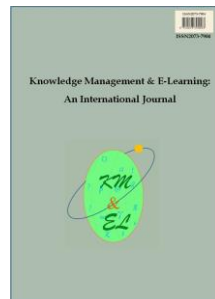

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Facebook-supported tasks for exploring critical and creative thinking in a physics teaching course

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Abstract: Research shows that traditional teacher-and-content-centered education doesn't give students good preparation in critical and creative thinking. This article presents a qualitative study of student performances in two original learning tasks, one related to critical thinking and the other related to creative thinking. The study was carried out in an obligatory physics teaching course for undergraduate students. The first learning task focused on critical thinking, in which students were asked to evaluate various defects in an artificially contextualized electrostatic exercise. Students' performances, collected via Google Classroom, show that they were able to detect and justify its contextual defects using real-world knowledge. A big challenge to students was to provide quantitative arguments against noticed huge electric charge allegedly created in described electrostatic cling. The second learning task focused on creative thinking, in which students engaged in a multi-step learning sequence to elaborate one explanation and two predictions related to enigmatic behavior of a tomato. A secret and closed Facebook group was administered to present the subtasks in the sequence and receive students' answers in real time. The results show that students performed better in the subtasks that called for a near knowledge transfer than in other ones calling for a far knowledge transfer. In their reflective comments about the sequence, students recognized the importance of "thinking out of the box" for deeper learning of physics. Based on the results, suggestions on the design of critical and creative thinking related tasks are discussed for future implementation.

Keywords: Critical thinking; Creative thinking; Interactive science learning environment; Self-regulated learning; Online learning; Knowledge inertia; Magic-based physics learning

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1. Introduction

Higher-education institutions have a very important social responsibility in education of “knowledge workers”, who should develop critical and creative skills to solve today’s known problems and, much more, future unknown problems which will appear in next decades (Cooke, 2001; Jarvis, 2001; Graham, 2002).

Nevertheless, the university teaching, even in the most industrialized countries like the USA, is slow-changing and unprepared to react adequately to these urgent economic needs. In their thought-provoking book “*We’re Losing Our Minds. Rethinking American Higher Education*”, Keeling and Hersh (2012) say:

*“The truth is painful but must be heard: we’re not developing the full human and intellectual capacity of today’s college students because they’re not learning enough and because the learning that does occur is haphazard and of poor quality. Too many of our college graduates are not prepared to **think critically and creatively**, speak and write cogently and clearly, solve problems, comprehend complex issues, accept responsibility and accountability, take the perspective of others, or meet the expectations of employers. Metaphorically speaking, we are losing our minds.” (Keeling & Hersh, 2012, p. 1).*

According to Keeling and Hersh, one of the main causes of this situation is teaching-centered culture of colleges and universities:

“Since teaching is what matters and what is measured, instruction is mostly lecture-driven and learning, to the extent that it occurs, is mostly passive, receptive enterprise. In other words, students should come to class, listen carefully, take good notes, and be grateful.” (Keeling & Hersh, 2012, p. 20)

To make things more disturbing, standards-based measuring of conceptual learning and knowledge applicability in solving real-world problem is rarely carried out or it is completely absent. Keeling and Hersh consider that learning, needed by actual knowledge-based economy,

“...requires that students be fully engaged participants in a powerful intellectual, social, and developmental process. That process requires rigorous self-discipline, effort, and commitment; demanding well-trained teachers; an inspiring, motivating, and diverse curriculum; and an intentionally designed, challenging, formative, and supportive learning environment.” (Keeling & Hersh, 2012, p. 20).

The general critique of higher-education common practice of teaching and learning, elaborated by Keeling and Hersh, was convincingly echoed by extensive specific research in physics education (McDermott & Redish, 1999; Van Aalst, 2000; Docktor & Mestre, 2014; Henderson & Heron, 2018; Yun, 2020).

In her lecture, given at the ceremony of receiving well-deserved Oersted Medal, Lilian C. McDermott, a pioneer of and a distinguished leader in practicing and promoting physics education research, made a summary of the most important findings and their teaching implications (McDermott, 2001) as follows.

1. Facility in solving standard quantitative problems is not an adequate criterion for functional understanding. Questions that require qualitative reasoning and verbal explanation are essential for assessing student learning and are an effective strategy for helping students learn.

2. Connections among concepts, formal representations, and the real world are often lacking after traditional instruction. Students need repeated practice in interpreting physics formalism and relating it to the real world.
3. Certain conceptual difficulties are not overcome by traditional instruction. (Advanced study may not increase understanding of basic concepts.) Persistent conceptual difficulties must be explicitly addressed in multiple contexts.
4. A coherent conceptual framework is not typically an outcome of traditional instruction. Students need to participate in the process of constructing qualitative models and applying these models to predict and explain real-world phenomena.
5. Growth in reasoning ability often does not result from traditional instruction. Scientific reasoning skills must be expressly cultivated.
6. Teaching by telling is an ineffective mode of instruction for most students. Students must be intellectually active to develop a functional understanding.

McDermott, in her diagnosis, didn't provide a detailed elaboration of what "scientific reasoning skills" are. These skills are surely connected with students' performances in proposing and evaluating explanations and predictions of scientific phenomena (Osborne, 2013). Such type of tasks calls for students' creativity and critical argumentative stance.

Critical and creative thinking are widely recognized as 21st century skills crucial for successful personal, professional and social life (Trilling & Fadel, 2009; Larson & Miller, 2011; Alismail & McGuire, 2015). These skills and their productive interplay are important in self-regulated learning in schools and companies. Some even believe that it is never too early to start to teach these skills even to children (Delamain & Spring, 2021; Thomas, 2016).

Serious theoretical and experimental studies of critical and creative thinking are very rare in physics education research. The term "serious" refers to studies published in journals with strong review process like "Physical Review Physics Education Research", "American Journal of Physics" or "The Physics Teacher". One example is the article on development and validation of the physics lab inventory of critical thinking (Walsh et al., 2019).

In an exploration of physics teachers' evaluation needs of non-content aspects of their courses (beyond physics concepts and laws), it was found that only 7 out of 23 faculty expressed their interest in research-based instrument for assessing "critical thinking" and there wasn't even a single teacher who mentioned "creative thinking" (Madsen et al., 2016).

Being so, it is hardly a surprise that a review article on research-based assessment instruments that go beyond physics topics has found only one instrument related to critical thinking "PLIC – Physics Lab Inventory of Critical Thinking" (Madsen et al., 2019). It is a little bit strange that this review didn't mention a very useful article on how to define operationally and develop pedagogically critical thinking in physics learning (Etkina & Planinšič, 2015).

A literature review of existing studies on students' critical and creative thinking skills shows the following. *First*, the studies are mainly published by the Institute of Physics as few-page reports in "Journal of Physics: Conference Series". These publications are characterized by a weak review process that can be easily noted by paying attention to poor quality of English language. *Second*, a majority of the studies are focused on measuring students' critical thinking skills in some physics topics, from static

fluid (Puspita, Kaniawati, & Suwama, 2017; Pamungkas, Aminah, & Nurosyid, 2019; Rosyidah et al., 2020) to harmonic motion (Umam et al., 2020). Reported levels of critical skills are generally low. *Third*, the studies on students' creativity are rather rare and found skill level is insufficient (Fadllan & Saptono, 2019). *Fourth*, the scientific quality and clarity of studies is problematic because readers are not informed about which physics problems or questions were used to explore critical or creative skills and, much more important, what were details of students' performances in those problems and questions.

The aim of this study is to address the gap by investigating the following two research questions (RQ):

RQ1: What are students' performances in a physics learning task that requires critical thinking?

RQ2: What are students' performances in a sequenced physics learning task that requires creative thinking?

For critical and creative thinking tasks students surely had enough previous conceptual and factual knowledge and calculation skills. Taking it into account, at a deeper level, the RQ1 and RQ2 questions explore how ready students are to activate these knowledges and skills in order to use them in dealing with two tasks very rarely or never proposed in traditional physics teaching.

2. Study context and participants

This study is a task-based qualitative exploration of physics students' performances (Creswell, 2002; Stake, 2010). It was carried out by real-time use a closed and secret Facebook group and by flexible-schedule answers delivery via Google Classroom (GCR).

The tasks were published on the group's wall and students' initial ideas and self-reflections were collected either in real time on the wall or via documents sent via GCR. The main reason for using Facebook as a communication platform is that all students have mobile phones and count with daily experience with the Facebook messaging. In addition, due to slow internet connections the use of Zoom or Meet video conferences, as teaching and learning platforms, was somewhere between very difficult and impossible.

2.1. Study context

The study was one of many learning activities in the obligatory course "Physics teaching." The key information of the course is described as follows.

2.1.1. Course aims and basic content

Two basic aims of the course are to: (1) introduce the future teacher in the design of guided programs, didactic units and action research with the students, in the constructivist framework of teaching / learning of physics; and (2) instruct the student in the use of new technologies (multimedia, hypermedia, internet, Virtual Reality) in physics teaching.

The content of course includes four parts: (a) psychology of learning scientific knowledge; (b) difficulties in learning physics; (c) elements of a physics course and curricular design; and (d) sociocultural constructivism and situated cognition.

Unfortunately, the course is seen by many students as unimportant one whose only role to fill up a “curricular hole”. About 25 % of them take the course among the last ones, having 80 % or more credits. The reason is very likely related to their beliefs about the nature physics learning and teaching. For them, learning physics isn’t much more than learning to manipulate efficiently mathematical formulas and physics teaching is basically a clear exposition of physics content. So, the first thing to do in the course is to show to the students, by some mathematical and physical puzzles, that these beliefs are wrong.

2.1.2. *Learning about human learning*

The next thing is to introduce students into the basic scientific facts about human learning. It is done by home reading and in classroom discussions of the introduction of the book “*How people learn*” (Bransford, Brown, & Cocking, 2000). In particular, students are informed of the following.

1. Students come to the classroom with preconceptions about how the world works. If their initial understanding is not engaged, they may fail to grasp the new concepts and information that are taught, or they may learn them for purposes of a test but revert to their preconceptions outside the classroom. (Bransford et al., 2000, pp. 14–15).
2. To develop competence in an area of inquiry, students must:
 - a) have a deep foundation of factual knowledge,
 - b) understand facts and ideas in the context of a conceptual framework, and
 - c) organize knowledge in ways that facilitate retrieval and application. (Bransford et al., 2000, p. 16).
3. A “metacognitive” approach to instruction can help students learn to take control of their own learning by defining learning goals and monitoring their progress in achieving them. (Bransford et al., 2000, p. 18).

These facts have important implications for teaching in the following aspects.

1. Teachers must draw out and work with the preexisting understandings that their students bring with them. (Bransford et al., 2000, p. 19)
2. Teachers must teach some subject matter in depth, providing many examples in which the same concept is at work and providing a firm foundation of factual knowledge. (Bransford et al., 2000, p. 20)
3. The teaching of metacognitive skills should be integrated into the curriculum in a variety of subject areas. (Bransford et al., 2000, p. 21)

As nobody can be a “constructivist teacher” without being previously a “constructivist learner”, the emphasis in learning activities is put on development of students’ metacognitive skills. They are always asked explicitly to monitor, describe and try to understand their mental processes while solving different physics-related tasks (describe, explain and predict physical phenomena). Questions they should try to answer are: What do I think? Why do I think that way? Which arguments might I give to convince others that my thinking is right? Am I able to detect any flaw in my thinking?

The last question is commonly very hard for the students. Being so, they are informed that good human thinking is productive dialog between “creative thinking” and “critical thinking” and that it can be developed and improved only by “becoming aware of the thinking process”, “carefully examining the thinking process” and “practicing the thinking process” (Chaffee, 2015, p. 3).

2.1.3. Most productive research-based practices in physics teaching

By assigned readings of suggested journal articles, written by eminent physics education researchers (Laws, 1996; Redish, 1994, 1999, 2014), students are expected to learn about the methodology and results which were the starting points developing most productive didactic designs for physics teaching.

In the course, students experience multiply first-hand practices with the learning sequence “predict – observe – explain” about different physics phenomena (Kearney, 2004; Corona, Slisko, & Planinsic, 2006; Marušić & Slisko, 2012; Radovanović & Slisko, 2013; Balukovic, Slisko, & Cruz, 2015). When they are presented a phenomenon, in the first instance students are asked to predict what would happen if a certain change is caused. Their prediction should be conceptually justified. When individual and group predictions are known, students observe and describe what really happened after the mentioned change was carried out. In the common case, when the observations differ from their prediction, students have to explain the difference, trying to find out which part of the conceptual justification was wrong.

The “predict – observe – explain” sequence, due to likely wrong predictions, might result in students’ frustrations (“I have always a wrong prediction!”). Therefore, they also practice more learner-friendly sequences “observe – explain – predict – test predictions – apply”, a central part of recognized teaching methodology, known as “*Interactive Science Learning Environment*” (ISLE) (Etkina, 2015, 2019). The sequence starts with a carefully designed “observation experiment”. Students are asked to describe recognized patterns and to propose different conceptual explanations. After they should suggest various “testing experiments” in order to verify (or falsify) the proposed explanations and select the best one that “survived” all testing experiments. The final step is to apply that explanation in new situations. Students are encouraged to be aware of their “reasoning modes” (inductive, hypothetico-deductive, analogical) and “reasoning tools” (different representations). Being so, students develop scientific habits of mind and are explicitly engaged in experimental design. Both learning results almost never occur in traditional physics teaching.

Students are very impressed when they learn about complexity of physics learning and the tremendous progress that has been made by physics education research. That happens in the course activity in which they revise the content of the online journal “*Physical Review – Physics Education Research*” and select the most interesting articles for PowerPoint presentations.

Students are especially surprised when told that a big contribution to research on physics learning and teaching is due to Carl Edward Wieman, the Nobel Prize winner in physics. Wieman vigorously promoted the idea that the only way to improve physics education is by applying the same methodology commonly practiced in science: real data – theoretical explanation – prediction (Wieman & Perkins, 2005; Wieman, 2007, 2014). His example clearly contradicts the belief many of them had before the course: physics teaching is a second-hand academic job “reserved” only for those who didn’t succeed in physics research.

2.1.4. *Self-regulated learning*

In the course, students were also introduced explicitly into the conception and practice of “self-regulated learning” (Pintrich, 1995; Low & Jin, 2012; Zimmerman & Schunk, 2013) with strong emphasis on metacognitive aspects of learning. Namely self-regulated learners plan, set goals, organize, self-monitor, and self-evaluate gained results at various points during the learning process. They are also very motivated, showing high self-efficacy, self-attribution and intrinsic task interest. In addition, self-regulated learners know and accept that learning results are better with more efforts and persistence and within an adequate learning environment (Zimmerman, 1990). The success of self-regulated learning depends on students’ abilities to activate and use in the best way metacognitive, motivational and behavioral resources and strategies.

Generally speaking, self-regulated learning process consists of three different phases: Forethought or planning phase; Performance phase; and Self-reflection phase (Zimmerman, 2002). In the Planning phase, students activate all necessary knowledge and skills to understand the given problem and make a plan how to solve it.

In the Performance phase, they monitor how they perform, whether some unexpected or unclear details appear, and verify validity of partial and final solution. Self-reflection phase is the most important part of self-regulated learning. In it, students are supposed to look back and evaluate critically their performance and what was learned and what was not. In the last case, they try to determine what possible causes might be of their unsuccessful learning.

2.2. *Participants*

The convenience sample was 40 students enrolled in the course, and 36 of them completed the study. Their mean age was 22.3 years. In the first two session of the course, students’ basic cognitive characteristics were measured by two paper-and-pencil tests. The first test was expanded Cognitive Reflection Test (Toplak, West, & Stanovich, 2015) that determines students’ inclinations toward fast or slow thinking (Kahneman, 2001). In the applied version, seventh item, related to a money inversion problem, was omitted. The results, for 36 students, are shown in the Table 1.

Table 1

Students’ performances in cognitive reflection test (six-question version)

Number of correct answers	Number of students
2	2
3	4
4	2
5	13
6	15

Although the mean score 4.97 seems rather good, when rescaled (2.49) and compared with the results of original Cognitive Reflection Test (Frederick, 2005), 22 % of students are still “fast thinkers”, prone to be guided by intuitive reasoning and missing cognitive reflection skills.

The second applied test was the Test of Logical Thinking (Tobin & Capie, 1981) in its Spanish version (Acevedo & Oliva, 1995). This ten-item test measures students' formal thinking skills. The results for 36 students are shown in the Table 2.

Table 2
Students' performances in the test of logical thinking

Number of correct answers	Number of students
5	3
6	2
7	1
8	5
9	10
10	15

The mean score was 8.7, a result much better than 4.4 reported by Tobin and Capie (1981) for general college students or 5.6 found by Vázquez and Anglat (2009) in the case of engineering students. Nevertheless, it is surprising that 6 of 36 physics students, after many semesters in the career, are still cognitively unprepared for formal (hypothetico-deductive) thinking.

3. Task 1 related to critical thinking: Working sheet and results

Palm (2009) proposed a useful taxonomy of characteristics that “authentic school problems” should have. In the first place, a school problem is “authentic” if (a) problem-related event or situation happens or could happen in the real world; (b) numerical data describing event or situation are real or, in principle, possible; and (c) the question asked in problem is reasonable.

A problem is “artificially contextualized” or has “questionable authenticity” if any of these characteristics is absent or violated. It is known that physics textbook authors frequently formulate electrostatic exercises and problems for which either given or calculated values of electric charges are highly unrealistic or, even, impossible (Slisko & Krokhin, 1995; Slisko, 2006). These problems can be rightly considered as “artificially contextualized”.

For the task related to critical thinking, the following electrostatic problem was used:

Example 2. Static cling

Jordan put her wool socks and a silk shirt together in a tumbling clothes dryer after washing them. When she took them out, she noticed that the wool sock and whatever was left of the silk shirt were stuck together because of an electrostatic force of attraction. If 3.7×10^{24} electrons were transferred between the wool and the silk, what is the amount of charge on the silk shirt? (Nowikow, Heimbecker, & Bosomworth, 2001, p. 530).

Answer: 5.9×10^5 C (Nowikow et al., 2001, p. 531).

It appeared in a physics textbook that had 12 reviewers and nobody of them noticed its explicit lack of authenticity. Namely, allegedly involved quantity of charge is huge and impossible to create on wool and silk in the real world.

3.1. Working sheet for the task

The working sheet for the task was published as a Word document on the wall of the course Facebook group. The task was presented as follows.

What is wrong in a “contextualized problem?”

In a recent physics textbook, the following “contextualized problem” appears:

Static cling. Jordan put her wool socks and a silk shirt together in a tumbling clothes dryer after washing them. When she took them out, she noticed that the wool sock and whatever was left of the silk shirt were stuck together because of an electrostatic force of attraction. If 3.7×10^{24} electrons were transferred between the wool and the silk, what is the amount of charge on the silk shirt? Given solution is 5.9×10^5 C.

A critical analysis leads to the conclusion of this problem, as many others in physics textbooks, is “artificially contextualized”.

1. Present all aspects of that “artificial contextualization”, considering reasonableness and feasibility of the situation, of the numerical data, of the question, of the solution, etc.
2. If you have seen before another example of “artificial contextualization” of physics problems or exercises, present what you remember and the reasons for considering it as “artificial”.

3.2. Students’ critical considerations of given artificially contextualized problem

In this task, 25 students sent their answers on specified time via Google Classroom. Their performance was analyzed as follows.

3.2.1. Situation of the problem

Dealing with the situation of the problem, students were able to activate their real-world knowledge and present justified and well stated critique of the problem formulation. Below are the responses from students.

“The nature of the problem is forced, no one would put together (into a drier) silk and wool cloths.”

“The situation is insane as cloths are usually classified into types and no one regularly mixes socks with shirts. To continue, each cloth, depending on its type, has a special type of washing and drying. In this case, it does say that the silk shirt was destroyed. That means it should not be dried. If persons wash clothes, in general, they are people trained to do it. They would not destroy the cloths on purpose, due to the cost and waste of materials and therefore of money.”

“Who would wash wool socks and a silk shirt together? Those must be taken to a dry cleaner or they will be ruined!”

“First of all, wool and silk are not machine washed, and using a dryer is suicidal.”

“First of all, I think most people would not put wool socks in a dryer, most of us know what would happen. I think the statement is not very sensible.”

“The first thing is: not people all have silk clothes like shirts. From there, the weird starts.”

3.2.2. Knowing the number of electrons

Students also targeted rightly something very common in physics textbook problems, for example, giving values to physical quantities without indicating how they were found experimentally. In the problem, the number of electrons was just taken out of sleeve. Here come some related critical comments:

“In principle, I don't think it is possible to know the number of electrons in an object.”

“It is difficult to know from where the number of electrons transferred between wool and silk was obtained.”

“How was it possible to count the number of electrons that were transferred during the washing action?”

“The exercise presents the number of electrons transferred between the two cloths. However, the way in which this quantity was obtained experimentally is not presented.”

“It is assumed that just by noticing that the sock and shirt stick together, the observer can easily determine the number of electrons that were passed from one object to another to obtain the charge. It is highly unlikely that it can be so easily determined.”

“Knowing the exact number of electrons that were transferred in an uncontrolled physical phenomenon through an experiment in a laboratory is unrealistic.”

3.2.3. Affirmations about the value of resulting charge

Critical considerations of the enormous number of electrons (3.7×10^{24}) or of the big value of resulting charge (5.9×10^5 C) are the most important insight into students' dealing with this task. Three different types of dealing were found.

In the first type, students just expressed their impression about greatness without providing any argument as follows.

“I think that the number of electrons is excessive, although I don't know if it is correct.”

“The amount of charge that is given in the answer is enormous.”

“I think 3.7×10^{24} electrons is a very large amount for objects like wool or silk.”

“The number of electrons is pretty impressive.”

In the second type, students related their affirmation to other physical concept like electrostatic force as follows.

“The proposed result is absurd. That amount of charge would produce an enormous force.”

“If that number of electrons were transferred, the resulting charge is immense, and the electrostatic force that is causing it would make it very difficult for us to separate the cloths, which in reality is not the case.”

In the third type, students based their critical consideration on factual knowledge they learnt in previous courses as follows.

“Transferred charge is foolish because, typically in common everyday situations, only charges in the order of nano and microcoulomb are transferred.”

“Generally, the electrostatic charge obtained by rubbing two materials is not usually greater than microcoulombs. Therefore, the amount of charge that is in the shirt may be impossible to obtain only because of the contact they have when they are in the dryer as mentioned in the statement.”

3.2.4. Demonstrating irreal value of supposed charge

It was expected that students would try, by a simple calculation based on Coulomb's law, to demonstrate the irreal value of supposed electric charge (5.9×10^5 C). Supposing the distance of 1 meter between the charged clothes, the resulting force would be about 3×10^{16} newtons, corresponding approximately to the weight of a body with the mass of 3×10^{15} kg or the weight of three million regular cars. If, for calculation, one supposes the distance of 1 centimeter, the resulting force would be 10,000 times bigger: 3×10^{20} newtons.

Only two students dealt with the task in that way, without providing the details of calculation. One student provided very wrong value of the resulting force as follows.

“Assuming that the clothes can be approximated as particles and are one centimeter apart, the attractive force is approximately 3.1 kN, which is absurd for two cloths.”

The value of force found by the other student was acceptable as shown below.

“If we consider the attractive force that this excess charged exerts on a body with exactly the same charge, it would end up being of the order of 10^{20} N at least.”

Two students explored alternative quantitative approaches to deal critically with the problem data. In the first approach, the student concluded that the number of electrons is too small as follows.

“To see if the number of electrons makes sense, let's think that in 1 mole of a certain substance there are approximately 6×10^{23} molecules, each with a certain number of electrons. To get the result of 3.7×10^{24} electrons, each molecule should have about 6 electrons. This is a very small number of electrons for a molecule. Therefore, this data seems unreal to me, that is, the number of electrons that are transferred should be greater. Remember that we are only considering one mole of substance.”

The second original dealing approach was much better as shown in the following response.

“The most serious problem is the number of electrons and therefore the charge that the exercise handles, since 5.9×10^5 C is too large a quantity to be generated

simply with static electricity, especially if we consider that the charge that travels in objects that are normally used to power devices, as AA batteries, is about 5000 C.

Putting this in context of the exercise, it tells us that the charge generated by static electricity is equivalent to 120 AA batteries, which clearly cannot happen in reality.”

3.2.5. Epistemological nature of the problem

Some students, without being asked, considered epistemological nature of the problem regarding its role in helping them learn physics, as shown in their responses below.

“So, in the end, the problem is simply an arithmetic calculation and all that verbiage that it gives is unnecessary because it presents a skewed image of reality. For me this is not a physical problem, it is an algebra problem disguised as a physical one.”

“Definitely, it is a problem only to do a mathematical calculation, without having a solid physical basis to support it to be applied in reality.”

“This type of problem does not allow us to visualize and understand the true physical meaning behind it, since only mathematical operations and calculations are carried out without really understanding why they are done and how they can give us an idea of a studied concept, so that in this way we can put it into practice in real life.”

3.2.6. Memories of artificially contextualized problems in previous courses

Ten of 25 students didn't provide any information in this subtask. In addition, three students declared that they don't remember a particular problem that was artificially contextualized. Two of them stated the arguments for that “absence of memories”. Both arguments shown below are very troubling.

“I don't pay attention whether given data have sense or not.”

“I don't remember because, according to me, the problems are always fictional and aren't worth of remembering as they would never happen in real life.”

The rest of the students did remember a particular artificially contextualized problem and were able to state an acceptable reason to justify their evaluation. In the case of two students, the memories go back to a physics problem they faced in high school.

4. Task 2 related to creative thinking: Subtasks and results

This task was designed as a multi-step learning sequence in which students were supposed to deal with creative processes of elaborating one explanation and two predictions related to enigmatic behavior of a tomato. All subtask questions were posted on the wall of the Facebook group and students were publishing their answers as comments in real time on the same wall. In this task, 35 students took part.

4.1. Explanation of “magical” behavior of a tomato

The first subtask was as follows.

“All who have washed a tomato know that it floats in water (Fig.1). Nevertheless, it can happen that a tomato does not float but it is at the bottom of a bottle with water (Fig. 2). How could the tomato have sunk and how it is held at the bottom of the bottle? Personal answer should be published as a comment to this task. Do not forget that the first step in self-regulated learning is to know how your mind works facing a question or a problem.”



Fig. 1. A tomato floating in water



Fig. 2. A tomato at the bottom of the bottle

Students didn't know that a light metal screw was inserted into the tomato and that a strong neodymium magnet was used to bring the tomato to the bottom and to keep it there. The magnet was hidden under the bottom of the bottle. The students' task, in dealing with this “magical situation”, was to creatively explain it. This task design followed the idea of magic-based teaching for fostering creative and flexible thinking (Li, 2020; Li & McCalla, 2020).

The task was implemented twice. In the first try, students gave their spontaneous density-based explanations. In the second try, they were *explicitly* informed of the following.

“The tomato is fresh; the change of the density is minimal; and it is still smaller than the density of water. The density is not a causal factor. You should be creative by “thinking-out-the-box” and search other possible explanations.”

Eight students only provided their explanations in the first try. Seven said that somehow the density of the tomato became bigger than the density of water and the tomato sunk. One student suggested that the buoyant force somehow became smaller than the weight of the tomato.

Twenty-seven students participated both in the first and the second try. Majority of them tried to keep density-based explanation (density of the tomato bigger than the density of water), proposing different ways to reduce the density of water. Some of these ways were, in principle, feasible (adding alcohol or increasing water’s temperature), while other were incorrect (adding sugar or salt).

Only few students proposed alternative explanations, not related to the densities of tomato and water. All of them show that they don’t have sound understanding of buoyant force. Some examples are: “buoyant force depends on the position or orientation of the tomato” or “buoyant force decreases with depth”. These ideas are something not expected from students of physics in the second part of the career. In the future, it would be informative to apply to similar group of physics students a test that verifies their conceptual understanding of floating and sinking (Yin, Tomita, & Shavelson, 2008).

Not a single student was able to “think-out-the box”, proposing creative idea to sink the tomato with inserted metal screw using a magnet. For the students “near transfer” (based on density) was easy, but a “far transfer” (based on magnetic attractive force) was out of their “creativity range”.

4.2. First prediction subtask

In the second step of the creativity task, students were given the following information that revealed the secret of “magical” behavior of the tomato.

“The unexpected position of the tomato is due to the following: a metallic screw was inserted into the tomato and a neodymium magnet was used to sink the tomato down to the bottom and to hold it there (Fig. 3). Attractive magnetic force and gravitational force, both acting downward, hold the tomato at the bottom, being in equilibrium with buoyant force and reaction bottom force that act upward.

What will happen with the tomato if the neodymium magnet is moved away from the bottom?

- (a) It will stay at the bottom.*
- (b) It will raise up to the middle of the bottle.*
- (c) It will raise up to the water surface.*

In the personal comment, select one answer and justify it.”

Nineteen students have chosen the option (c), predicting correctly that the tomato will raise up to the water surface when the magnet is far away. Many, but not all, had the

right argument: the density of the tomato with inserted metal screw was still less than the density of water.

Surprisingly, sixteen students opted for the answer (b), predicting incorrectly that the tomato will raise up to the middle of the bottle. They forgot what they were told: the tomato has smaller density than water. Their logic was the following one: with the screw the weight of the tomato is increased, and it can't raise up to the surface but only up to the middle of the bottle.



Fig. 3. The neodymium magnet holding the tomato at the bottom

4.3. The second prediction subtask

In the next step, students were first told and shown how the tomato raised up to the water surface when the neodymium magnet was removed (Fig. 4).

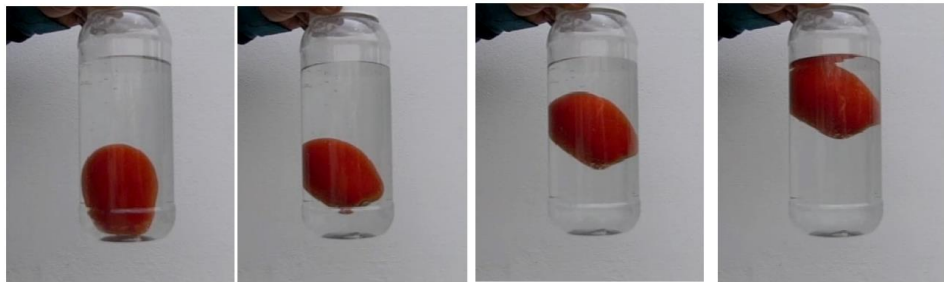


Fig. 4. A tomato going up to the surface after the magnet was moved away

The second prediction subtask was presented as follows.

“Now again the tomato is at the bottom of the bottle, attracted by the neodymium magnet (Fig. 5).

What will the tomato do, if the magnet is moved away and, in the same moment, the bottle is free to fall?

(a) The tomato will stay at the bottom of the bottle.

(b) The tomato will move up to the water surface.

(c) *The tomato will move up to the middle of the bottle.*

In the personal comment, one answer should be selected and justified.”

This time 34 students chosen the correct prediction (a): The tomato will stay at the bottom of the bottle.

Almost of them justified this prediction by saying that in free-falling bottle the buoyant force is absent. This is again a case of “near transfer” because in previous activities they learned that inside free-falling systems there is no gravitation field and that, consequently, all forces related to weight disappear.

Only one student had incorrect prediction, choosing the option (b). The argument was based on previous behavior of the tomato in the stationary bottle: without the magnet, the tomato has raised to the water surface due to buoyant force (Fig. 4).



Fig. 5. The neodymium magnet holding the tomato at the bottom before the bottle was free to fall

4.4. *Reflective closing of the creative learning task*

In this reflective task, students were asked to provide personal comments on what they learnt from the tasks with the tomato. Before the task, students could see on the wall that their prediction was correct, that is, if the neodymium magnet is moved away and the bottle falls freely, the tomato stays at the bottom of the bottle (Fig. 6).

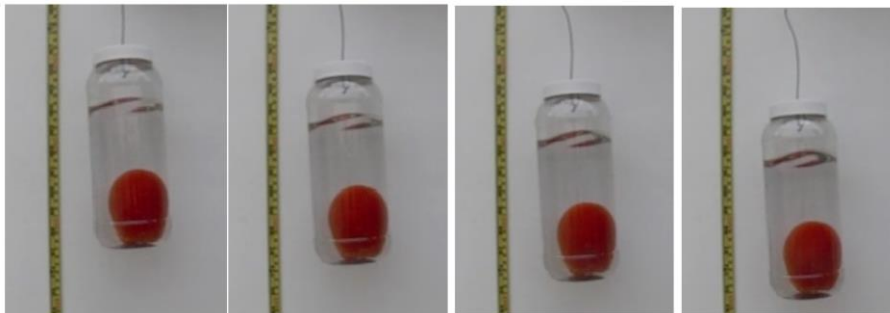


Fig. 6. When the bottle is in free fall, the tomato stays at the bottom of without the presence of the neodymium magnet

The students' comments shown below demonstrate that they understood well that the "knowledge management" in dealing with a creative task is a complex process in which they must overcome "knowledge inertia" (Liao, 2002) fostered by traditional teaching and learning.

"In this sequence I again realized that it is difficult to think "beyond", since we try to associate everything with concepts that we have mastered, without thinking that the same effect can be achieved in other ways, as seen by using the magnet. In the end, it was a good sequence and it gave me a good learning."

"Sometimes we believe that only what we see is what is happening and we cling to that. If we do not think further, we will never have original ideas when facing a problem."

"I really didn't expect the answer to this sequence to be the use of a screw and a magnet. We are used to using concepts related to the subject and we overlook many other phenomena that could explain it. It is necessary to expand the use of ideas, to think "out of the box", in order to access new approaches."

"It is not at all simple to move away from the limits imposed personally, even understanding what makes it possible to explain a phenomenon in different ways, we do not apply it. It has become clear to me that practice of this type is of great help in overcoming these limits and thus, in truth, mastering the knowledge that usually seems superficial."

"The phenomenon that the tomato in free fall stayed in the bottom quite impressed me, since it is another very creative way to demonstrate the phenomenon of weightlessness."

"Analyzing out of the ordinary is something that matters to me as a physicist, as there are phenomena that seem like "magic". However, it's just a matter of analyzing further and thinking out of the box, as it was with this example. In normal education this type of problem is not carried out and that is why it becomes complicated when we are presented with this type of problem."

"It is important to explore our thinking and creativity in situations with which we are apparently familiar. Therefore, it is interesting to be able to explore new ideas and with them build a stronger knowledge."

"This sequence was very interesting. It makes us realize that sometimes our mind can be so limited to thinking of only one thing regarding the phenomenon. However, there are many possibilities for the phenomena to occur. "Getting out of the box" was the hardest part as we are used to only having one explanation."

"I learned that it is necessary to get out of traditional thinking to find the solution to a problem. The expert feedback helped me to reaffirm my knowledge, but what I take away from this experience has more to do with the importance of thinking "out of the box.""

"The most significant learning achieved in this sequence is that many times there are "captive" questions to which we are not used to answering since, despite the fact that many things occur to us including the "correct" answer, we do not put it since we believe that it is not possible for someone to do that because it would be very misleading to do so. You have to take the risk of answering with those kinds of answers regardless of whether you might be wrong."

“When one finds or knows the solution to a problem, it is very difficult to see other answers and even more so when they are out of the ordinary. I was able to learn that if something has not been specified one is free to think of any answer that one imagines.”

“I think it must be emphasized that creativity is one of the most important processes in the life of a scientist, but also one of the most complicated. Either way, the creativity that we seek must be based on our knowledge and on how we “see” the world. This example is clear. The answer is something that we could not see with the naked eye without prior knowledge of the structure of the tomato.”

“I learned that it is important to consider all possible explanations of a physical phenomenon since if I only keep one, situations, like forcing an explanation with densities in the first task, can happen.”

The use of “tricky task” was seen as a controversy, and some students perceived it as too demanding while others liked it as follows.

“It seemed like an interesting way to illustrate different phenomena with the same experiment, especially the effects of weightlessness. But the fact of having put a screw into a tomato to make it stay at the bottom seems quite tricky and very demanding if we are to guess it.”

“This experiment is closely related to the activities we have been doing and I think using “tricks” is good because it broadens our panorama. I feel that every time I understand the idea of weightlessness a little more and that seems very good to me.”

“Although this exercise is a bit “tricky”, since it is not normal to put a nail in a tomato, I liked the exercise because it made our imagination and our physical knowledge go.”

5. Discussion

The findings of the study are discussed under two research questions.

RQ1: *What are students’ performances in a physics learning task that requires critical thinking?*

When dealing with a task that calls for critical considerations related to an artificially contextual problem, students were able to detect and justify its contextual defects using real-world knowledge about cloths washing and drying. Some of them also noticed that is not possible to know precise number of electrons that were allegedly involved in the process of cloth charging. It is important to stress that neither the authors nor reviewers had this critical consideration of the problem situation.

Bigger challenge for students was to provide quantitative arguments against noticed huge electric charge allegedly created in described electrostatic cling. Namely, only two students use presented a value of the electrostatic force that should appear in the described situation, without giving calculation details based on Coulomb’s law. One value was too small and the other was acceptable. This result is rather disappointing because all of them would be able to calculate successfully that force if asked explicitly to do.

Memories of artificially contextualized physics problems show that some students developed spontaneous inclination toward critical consideration of their learning even in high school while others took a self-defense decision not to pay attention to the meaning of the problems' situation and data. The second posture in problem solving, called "suspension of sense making", was extensively considered in mathematics education literature (Carotenuto, Di Martino, & Lemmi, 2021).

RQ2: What are students' performances in a sequenced physics learning task that requires creative thinking?

In dealing with creative subtask, as it was the explanation of how the tomato could have sunk and stayed at the bottom of the bottle, students were unable to free themselves of a previously learned principle: In order to sink, the tomato must have a bigger density than water. They were unable to invent a new explanatory principle of "magnetic sinking", even when they were informed explicitly that the density of the tomato is still smaller than the density of water. Being so, students' performances show an inclination toward "near transfer" and a resistance to "far transfer" (Zu, Munsell, & Rebello, 2019).

In dealing with two creative subtasks, related to prediction of tomato's behavior when the neodymium magnet was taken away, students' performances were conditioned by two thinking and learning phenomena.

The first one is "knowledge inertia", characterized by following uncritically previous knowledge and experiences. Namely, for almost half of students a tomato with a screw is heavier and can't raise up to the water surface even when the neodymium magnet isn't near the stationary bottle. They didn't take into account the repeated information that density of the tomato with the screw is smaller than the density of water and that the reason for its sinking was the presence of the neodymium magnet.

The second one was again "near transfer" revealed in prediction related to the situation when the neodymium magnet is taken away and simultaneously the bottle was allowed to fall freely. Namely, as in previous activities they learned that the water in free-falling bottle doesn't exert buoyant force, almost all students have chosen the right second prediction: The tomato stays at bottom of free-falling bottle even without magnetic attraction.

It is worth to stress, that many students, when dealing with creative tasks, were able to learn a very important epistemological lesson:

Deeper physics learning calls for "thinking-out-of-the box" which includes a whole spectrum of processes, from overcoming "knowledge inertia" to activate and apply, at first sight, unrelated knowledge needed for a "far transfer".

6. Conclusions

The results reported in this article show that future physics teachers should have more multi-step opportunities to learn themselves about complexity of human learning, avoiding "knowledge inertia" and gaining enough experiences in successful "far learning transfer". Knowing and managing this complexity is the first step and *condition sine que non* for successful learning. Those opportunities are commonly absent in traditional physics courses that are focused, both in teaching-learning practice and exams, on algorithmic formula-based problem solving. Being so, it's not a surprise that in-service physics teachers, even those with PhD in physics, may show themselves poor performances in tasks related to critical thinking (Viennot & Décamp, 2020). Only those

physics teachers who experienced themselves self-regulated learning will be able to help their students to know, practice and improve their learning skills.

“Powerful, passionate, accomplished teachers are those who... focus on students’ cognitive engagement with the content of what it is that is being taught.” (Hattie, 2012, p. 19).

“Teachers are successful to the degree that they can move students from single to multiple ideas then to relate and extend these ideas such that learners construct and reconstruct knowledge and ideas. It is not the knowledge or ideas, but the learner’s construction of the knowledge and ideas that is critical.” (Hattie, 2009, p. 37)

It is important to stress that the best predictor of high-school students’ critical thinking in physics learning is their metacognitive self-regulation (Gurcay & Ferah, 2018). The same is true in mathematics education: students who learn metacognitive strategies through personal experiences have better performances both on routine textbook problems and on complex, unfamiliar and nonroutine tasks than those in the control groups whose teachers don’t promote metacognition (OECD, 2014, p. 121). In online learning environments, students’ self-regulation behavior leads to better academic achievements, with scaffolding (Valencia-Vallejo et al., 2019) or without it (Ejubović & Puška, 2019).

Students’ metacognitive experiences and dispositions are necessary preconditions for learning specific skills of critical and creative thinking, crucial elements of all versions of “knowledge management” in real-world personal and professional activities. Practicing consciously and improving procedurally these skills require enough number of adequately designed tasks.

Unfortunately, physics textbooks, that shape practices of teaching and learning, aren’t very helpful. Only one of best-selling textbooks introduced so-called “impossibility problems” that are designed for activation of critical thinking (Serway & Jewet, 2014). A situation is verbally described, a related partial numerical information is given, and no question is asked. Students themselves must determine what needs to be calculated and why the situation is impossible.

Regarding creativity tasks, the absence is even worse. No single physics textbook promotes explicitly creative thinking by asking students to find different solution paths for some physics problem. Such an approach in mathematics education gives very promising results. Namely, a third-grade math teacher in China asks her students to accurately solve presented word problems, encouraging them “to come up with as many solutions as possible” (Niu & Zhou, 2017). As a result of such a pedagogical design, in a motion problem the students generated 15 novel and mathematically accurate solutions.

In this study students’ performances were explored in two specific learning tasks: critical analysis of a defective electrostatic exercise and creative explanation of a “magical” situation. Students were much better in the first than in the second tasks.

Based on these results, it is suggested that schools and university should provide regularly, both in learning and evaluation phase, the tasks that call explicitly for critical considerations of problems’ situations, data and questions in order to prepare students for real-life “knowledge management”. When such an approach is implemented, there are even physics freshmen who show very good performance, finding, without teacher help or hints, data errors in one of the best physics textbooks in the world (Halliday, Resnick, & Walker, 2009). One example is related to an impossible sphere with radius of 3 cm and

mass of 6 kg, mentioned in an exercise related to terminal speed. The density of such a sphere would be two times bigger than the density of osmium, the densest material on Earth (Slisko, 2017). The process of checking given numerical data in physics problems is today much easier with use of search engine like Google and students use it spontaneously.

Analysis of results of the mentioned tasks suggests that a hint and a slight redesign might be welcome. In the case of impossible electrostatic cling, to improve students' performances, they will be asked explicitly to try to demonstrate by a simple numerical calculation that the charge allegedly created is too big. In the case of magically sunken tomato, instead of showing to students only initial and final photo, it might be effective to show them a video in which a neodymium magnet (hidden in hand) attracts and leads the tomato to the bottom. By doing so, students would not persist in trying to explain tomato's behavior by using the concept of density and many would be (very likely) able to active the explanatory idea of magnetic attraction ("far transfer"). In addition, social idea sharing through group discussion could foster students' collective creativity (Lim et al., 2019; Lee et al., 2019). The effects of such a hint and redesign will be explored in a future version of the course.

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