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Thought Experiments in Teaching Free-Fall Weightlessness: A Critical Review and an Exploration of Mercury's Behavior in "Falling Elevator"

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ABSTRACT
Different "thought experiments" dominate teaching approaches to weightlessness, reducing students' opportunities for active physics learning, which should include observations, descriptions, explanations and predictions of real phenomena. Besides the controversy related to conceptual definitions of weight and weightlessness, we report another controversy regarding the position of the person that weighs herself or himself in a freely-falling elevator, a "thought experiment" commonly used for introducing the concept of weightlessness. Two XIX-century "thought experiments", one from America and one from Russia, show that they have a long tradition in physics teaching. We explored experimentally a "thought experiment" that deals with the behavior of a mercury drop in a freely-falling elevator. Our experimental results show that the mercury drop neither took the expected spherical shape nor performed oscillatory motions predicted by theory. Teachers should encourage students to enrich active learning of weightlessness by thinking how to test experimentally the answers to some conceptual questions, a subclass of "thought experiments".
Keywords: Active learning, pedagogical content knowledge, scientific "habits of mind", thought experiments, weightlessness in physics textbooks

INTRODUCTION

Recent advances in physics education were possible thanks to robust results resulting from many studies related to physics learning and teaching (McDemott & Redish, 1999; Thacker, 2003):

(1) Students have "strong" or "soft" alternative conceptions about all studied physical concepts and phenomena whose presence can be detected in some

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State of the literature

- Documental investigations on physics textbook treatments of weightlessness testify that there is no agreement between authors on a "scientific" definition of weight and weightlessness. For those who define weight "gravitationally", the weightlessness of floating astronauts is "apparent", while authors who define weight "operationally" consider weightlessness as real.
- Research on students' conceptual understanding of weightlessness has been carried out almost exclusively with a focus on floating astronauts in spaceships. The most common alternative conception is that the astronauts float because there is no gravity.
- There are very few studies on how students conceptualize weightlessness phenomena in freely-falling systems that are feasible for classroom exploration.

Contribution of this paper to the literature

- We provide evidence that physics textbooks (1) introduce the concept of weightlessness using a controversial "thought experiment" (person on scale in freely-falling elevator), and (2) formulate conceptual questions related to physical events in situations beyond the students' practical experience.
- We argue that such an approach is adverse to students' active learning of weightlessness phenomena that should be based on different types of feasible experiments.
- By experimental exploration of a "thought experiment", we've shown that theoretical predictions should be taken always cum grano salis. We believe students are able to carry out similar experimental explorations of events described in conceptual questions.

physics domain by established "concept inventories" (Hestenes, Wells & Swackhamer, 1992) or "conceptual surveys" (Maloney *et al.*, 2001).

(2) Those tests show that traditional lecture-based teaching is unable to improve many flaws in students' conceptual understanding.

(3) Designs of active physics learning are the most promising teaching strategies for feasible improvements of conceptual understanding (Meltzer & Thornton, 2012; Hake, 2007).

In effective active-learning sequences, the experiments, actually performed by students or by teachers, play a crucial role. Thanks to them, students learn to know, without being told, what really happens in studied physical phenomena and in their further modifications. Depending on its place in students' learning, an experiment can be (a) an "observation experiment" (students observe a phenomenon, determine its main features and propose different explanations for the phenomenon), (b) a "testing experiment" (students, alone or helped by their teacher, propose experiments to test their explanation scheme through logically-derived predictions), and (c) an "application experiment" (students propose new experiments to further test a provisionally accepted explanation) (Etkina *et al.*, 2002; Etkina & van Heuvelen, 2007; Etkina, Gentile, & van Heuvelen, 2014).

When students investigate physical phenomena in such a way they develop important "habits of mind" that make scientific work possible (Etkina *et al*., 2010) and are necessary for having more creative problem-solvers and decision-makers in today's societies (Etkina & Planinšič, 2014).

During the last three decades, philosophers of science were paying considerable attention to the role of "thought experiments" in development of scientific knowledge (Brown, 1991; Sorensen, 1992). Consequently, many physics and science educators were analyzing conceptual meaning and educational potentials of thought experiments, stressing their importance for introducing the "*nature of science*" into physics curricula and students' learning of school physics (Helm, Gilbert & Watts, 1985; Reiner, 1998; Gilbert & Reiner, 2000; Reiner & Gilbert, 2000; Reiner & Gilbert, 2004; Reiner, 2006; Galili, 2009). After a careful analysis of many definitions found in the literature, Galili defines a "thought experiment" as "a set of hypothetico-deductive considerations regarding phenomena in the world of real objects, drawing on a certain theory (principle or view) that is used as a reference of validity" (Galili, 2009, p. 12).

Velentzas and his collaborators carried out an important initial work on the implementation of some historical "thought experiments" (TE in what follows) in physics teaching and learning. They started by revising the presence and the forms of TEs in physics textbooks and trade books dealing with science popularization (Velentzas, Halkia & Skordoulis, 2007). Later they were able to show that a few historical TEs have a great potential to make possible learning of different, conceptually-demanding physics topics, such as elementary quantum theory (Velentzas & Halkia, 2011), satellite physics (Velentzas & Halkia, 2013a) and basic relativity (Velentzas & Halkia, 2013b).

In Section 2, we present a polemic applicative TE, imagined by Pascal and exposed to a strong critique by Boyle. Possible sources of errors in elaboration of TEs are described, too. Section 3 provides a brief argument why public understanding of weightlessness is important. In Section 4 we report a conceptual controversy related to some fine details of the "thought experiment" with a freely-falling elevator that is commonly used for introducing the concept of weightlessness and formulation of some of conceptual questions. In Section 5, two old "thought experiments", dealing with the unlikely behavior of falling liquids, are briefly described and commented. Section 6 brings an account of different experiment recreations of an "applicative TE" related to the behavior of a mercury drop in a free-falling elevator. In the closing section, we formulate some implications of our results for better teaching and learning of free-fall weightlessness.

AN INSTRUCTIVE APPLICATIVE THOUGHT EXPERIMENT: BOYLE VS. PASCAL

Important and far-reaching "thought experiments", that strongly attracted the attention of philosophers of science, are relatively rare because they mark "death of old theories" or "birth of new theories". Brown (1991) calls them "destructive TE" or "constructive TE". More frequent in daily scientific work are modest "applicative TE" in which scientists explore conceptually and mathematically what should happen in a particular situation if an established theoretical model is applicable.

Similarly, physics textbook authors and teachers commonly ask students to try to carry out mini "applicative TEs" by posing "conceptual questions". Students' tasks are to provide justified qualitative predictions about the course of physical events in different situations, from slightly modified ones that students know to those that are completely new to them.

The popularity of these questions got a strong boost by the books of Hewitt (1971, 1993), Epstein and Hewitt (1979), and Epstein (2002), skillful and convincing advocates of the pedagogical *credo*: Conceptual understanding should be practiced and learned before numeric and algebraic manipulations. In the article, based on his Millikan lecture (Hewitt, 1983), Hewitt stressed:

> *Physics is easy to teach mathematically, but we make a mistake by then assuming it is easy to learn mathematically… By conceptual physics I mean a qualitative study of the central concepts of physics with emphasis on mental imagery that relates to things and events that are familiar in everyday environment… A physics student who lacks a conceptual understanding of physics and who is working physics problems is akin to a deaf person writing music or a blind person painting.*

Epstein (2002) went much further: "Algebra is a wonderful invention. It enables fools to do physics, without understanding."

Conceptual questions were present sporadically in physics textbooks, at least, two decades before the time of Hewitt and Epstein. Some of them show potential negative effects if students' learning is supposed to happen only at the conceptual level:

> *"Two tall cylinders are filled with liquid to the same height. One contains water, the other mercury. In which cylinder is the pressure greater at a given depth? If small holes are opened in the wall halfway up the cylinders, from which will the liquid emerge at higher speed? Which jet will travel further before striking the table top?" (Weber, White & Manning, 1952, Question 17, p. 207)*

Only in an ideal situation, both water and mercury jets would have the same emerging speed and the same horizontal range (the liquid density does not appear in Torricelli's formula for efflux speed). In a real experiment, the "correct" answers might be different. For instance, the mercury jet might have a longer range because it is less affected by air friction. In addition, some students might base their prediction using some uncritically accepted ideas: "emerging speed of mercury jet is bigger because the mercury has bigger pressure at the hole" or "heavier mercury jet falls faster and, in consequence, it has shorter range." If a "testing experiment" is not carried out, as it commonly happens, then such students would not have a chance to conclude by themselves that real experiments disprove some of their ideas. Instead of learning to construct "a truth" through an interplay between internal thinking and external discussions and observations, they might rightly switch off their authentic thinking and wait to be told what "the truth" is or should be.

Having in mind what we will discuss later, a well-known historical episode is worth presenting in detail. In his important initial treatise on equilibrium of liquids, Pascal presented an account of a particular event:

> *… If a man sets one end of a glass tube twenty feet in length upon his thigh, and then sits down in tank full of water with the upper end of the tube just emerging (**Figure 1**), his flesh will rise under the mouth of the tube and a big and painful swelling will be formed there, as if his flesh were sucked up as it is in the process of cupping. The weight of the water compresses his body everywhere save at the mouth of the tube, where the water cannot reach since it is kept away by the walls of the tube. The flesh is driven from where it is compressed to the spot where it is not compressed. The higher the water-level, the greater the swelling. On withdrawing the water the swelling disappears, just as it does if water is poured down the tube; for as the weight of the water then bears upon that spot as well as everywhere else, there is no more swelling there than elsewhere. (Pascal, 1663, Chapter VI "On immersed compressible bodies", pp. 32-33).*

Perceiving this report as a paradigmatic exercise of a "mathematical mind" that pays no attention to practical details, Boyle expressed doubts about the authenticity of Pascal's "experimental report" and stressed his methodological disagreement. Here we present Boyle's strong words in old English:

Figure 1. Drawing that illustrated Pascal's account of a possible demonstration of hydrostatic pressure

> *First, Because though the Experiments he mentions be delivered in such a manner, as is usual in mentioning matters of fact; yet I remember not that he expressly says that he actually try'd them, and therefore he might possibly have set them down as things that must happen, upon a just confidence that he was not mistaken in his Ratiocinations…*
>
> *Secondly, Whether or no Monsieur Paschall ever made these Experiments himself; he does not seem to have been very desirous, that others should make them after him. For he supposes the Phaenomena he builds upon to be produc'd fifteen or twenty foot under water. And one of them requires, that a Man should sit there with the End of a Tube leaning upon his Thigh. But he neither teaches us how a Man shall be enabled to continue under water, nor how in a great Cistern full of water, twenty feet deep, the Experimenter shall be able to discern the alterations, that happen to Mercury and other Bodies at the Bottom.*
>
> *And Thirdly, These Experiments require not only Tubes twenty feet long, and a great Vessel of at least as many feet in depth, which will not in this Countrey be easily procured, but they require Brass Cylinders, or Pluggs, made with an exactness, that, though easily supposed by a Mathematician, will scarce be found obtainable from a Tradesman. (Boyle, 1666, pp. 4-6)*

The moral of this historical episode, especially important for physics teaching and learning, is that an "applicative TE" should always be presented as an event that *might likely happen* and never as an event that *must inevitably happen*. The worst case occurs when an impossible or unlikely physical event is presented verbally as an event that *has "actually" happened* in the real world. It seems that Boyle considered that, due to technological and contextual limitations, the event, so vividly described and justified by Pascal, belonged more to the world of theoretical ideas and less to the world of experimental facts Boyle so fervently advocated.

Whether an experimental recreation of an event will have features that are identical or close enough to the predicted features of a theoretical "applicative TE" depends on two considerations:

(1) How correct are the explicit and implicit assumptions that were made about the situation in question?
(2) How feasible are technological "replicas" of these assumptions?

Reiner (1998) and Reiner and Burko (2003) have shown that constructive TEs, even when elaborated by capable physicists, can lead to erroneous conclusions if they do not contain realistic assumptions or features of the world. They considered that the most common errors are caused by Intuition, Incompleteness and Irrelevancy:

1. Intuition may override the conventional theoretical framework. Novel ideas are indeed frequently judged based on our prejudices.

2. **2.** Incompleteness of the set of assumptions concerning the imaginary world of a TE. Omission of a crucial generic ingredient may indeed lead to erroneous conclusions.
3. **3.** Irrelevancy of assumptions that were included in the features of the imaginary world in the TE. If such are included, the logical conclusions of the TE may not be relevant for natural phenomena.

Galili (2009) also comments on the erroneous elaboration of TE in physics history and connects the failure of a TE with "deficient logic" or with "incorrect application of the theory".

When dealing conceptually with situations of free-fall weightlessness, either in predictive or explanatory tasks, students are prone to make different types of errors. The most important are those that are consequences of "correct application of incorrect conceptions" (Slisko, 2014; Balukovic, Slisko & Corona, 2015b; Balukovic & Slisko, 2016a; Balukovic & Slisko, 2016b). For example, students think that a water jet stops flowing out of a freely-falling bottle because the water moves up and places itself above the hole. Their "reason" is that the water is "heavier than the bottle and falls slower".

For design and implementation of effective active learning sequences, it is important that experimental recreations and observations of studied situations are practically feasible, either with common items (Etkina & van Heuvelen, 2007) or with use of computer-based measuring tools (Sokoloff & Thornton, 1997). Only then, students can compare their ideas and conceptual frameworks with reality and, in the case of perceived incompatibility, improve their way of thinking and further develop scientific "habits of mind".

Otherwise, students would "learn" about the right knowledge in a passive way, by being told, through an authoritative voice (of a teacher or a textbook author) what is correct and what is not. This outcome was described by other researchers, too: "When science is presented as an unequivocal and unquestionable body of knowledge, students lose motivation to actively pursue truth choosing instead to passively assimilate answers to questions they never asked." (Henderson et al., 2015)

THE IMPORTANCE OF WEIGHTLESSNESS: FROM BASIC RESEARCH TO PUBLIC CURIOSITY

Long before the era of space flights began, weightlessness phenomena were brought to the general public through their descriptions in science-fiction literature. Some of these descriptions were scientifically wrong. For instance, in the book "From the Earth to the Moon", written by Jules Verne in 1865, the concept of weightlessness was erroneously attributed only to the "neutral point" at which the attractive forces of the Earth and the Moon on Verne's imaginary spaceship, launched by a gigantic cannon, are cancelled.

Today, thanks to an ever-increasing number of free-to-watch videos on YouTube, many *real* and amazing weightlessness phenomena happening in spaceships, like the International Space Station (ISS), are widely known to the general public: from a liquid ping pong game, played with a water sphere that goes up and down between two hydrophobic paddles (**Figure**

2) to a floating water ball that changes its shape when an effervescent tablet is dissolved in it (Figure 3).

Figure 2. NASA astronaut Scott Kelly shows liquid ping pong game. https://www.youtube.com/watch?v=TLbhrMCM4_0

Figure 3. A floating ball of water changes its form due to an effervescent tablet dissolved in it. https://www.youtube.com/watch?v=bKk_7NIKY3Y

Needless to say, the astronauts are not in space flights to have fun. Quite the contrary, they are there to carry out serious basic research programs in many areas of physical and life sciences (Sirignano, 1995; Robey, 2000).

Nevertheless, along with its carefully planned scientific mission, ISS facilities are commonly used for education and popularization of space research (Mayorova *et at*., 2014). That is important because funding for basic space research comes mainly from taxpayers' money. People have a right to know that their money is well spent because, sooner or later, technological applications of knowledge generated by basic research would bring social and economic benefits.

Public curiosity about weightlessness is very high. That fact explains why it is possible that a new business market has been established and it is in expansion. Namely, both in Europe and America, there are companies that sell airplane flights in which buyers can have first-hand experience of weightlessness. Some fans of weightlessness even organize their "weightless wedding" (http://www.weightlesswedding.com).

CONTROVERSIAL THOUGHT EXPERIMENT AND CONCEPTUAL QUESTIONS FOR TEACHING WEIGHTLESSNESS: INDIRECT INDICATORS OF A "PEDAGOGICAL CONTENT KNOWLEDGE" IN CONSTRUCTION?

For such a topic, that is technologically important, conceptually challenging for the general public and taught for a long time, one would expect that the teaching community has developed a well-structured and verified "pedagogical content knowledge (PCK)" (Shulman, 1986; Shulman, 1987; Etkina, 2010) for teaching weightlessness successfully. Such a complex construct, that makes good physics teaching possible, should contain, at least, knowledge about (i) clear conceptual and representational network around weightlessness, (ii) related research-based students' alternative conceptions and learning difficulties and (iii) specific classroom-proven teaching strategies that help students to overcome these difficulties.

Although one can find some published studies about different elements of PCK that prospective physics teachers reveal in the classroom (Halim & Meerah, 2002; Sperandeo-Mineo, Fazio, & Tarantino, 2006) or how PCK can be generated in the preparation of physics teachers (van den Berg, 2015), these were not focused on teaching weightlessness.

In a recent report "*Transforming the Preparation of Physics Teachers: A Call to Action*" (Meltzer, Plisch & Vokos, 2012), there is an important recommendation: "Teaching in physics courses at all levels should be informed by findings published in the physics education research literature."

In the case of weightlessness, it might turn out to be a recommendation that is hard to follow because a completed, generally recognized and research-based PCK for teaching that topic does not yet exist. Being so, the teaching of weightlessness is shaped, at least partially, by personal pedagogical intuitions and tastes of textbook authors that have not been exposed to any sort of experimental testing. Namely, thanks to pre-publishing reviews and professional feedback after their usage in teaching, both processes planned and carried out by publishers, the content of physics textbooks represents a middle point between personal tastes and intuitions of authors and tacitly established instructional "standards" of the teaching community.

Such "standards" are very resistant to change, even when some their elements are proven to be controversial. That is the case for the coexistence of conflicting "gravitational" and "operational" definitions of weight in physics textbooks that was very well documented by Galili (Galili, 1993; Galili & Kaplan, 1996; Galili, 2001). He also demonstrated experimentally that an "operational" definition leads to better students' learning of weightlessness.

In a recent documental research, carried out with twenty introductory college physics textbooks, it was found that language-related issues, such as different, inconsistent, or ambiguous uses of the terms “weight”, “apparent weight,” and “weightlessness,” were prevalent (Taibu, Rudge & Schuster, 2015). The physics of the related constructs was not always clearly presented, particularly for accelerating bodies such as astronauts in spaceships, and the language issue was rarely addressed.

In addition, real experimental demonstrations and active-learning sequences are commonly absent from the physics textbooks. As far as a pilot textbook revision could find out, only in three of 37 American physics textbooks for university-level students are informed about a well-known demonstration of free-fall weightlessness (water jet stops flowing out of a freely-falling bottle) or are supposed to carry out a corresponding “observation experiment”. In both cases, they are asked to explain why the water stops flowing out.

It is a strange situation because up to now, there were many published weightlessness demonstrations in the educational journals and booklets suitable for being pedagogically used in the classroom or in the schoolyard, with less or more technological support (Kruglak, 1962; Kruglak, 1963; Chakarvarti, 1978; Smith, 1989; Vogt & Wargo, 1992; LaCombe & Koss, 2000; Corona, Slisko & Planinsic, 2006; Slisko & Planinsic, 2010; Slisko & Corona, 2011; Ayala, Slisko & Corona, 2011; Balukovic, Slisko & Corona, 2015a; Balukovic, Slisko & Corona, 2015b; Mayer & Varaskina, 2015)

Physics textbook authors commonly introduce the concept of apparent or real weightlessness through a “thought experiment” in which a person measures her/his weight with the help of a spring balance in a free-falling elevator (Cutnell & Johnson, 2004, pp. 94-95; Giancoli, 2005, p. 124; Walker, 2007, p. 126;Young & Freedman, 2008, p. 145). Closer analysis of textbook drawings, that represent the positions of the person and the spring balance in a freely-falling elevator, shows that there is no consensus in the teaching community about what should happen physically with the person in such a “thought experiment”.

Some drawings visualize the idea that the person and the spring balance would float in midair (after being launched upward by the elevator floor) (Hewitt, 2010, p. 243; Katz, 2016, p. 139). From other drawings, one should conclude that the person would be still standing on the spring balance that maintains contact with the floor (Cutnell & Johnson, 2004, pp. 94-95; Wilson, Buffa & Lou, 2007, p. 253). So, these controversial drawing differences, when added to the known differences in gravitational and operational definitions of weight and true and apparent weightlessness (Taibu, Rudge & Schuster, 2015), provide disturbing evidence that even “content knowledge” is not yet in its universally accepted form.

An imaginary, freely-falling elevator is used as a context for posing conceptual questions, too. Good examples are those questions related to the behavior of released heavy and light objects. Students know their different behaviors in a normal gravitational environment. For instance, a heavy ball falls downward while a helium-filled balloon rises upward. Information provided to students in describing the task usually differs.

Hewitt describes what happens to the ball and asks a prediction about the future behavior of the helium-filled balloon:

If you release a ball inside a freely-falling elevator, it stays in front of you instead of "falling to the floor" because you, the ball, and the elevator are all accelerating downward at the same acceleration, g. If you similarly release a helium-filled balloon, the balloon will

- **a)** also stay in front of you
- **b)** press against the ceiling
- **c)** press against the floor. (Hewitt, 1993, Fourth question for Chapter XIII)

Eisenkraft (2000) provides a drawing of a girl and a boy in an elevator at rest. The girl holds a balloon on a string that floats near the ceiling. Students should infer that the balloon is helium-filled. The boy holds an anvil. The conceptual task for students is: "If the elevator were in free fall, predict the direction that the balloon and the anvil will move once they are released. Provide an explanation for your prediction." (Eisenkraft, 2000, p. 123)

The general inclination of textbook authors toward "thought experiments", which are adverse for active learning of weightlessness, can be illustrated by further examples. Even when the absence of a buoyant force in freely-falling water can be relatively easily demonstrated by an "observation experiment" (Kruglak, 1963, Slisko & Planinsic, 2010), students are given conceptual questions that bear the strong flavor of "thought experiments":

> *"Suppose that an orbiting space station of the future had a swimming pool in it. If there is no artificial gravity, would a buoyant force be exerted on a swimmer? Explain." (Cutnell & Johnson, 2004, p. 329)*

> *"A block of wood floats half submerged in a container of water. If the same container were in an Earth-orbiting satellite, how would the block float? Explain your reasoning." (Jones & Childers, 1999, p. 336)*

So, textbook authors, in the case of weightlessness, are more likely to invent hard-to-carry-out "thought experiments" than to recommend to teachers and students feasible "observation experiments" published in the pedagogical literature.

Textbooks' situations in research on students' understanding of weightlessness

Researchers who explore students' understanding of weightlessness have taken situations related to spaceships or freely-falling elevators from textbooks and integrated them into research instruments. For example, Sharma and her collaborators (Sharma *et al*., 2004) used in their investigation the following explanatory task:

> *In a spaceship orbiting the earth, an astronaut tries to weigh himself on bathroom scales and finds that the scale indicates a zero reading. However, he is also aware that his mass hasn't changed since he left the earth. Using physics principles, explain this apparent contradiction.*

Their conclusions contain a timid suggestion for a necessary revision of informally established "standards" for teaching weightlessness:

> *It is apparent from our results that many students find it acceptable to say that gravity (whatever that may be) is effectively zero inside an orbiting spacecraft. On the other hand, the orthodox version of school physics denies the validity of that conception…It makes sense to suggest that school and university physics should be restructured to accommodate the widespread student view. One way of doing that would be to start with an operational definition of weight … as the quantity that is measured by a spring scale, so that the weight of the astronaut becomes zero by definition.*

In fact, students' idea of "zero effective gravity inside an orbiting spacecraft" should not be at all classified as an unscientific "alternative conception". Quite the contrary, the "principle of equivalence" makes it a regular physical account of events happening in freely-falling systems in a gravitational field. According to Pais' book "Subtle is the Lord", in an unpublished article on development of general theory of relativity, Einstein wrote about the "happiest thought" of his life:

> *The gravitational field has only a relative existence in a way similar to the electric field generated by magnetoelectric induction. Because for an observer falling freely from the roof of a house there exists - at least in his immediate surroundings - no gravitational field... Indeed, if the observer drops some bodies then these remain relative to him in a state of rest or of uniform motion, independent of their particular chemical or physical nature (in this consideration the air resistance is, of course, ignored). The observer therefore has the right to interpret his state as 'at rest.' (Pais, 2005, p. 178)*

Einstein and Infeld elaborated further for the general readers the same idea about the "relative existence" of a gravitational field. In their book "The Evolution of Physics" they stressed that descriptions of physical phenomena in a freely-falling elevator by an outside observer on the Earth and an internal observer in the elevator are different but equally consistent: "The gravitational field exists for the outside observer, it does not for the inside observer. Accelerated motion of the elevator in the gravitational field exists for the outside observer, rest and absence of the gravitational field for the inside observer." (Einstein & Infeld, 1961, p. 217).

It seems that the "principle of equivalence" and the "relative existence" of a gravitational field should be taken seriously into account in order to revise the problematic idea of "apparent weightlessness" that comes out of a dogmatic insistence that the only "scientific account" of phenomena in freely-falling systems is the specific one given by an external, Earth-bound observer.

In a study on how 75 high-school physics teachers and 28 university students understand weightlessness, Galili and Lehavi (2003) reformulated that conceptual task of Hewitt and Eisenkraft, supposing a person releases simultaneously a steel ball and a helium-filled balloon: "A passenger in a sealed free-falling elevator releases a steel ball and a helium-filled balloon… Explain the passenger's observation regarding the motion of the two objects."

It was found that 34 physics teachers (45 %) and 22 students (79 %) wrongly predicted that the helium-filled balloon would ascend. As it was said before, due to the imaginary character of the situation, students and teachers were not in a position to carry out a "testing experiment" to find out that their prediction would not fit reality.

As far as we know, there are very few studies in which students' learning tasks were related to feasible free-fall weightlessness demonstrations known from pedagogical literature. In the first (Tural, Akdeniz, & Alev, 2010) three demonstrations were used, while in the second (Bharambe, 2014) the researcher carried out five demonstrations. Surprisingly, these studies do not describe students' performance and which conceptual difficulties and alternative conceptions they revealed.

It is important to comment that in the first study (Tural, Akdeniz, & Alev, 2010) researchers explored the effects of 5E active learning strategies. Nevertheless, they started and carried out an "exploration stage" not by an "observation experiment" but with a "thought experiment", asking students about different scale readings a person would possibly register if weighing herself/himself inside an elevator in upward and downward accelerated motions. When the elevator is supposed to be in free fall, the researchers contribute to the mentioned controversy by drawing the unfortunate person and the scale as floating in the middle of the elevator. So, the inadequate treatment of weightlessness in physics textbooks affects negatively not only students' learning from those textbooks, but also the research projects that should generate knowledge whose role would be to improve students' learning!

TWO HISTORIC "THOUGHT EXPERIMENTS" RELATED TO SHAPE OF WEIGHTLESS WATER OR LIQUID

As far as we know, the first classroom demonstrations of free-fall weightlessness were designed and carried out by Professor Nikolaj Alekseevich Ljubimoff (1830–1897) of Moscow State University, during the years 1892 and 1893. Their designs and physical operation were described in a booklet with the title "About physics of systems having changing motion" (Ljubimoff, 1893). After Ljubimoff's death, these demonstrations were popularized in Germany, first in a weekly magazine on physical science (Ljubimoff, 1898) and later in a book on school experiments (Hahn, 1905, pp. 86-87).

Parts of one of Ljubimoff's devices for demonstrating weightlessness and their mutual positions at rest and in free fall are presented in **Figure 4**.

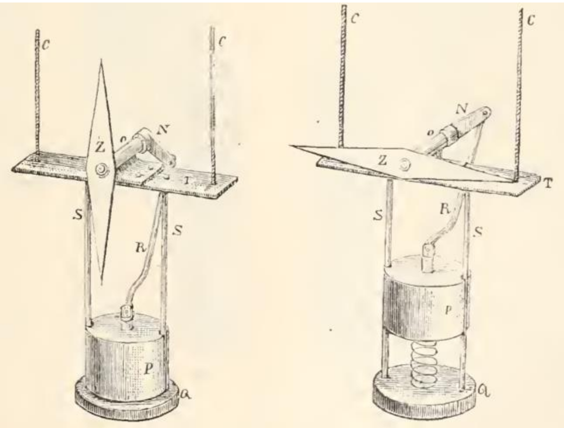

Figure 4. The parts of one of Ljubimoff's device for demonstrating free-fall weightlessness

When at rest, the cylinder P compresses a spring and a connected pointer Z is in vertical position (left side of **Figure 4**). When in free fall, the cylinder P becomes weightless, the spring lifts it up and the pointer Z takes its horizontal position (right side of **Figure 4**).

Before this experimentally-feasible type of weightlessness was known, the weightlessness of a body was imagined only for purely hypothetical situations: a body is very far from all cosmic bodies, a body is at a point where gravitational forces of cosmic bodies are cancelled out (mentioned "neutral line" of Verne) or a body is inside of a massive spherical shell.

De Volson Wood (1832-1897), American civil engineer and educator, used that last situation for proposing seemingly the first "thought experiment" related to weightlessness in American textbooks:

> *"If a vessel filled with water were placed at rest in a hollow space at the centre of the earth…, and the vessel should suddenly vanish, would the liquid disperse? Would it remain in the same form as that of the vessel before it vanished?" (Wood, 1878, p. 259)*

A very similar conceptual question was given by Gage: "If a cubical vessel filled with water were placed at rest in a hollow space at the center of gravity of the earth, and the vessel should suddenly be annihilated, what would happen to the liquid? (Gage, 1890, Problem 55, p. 4)

As Gage did not present the correct answer, let us consider the answer given by Wood: "It would not disperse, but would remain in the same form." (Wood, 1882, p. 194)

Wood obviously supposed that the weightless water was able to keep its shape. He did not know that, in a weightless condition (gravity-free environment), a quantity of water, not contained in a vessel, would be exposed only to a surface-tension force and would eventually, after a sufficient time, take a spherical form, no matter what was its initial shape.

The same idea of water-keeping-its-shape in weightlessness was presented in Russian literature, too. It is described by Yakov Isidorovich Perelman (1882-1942), the most famous Russian and Soviet writer about physics, astronomy and mathematics for the general public. He was very interested in learning about free-fall counter-intuitive weightlessness phenomena from physics textbooks he had access to. In his book "Interplanetary journeys", published in 1915, Perelman wrote the following about the behavior of a weightless liquid in free fall (Perelman, 1915, pp. 102-104):

> *"Very instructive are experiments, carried out by Kiev-University Professor G. G. de-Metz, that obviously demonstrate weightlessness of falling liquids. Liquids' property to spread out in horizontal direction is caused exclusively by their weight. Therefore, one must expect that a liquid in a falling container might not have horizontal level. Professor de-Metz has shown that by experiments. He made a special container that was divided by a vertical plate in two compartments… Water is poured into one compartment (B), while the other is left empty. In the experiment, the separating plate (A) is rapidly lifted up in the very moment when the container starts to fall freely. During all time of the fall, it is possible to observe the liquid in the container. It turns out that, while the vessel falls, the liquid, contrary to expectations, does not spread over the bottom of the vessel. Only when the vessel stops, it covers the bottom and takes horizontal level."*

The text is illustrated by a very schematic drawing of de-Metz's container and its caption text (**Figure 5**):

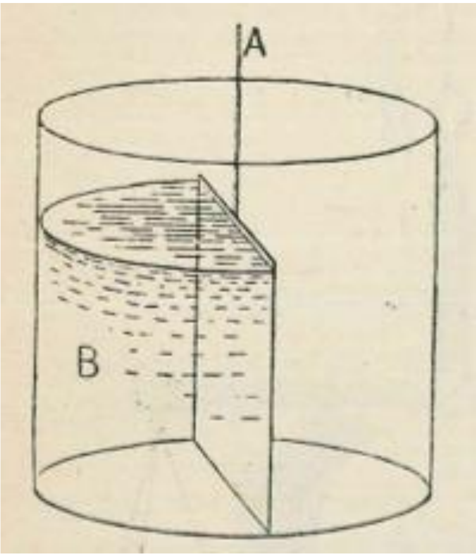

Figure 5. When the partition plate is taken away, the liquid does not spread if the vessel falls

We were not able to find the original description of the mentioned experiment to check if (a) de-Metz had given more technical details of its design, and if (b) he had provided some evidence that the experiment has been actually carried out. In Perelman's very general verbal description and quite schematic visual illustration of design, de-Metz's experiment for showing a non-spreading liquid in free fall has questionable technological feasibility. At least, any follower of Boyle's experimental philosophy might want to know the secret of the vertical separating plate with conflicting properties (it does not allow liquid to flow into the empty container part but it can be taken out instantaneously) or how it was possible to observe (unspecified!) the liquid behavior during the short and very rapid motion of the container.

As can be seen in **Figure 4**, Ljubimoff's demonstration devices had complex mechanical mechanisms in order to provide credible (although indirect!) evidence that the expected internal motions in freely-falling systems indeed took place.

Today, the fine details of weightlessness events that happen in a free-falling system can be captured in a much simpler and direct way by using fast video cameras, attached directly to the falling system (Slisko & Corona, 2011; Balukovic, Slisko & Corona, 2015a; Balukovic, Slisko & Corona, 2015b; Balukovic, Slisko & Corona, 2015c).

In the fourth edition of his book on interplanetary journeys, published in 1923, Perelman replaced the de-Metz experiment with Lyubimov's more convincing demonstrations of free-fall weightlessness.

It is interesting to note that Perelman never mentioned Lyubimov's demonstrations of free-fall weightlessness in his books on physics: "Interesting physics" (known in English translation under the modified title "Physics for Entertainment") and "Do you know physics?"

In the second book, Perelman used, seemingly for the first time, a freely-falling elevator as an appropriate context for conceptual questions related to weightlessness:

"**Question 53**

You stand on balance platform in the elevator's cabin…. Suddenly the cables break, and the cabin starts to fall at the speed of free-falling body.

a) What does the balance show during that fall?
b) During fall, will water flow out from an open inverted jug?" (Perelman, 1935, p. 21)

This particular case is very important. Namely, it shows that even those experienced and dedicated educators who know feasible demonstrations of free-fall weightlessness may have unrevealed reasons to use "thought experiments" for posing conceptual questions.

OSCILLATORY MOTON OF A MERCURY DROP IN FREE-FALLING ELEVATOR: THEORY VS. EXPERIMENT

While the situation imagined by Wood was impossible to create in the real world, the scheme suggested for de-Metz's experiment seemed very unfeasible for an experimental exploration. Being so, we decided to try to carry out a few "testing experiments" for another, relatively unknown, "thought experiment" related to free-fall weightlessness.

Theoretical prediction of mercury drop's behavior

The "thought experiment" we selected for experimental testing of its theoretical prediction was formulated by Dutch mathematician Fred Schuh (1875-1966) in 1943. Its English translation was published in 1968. The description of the situation imagined in this "thought experiment" and the predicted behavior of mercury are as follows:

> *"The cable supporting an elevator breaks, and the elevator falls. It is assumed that this occurs without friction, so that the elevator falls with the acceleration of gravity. On the bottom of the elevator lies a drop of mercury… What happens to the drop of mercury… after the cable breaks?*
>
> *If an object which initially has no velocity relative to the elevator is released in the elevator, then this object moves downward with uniform acceleration relative to the elevator shaft, and hence has exactly the same motion as the falling elevator; it thus remains floating in the elevator. Therefore, as a consequence of the breaking of the cable, a situation has arisen in the elevator just as if gravity had disappeared, and as if the bodies no longer had any weight…*
>
> *The drop of mercury, which was flattened by gravity, resumes its spherical shape since its surface tension still exists. Thus, the center of gravity of the drop of mercury moves upward relative to the elevator and retains the upward velocity thus acquired, since there are no forces that reduce this velocity. Hence the drop of mercury moves upwards in its entirety, always relative to the elevator. The form of the drop of mercury fluctuates between an oblate and a prolate spheroid. When the drop of mercury has reached the ceiling of the elevator, it is impelled back down again, and it keeps oscillating in this way between the floor and the ceiling." (Schuh, 1968, pp. 420-421)*

This prediction would make an inside observer at rest in the elevator, taking as granted the absence of a gravitational field. An outside observer on the ground, who insists on the presence of a gravitational field and the mercury weight, would have to formulate a much more complex predictive scheme.

Figure 6. Our "elevator" was a semi-open wood book whose fall was guided by four nylon springs

Exploring experimentally behavior of mercury drop in freely-falling "elevator"

The role of the freely-falling "elevator" was played by a wooden, home-made open "box" (**Figure 6**). Its dimensions are 35 cm x 40 cm x 25 cm. Four plastic strings controlled the box's free fall (height of 2.7 meters and duration of 0.73 seconds). A heavy metal sphere, attached to the ends of strings, helped ensure that the box's motion would be closer to free fall. Before "meeting" the sphere, four strings passed through a strong spring in order to reduce box's speed and avoid its crushing landing. These details are not presented in **Figure 6**.

Mercury drop is initially on a rigid surface

Supposing that the floors of real elevators are rigid surfaces, we first explored what would mercury drop do in such an initial condition.

A drop of mercury (volume 2 cm^3) was placed on a slightly concave glass surface (diameter of 6 cm), glued to the bottom of a plastic bottle (volume 250 ml). The behavior of the mercury drop in free fall was recorded by the video camera "Casio EXF1 Exilim", fixed to the box (**Figure 7a**). The initial shape of the mercury drop, as "seen" by the camera, is given in **Figure 7b**.

Figure 7a. Placing mercury on the glass surface in front of the video camera

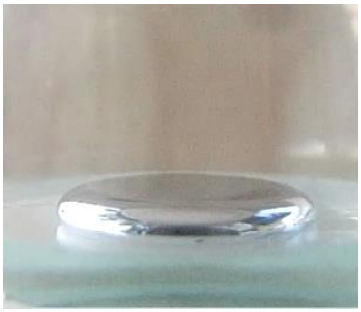

Figure 7b. Initial form of the mercury drop on glass surface as "seen" by the camera when the box is at rest

As the camera takes 300 frames per second, it was possible to have about 220 frames. Taking every tenth frame, we obtained 22 frames showing the behavior of the mercury drop in free fall.

In **Figure 8**, we present a selection of 12 frames that give visual information about how the shape of the drop was changing. A higher number for the frame corresponds to a later moment of time.

It can be seen that the mercury drop did not behave according to Schuh's theoretical prediction, namely, (1) the drop did not take spherical form, and (2) it was not launched upward sufficiently, instead being always in contact with the glass surface.

Mercury drop on an elastic surface

In the case of a rigid (hardly deformable) surface, the kinetic energy corresponding to the upward motion of the mercury drop comes only from the initial potential energy of its deformation caused by the gravity force against surface-tension forces, when the drop is at rest. To increase the drop's possible kinetic energy, more initial potential energy is needed. This can be accomplished by initially placing the mercury drop on an elastic (easily deformable) surface.

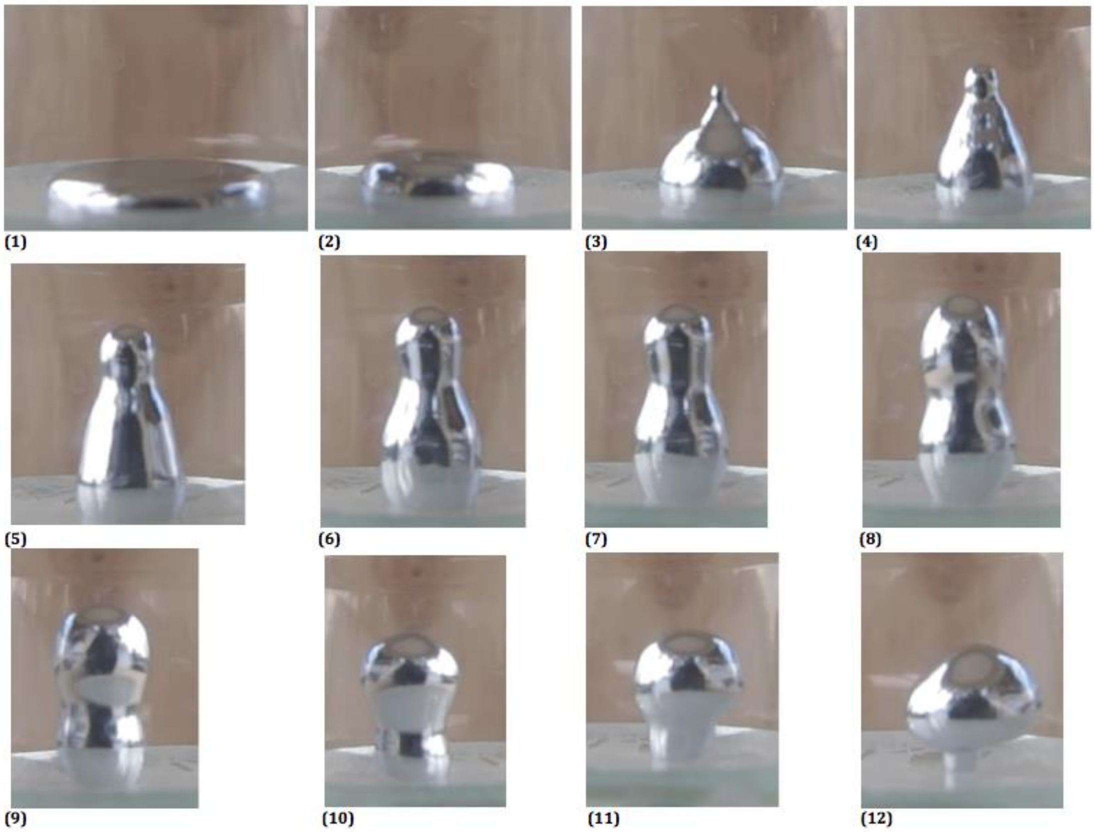

Figure 8. Changing shapes of freely-falling mercury drop that was initially on a hard surface

Such a surface was obtained by stretching a part of a surgical latex glove over a plastic cylinder. The stretched latex was tied to the cylinder by various windings of a strong woolen string.

After having such an elastic surface, a drop of mercury (2 cm^3) was placed on it (**Figure 9**). The initial shape of the mercury drop on the elastic surface, as "seen" by the camera, is given in **Figure 9b**.

Figure 9a. Placing mercury on an elastic surface in front of the video camera

Figure 9b. Initial form of the mercury drop on elastic surface as "seen" by the camera when the box is at rest

With such an initial condition, the behavior of the mercury drop in free fall was, in some details, closer to the theoretical prediction, as can be observed in **Figure 10**. A higher number for the frame corresponds to a later moment of time.

The most important difference can be noted by comparing the last frames (number 12) in **Figure 8** and **Figure 10**. Starting on a rigid surface, the mercury drop did not separate from the surface. Nevertheless, starting on an elastic surface, the drop was able to lose contact with it, at least for a very short time (frame 12 in **Figure 10**).

If getting a slight separation of "the mercury drop" and "the floor" would require designing a special "elastic floor", it is easy to imagine how many non-trivial real-world obstacles one would have to overcome to recreate the theoretically-predicted oscillatory motion of the mercury drop in the falling elevator.

Besides a frictionless free fall, hardly possible in real elevators, one would need to determine theoretically and experimentally optimal values for the quantity of mercury and the elasticity of the floor to obtain the maximal launching speed of the drop. If that speed turns out to be too low, then even one upward-and-downward motion of the mercury drop would require an overly extended falling time for the elevator.

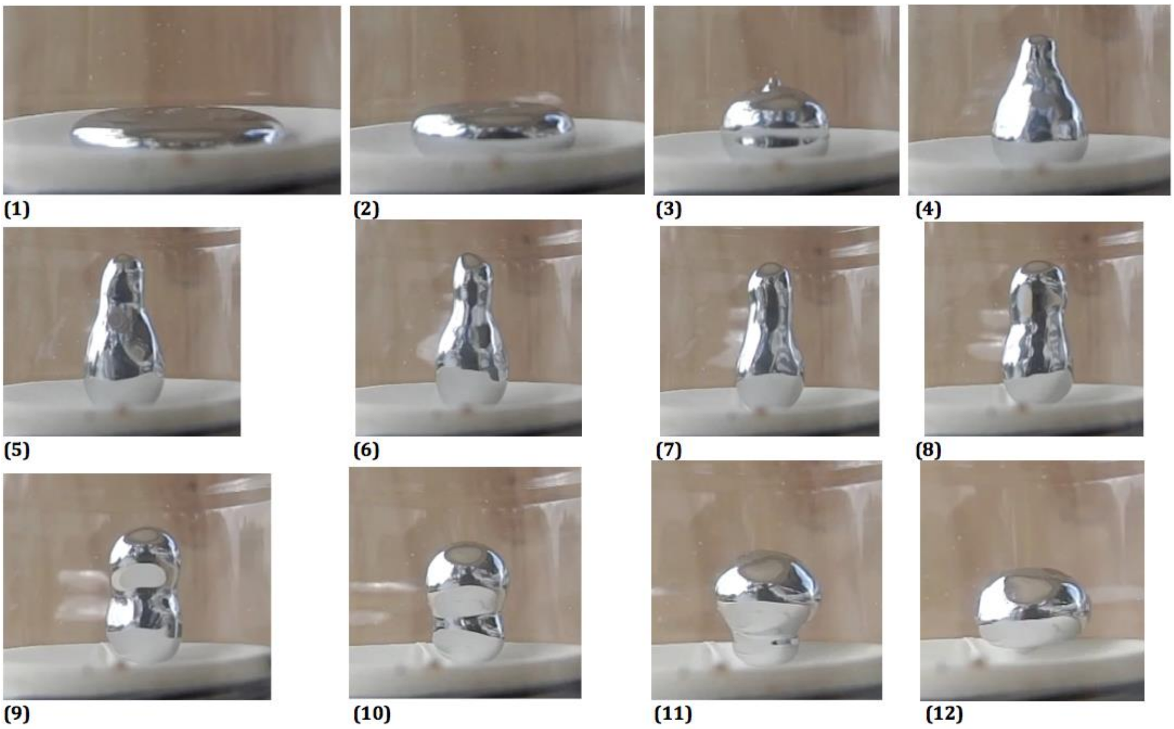

Figure 10. Changing shapes of free-falling mercury drop that was initially on an elastic surface

One might argue that the aforementioned unfeasible oscillatory motion of a spherical mercury drop in a freely-falling elevator is an exaggerated theoretical extravaganza invented by a mathematician and that such an extravaganza does not affect the teaching and learning of weightlessness.

This argument is wrong, because, like it was shown in this article, a freely-falling elevator is commonly used by physicists as an "adequate" context for introducing (apparent or real) weightlessness. In addition, in physics teaching a spherical shape of weightless mercury is presented to students as an unquestionable "empirical fact" that they are supposed to take as granted. It happens in expository texts, like the one written by MIT Professor Anthony P. French:

> *"An object that is prevented from falling, by being restrained or supported, inevitable has internal stresses and deformations in its equilibrium state. This may become very obvious, as when a drop of mercury flattens somewhat when it rests on a horizontal surface. All such stresses and deformations are removed in the weightless state of free fall. The mercury drop, for example, is free to take on a perfectly spherical shape."* (French, 1971, p. 285) (Emphasis added)

Even worse, it happens also in evaluation tests: "Mercury in a glass in weightlessness: a. Fills the whole glass also from outside; b. ***Creates a spherical shape***; c. Spills across the bottom;

d. Remains in original state." (emphasis added) (Krišťák, Němec & Danihelová, 2014, Question 20, p. 69)

If students did not have an opportunity to observe that a horizontal mercury drop in a glass at rest takes a spherical shape when the glass is in free fall, then their learning is reduced to senseless memorization of the "right answer" that will be forgotten after the test is over. As our results show, such a shape change for the mercury may be quite unlikely under the real conditions in which experiments are supposed to be carried out

IMPLICATIONS FOR PHYSICS TEACHING AND LEARNING OF WEIGHTLESSNESS

We have shown that the teaching of weightlessness, as presented in physics textbooks, is dominated by an uncritical usage of various "thought experiments". Such an approach to teaching this counter-intuitive topic is adverse for students' learning. Instead of being involved in active hands-on and minds-on exploration of some of the feasible weightlessness phenomena in free-falling systems, known from published articles in pedagogical journals, students are obliged to "learn" about these conceptually-challenging phenomena in hypothetical (and often bizarre) situations, treated theoretically with many implicit assumptions that are highly questionable.

Serious research on active students' learning of free-fall weightlessness, designed around feasible demonstrations, is practically nonexistent. That absence means that there is no research-based knowledge on students' conceptual difficulties related to classroom demonstrations of free-fall weightlessness. As it was said before, such knowledge is a very important part of PCK that is necessary for adequate design of active-learning sequences. In addition, the informally established "content standard" for teaching reflected in physics textbooks, containing controversial elements (definition of weight and position of the person in a freely-falling elevator) and wrong classification of students' ideas (gravity-free interior of orbiting spacecraft), calls for a serious reconsideration that should take into account the previously neglected Einstein's "principle of equivalence" and "relative existence" of a gravitational field. It is strange that the physics teaching community accepted that the trajectory of a moving body depends on the observer's reference frame (relativity of trajectory) but is reluctant to recognize and accept the "relativity of gravitational field".

We have demonstrated that the experimental examination of "thought experiments", like that one with a drop of mercury in a freely-falling elevator, is possible. If students are asked to carry out similar examinations of other weightlessness-related "thought experiments" (that do not imply usage of dangerous substances like mercury which are rightly prohibited in schools and colleges!), they would get a very informative insight into the dialectic of theoretical and experimental research methodologies in physics learning, which are important for systematic cultivation of scientific "habits of mind".

Our experimental tool (freely-falling, string-guided home-made box with attached video camera) was already used in teaching weightlessness in informal settings (Dooling, 2014) and in students' research projects, designed to explore experimentally their theoretical predictions related to different weightlessness phenomena (Vreeland, 2002). One of these students' projects was related to the behavior of a helium-filled balloon in a gravity-free environment established in a freely-falling box (a real-world reenactment of the "thought experiment" used by Hewitt, Eisenkraft, Galili and Lehavi). The balloon was attached by a string to the box's floor and, due to the action of the buoyant force of air, stretched it when the box was at rest. Students expected that in free fall the balloon would try to ascend additionally, stretching the string even more. The "testing experiment" was actually performed and had disproving and surprising outcome: in free fall the balloon fell on the floor "like a rock". In such a way, students have checked one of their own ideas and have gotten an unforgettable answer to a question they have asked! If active learning of weightlessness, based on the experimental exploration of feasible events in free-falling systems, replaces a considerable part of the learning activities dealing exclusively with "thought experiments", then authentic learning episodes, like the one described above, would not be an exception but rather would become a common part of students' classroom experiences.

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