot be operated as a heat engine.

Two experiments were shown to the students to demonstrate both the heat engine and the heat pump with the same device. The first one, the thermoacoustic heat engine is easy to build from a test tube (that is approx. 20 cm long and has a diameter of 1 cm) and a piece of steel wool [16]. A piece of steel wool approximately 2 cm long, called the stack, is placed into a test tube closer to the closed end of the tube. (The threads of the wool should be parallel to the test tube.) Then the end of the wool closer to the closed end of the tube is heated with a spirit burner, whilst the other end of the wool is cooled by a piece of wet paper towel wrapped around the tube such that it covers approximately 1 cm of the wool. Soon after the heating began, the test tube emitted a loud sound of approximately 75 dB. The loudness, the frequency can be measured with a smartphone application. In addition, an oscilloscope app can be used to visualize the sound. (Strictly speaking, it is not a real engine, but it converts heat to the mechanical energy of sound.)

The reverse of the experiment is that with a loud speaker and a sound generator loud sound of appropriate frequency can be generated [17]. The woofer of the loud speaker was covered with a board, having only a small hole at its centre, into which the open end of the test tube was inserted. Next to the ends of the stack small holes were drilled into the wall of the tube, through which the temperature sensors were inserted into the tube. Soon after the sound was turned on, the thermometers showed the temperature difference between the two ends of the stack. The end of the stack that was closer to the closed end of the tube warmed up, by a few degrees and the other end cooled down by a few degrees, producing a temperature difference of approximately 10°C. Figures 5 and 6 show the two apparatuses.

The first experiment is relatively easy to build, students enjoy to play with it, the surprising result of the experiment – the emitted loud sound amuses them. Also they can use their smartphones or tablets to do the measurements, which make the experiment more meaningful and engaging. The second experiment is a bit more demanding, and once it works it might be a good idea to record the experiment with a video camera, and if there is not enough time to prepare for the experiment, the video can be used in its stead.

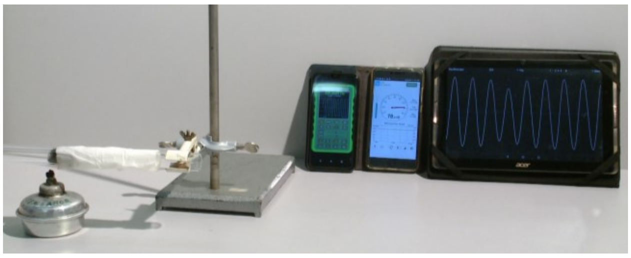

Figure 5. The test tube heat engine

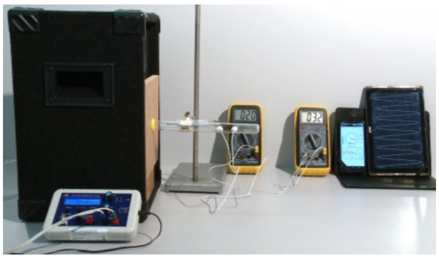

Figure 6. The test tube heat pump

3.5. A possible explanation for the test tube heat pump

Figure 7 helps to provide a rough qualitative explanation of the test tube heat pump. The fine threads of the steel wool (called stack plates) are represented by the two narrow dashed rectangles. Between the threads there is air and the thermal conduction between the air and the stack is not very good. The different states of an air parcel moving back and forth between the plates are represented by the coloured squares. The loud sound generates standing waves in the tube, which causes compressions and rarefactions in the tube. So a larger volume of air parcel at temperature T_0 (a yellow square) is forced to move towards the left where there is compression. So it shrinks adiabatically and thus heats up to temperature T_1 (a red square), which is higher than the temperature of the stack at the left end. It stops there and releases some heat Q_r to the stack, cooling to reach temperature T_2 (a pink square). Then it is forced to move towards the right, where there is a rarefaction so a smaller pressure. It expands and cools adiabatically to temperature T_3 (a blue square), which is colder than the temperature of the stack at the right end. There it stops and absorbs some heat Q_a from the stack [18, 19]. (A more detailed secondary-school level explanation can be found elsewhere [20].)

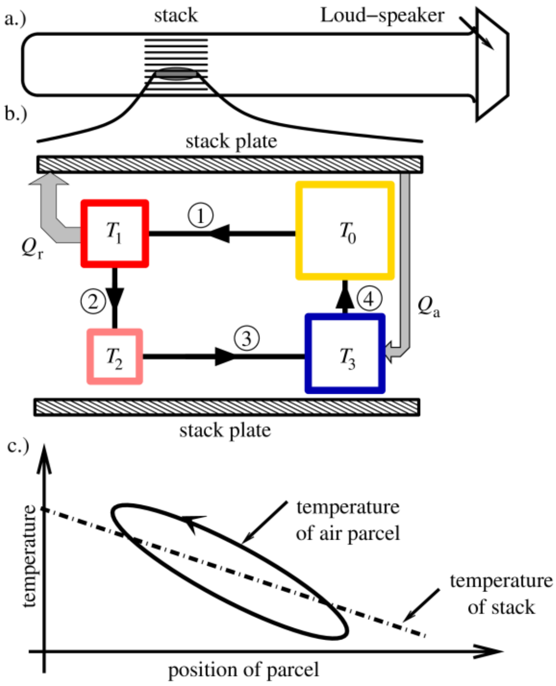

Figure 7. a) A schematic view of the test tube refrigerator, b) An air parcel between the stack plates (represented by the coloured squares); (The air parcel does not move in the vertical direction, just along the horizontal, once it moves towards the left shown by the squares in the top line and then it goes back to the right end, shown by the squares in the bottom line.) and c) The corresponding temperature values.

3.6. Conclusions
In the 21st century, it is important to introduce novel applications to students, clear explanations and effective classroom experiments raise student interest. New technical devices (smartphones) can help take the measurements to make the experiments more engaging to the students. Videotaping the experiments may help the teacher, especially when the apparatus is not available. However, live classroom experiments are always more enjoyable and authentic.

4. The Rotating Balance of Eötvös

4.1. Introduction
The famous Hungarian scientist baron Loránd Eötvös (1848 – 1919) died 100 years ago. UNESCO has declared 2019 as Eötvös year to commemorate his outstanding scientific achievements. One of his well-known contributions to the determination of the gravitation field around the Earth was that he pointed out that the Coriolis force has to be taken into account if the measurement is carried out on a moving ship. This is called the "Eötvös effect". In order to demonstrate this, he invented a device called "a rotating balance". In the Section we briefly summarize how it works and show how it can be used in a modern physics classroom.

The first direct evidence that the Earth indeed rotates was the famous Foucault experiment conducted in 1851 [21, 22]. The swinging plane of the pendulum rotates due to the Coriolis force that is proportional to the velocity of the moving object and the angular velocity of the rotating frame. The Foucault pendulum, however, requires a high hall to be set up and it takes several minutes or hours to see the effect. At the beginning of the 20th century, Eötvös invented another device to demonstrate the rotation of the Earth. It is compact, so it easy to set up anywhere, and it is "quick" in the sense that the rotation of the Earth can be proved in few seconds due to the fact that it is based on a resonance effect.

4.2. Theory of the rotating balance
Let us consider two equal masses on the two ends of a rod that can swing around a horizontal axis that does not go through the center of the gravity of the system (see Fig. 8). Like for any physical pendulum, the balance is in equilibrium position when the center of the gravity is just precisely below the axis. Now what happens if on the Earth with a given angular velocity ω we start to rotate the balance around a vertical axis perpendicular to the swinging one? Due to the Coriolis force a periodic torque starts to act on the balance. Like any excited damped oscillator, after a transition period determined by the level of dumping, the balance starts to swing with the frequency of excitation ω with an amplitude A depending on ω. After a long but quite elementary calculation one can find that

$$A = \frac{2\omega\omega_E \sin(\lambda) l^2}{\sqrt{\left(gs - 2\omega^2\left(s^2 + a^2\right)\right)^2 + 4\omega^2\beta^2 l^4}} \qquad (6)$$

where ω_E is the angular velocity of the Earth, λ is the latitude at the experiment, g is the gravitational acceleration, s is the distance between the swinging axis and the center of gravity of the balance body, β is the damping constant, and l and a are constants determined by the geometry of the balance body. Since for the common setup a is much larger than s, one can see that the resonance frequency ω_r is proportional to the square root of s:

$$\omega_r = \sqrt{\frac{gs}{2a^2}} \qquad (7)$$

4.3. Experiments with the balance
For the third experimental round of the Hungarian National Competition in Physics 2019 (OKTV), we have build a rotating balance (see Fig. 8) that is in principle, the same as Eötvös' original one but it is controlled by modern electronics. The balance is rotated by a stepper motor, which is controlled by an

Arduino microcontroller. The swinging of the balance is detected by a laser beam reflected off a mirror located at the top of the body of the balance.

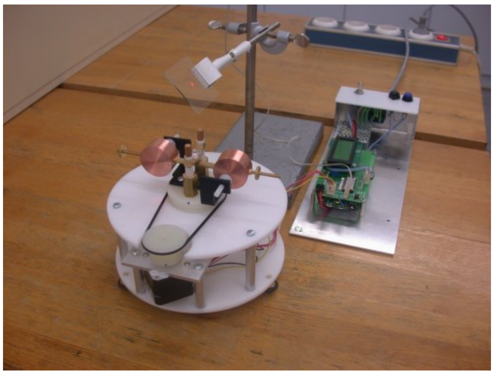

Figure 8. The rotating balance of Eötvös

Typical resonance curves obtained at three different *s* values are shown in Fig. 9.

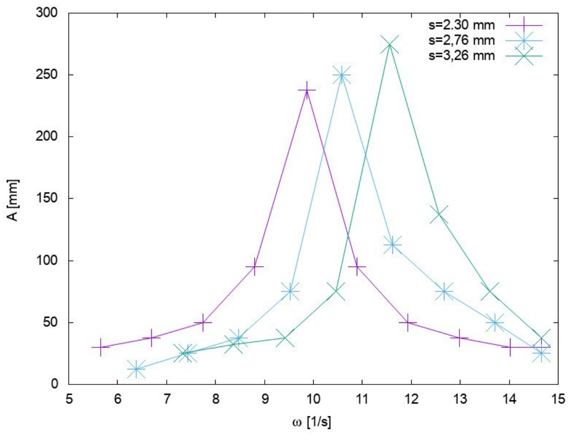

Figure 9. Resonance curves at three different *s* values

As it is seen in Fig. 10, the resonance frequency is indeed proportional to the square root of the distance between the point of suspension and the center of gravity of the rotating balance.

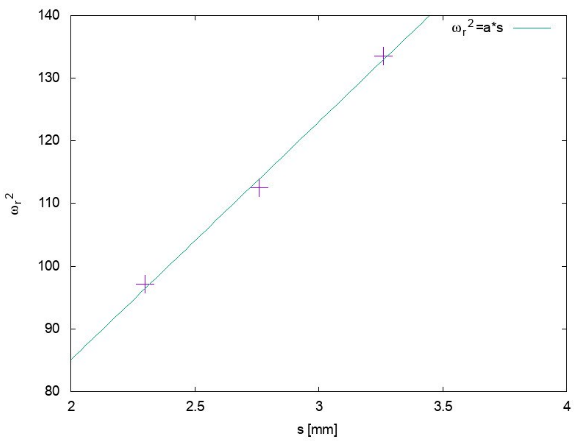

Figure 10. The square of the resonance frequency versus *s*.

4.4. Conclusions
To sum up, it can be stated the rotating balance of Eötvös is an easy to use tool to demonstrate the existence of the Coriolis force acting on a moving body on the Earth. Moreover, it is a good example that by applying a resonance technique a small effect, which is otherwise difficult to detect with static experiments, can be enhanced. Since the implementation involves a modern Arduino-based controller it makes this experiment suitable for using as a lab experiment, an experimental project, or as a physics competition challenge.

5. Reducing Barriers in Experiments for Students with Special Needs by Using Tablets

5.1. Introduction
"In the PISA study scientific literacy is defined as the ability to understand the characteristics of science and the significance of science in our modern world, to apply scientific knowledge, identify issues, describe scientific phenomena, draw conclusions based on evidence, and the willingness to reflect on and engage with scientific ideas and subjects" [23]. The metaphor "scientific literacy" emphasizes that scientific knowledge has the same prestige as a cultural technique (reading, writing or counting), which should enable someone to participate in a modern society [24].

The debate as well as the developed concepts about scientific literacy in the industrial countries show that one's social ability to participate in society is seen as one of the main aims of science education. Therefore, it is imperative that physics and physics education are not withheld from any person regardless of their ability level. Every student should get equipped with the knowledge and skills that will help them manage their lives as adults within our scientifically-oriented world [25].

5.2. Inclusive science education
In order to reduce and eliminate exclusion within and from physics education and engage all students in physics learning, it is important to raise awareness of the barriers and obstacles faced by the students with diverse backgrounds. Therefore, the diversity and different needs of all students should be addressed by identifying their individual resources in order to compensate, minimize or avoid barriers in physics learning [26], which can exist in many learning activities. Therefore, it is important to take all dimensions into account that people differ in: gender, age, culture, ethnicity, socio-economic background, religion etc. and not to focus only on the diversity dimension of ability and disability [27]. Unfortunately, a dialogue between domains of inclusive pedagogy and specific subjects, like science education, is very uncommon. We are aware of only a few relevant studies and publications [28]. Therefore, this research on reducing barriers on science experiments for students with special needs by using tablets will contribute to this research area. It will also widen the area of research via combining inclusive pedagogy and science education.

5.3. Digital devices as an access to science
The use of digital devices offers many advantages. A recent meta-study points out that the use of digital teaching-media in science education leads to an increased students' motivation for the subject [29]. Besides that, a higher level of autonomy can be reached by using smartphones or tablets, because the students are able to experiment independently with those devices [30]. Furthermore, tablets are capable of integrating different senses (multimediality) as well as representing phenomena in different code-systems (multiple coding) [31]. In addition, accessibility features like a (gesture-based) screen reader, voice control, a switch control or a guided access are already integrated in tablets [32]. Apart from that, screen contents can be zoomed, a Braille keyboard can be connected, the colour as well as the contrast can be adopted, multiple access options (audios, pictures, videos etc.) can be offered and the complexity can be reduced by using easy language for example. Hence, learning processes can be designed to address the students' individual specific needs, to reduce barriers and/or challenges in order to provide access to experiments. In this way, the stigmatizations of students can be reduced if not avoided by not using any extra devices [33]. Therefore, tablets, as gadgets, have the potential to fulfill the students'

right to participate in (science) education, and the right to equity in physics teaching and learning, i.e., to support the physics education for all students. In addition, the stigmatizations of students could be avoided by using tablets and not any extra devices [33].

5.4. The research project

For this research special digital books (e-books) for mentally disabled students were designed. During the design, both the theoretical and the individual learning preconditions were considered. All e-books followed the four dimensions of accessibility (perceiving, operating, understanding and technical usability) [34], the design principles for multimedia applications like segmentation principle, consistency principle, signaling principle, spatial and temporal contiguity principle, multimedia principle [35] as well as the principles of Universal Design for Learning (UDL) provide multiple means of "engagement", "representation", and "action and expression" [36].

Every student got an individualized e-book with working instructions for hand-on-experiments (see Fig. 11). The students were filmed and the didactical intervention was examined. For that the students' ability of doing science, i.e., to experiment and, therefore, to participate in science education, was analyzed on the base of a coding manual.

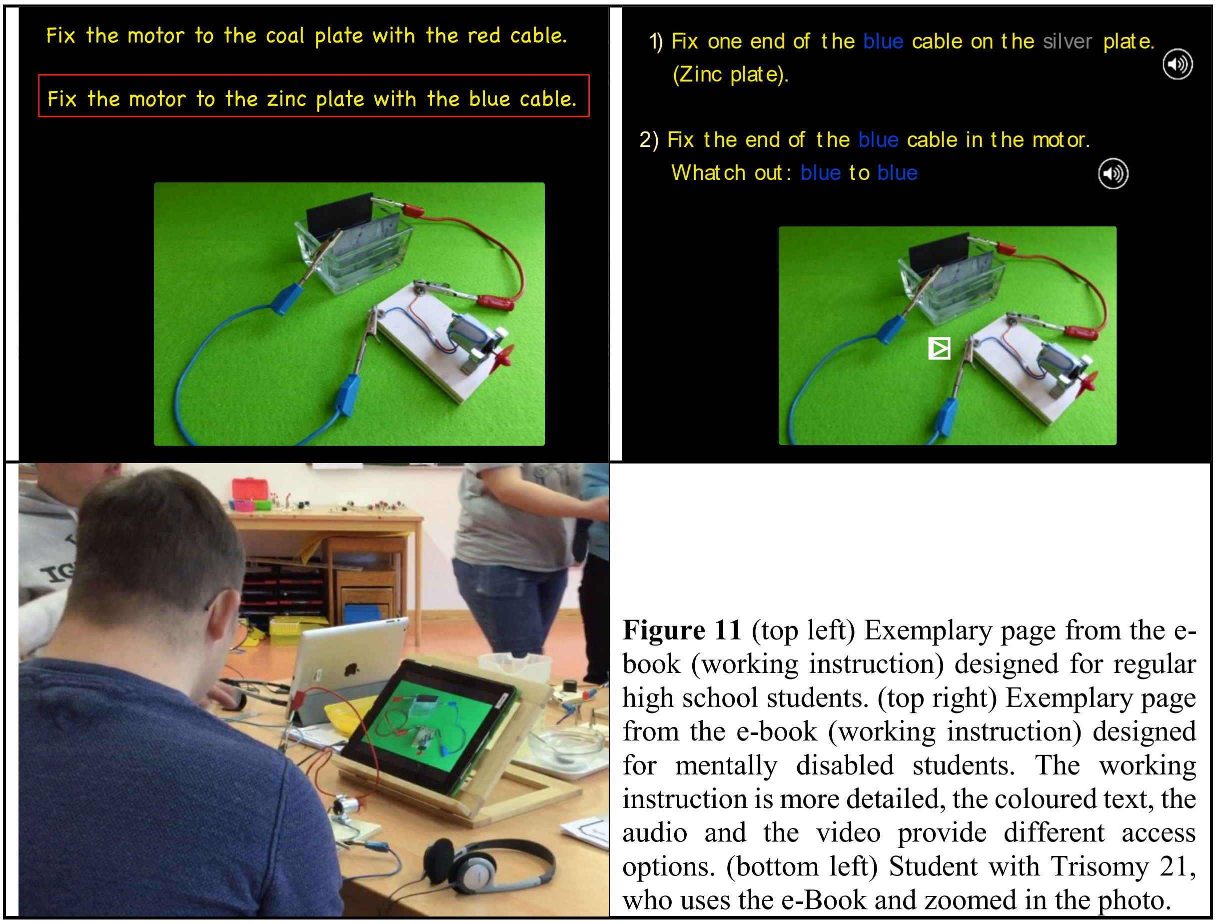

Figure 11 (top left) Exemplary page from the e-book (working instruction) designed for regular high school students. (top right) Exemplary page from the e-book (working instruction) designed for mentally disabled students. The working instruction is more detailed, the coloured text, the audio and the video provide different access options. (bottom left) Student with Trisomy 21, who uses the e-Book and zoomed in the photo.

The first preliminary results point out that students with mental disabilities:

- have fewer barriers when learning with tablets due to the fact that they require less help from teachers to understand the learning task;
- need to be engaged with multi-sensory experiences through balanced multi-media designs to find an access to the current experiment, scientific issue and content;

- switch independently between multiple access options (audios, pictures, videos, font) instead of asking for help and are sensitized to look for specific help to compensate possible weaknesses;
- benefit from as much opportunities as possible to interact directly with scientific materials;
- benefit from the photos in the e-books, which are attributed to enable the students to get the required equipment, tools and materials by themselves;
- experiment significant more independently, i.e., implement experimental plans and build experiments accordingly to experiment with instructions in the e-book;
- get the opportunity to make a start to vary given variables (some add variation possibilities independently) and minimize experimental errors by themselves, because the tablets decrease their cognitive load;
- are actively engaged, because they can work at their own pace, can replay their videos as often as they need or capture the screen, which is helpful, especially for those students who need more support;
- occupy themselves at their own specific level with the topic thanks to adjusted e-books and are able to acquire or rather increase their (first) physical knowledge and/or their processes and procedures of doing science.

Therefore, the use of tablets in science education can combine "minimizing barriers", "doing science" and "enabling participation" for all students. Enabling participation implies giving students a chance to co-determine the choice of contents and to consider their individual ideas, interests or abilities as fruitful. Since each individual person develops different interests and motivations, inclusive pedagogy should address a wide range of contexts and methods to which the students can relate.

To realize "science for all" or inclusive science education should impart scientific literacy with regard to the educational needs of each student. Science for all can only be achieved when both - the inclusive and the scientific perspective- are taken into consideration. However, inclusive science teaching and learning is more than just the sum of individual perspectives.

By presenting the results of this research other educators and researches should be encouraged to start thinking about inclusive science education from two perspectives to tailor the few existing concepts individually to the students in order to reduce and eliminate the still existing exclusion. More research could provide important information on how learning could be facilitated and maximized for those students and how they could take a greater part in the scientific learning community.

6. Summary

The challenges of the 21st century require physics teachers to develop novel experiments and demonstrations. In this paper four such different classroom experiments have been described.

In some way, all of them is an interpretation of the so called Model of Educational Reconstruction (MER). A key feature of the model according to R. Duit et al. [37] is that "science subject matter issues as well as student learning needs and capabilities have to be given equal attention in attempts to improve the quality of teaching and learning". The first component of the model is the clarification of subject matter and analysis of its educational significance, the second is the research on teaching and learning, and the third component is the design of instructional materials, learning activities, and teaching and learning sequences. In this paper, four examples of how to teach new physics materials were gathered, and all have a common feature that physics experiments are involved. The instructional materials were designed to address students of different age abilities.

In Section 2, it was shown how slow speed cameras can be utilized in order to visualize physical phenomena occurring on very small timescales. The proposed spectacular method was shown to be capable of greatly increasing student engagement. Section 3 described a thermoacoustic experiment that proved ideal for teaching heat engines and heat pumps thus addressing the core physics of green energy applications. In Section 4, the classical rotation balance experiment of Eötvös was revisited by using modern technologies. It has now become an excellent activity for experimental project work or physics competitions. Finally, Section 5 introduced a method of using tablets in order to provide opportunities for students with special needs to conduct simple physics experiments. It was shown that the method was helpful in reducing the barriers these students face and to increase their engagement.

In summary, we believe that the experiments and demonstrations described above will stimulate further development of the experimental toolbox of secondary and university physics teachers. We also hope that these experiments and demonstrations will inspire secondary physics teachers and university instructors to consider how novel technologies can be incorporated in physics education to make physics learning more meaningful, authentic, and engaging for all students.

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7. References

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