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The Post-Instruction Conceptions about Conservation of Mechanical Energy: Findings from a Survey research with High School and University Students

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ABSTRACT
In this study, our aim was to identify high school and university students' post-instruction conceptions about the law of conservation of mechanical energy (LCME). A cross-sectional survey design was used. Firstly, a test consisting of 14 multiple-choice questions was developed. 23 physics teachers analysed the test and concluded that our questions are useful for measuring understanding about the LCME. Next, the test was administered to a convenient sample of high school and university students who had already received conventional instruction about the energy concept. The sample consisted of 138 students from the University of Zagreb (Croatia), and 115 high school students from two different schools in Sarajevo (Bosnia and Herzegovina). While the distribution of item difficulties was good, the reliability of test scores proved to be barely acceptable. Therefore, we primarily focused on analysing how frequently the students chose the individual distractors and drew corresponding conclusions about students' conceptions. It has been shown that many students associate conservation of mechanical energy with certain surface features of physical problems (e.g., "pulley problems"), instead of reasoning about the processes a chosen system undergoes over time. Students often believe that mechanical energy is conserved even for phenomena in which air resistance cannot be neglected. Similarly, they sometimes do not recognize that most collisions of everyday objects necessarily include the conversion of mechanical energy into thermal energy. We could conclude that many students from all educational levels in Bosnia and Herzegovina and Croatia still fail to apply a system-based approach to energy analysis.

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Introduction

The concept of energy has an important role in the development of students' conceptual frameworks in science (National Research Council, 2012). However, for students energy is a complex concept even after years of learning about the topic (Herrmann-Abell & DeBoer, 2018; Neumann et al., 2013). Research about students' conceptions of energy shows that many students have significant difficulties with a wide range of topics concerning energy and work in general (Seeley et al., 2019; Van Huis & Van den Berg, 1993). For example, students often do not understand the relationship between energy and work and do not see the connection between work being done on a body and an increase in its kinetic energy (Topalsan & Bayram, 2019; Bryce & MacMillan, 2009; Lawson & McDermott, 1987). Students also struggle with energy degradation and conservation (Chen et al., 2014; Goldring & Osborne, 1994; Liu & McKeough, 2005; Neumann et al., 2013). Research by Lee and Liu (2010) has shown that students find forms of energy easiest to understand, energy transfers are more difficult, and understanding of conservation of energy is the most difficult. In fact, only very few students have a deeper understanding of energy conservation at the time they finish secondary school (Herrmann-Abell & DeBoer, 2018).

A possible source of students' difficulties with learning the energy concept is that some students seem to mix the term energy with other concepts, for example, force or momentum (Bryce & MacMillan, 2009; Duit, 1981). On the other hand, reasoning about the conservation of mechanical energy also includes reasoning about forces acting on and within the system (Samsudin et al., 2021). In fact, according to the law of conservation of mechanical energy (LCME), the mechanical energy of a system is conserved if the work done on the system by external forces, as well as the work done by internal non-conservative forces is zero. Therefore, for successful application of the conservation law, students are expected to correctly categorize forces (e.g., internal-external, conservative - non-conservative) and understand the implications if any of these forces perform work. However, this "forces approach" to energy analysis is regarded as complex. Concretely, many students struggle with identifying forces doing work on the system, or with identification and categorization of the system as isolated or non-isolated (Jewett, 2008). In addition, our earlier research that included 441 high school students from Bosnia and Herzegovina showed that only a few students were able to identify internal/external or conservative/non-conservative forces in the described physical situations (Halilovic et al., 2021a). This finding could be related to the fact that the students failed to develop a basic understanding of the crosscutting concept of a physical system (Seeley et al., 2019; Van Heuvelen & Zou, 2001). Indeed, the categorization of forces into internal or external forces largely depends on the choice of the physical system. In addition, students are often not aware of the fact that choosing a physical system has a role in defining an isolated system (Grimellini-Tomasini et al., 1993; Lindsey et al., 2012).

Besides defining systems, another important aspect of energy analysis is determining a time interval in which we observe the system. Research by Van Heuvelen and Zou (2001) with university students pointed out that while observing what happens with energy, the situation can change drastically as the timeline of an observed process changes. Similar results were obtained in the research with secondary students by Papadouris and Constantinou (2016). That is why reasoning about the conservation of mechanical energy should also include consideration of the temporal evolution of a system, i.e. about the processes that happen between the initial and final state of the system.

Conventional teaching approaches, particularly at the high school level, often do pay not sufficient attention to system choice (Papadouris, et al., 2014) and analysing system evolution over time (Halilovic et al., 2021a). In fact, in many textbooks, (e.g., Abasbegovic & Musemic, 2012; Colic, 2001; Crundell et al., 2014; Kulisic, 2005; Sang et al., 2012) mathematical approach to the analysis of simple energy problems of isolated objects prevails, and it seems that students are expected to develop "a feeling" about LCME applicability by mere solving of a large number of traditional, quantitative problems. In such an approach even high-achieving students often learn by rote memorization about situations in which LCME may be applied. For example, they memorize that LCME may be applied for connecting different oscillatory states of a simple pendulum, without understanding that this is only possible because the perpendicular tension force performs zero work. They develop similar "rule-of-the thumb" knowledge for other situations typically encountered in introductory physics courses (e.g., the motion of an object along an incline or motion of an object attached to a spring). However, students typically fail to develop a deeper understanding of LCME which makes them struggle with problems that minimally differ from the standard textbook problems.

We can conclude that in earlier LCME educational research, the authors mainly studied: students' ideas about the importance of system choice (Papadouris, et al., 2014; Seeley et al., 2019; Van

Heuvelen & Zou, 2001), how the energy transformation approach compares to the system-based approach (Duit, 2014; Fortus et al., 2019), how analysis of physical processes helps the students to correctly apply LCME (Papadouris & Constantinou, 2016) and how conservation of mechanical energy may be affected by the time evolution of the system (Papadouris & Constantinou, 2016; Solbes et al., 2009; Van Heuvelen & Zou, 2001). Thereby, it has been found that a systematic approach to energy analysis is very important for developing students' understanding of LCME. However, to the best of our knowledge, in only a small number of studies, the researchers investigated students' combined reasoning about *both*, the system and time interval choice, in the application of LCME (Papadouris & Constantinou, 2016; Solbes et al., 2009; Van Heuvelen & Zou, 2001). Moreover, none of these studies provided an overview of post-instruction conceptions about LCME for students from different educational levels. Finally, the studies only rarely included an analysis of a wide spectrum of physical situations that would reflect well the typical introductory physics curriculum (e.g., various types of forces, forces that perform zero or non-zero work, various real-life contexts). Taking into account that educational phenomena are context-sensitive (Radford & Sabena, 2015; Redish, 2004), it is recommended to explore how students from a wider range of educational contexts reason about LCME.

The research presented in this paper is potentially significant because it helps answer the question of whether combined reasoning about system and time interval choice in LCME application may be implicitly developed in an educational setting which is primarily characterized by solving a large number of traditional, quantitative problems. Such an educational setting is still very prevalent in many physics classrooms in Croatia and Bosnia and Herzegovina and there is not sufficient information on its effectiveness when it comes to developing an understanding of LCME.

Research Aim

For developing a more effective approach to teaching about the energy concept, it is very important to first gain insight into students' reasoning about LCME for a wide range of physical situations. The aim of this research was to explore the high school and university students' post-instruction conceptions about the law of conservation of mechanical energy, in Croatia and Bosnia and Herzegovina. Particularly, we wanted to answer the following research question:

What are the high school and university students' post-instruction conceptions about the law of conservation of mechanical energy, in Croatia and Bosnia and Herzegovina?

This research question was further divided into the following sub-questions:

1) What are the students' post-instruction conceptions about some basic aspects of reasoning about conservation of mechanical energy, such as: energy forms, energy transformation and mechanical work?
2) What are the students' post-instruction conceptions on how system choice may affect the conservation of mechanical energy?
3) What are the students' post-instruction conceptions on how the temporal evolution of the system may affect the conservation of mechanical energy?
4) What are the students' post-instruction conceptions on how *both* the system choice *and* temporal evolution of the system may affect the conservation of mechanical energy?

This research is expected to shed further light on the outcomes of the conventional approach to energy analysis, at the high school as well as at the university level in Croatia and Bosnia and Herzegovina. Consequently, the findings from this research may lay the foundation for the systematic revisiting of the approach to high school and university learning about energy in these two countries. It is also expected that this research will contribute to the current literature by deepening our understanding of students' combined reasoning about system and time interval choice in applying LCME within the context of a wide spectrum of situations that are typically encountered in introductory physics courses. Also, it will provide us deeper insight into the outcomes of energy instruction that is mainly based on solving a large number of traditional, quantitative problems. Finally, as far as we know, currently, there are no research-based instruments specifically designed for measuring students' conceptual understanding of LCME. Therefore, the LCME instrument presented in this paper may be a significant contribution to the physics education community.

Methods

Design of the Study

For purposes of fulfilling the research aim, we decided to follow the quantitative research paradigm and implement a cross-sectional survey design. Firstly, an instrument that probes into students' conceptual understanding of conservation of mechanical energy has been developed and corresponding validity evidence has been gathered. Next, samples of high school and university students who had already received conventional instruction about the conservation of mechanical energy were selected. These samples were administered the conceptual test in an online environment. They were given 45 minutes to solve the test. The students were required to have their cameras and microphones switched on while solving the test.

The students' answers to all questions were entered into a database and statistically analysed. The frequency of distractor occurrences for each question were calculated. For purposes of further discussion of research findings, the items were grouped into four categories/themes, depending on what the items assess:

1) Basic aspects of the law of conservation of mechanical energy – energy types, transformations and work
2) For what system choice is the mechanical energy conserved (time interval is given)?
3) For what time interval is the energy conserved (system choice is given)?
4) For what system choice and time interval is the mechanical energy conserved?

Finally, a discussion of high school and university students' post-instruction conceptions related to the four abovementioned themes (i.e., categories of items) could be provided, based on the observed distractor frequencies.

Student Sample

In this study, the population of interest consisted of high school and university students from Bosnia and Herzegovina and Croatia who had already received instruction about the conservation of mechanical energy at the corresponding educational level. The student sample consisted of 253 students from two different high schools in Canton Sarajevo (Bosnia and Herzegovina), and the University of Zagreb (Croatia). Such a sample composition helped us to gain certain insight into and compare the outcomes of conventional energy instruction at two educational levels, in Bosnia and Herzegovina and Croatia.

Specifically, the university group (UNIV) included a total of 138 first-year students (mostly 19-year-olds) from the Faculty of Chemical Engineering and Technology in Zagreb. In addition, we also included a total of 70 fourth year high school students from First Bosniak Gymnasium (FBG) Sarajevo, as well as 45 fourth year high school students from the Third Gymnasium (TG) Sarajevo. High school students from FBG and TG groups were mostly 18-year-olds.

The University of Zagreb is ranked 401 at the *Shanghai Academic Ranking of World Universities* and is considered to be amongst the top universities in Western Balkans. In addition, based on their students' results in physics competitions, the two sampled high schools may be considered to be of above-average quality compared to other high schools in Bosnia and Herzegovina.

Gender distribution of the student sample in all groups was as follows: in UNIV out of 138 students, 28.3 % were male, and 71.7 % female; in FBG out of 70 students, 42.9% were male, and 57.1% female; in TG out of 45, 37.8 % were male, and 62.2% female.

For purposes of strengthening the external validity of this study, in the sample of 253 students, we also included 33 students enrolled in the Cambridge International Program at the First Bosniak Gymnasium Sarajevo. These students learned about energy and conservation laws in line with the *AS/A level Physics Syllabus*, and not the national curriculum like the rest of the sampled high school students.

Characteristics of the Curriculum

In Croatia and Bosnia and Herzegovina, students start learning about the energy concept already in primary school. As part of physics instruction, they usually learn about energy when they are on average 13 years old. The main focus of energy instruction in primary school is on forms and transformations of energy, and relationships between energy, work and power. Students also learn about the law of conservation of total energy, but the textbooks typically do not promote reasoning about physical systems.

In high school, students are expected to extend their understanding of the conservation of mechanical energy in Year 1, and Year 3 if they take Physics as an elective subject. The high school curriculum shows that students in Year 1 are expected to quantitatively apply the law of conservation of mechanical energy in standard quantitative problems (Colic, 2001). In Year 3 students are supposed to learn the concepts that are important for applying the law of conservation of mechanical energy, e.g., isolated system, internal and external forces, conservative and non-conservative forces, and to use these concepts for solving work-energy and LCME problems (Abasbegovic & Musemic, 2012).

At the university level, science and engineering students typically learn again about the conservation of mechanical energy, in a mathematically more rigorous manner and with a higher emphasis on the work-energy theorem.

It is important to note that high school students from this study had learned about all different aspects of the energy concept in line with the conventional instruction in primary school, and also during the first 3 years of high school. Students from the University of Zagreb learned about energy in primary school, high school, as well as at university level. They took the test one week after learning about the concept of energy in their introductory physics course.

Assessment Instrument

In order to fulfil the research aim, we had to design a test that measures students' conceptual understanding of the mechanical energy concept with a special focus on the conservation of mechanical energy. Particularly, we wanted to test students' ability to decide whether for various situations, described in terms of system choices and time intervals, mechanical energy is conserved. To that end, we designed a 14-item long instrument. For each item, there was a single correct answer and three distracters.

We attempted to choose or design the items in a way that ensures valid coverage of typical contexts usually encountered in introductory physics courses. Concretely, we attempted to design tasks that include: different forms of energy, situations for which different types of forces are acting over time, situations where external forces are acting but the work done by these forces is zero, situations that include non-conservative forces, and situations which include different system and time interval choices.

Five items we used were the result of an adaptation of items from widely known and extensively validated surveys such as Energy and Motion Conceptual Survey (EMCS) by Singh and Rosengrant (2003), and Energy Concept Assessment (ECA) by Ding et al. (2013). Concretely, items 8, 13 and 14 were adapted from EMCS, and items 1 and 6 from ECA. The remaining 9 items were our original contribution, based on open-ended tasks we previously used in the research with upper-secondary school students from Canton Sarajevo (Halilovic et al., 2021a).

A short description of the LCME test items is provided in Appendix A. The test as a whole is available on the following web address: http://pierre.fkit.hr/~avidak/LCME.pdf.

For purposes of facilitating the discussion of survey results, we grouped the survey items into four conceptual themes that corresponded to our 4 research sub-questions: Energy forms, energy transformation and work; Conservation of mechanical energy – reasoning about system choice; Conservation of mechanical energy – reasoning about the temporal evolution of the system; Conservation of mechanical energy – *combined* reasoning about system choice and temporal evolution (Appendix B). It should be noted that we do not consider the above-mentioned conceptual themes to be mutually independent. For example, we strongly believe that some difficulties with work and energy appear as a result of students' difficulties with system reasoning, and temporal evolution of the system.

Validity and Reliability

Validity evidence for LCME score interpretations was gathered through an online survey that included 23 high school physics teachers. Concretely, for each of the 14 items, the teachers were asked whether or not the item is relevant for measuring understanding of conservation of mechanical energy, as well as whether the item is physically correct (i.e., no subject matter errors). Also, they were asked how much they like each item on a scale from 1 (not at all) to 5 (very much). Only for one item (item 1), one teacher stated that the item is not relevant for measuring conceptual understanding of conservation of mechanical energy which indicates that a large majority of teachers believed that each of the 14 items is relevant for drawing conclusions about students' understanding of conservation of mechanical energy. For another item (item 13), one teacher stated that we should emphasize that friction is neglected, although motion along a rough inclined plane was analysed in the given question. In other words, no subject matter errors were detected by the teachers. Furthermore, the average "like measure" for our conceptual items was 4.52 out of 5 points which meant that the LCME instrument items has been well received by the teachers.

The reliability of the test scores, as measured by Cronbach's alpha, amounted to .49 which is very close to the acceptable value of .5 (Bowling, 2005, p. 397). Similarly, low values of Cronbach's alpha have been already obtained for other well-known instruments (McKagan, et al., 2010). When the reliability of test scores is low, one has to be careful with the interpretation of summed scores (Liu, 2010) and it is recommended to base the interpretation of results on findings on individual items. In other words, a low-reliability value does not compromise the power of an instrument to diagnose students' misconceptions and gain insight into their conceptual understanding, in general.

Survey Procedures

The survey has been administered to students in November 2020 in Sarajevo, Bosnia and Herzegovina, and in December 2020 in Zagreb, Croatia. Testing took place during COVID pandemics. At that time, in both countries schooling was moved to an online environment. Therefore, we also had to administer our conceptual test in an online environment. Concretely, a Google Meet video call was organized. At the beginning of the class, students were given access to the test via a Google Form link. We have used an option of random question assignment, and students could not go back to particular questions once they submitted the answer. Once the class ended (after 45 minutes), access to the link was locked and we did not allow any late submissions. Furthermore, in order to increase the quality of our measurement, testing took place with switched-on cameras. The teacher gave students an explanation about testing purposes and pointed out that the results of testing would have no effect on their final grades.

Data Analysis Procedure

Students' answers for each of the test items were entered into a database. Then, for each item, we determined how often each of the answering options has been chosen by the students. For purposes of calculating Cronbach's alpha, the database has been re-coded: each correct answer was coded as "1" and each incorrect answer as "0". However, considering that Cronbach's alpha proved to be barely acceptable, we avoided constructing summed scores but decided to answer our research question by conducting and combining analyses at the level of *individual* items.

Results

The percentages of correct answers on individual LCME items are given in Table 1.

Table 1

The Percentages of Correct Answers on Individual LCME Items

Group	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7
UNIV	37.0%	29.7%	35.5%	34.8%	18.1%	74.6%	38.4%
FBG	31.4%	22.9%	25.7%	48.6%	30.0%	58.6%	30.0%
TG	24.4%	31.1%	35.6%	35.6%	26.7%	53.3%	28.9%
TOTAL	33.2%	28.1%	32.8%	38.7%	22.9%	66.4%	34.4%
Group	Item 8	Item 9	Item 10	Item 11	Item 12	Item 13	Item 14
UNIV	44.2%	55.1%	21.0%	24.6%	47.8%	45.7%	52.2%
FBG	25.7%	42.9%	15.7%	18.6%	55.7%	35.7%	22.9%
TG	26.7%	33.3%	20.0%	20.0%	33.3%	53.3%	20.0%
TOTAL	36.0%	47.8%	19.4%	22.1%	47.4%	44.3%	38.3%

From Table 1 it is evident that item difficulty indices for all but one item were in the recommended interval between 0.2 and 0.8 (Cohen & Swerdlik, 2010). Specific difficulties with reasoning about LCME may be detected through an analysis of distractors. Information about the most frequently chosen distractors is given in Table 2.

Table 2

Most Frequently Chosen Distractors for Individual LCME Items

Group	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7
UNIV	A (39%)	B (30%)	C (37%)	D (28%)	C (41%)	B (17%)	C (36%)
FBG	A&B (24%)	A (34%)	C (40%)	C (29%)	C (27%)	B (29%)	A (34%)
TG	A (47%)	A (44%)	C (31%)	C (36%)	A &C (27%)	B (33%)	C (36%)
TOTAL	A (36%)	A (34%)	C (37%)	C (27%)	C (34%)	B (23%)	C (32%)
Group	Item 8	Item 9	Item 10	Item 11	Item 12	Item 13	Item 14
UNIV	D (23%)	C (17%)	C (33%)	C (34%)	C (25%)	C (30%)	A (23%)
FBG	D (37%)	D (21%)	C (33%)	D (29%)	C (20%)	D (30%)	C (40%)
TG	B (33%)	D (29%)	C (33%)	D (33%)	D (27%)	C (18%)	C (47%)
TOTAL	D (27%)	D (20%)	C (33%)	C (29%)	C (23%)	C (23%)	C (30%)

From Table 2 it is evident that many distractors have been chosen by more than 30% of students.

A more detailed insight into how students from different groups answered questions related to the four different conceptual themes (corresponding to the four research sub-questions) is provided through diagrams from figures 1-5. These diagrams show what percentage of students from the three student groups (UNIV, FBG, TG) chose each of the answering options (A–D) from the conceptual questions at hand. Figures 1 and 2 are related to students' post-instruction conceptions about types of energy, energy transformations and work.

Figure 1

The Students' Ideas about Energy Forms (Items 1, 6); Percentages of Students Who Chose Individual Answering Options Are Presented

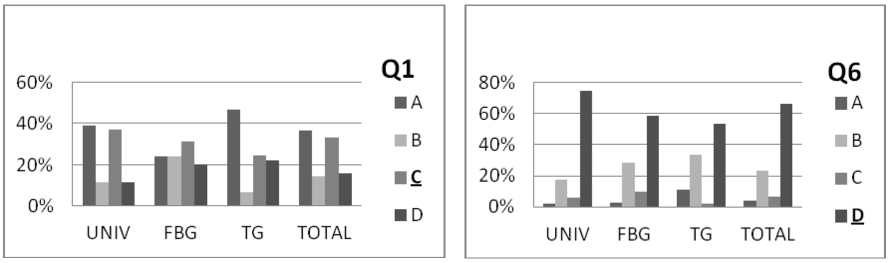


Figure 2

The Students' Ideas about the Concept of Work and Its Relation to Energy (Items 8, 13, 14); Percentages of Students Who Chose Individual Answering Options Are Presented

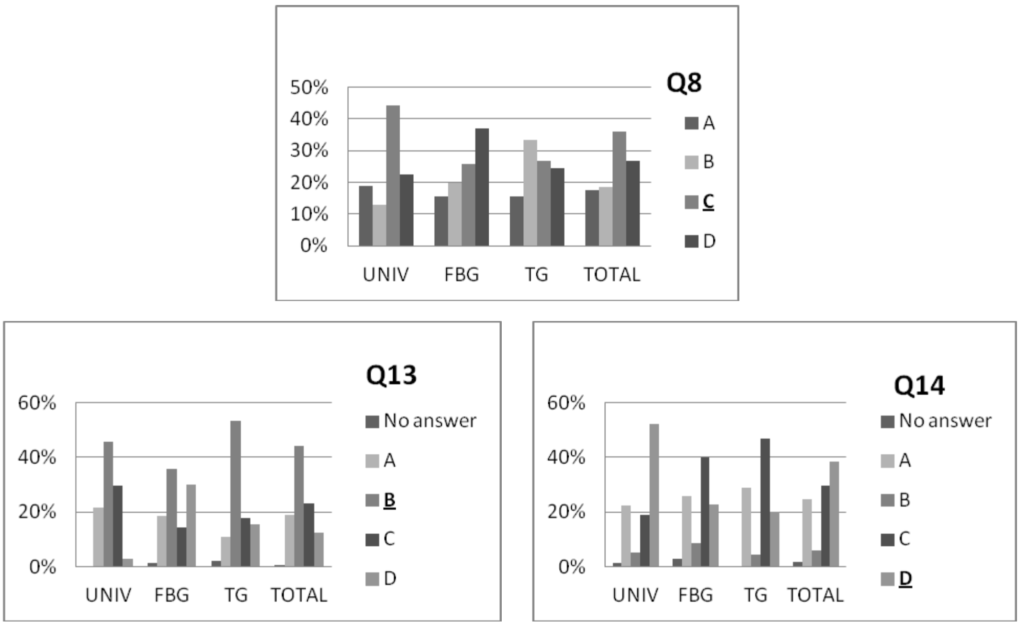


Figure 3 allows insight into students' ideas related to the effect of system choice on the conservation of mechanical energy.

Figure 3

The students' Ideas on Conservation of Mechanical Energy for Different Systems (Items 2, 3, 5, 12); Percentages of Students Who Chose Individual Answering Options Are Presented

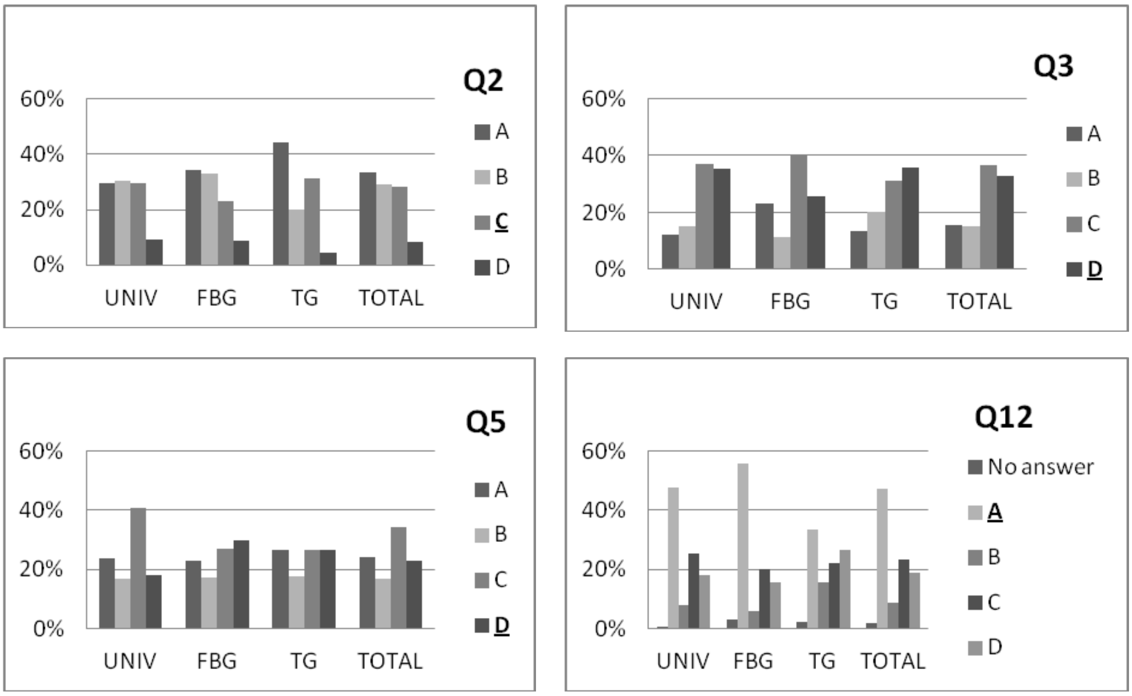
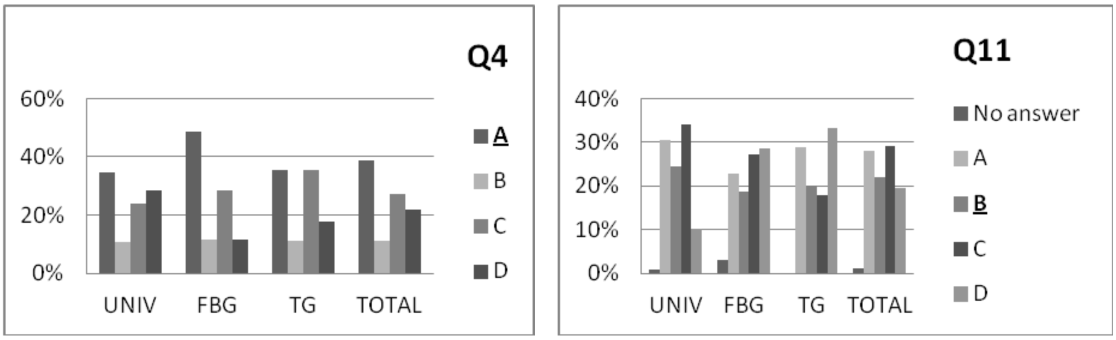


Figure 4 shows how students answered questions in which they had to reason how the temporal evolution of a system may affect the conservation of mechanical energy.

Figure 4

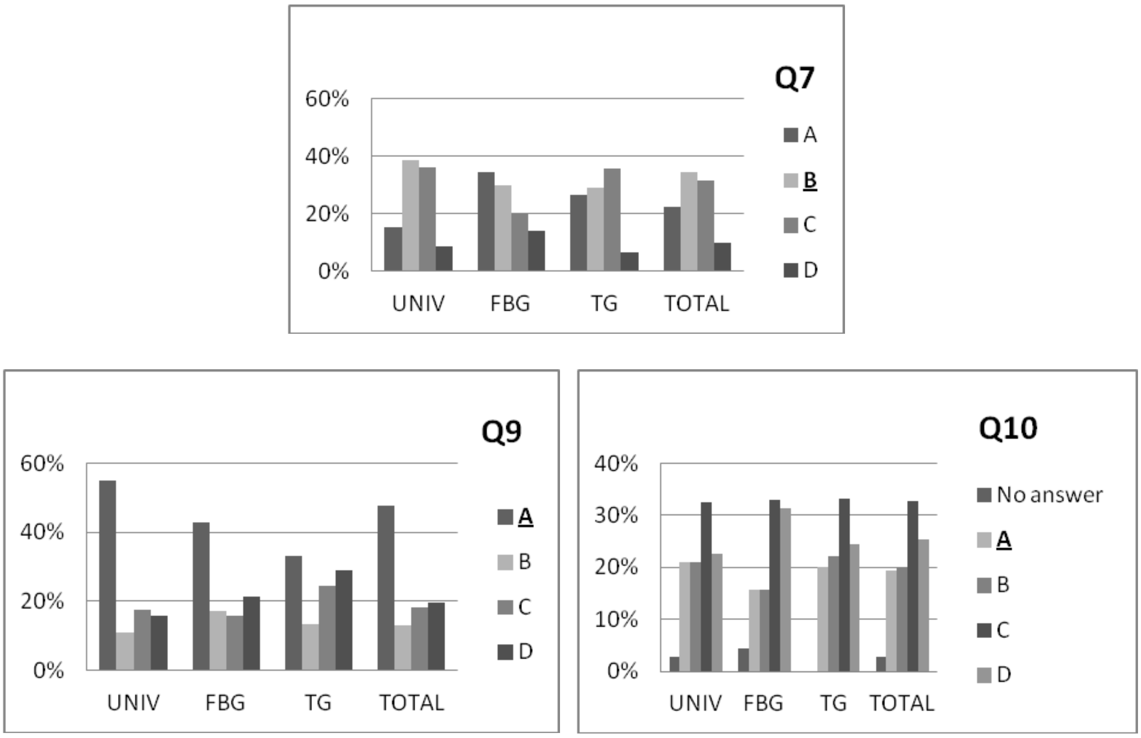
The Students' Ideas about Conservation of Mechanical Energy over Time (Items 4, 11); Percentages of Students Who Chose Individual Answering Options Are Presented



Finally, Figure 5 shows how students answered questions that required them to combine thinking about system choice *and* time interval for which mechanical energy is or is not conserved.

Figure 5

The Students' Ideas about Conservation of Mechanical Energy for Different Systems and Time Intervals (Items 7, 9, 10); Percentages of Students Who Chose Individual Answering Options Are Presented



Please note that because initial analyses showed similar answering patterns for all students from FBG (national and Cambridge International Program), we decided to provide a single analysis for the FBG group which holds equally for both curricula.

Discussion

Generally, the LCME items proved to be demanding for our sample of students which is in line with the expectation that conventional energy instruction in Bosnia and Herzegovina and Croatia result in non-functional knowledge of LCME. In fact, the situations covered in the items did not resemble typical textbook problems and thus could not be solved by rote remembering. Thus, our findings support the idea that solving a large number of standard, quantitative problems is not effective for developing deep conceptual understanding (Kim & Pak, 2002) or competencies needed for real-life problem solving (Bryce & MacMillan, 2009).

Next, it is interesting to note that for many test items the most frequently chosen distractor was the same for all three student groups. Also, for 7 out of 14 items the most frequently chosen distractor has been chosen by at least 30% of students. The presented findings indicate that many LCME questions include powerful distractors which are very successful in identifying students' common difficulties with the law of conservation of mechanical energy. These difficulties will be discussed within the context of four conceptual themes and the discussion will be based on diagrams shown in Figures 1–5.

Energy Forms, Energy Transformation and Work

In item 1, students were expected to reason about the total kinetic energy of a system consisting of only two objects with the same mass m and velocity v, but moving in opposite directions. The correct answer is that the kinetic energy of the system is simply a sum of the kinetic energies of the two objects. Taking into account that kinetic energy is always positive, the sum amounts to mv^2. The most frequently chosen distractor was A (36.4%), which reflects the belief that the kinetic energies of the two objects moving in opposite directions simply cancel out. In other words, the students added the two kinetic energies of the two objects but assumed them to have opposite signs because the objects moved in opposite directions.

In item 6, an object that oscillates on an elastic spring is observed, and it is pointed out that the system has kinetic energy, gravitational potential energy and elastic potential energy. The students were expected to answer for what system choice these types of energy forms could be observed. In fact, these energy forms may be only observed for a system consisting of an object, Earth and spring. Many students, particularly from the university level, answered this question correctly. Concretely, for item 6 the largest percentage of correct answers was detected. However, a considerable percentage of students from all groups answered that the system consists of the object and the spring (23.3%), which reflects the misconception that an object may have gravitational potential energy on its own, even when the other object (here Earth) is not included in the system Earlier this misconception has been also observed by Lindsey et al (2009). In our study, the misconception was detected for almost one-third of all high school students, as well as for 17.4% of university students.

In item 8, students were shown a satellite orbiting around the Earth with constant speed. They were expected to reason about the work performed by the gravitational force on the satellite, as it moves from point A to point B of the circular orbit. The correct answer is that the gravitational force (centripetal force) is perpendicular to the displacement vector for all positions of the satellite, which means that the work performed by this force is zero. The most frequently chosen distractor for item 8 was D (26.9%), which reflects the belief that gravitational potential energy increases as the satellite moves between two points of the circular orbit. However, we know that the satellite may only have gravitational potential energy if the system consists of satellite and Earth. In addition, we know that kinetic energy is constant (satellite speed is assumed to be constant), that there are no external forces doing work on the system, and that there are no internal non-conservative forces. Consequently, the mechanical energy of the system is conserved during the motion of the satellite between the given points, which means that gravitational potential energy does not change.

In item 13 students were expected to compare the work that has to be performed for raising an object to height h by pulling it vertically upwards or by pulling it along a rough incline. From the work-energy theorem, we can state that for a smooth incline the performed work would be exactly equal to an increase of gravitational potential energy (system: object-Earth). In other words, if the incline were smooth, the performed work would be the same for the two described methods of raising the height. However, for a rough incline, as we pull the object along the incline, mechanical energy is continuously converted to thermal energy, due to the work done by the friction force. Consequently, more pulling work has to be done than for the smooth incline if we in both situations want to raise the object to the same final height h. That is why more pulling work is done in the situation with the rough incline than in the situation where we pull the object vertically upwards. The most frequently chosen distractor for item 13 was C (23.3%), which reflects the belief that less work is done when pulling the object along the incline than pulling it vertically upwards. That could be accounted for by the fact that many students mix the concepts of force and perform work. For example, using an incline typically allows us to act with a smaller pulling force, but at the same time, the distance through which this force acts becomes larger. In some earlier studies, it has been already found that students mix the energy concept with other concepts, such as the concept of force (Duit, 2014). Students also often use force ideas when describing energy changes (Fortus et al, 2019).

In item 14, the students were shown two smooth playground slides of the same height, but different shapes. The students were expected to compare the speeds one would have at the mere bottom of these slides. If we assume the system to consist of the person and Earth, then the only external force that would act on the system is the normal force between the person and the slide. However, the whole time this force is perpendicular to the displacement vector and consequently the work done by this force is zero. Therefore, mechanical energy is conserved for the person's motion down the slide. Because initial and final heights are the same (top of slide and bottom of slide), the increase in kinetic energy is the same for both slides. The most frequently chosen distractor was C (e.g., in FBG and TG chosen by even 40% and 47% of students, respectively). Although it has been pointed out that the slide is smooth, probably the everyday context of the item activated in many students intuitive mental models led them to the conclusion that mechanical energy is less dissipated if we slide down a shorter slide.

Conservation of Mechanical Energy – Reasoning about System Choice

In 4 out of 14 items, the students were presented with physical situations that involved various objects and they were expected to identify systems for which mechanical energy is or is not conserved for a given interval of time. Three items were situated within the context of a falling rubber ball, and one item was situated within the context of a block sliding down a smooth incline. It is useful to note that these contexts are often described in standard physics textbooks (see e.g., Abasbegovic & Musemic, 2012; Colic, 2001; Crundell, et al., 2014; Kulisic, 2005; Sang, et al., 2012).

In item 2 the students were presented with a situation in which a rubber ball is falling (assumption: air resistance is negligible). The observed time interval was from the instant the ball started falling until the instant just before it hits the ground. Students were expected to identify a system for which mechanical energy is conserved for the given interval of time. The correct answer is that mechanical energy is conserved for the system ball-Earth, because there are neither dissipative forces nor external forces that are doing work on such a system. However, this simple question has been correctly answered by only 28.1% of students. For high school students the most frequently chosen distractor was A which stated that conservation of mechanical energy holds for the system consisting only of the ball, as well as for the system ball-Earth. This result is consistent with previous research findings that some students believe that the energy of a system always remains constant (Lindsey et al., 2012; Thomas & Schwenz, 1998). However, when the system consists only of the ball then there is an external force (gravitational force) that performs work on the system and mechanical energy is not conserved. A system consisting only of the ball was the most popular choice amongst university students.

In item 3 the same situation and time interval are observed, with the only difference that now it is pointed out that air resistance cannot be neglected. Taking into account that in this situation there is air resistance acting on the ball, mechanical energy is converted into thermal energy for any choice of the system. However, only 32.8% of students provided a correct answer. The most frequently chosen distractor was C (36.8%), which reflects the belief that mechanical energy is conserved for the system ball-Earth. This could indicate that many university students from our sample have difficulties with the mere concept of mechanical energy and probably they mixed it with the concept of energy, in general. In fact, energy in general (including all forms of energy) is conserved for the system ball-Earth, including the Earth's atmosphere, but mechanical energy is not because internal thermal energy is increasing as the ball is falling through the air. An alternative explanation is that many students are simply not aware of the fact that nearly all collisions of everyday objects include the conversion of some mechanical energy into heat.

In item 5, again the falling rubber ball is considered with air resistance being negligible. However, now we observe the time interval from the instant the ball starts falling until the instant it comes to rest after having hit the ground. Taking into account that this time interval also includes the ball's collision with the ground which results in mechanical energy being converted to internal thermal energy, the mechanical energy is not conserved or for the ball nor for the ball-Earth system, because it is not realistic to assume that the ball-ground collision is ideally elastic. However, this has been recognized by only 22.9% of students. The most frequently chosen distractor was C (34.4 %), which similarly in item 3 indicates that many students mix mechanical energy with energy in general, and consider it to be conserved for the ball-Earth system. From items 3 and 5, it is evident that even many university students do not understand the effects of non-conservative forces on systems' mechanical energy, at least in the context of collisions and air resistance.

Finally, in item 12 students were presented with a situation in which a block may slide down a rough or smooth incline. The students were expected to recognize that mechanical energy is conserved for the system consisting of Earth, block and smooth incline, but not for the rough incline. It is interesting to note that in this context more students chose the correct answer than in item 5 which also included reasoning about non-conservative forces. A possible explanation is that in conventional energy instruction the context of a smooth incline is very often analysed (Bryce & MacMillan, 2009), unlike contexts that involve impact forces.

Conservation of Mechanical Energy – Reasoning about the Temporal Evolution of the System

In two items the students were presented with physical situations which involved various objects and they were expected to identify time intervals for which mechanical energy of the given systems is conserved.

In item 4 students were again presented with the falling rubber ball, with air resistance being negligible. However, this time the choice of the system was explicitly specified; it consisted of ball and Earth. The students were expected to identify the time interval for which mechanical energy is conserved. Evidently, this item was very similar to item 2, and the correct answer is that mechanical energy is conserved between the instant the ball starts falling and the instant just before it hits the ground. The most frequently chosen distractor was C (27.3%), which includes a time interval from the instant the ball starts falling until the instant the ball just starts rising after having hit the ground. Taking into account that this time interval includes the ball's collision with the ground, this again indicates that many students from all educational levels believe that impacts do not result in the conversion of mechanical energy into internal thermal energy.

In question 11 the students were presented with a large and a small block connected with a massless string over a frictionless, massless pulley. The large block is falling, and after it hits the ground the small block continues rising until it reaches maximum height. The system was assumed to consist of the small block and Earth, and students were expected to identify a time interval for which mechanical energy of the system is conserved. It should be noted that the mechanical energy of the given system is conserved between the instant just after the big block collided with the ground (i.e., after collision already happened) until the instant the smaller block reaches its maximum height. In fact, during that interval, neither non-conservative forces are acting on the system (e.g. no impact, no friction), nor external forces doing work on the system. This answer has been chosen by only 22.1% of students. The most frequently chosen distractor was C (29.2%), which indicates the belief that for the given system (small block-Earth) the mechanical energy is conserved from the instant the large block starts falling until the instant the small block reaches its maximum height. However, this cannot be considered correct because during that interval there is an external force (i.e., the tension in the string) doing work on the small block, and there is also a conversion of mechanical energy into internal thermal energy during the collision of the large block with the ground. Probably, the students generally remembered that they used to apply LCME with "pulley problems", but this research showed that they do not have a deep understanding of the matter. In fact, a slight change of the system from "both blocks-Earth" (implicitly taken in conventional instruction) to "small block-Earth" made the students struggle with reasoning about the conservation of mechanical energy in the pulley context. This finding is in line with the fact that novices often categorize problems based on their literal, surface features (e.g., "pulley problems", "incline problems", etc.) (Chi, et al., 1981). Recently, Chen et al (2020) found that the primary problem-solving strategies of novices often rely on memorized fragments that are based on problems' surface features.

Conservation of Mechanical Energy – Combined Reasoning about System Choice and Temporal Evolution

In 3 out of 14 items, the students were presented with physical situations that involved various objects and they were expected to identify both, systems as well as time intervals, for which mechanical energy is or is not conserved.

In item 7 students were expected to reason about a stone that is falling towards the ground, with air resistance being negligible. Concretely, they were asked to identify a system and time interval for which mechanical energy is conserved. The correct answer is that mechanical energy is conserved for the stone-Earth system from the instant the stone starts falling until the instant just before it hits the ground. In that case, there are neither dissipative forces nor work performed by external forces. However, many students chose distractor C (31.6%) which reflects the belief that mechanical energy is conserved for the stone-Earth system for the whole time interval from the instant the stone starts falling until the instant it comes to rest after having hit the ground. This answer is very similar to the answer we already discussed for items 5 and 11. Again, the students do not realize that stone-ground collision involves the conversion of mechanical energy into heat, although this collision is clearly inelastic.

In items 9 and 10 students were shown an object that is initially at rest on a compressed, massless spring. At some instant, the spring is released. Eventually, the object is ejected from the spring in the vertical direction and after some time it reaches its maximum height. All friction forces, including air resistance, were considered negligible for both items.

In question 9 the students were expected to identify a system and time interval for which the mechanical energy is conserved. The correct answer is that mechanical energy is conserved for a system consisting of the object, spring and Earth for the whole time interval in which the object is in contact with the spring. In fact, for such a choice of the system and time interval, there are neither external forces performing work on the system, nor conversion of mechanical energy into thermal energy. The most frequently chosen distractor was D (19.8%) which differs from the correct answer only to the point that the system does not include the spring. However, if the system does not include the spring then there is some non-zero work performed by the external elastic force on the object.

In question 10 the same physical situation as in item 9 has been described. The only difference is that now the students were expected to identify a system and time interval for which the mechanical energy is *not* conserved. Also, some new distractors were offered in item 10 compared to item 9. When it comes to the correct answer the same discussion applies as for item 9: mechanical energy is not conserved for the object-Earth system if we observe the time interval during which the object is in contact with the spring. The most frequently chosen distractor in item 10 was D (25.3%) which says that mechanical energy is not conserved for the object-Earth system for the time interval from the instant the object leaves the spring until the instant the object reaches maximum height. However, for the chosen system and time interval there are neither external forces performing work on the system nor conversion of mechanical energy into thermal energy.

Conclusion and Implications

The conventional energy instruction relies on the idea that understanding of the LCME may be developed by letting the students solve a large number of standard, quantitative problems. These problems typically cover idealized situations that had been *initially designed to allow for* the application of LCME. Thus, students are rarely required to reason whether LCME is even applicable for certain situations, i.e., they are only rarely required to apply relevant strategic knowledge.

This study showed that both, high school and university students from Croatia and Bosnia and Herzegovina, hold deficient post-instruction conceptions about LCME, particularly when it comes to the understanding that system and time interval choices may affect the conservation of mechanical energy. Taking into account that similar difficulties were observed in high school and university students, we can conclude that simply adding more hours of conventional instruction about the energy concept cannot solve the problem of students' non-functional knowledge about LCME.

It is evident that for purposes of deciding whether mechanical energy is conserved, many students primarily rely on surface features of the described physical situations because they lack corresponding strategic knowledge about LCME. For example, many believe that mechanical energy is conserved for all situations that include a smooth incline or two objects connected over the massless pulley and that this holds true no matter what system or time interval we observe. Some students also seem to mix mechanical energy with total energy which results in the misconception that mechanical energy maybe even conserved when air resistance is not negligible and inelastic collisions are included.

It is not reasonable to expect that students will develop the necessary strategic knowledge only by solving standard, quantitative problems (Halilovic et al, 2021b). However, it is also not reasonable to expect that only teaching about basic physical principles will result in more functional knowledge (Quilici & Mayer, 1996). In fact, the application of a principle through several examples increases and facilitates the possibility of knowledge transfer (Catrambone & Holyoak, 1989; Renkl, 2011). Therefore, we advocate for a middle way approach to energy instruction. This should include developing strategic knowledge based on a systems approach to energy analysis combined with the application of this knowledge through a variety of conceptually different problem situations. Concretely, we strongly recommend developing a conceptual understanding of LCME by providing examples *and non-examples* of conservation of mechanical energy for different system and time interval choices. Providing examples and non-examples is generally known as an effective approach to developing conceptual understanding (Renkl, 2011). Generally, as learning progression in the understanding of the energy concept includes conceptions of energy forms, transformation, degradation, dissipation and conservation of energy (Herrmann-Abell & DeBoer, 2018; Neumann et al., 2013), teaching should promote learning about all of those different aspects of energy concept in a form of a learning progression framework (Jin & Anderson, 2012). Thereby, the LCME questions may be a powerful tool for diagnosing students' difficulties with the energy concept and sparking productive classroom discussions.

One possible limitation of this research is that it included only two high schools from Canton Sarajevo (Bosnia and Herzegovina) and one university from Zagreb (Croatia). This partly limits our ability to generalize the results to other high schools in Bosnia and Herzegovina, and engineering studies in Croatia. However, the external validity of our findings is strengthened by the fact that for FBG students who were taught in line with Cambridge International Program similar difficulties were detected as for other high school students from this sample. Furthermore, the university sample from Zagreb included students who finished high school all over Croatia.

Another possible limitation of this research is related to the fact that we did not conduct detailed validation studies for our LCME instrument. In addition, the reliability of the instrument proved to be relatively low for the given student sample. However, this was not a serious threat to the quality of this study because we decided to interpret the results of the study at the level of individual items.

The next step in our research will be to conduct further validation studies for our LCME instrument (e.g., collecting cognitive validity evidence through think-aloud interviews), after which the test will be administered to more high school and university students in the Western Balkans region.

References

Abasbegović, N., & Musemić, R. (2012). *Fizika za 1. razred gimnazije* [Physics textbook for the 1st year of secondary school]. Svjetlost.

Bowling, A. (2005). Techniques of questionnaire design. In A. Bowling & S. Ebrahim (Eds.), *Handbook of health research methods: Investigation, measurement and analysis* (pp. 394-428). Open University Press.

Bryce, T. G. K., & MacMillan, K. (2009). Momentum and kinetic energy: Confusable concepts in secondary school physics. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *46*(7), 739-761. https://doi.org/10.1002/tea.20274

Catrambone, R., & Holyoak, K. J. (1989). Overcoming contextual limitations on problem-solving transfer. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*(6), 1147. https://doi.org/10.1037/0278-7393.15.6.1147

Chen, R. F., Eisenkraft, A., Fortus, D., Krajcik, J., Neumann, K., Nordine, J., & Scheff, A. (Eds.). (2014). *Teaching and learning of energy in K-12 education*. Springer International Publishing.

Chen, Q., Zhu, G., Liu, Q., Han, J., Fu, Z., & Bao, L. (2020). Development of a multiple-choice problem-solving categorization test for assessment of student knowledge structure. *Physical Review Physics Education Research*, *16*(2), 020120. https://doi.org/10.1103/PhysRevPhysEducRes.16.020120

Chi, M. T., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive science*, *5*(2), 121-152. https://doi.org/10.1207/s15516709cog0502_2

Cohen R. & Swerdlik M. (2010). *Psychological testing and assessment*. McGraw-Hill Higher Education.

Čolić, A. (2001). *Fizika za 1. razred srednjih škola* [Physics textbook for the 1st year of secondary school]. Harfo-graf.

Crundell, M, Goodwin, G., & Mee, C. (2014). *Cambridge International AS and A Level Physics*. Hodder Education.

Ding, L., Chabay, R., & Sherwood, B. (2013). How do students in an innovative principle-based mechanics course understand energy concepts?. *Journal of research in science teaching*, *50*(6), 722-747. https://doi.org/10.1002/tea.21097

Duit, R. (1981). Understanding Energy as a Conserved Quantity-Remarks on the Article by RU Sexl. *European journal of science education*, *3*(3), 291-301. https://doi.org/10.1080/0140528810030306

Duit, R. (2014). Teaching and learning the physics energy concept. In R. F. Chen, A. Eisenkraft, D. Fortus, J. S. Krajcik, K. Neumann, J. C. Nordine, & A. Scheff (Eds.), *Teaching and learning of energy in K – 12 education* (pp. 67–85). Springer International Publishing.

Fortus, D., Kubsch, M., Bielik, T., Krajcik, J., Lehavi, Y., Neumann, K., Nordine, N., Opitz, S., & Touitou, I. (2019). Systems, transfer, and fields: evaluating a new approach to energy instruction. *Journal of Research in Science Teaching*, *56*(10), 1341-1361. https://doi.org/10.1002/tea.21556

Goldring, H., & Osborne, J. (1994). Students' difficulties with energy and related concepts. *Physics education*, *29*(1), 26-31. https://doi.org/10.1088/0031-9120/29/1/006

Grimellini-Tomasini, N., Pecori-Balandi, B., Pacca, J. L., & Villani, A. (1993). Understanding conservation laws in mechanics: Students' conceptual change in learning about collisions. *Science Education*, 77, 169-189. https://doi.org/10.1002/sce.3730770206

Halilović, A., Mešić, V., Hasović, E., & Dervić, D. (2021a). Students' Difficulties in Applying the Law of Conservation of Mechanical Energy: Results of a Survey Research. *European Educational Researcher*, *4*(2), 171-192. https://doi.org/10.31757/euer.423

Halilović, A., Mešić, V., Hasović, E., & Vidak, A. (2021b). Teaching upper-secondary students about conservation of mechanical energy: Two variants of the system approach to energy analysis. *Journal of Baltic Science Education, 20(2), 223-236.* https://doi.org/10.33225/jbse/21.20.223

Herrmann-Abell, C. F., & DeBoer, G. E. (2018). Investigating a learning progression for energy ideas from upper elementary through high school. *Journal of Research in Science Teaching*, *55*(1), 68-93. https://doi.org/10.1002/tea.21411

Jewett Jr, J. W. (2008). Energy and the confused student II: Systems. *The Physics Teacher*, *46*(2), 81-86. https://doi.org/10.1119/1.2834527

Jin, H., & Anderson, C. W. (2012). A learning progression for energy in socio-ecological systems. *Journal of Research in Science Teaching*, *49*(9), 1149-1180. https://doi.org/10.1002/tea.21051

Kim, E., & Pak, S. J. (2002). Students do not overcome conceptual difficulties after solving 1000 traditional problems. *American Journal of Physics*, *70*(7), 759-765. https://doi.org/10.1119/1.1484151

Kulišić, P. (2005). *Mehanika i toplina* [Mechanics and heat]. Školska knjiga.

Lawson, R. A., & McDermott, L. C. (1987). Student understanding of the work-energy and impulse-momentum theorems. *American Journal of Physics*, *55*(9), 811-817. https://doi.org/10.1119/1.14994

Lee, H. S., & Liu, O. L. (2010). Assessing learning progression of energy concepts across middle school grades: The knowledge integration perspective. *Science Education*, *94*(4), 665-688. https://doi.org/10.1002/sce.20382

Lindsey, B. A., Heron, P. R., & Shaffer, P. S. (2009). Student ability to apply the concepts of work and energy to extended systems. *American Journal of Physics*, *77*(11), 999-1009. https://doi.org/10.1119/1.3183889

Lindsey, B. A., Heron, P. R., & Shaffer, P. S. (2012). Student understanding of energy: difficulties related to systems. *American Journal of Physics*, *80*(2), 154-163. https://doi.org/10.1119/1.3660661

Liu, X. (2010). *Using and developing measurement instruments in science education: A Rasch modeling approach*. Iap.

Liu, X., & McKeough, A. (2005). Developmental growth in students' concept of energy: Analysis of selected items from the TIMSS database. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *42*(5), 493-517. https://doi.org/10.1002/tea.20060

McKagan, S. B., Perkins, K. K., & Wieman, C. E. (2010). Design and validation of the quantum mechanics conceptual survey. *Physical Review Special Topics-Physics Education Research*, *6*(2), 020121. https://doi.org/10.1103/PhysRevSTPER.6.020121

National Research Council (2012). *A framework for K-12 science education*. The National Academies Press.

Neumann, K., Viering, T., Boone, W. J., & Fischer, H. E. (2013). Towards a learning progression of energy. *Journal of research in science teaching*, *50*(2), 162-188. https://doi.org/10.1002/tea.21061

Papadouris, N., & Constantinou, C. P. (2014). An exploratory investigation of 12-year-old students' ability to appreciate certain aspects of the nature of science through a specially designed approach in the context of energy. *International Journal of Science Education*, 36(5), 755-782. https://doi.org/10.1080/09500693.2013.827816

Papadouris, N., & Constantinou, C. P. (2016). Investigating middle school students' ability to develop energy as a framework for analyzing simple physical phenomena. *Journal of Research in Science Teaching*, *53*(1), 119-145. https://doi.org/10.1002/tea.21248

Radford L., Sabena C. (2015) The Question of Method in a Vygotskian Semiotic Approach. In: A. Bikner-Ahsbahs, C. Knipping, & N. Presmeg (eds) *Approaches to Qualitative Research in Mathematics Education* (p. 157-182). Springer.

Redish, E. F. (2004). *Teaching physics with the physics suite*. Wiley.

Renkl, A. (2011). Instruction based on examples. In R. E. Mayer and P. A. Alexander (Eds.) *Handbook of research on learning and instruction* (pp. 286-309). Routledge.

Quilici, J. L., & Mayer, R. E. (1996). Role of examples in how students learn to categorize statistics word problems. *Journal of Educational Psychology*, *88*(1), 144. https://doi.org/10.1037/0022-0663.88.1.144

Samsudin, A., Afif, N. F., Nugraha, M. G., Suhandi, A., Fratiwi, N. J., Aminudin, A. H., ... & Costu, B. (2021). Reconstructing Students' Misconceptions on Work and Energy through the PDEODE* E Tasks with Think-Pair-Share. *Journal of Turkish Science Education*, *18*(1), 118-144.

Sang, D., Jones, G., Woodside, R., Chadha, G. (2012). *Cambridge International AS and A level Physics*. Cambridge University Press.

Seeley, L., Vokos, S., & Etkina, E. (2019). Examining physics teacher understanding of systems and the role it plays in supporting student energy reasoning. *American Journal of Physics*, *87*(7), 510-519. https://doi.org/10.1119/1.5110663

Singh, C., & Rosengrant, D. (2003). Multiple-choice test of energy and momentum concepts. *American Journal of Physics*, *71*(6), 607-617. https://doi.org/10.1119/1.1571832

Solbes, J., Guisasola, J., & Tarín, F. (2009). Teaching energy conservation as a unifying principle in physics. *Journal of Science Education and Technology*, *18*(3), 265-274. https://doi.org/10.1007/s10956-009-9149-3

Thomas, P. L., & Schwenz, R. W. (1998). College physical chemistry students' conceptions of equilibrium and fundamental thermodynamics. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *35*(10), 1151-1160. https://doi.org/10.1002/(SICI)1098-2736(199812)35:10<1151::AID-TEA6>3.0.CO;2-K

Topalsan, A. K., & Bayram, H. (2019). Identifying Prospective Primary School Teachers' Ontologically Categorized Misconceptions on the Topic of" Force and Motion". *Journal of Turkish Science Education*, *16*(1), 85-109.

Van Heuvelen, A., & Zou, X. (2001). Multiple representations of work–energy processes. *American Journal of Physics*, *69*(2), 184-194. https://doi.org/10.1119/1.1286662

Van Huis, C., & van den Berg, E. (1993). Teaching energy: a systems approach. *Physics Education*, *28*(3), 146-153. https://doi.org/10.1088/0031-9120/28/3/003

Appendix A

Short description and sources of the LCME items

Item 1	Item 2	Item 3	Item 4	Item 5
Assessing the misconception about the total kinetic energy of a system consisting of objects that move in opposite directions	Conservation of mechanical energy – system choice (context: falling rubber ball; conservative forces)	Conservation of mechanical energy – system choice (context: falling rubber ball; non-conservative forces)	Conservation of mechanical energy – time interval (context: falling rubber ball; conservative and non-conservative forces)	Conservation of mechanical energy – system choice (context: falling rubber ball; conservative and non-conservative forces)
ECA	Original	Original	Original	Original
Item 6	**Item 7**	**Item 8**	**Item 9**	**Item 10**
How do energy forms depend on the system choice (object on an elastic spring)?	Conservation of mechanical energy – combined reasoning about system choice and time interval (context: falling rock)	Assessing the misconception about work done by a centripetal force (context: satellite motion)	Conservation of mechanical energy – combined reasoning about system choice and time interval (object ejected by a vertical spring)	Non-Conservation of mechanical energy – combined reasoning about system choice and time interval (object ejected by a vertical spring)
ECA	Original	EMCS	Original	Original
Item 11	**Item 12**	**Item 13**	**Item 14**	
Conservation of mechanical energy – time interval (context: two objects connected over a massless pulley)	Conservation of mechanical energy – system choice (context: motion along an incline; non-conservative forces)	Comparing negative work done by conservative and non-conservative forces (context: vertical raising vs moving along rough incline)	Reasoning about the transformation of gravitational potential energy into kinetic energy (context: sliding down a smooth ramp)	
Original	Original	EMCS	EMCS	

Appendix B

Categorization of survey items into conceptual themes

Conceptual themes	Items
A Energy forms, energy transformation and work	1,6,8,13,14
B Conservation of mechanical energy – reasoning about system choice	2,5,3,12
C Conservation of mechanical energy – reasoning about the temporal evolution of the system	4,11
D Conservation of mechanical energy – combined reasoning about system choice and temporal evolution	7,9,10