Students' explanations of events in an electrostatic demonstration of free-fall weightlessness: An initial taxonomy of explanatory models and their features

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Abstract

Scientific explanations were always considered as an important product of scientists' collective work. Recently, in reform trends in science education, there are repeated claims that students should have more opportunities to deal with scientific and their own explanations. In international evaluations of students' scientific competences, their explanatory skills are measured. In Bosnia and Herzegovina, curricular framework for 9-year primary school plans, explicitly, a students' explanatory activity related to the state of weightlessness. In this article, we report explanatory models of 347 primary and high school students, related to an electrostatic demonstration of free-fall weightlessness. We provide an initial taxonomy of these explanatory models, along with an analysis of their conceptual elaboration, argumentative structure and causal coherence. Generally speaking, in many students the quality of all these elements is not satisfactory. Students also revealed serious flaws in their understanding of "at rest" condition of a body in terms of acting forces.

Keywords: Demonstrations of weightlessness, students' understanding of weightlessness, students' scientific explanations, coherency of students' explanations, students' understanding of forces acting on a motionless body.

Resumen

Las explicaciones científicas siempre fueron consideradas como un producto importante del trabajo colectivo de los científicos. Recientemente, en las tendencias de reforma en la educación científica, se repiten las afirmaciones de que los estudiantes deben tener más oportunidades de tratar los científicos y con sus propias explicaciones. En las evaluaciones internacionales de las competencias científicas de los estudiantes, se miden sus habilidades explicativas. En Bosnia y Herzegovina, el marco curricular de los planes de la escuela primaria de 9 años, se presenta la actividad explicativa por parte de los estudiantes, relacionada con el estado de ingravidez. En este artículo, nos informan de los modelos explicativos de 347 estudiantes de la escuela primaria y secundaria, en relación con una manifestación electrostática de la ingravidez de la caída libre. Proporcionamos una taxonomía inicial de estos modelos explicativos, junto con un análisis de su elaboración conceptual, su estructura argumentativa y la coherencia causal. En general, en muchos estudiantes la calidad de todos estos elementos no es satisfactoria. Los estudiantes también revelaron graves deficiencias en la comprensión del estado "en reposo" de un cuerpo, en términos de fuerzas que actúan.

Palabras clave: Demostraciones de ingravidez, entendimiento de estudiantes sobre ingravidez, explicaciones científicas de los estudiantes, coherencia de las explicaciones de estudiantes, entendimiento de los estudiantes sobre fuerzas actuando en un cuerpo en reposo.

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I. INTRODUCTION

Two basic aims of physics are (1) to explain observed features of physical phenomena and (2) to predict –using current explanatory models– the outcomes of future, still unobserved physical phenomena. The progress in that permanent interplay between explanations and predictions is a hallmark of physics.

Although, ontological and epistemological aspects of the processes of building, revising and accepting scientific explanations are still controversial issues in philosophy of science [1], in the field of science education there is a general consensus regarding the importance of building more opportunities for students to have authentic experiences with scientific explanations.

In the book *"A Framework for K-12 Science Education: Practices, crosscutting concepts, and core ideas"*, one can read various description of scientific explanations:

"*The goal of science is the construction of theories that can provide explanatory accounts of features of the world. A theory becomes accepted when it has been shown to be superior to other explanations in the breadth* *of phenomena it accounts for and in its explanatory coherence and parsimony. Scientific explanations are explicit applications of theory to a specific situation or phenomenon, perhaps with the intermediary of a theory-based model for the system under study*" [2].

"*Scientific explanations are accounts that link scientific theory with specific observations or phenomena—for example, they explain observed relationships between variables and describe the mechanisms that support cause and effect inferences about them. Very often the theory is first represented by a specific model for the situation in question, and then a model-based explanation is developed"* [2].

After 12 years of schooling, students should be able to:

"*Construct their own explanations of phenomena using their knowledge of accepted scientific theory and linking it to models and evidence;*

Use primary or secondary scientific evidence and models to support or refute an explanatory account of a phenomenon;

Offer causal explanations appropriate to their level of scientific knowledge;

Identify gaps or weaknesses in explanatory accounts (their own or those of others)" [2].

According to another important book "Taking science to school", students who are proficient in science:

1. "1. *Know, use, and interpret scientific explanations of the natural world;*
2. *Generate and evaluate scientific evidence and explanations;*
3. *Understand the nature and development of scientific knowledge; and*
4. *Participate productively in scientific practices and discourse*" [3]

Students' explanatory and predictive skills are evaluated in the international program PISA, in which abilities to construct scientific explanations of phenomena should be demonstrated by:

"Applying knowledge of science in a given situation;

Describing or interpreting phenomena scientifically and predicting changes;

Identifying appropriate descriptions, explanations, and predictions" [4, 5].

II. HOW WEIGHTLESSNESS IS COMMONLY TAUGHT AND WHAT STUDENTS LEARN?

Amazing videos and photos of uncommon physical phenomena in spaceships (astronauts floating inside, vibrations of a floating water sphere, spherical candle flames, toys do not function as they do on the Earth,…) have caught wid public attention and provoked interest of many people in knowing better what is exactly going up there. Being so, it is not a surprise that "Weightlessness" was included among the most interesting and most important physics topics "every world leader needs to know" [6].

It is difficult to explore how weightlessness is actually taught in classrooms, unless a researcher is allowed to be there, what is a situation many physics teachers would not be happy with. The other, rather rare possibility is opened when a teacher records a video of the lecture dealing with the concept of weightlessness and publishes it on YouTube, as was done by MIT Prof. Walter Lewin [7]. That particular teaching is a traditional pedagogical discourse, delivery of the content, enriched by a few, low-tech (Figure 1) and high-tech demonstrations. Students didn't have any possibility for active physics learning, being just movable parts of classroom setting.

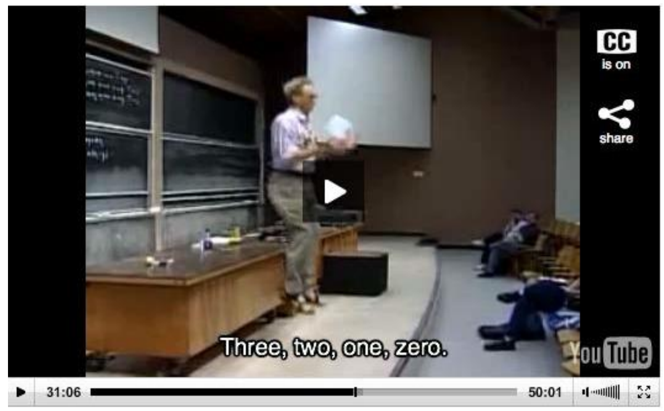

FIGURE 1. Prof. Lewin is performing a low-tech classroom demonstration of weightlessness with a gallon of water in free fall.

An indirect way to study teaching of weightlessness is to analyze how that concept is treated in various physics textbooks, supposing that the authors and those teachers, who recommend them to their students, follow the textbook approach in classroom.

In a recent documental research, carried out with twenty introductory college and university physics textbooks used in the USA, it was found that language-related issues, such as different, inconsistent, or ambiguous uses of the terms weight, "apparent weight," and "weightlessness," were prevalent [8].

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. These unresolved language issues make teaching and learning of involved concepts very difficult.

In an on-going documental research with American physics textbooks, we have found that only three textbooks [9, 10, 11] give students an opportunity for a near-ground observation of weightlessness. So, these authors go beyond common, thought-experiment-based approach to introduce the concept of weightlessness: Students should imagine a situation in which a person measures her or his weight with a scale in an elevator, that performs upward and downward accelerated motion and finally falls freely (after, the cable has broken) [12, 13, 14, 15].

The mentioned students' opportunity for hands-on and minds-on active physics learning is well known demonstration of free-fall weightlessness with plastic cup from which two water jets flow out when the cup is hold motionless and stop flowing when the cup is falling freely.

Wilson, Buffa and Lou present a photo of a plastic cup hold at from which two jets of water are flowing out. Their photo is similar to the one in the Figure 2.

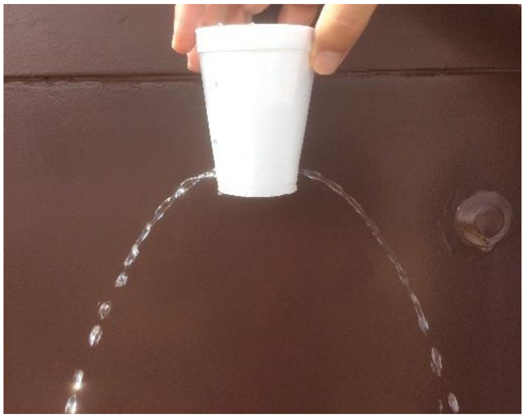

FIGURE 2. Two jets flowing out of a plastic cup.

That photo is the basis for the following explanatory question:

"*If the cup… were dropped, no water would run out. Explain*" [9].

As was already said, in the physics textbooks the concept of "apparent weightlessness" is introduced commonly with a "freely-falling elevator" and "extended" to an "orbiting spaceship". The two situations are very far from students' sensorial and practical experiences and do not represent a good learning opportunity.

In addition, a closer analysis shows that the textbook authors strongly disagree about what happens with a person weighing herself or himself in the falling free-falling elevator.

According to some authors, in free fall the person continues to stand on the balance [9, 15]. Quite contrary, other authors provide a drawing that shows that in free fall both the person and the balance float above the floor of the elevator [10].

If one adds that only three physics textbooks provide the same single opportunity to explore the phenomenon in classroom or school yard, then nobody should be surprised that students have conceptual difficulties to gain sound understanding of why and how the bodies behave as being weightless [16, 17]. Even researchers who explore the effects of active learning strategies [18], start and carry out "exploration stage" with "though experiment". They ask students about different scale readings a person would register if he weighs himself in a lift upward and downward accelerated motions. When the lift is in free fall, they take side in the controversy and draw that the unfortunate person and the scale would float in the middle of the lift. So, the inadequate treatment of weightlessness in physics textbooks affects negatively not only students' learning from those textbook, but also the research projects that should generate knowledge whose role would be to improve students' learning!

III. GENERAL AND PARTICULAR REASONS FOR CARRYING OUT THIS RESEARCH

In this section, we describe briefly general and particular reasons that were our inspiration to design and carry out the research.

A. General reasons

We noted a strange discrepancy between (1) the presence of many feasible classroom demonstrations of weightlessness and active learning methodologies and (2) almost complete absence of research reports on how students learn the concept of weightlessness exploring actively one of these demonstrations or, even better, a carefully designed learning sequence with two or three of them.

As the phenomena related to weightlessness in spaceships are so uncommon and counter-intuitive, in the last 50 years numerous articles were published in physics teaching journals, whose aim was to show that is possible to demonstrate some of these phenomena on the ground, in a classroom or in a school yard [19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31].

Many of these demonstrations could be useful for students to explore and learn actively the weightlessness phenomena.

In the NASA manual for classroom teaching of microgravity (term used instead of weightlessness), teachers are suggested to engage students in active-learning tasks (for example, to predict outcome of a demonstration before it is carried out) [23].

In science and physics education literature [32], there are many research-based designs for giving students opportunities to "learn physics by doing physics". For instance, some of these designs are:

"Interactive Lecture Demonstration" [33], that uses the sequence predict-observe-explain, or

"Investigative Science Learning Environment" [34], that employs the sequence of "observation experiment"–explanations-"testing experiment"-"application experiment".

In various implementations of active learning approach to weightlessness phenomena in a course on physics teaching [35], it was found that students' causal reasoning is much easier with the idea that inside of free-falling systems gravity force and all gravity-related forces (for instance, friction force and buoyant force) disappear, while other forces (for instance, elastic force, magnetic force or electrostatic force) are not affected if the system performs free fall. In other words, although the gravity force is responsible for free fall of the system, for an observer inside of the system the objects behave in the same way as those objects being in gravity-free environment. Such approach culminates in some demonstrations that show students' creativity [28, 35].

In spite of these favorable conditions, research literature on students' performances in active learning of weightlessness is almost nonexistent. As we could find only one study with such research goal [18], that has used three demonstrations, we decided to explore more carefully students' explanations related to six different demonstrations of weightlessness events in free-falling systems:

1. Bottle and water jet [20, 36, 37];
2. Balloon and weight with a sharp needle [23];
3. Balloon and elastic spring in water-filled bottle [26];
4. Charged balloon and aluminum sphere [30];
5. Two attracting magnets in vertical test tube [28];
6. Two attracting magnets on horizontal plastic straw [27].

In this article, we report the findings for students' understanding of an electrostatic demonstration of free-fall weightlessness (Number 4 above). Other results will be published elsewhere.

B. Particular reason

The particular reason for the study was the fact that "*Framework for teaching plan and program of 9-year long primary school in Federation of Bosnia and Herzegovina*" contemplates explicitly a learning activity in that students should "describe and explain the state of weightlessness". So, we wanted to explore what are the lasting results such an active learning task they, in principle, should have experienced in some form.

IV. METHODOLOGY AND SAMPLE OF STUDENTS

Research questions for this qualitative, paper-and-pencil study, were:

(1) What are students' explanatory models of a particular electrostatic demonstration of free-fall weightlessness?

(2) What are main features of these explanatory models?

Explanations were sought for two conceptually-related situations (the first one, when the system in question is at rest, and the second one, when the system is in free fall). The rational is twofold.

In the first task, students activate an initial causal explanatory model and later, after knowing what happened in free fall, they have a chance to revise and precise it.

So, we intentionally avoided that students start with their predictions, like in «Interactive Lecture Demonstration» [33], that is not only more demanding cognitive task but frequently leads to students' frustrations. It happens when students are always in position to observe that their predictions are not fulfilled when demonstrations are carried out. Some students, even, develop an «answering strategy» that goes like this: «I first look which of the optional answers looks more convincing to me. When I detect it, then I am sure that is an incorrect one, and and search among the rest ones which looks most unlikely. That one is the one I finally choose».

Students' working sheet (consisting of descriptive texts, photos and two related explanatory tasks), is given in figures 3 and 4.

Our primary research data were students' written answers to explanatory tasks related to stationary and free-fall situations.

The research sample consisted 347 students belonging to two groups. Primary-school group was formed by 131 students with age interval between 13 and 14 years (average age: 13 years and 7 months). Among them, were 65 girls (49.62 %) and 66 boys (50.38 %). High-school group had 216 students (56.94 % girls and 43.06 % boys), coming from the first grade, with age interval between 15 and 16 years, and from the third grade, with age interval between 17 and 18 years.

Charged balloon and sphere made aluminum foil

On the bottom of a plastic container at rest, there is a sphere made of a thin aluminum foil. The plastic container is closed by an inflated balloon. The balloon is electrically charged by being rubbed strongly against a wool fabric (**FIGURE 3**).

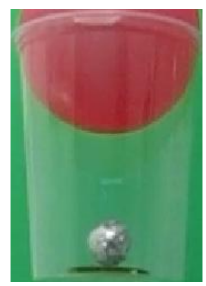

FIGURE 3. Electrically charged balloon, plastic container a sphere made of aluminum foil.

1. Why aluminum sphere is motionless at the bottom of the plastic container, although the charged balloon attracts it by electrostatic force?

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When the plastic container is allowed to fall freely, the aluminum sphere gets closer to the balloon (**FIGURE 4**).

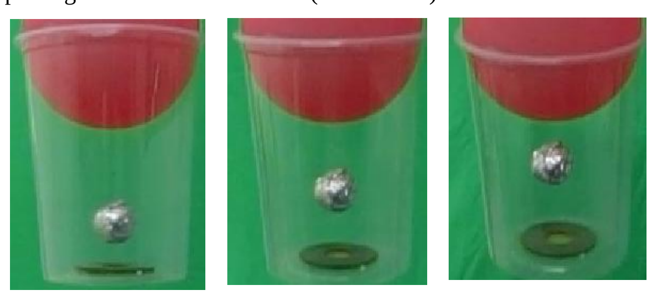

FIGURE 4. In free fall, the aluminum sphere gets closer to the balloon.

2. Why, during free fall, did the aluminum sphere get closer to the balloon?

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IV. THE MOST IMPORTANT RESULTS: AN INITIAL TAXONOMY OF EXPLANTORY MODELS AND THEIR FEATURES

Generally speaking, students' explanatory answers are frequently very short ("due to gravity" or "distance is big"), focused on only one causal factor and have a low level of conceptual argumentation.

In addition, students very rarely provide coherent explanatory models for both stationary and free-fall situations.

More common is that their causal factors are situation-specific. In other words, the situation with motionless sphere is "explained" with one causal factor and explanation of sphere's upward motion in free fall is based on other causal reasoning.

A. Explanatory models for stationary situation

The explanatory task for students was formulated through the questions:

"Why aluminum sphere is motionless at the bottom of the plastic container, although the charged balloon attracts it by electrostatic force?"

Scientific answer to this question is well known:

The aluminum sphere is motionless because there isn't net force acting on the sphere. In other words, the vector sum of all forces is equal to zero.

In this situation, three forces are involved. Two forces, electrostatic attractive force and bottom reaction force, are pointing up and gravitational force is pointing down.

Although they differ in number of schooling years, no crucial difference was observed in students' explanatory models. In both groups, students were unable to identify "bottom reaction force" as one of relevant causal factors in their explanations why the aluminum sphere is at rest. This result is in resonance with known conceptual difficulties students reveal when if asked to explain why a book on a table is at rest. Teachers should use sophisticated technology-based teaching strategies to help students overcome these difficulties [38, 39].

Only one high-school student expressed the idea of "force cancellation" as an explanation of the stationary situation (without including bottom reaction force):

"Gravity force (gravitation) acts in opposite direction with equal strength".

There were many alternative explanatory models given by the students. Many of them were focused on the causal role of only one force. If the single considered force is electrostatic force, then it is said:

"Electric force isn't strong enough to attract the sphere towards charged balloon".

Some students gave different reasons why the electrostatic force isn't strong enough: due to big distance (very frequently) or to small electric charge.

It was even found that the weakness of the electrostatic force is, in a few cases, attributed to *ad hoc* stipulated existence of the vacuum or the absence of air in the container:

"An artificial vacuum has been formed and the force isn't strong enough to pull the sphere of aluminum foil".

"Maybe there is no air, and then the force become weak".

These ideas show that known alternative conception "no air-no gravity" [40, 41] might be a part of a more general alternative conception "no air-no force".

In only-one-force causal models, unspecified role of gravity force is less frequently used:

"Because gravitational force acts".

When electrostatic and gravitational forces are used to explain at rest condition of the sphere, the last one is considered bigger or stronger:

"Aluminum sphere is at rest because mg is bigger than the force F by which the balloon is attracted."

"Because the Earth's force is bigger than the electrostatic force".

"Because the gravitational force is stronger that attraction force acting on the balloon."

Some students' explanations go against the description of the situation "charged balloon attracts aluminum sphere by electrostatic force". One approach is to "eliminate" the existence of the electrostatic force:

"Because the plastic (of the balloon) and the aluminum don't attract themselves".

"Because electrostatic force does not attract aluminum".

The other one is an *ad hoc* "conversion" of attractive into a repulsion force:

"Because they are charged with same charges".

"Because aluminum and balloon are equally charged".

B. Explanatory models for free-fall situation

The explanatory task for students was formulated by the questions:

"Why, during free fall, did the aluminum sphere get closer to the balloon?"

The conceptual structure of a scientific answer depends on the reference frame from which the event is explained.

In the reference frame attached to the ground, a qualitative explanation is: In the moment when the container starts to fall freely downwards, due to presence of the attractive electrostatic force upward and gravitational force downward, the downward acceleration of the sphere is slightly less than the free-fall downward acceleration. The balloon is under action of two downward forces: gravitational force and sphere's attractive electrostatic force and its downward acceleration is slightly bigger than free-fall acceleration.

Consequently, the balloon and the container fall faster and the balloon reaches the falling sphere.

In the reference frame attached to the falling container, a qualitative explanation is different: The interior of a free-falling system is a gravity-free space, so the aluminum sphere is only under influence of balloon's attractive electrostatic force. Consequently, the sphere moves up and gets closer to the motionless balloon (in the considered reference frame).

As in previous explanatory task, students were not able to formulate a precise scientific explanation. Only one high-school students was able to get near to explanation for the reference frame attached to the ground:

"Aluminum sphere gets closer to the balloon because it is acted by the force mg and electric force and its acceleration is smaller than g."

Only one primary-school student gave an unelaborated explanation of sphere's motion, based on different acceleration:

"The container has bigger acceleration than the sphere."

A few primary school students were able to get near to the explanation in the reference frame attached to the falling container:

"During free fall, the aluminum sphere is the state of weightlessness and electrostatic force acts strongly enough to attract the sphere toward the balloon."

"Because the sphere is in the state of weightlessness and the electrostatic force moves it slowly toward the balloon."

In this task a few differences between primary- school and high-school students were found. In their explanations, primary-school students used the concept "state of weightlessness" much more frequently than high-school students.

Additional difference is: Only in explanations formulated by high-school students, the concepts "inertia" and "inertial force" appear as single causal factors. Nevertheless, both of these frequent explanations are not commonly very elaborated:

"Because it is in the state of weightlessness.

"Inertia."

"Due to the inertia"

"Inertial force."

"Inertial force acts."

Although it is not stated explicitly, the idea of sphere's inertia was likely in minds of high-school students who explained its behavior by different motions:

"Due to different velocities. The container falls and gets speed, but the sphere is at rest and starts to move upward".

"The sphere is at rest and the container and the balloon move (downward)".

"The balloon moves, while the aluminum sphere is at rest".

Some students present very peculiar alternative models:

"Because during the free fall, the balloon gets more and more inflated and the attraction of foil happens."

"Aluminum sphere gets closer to the balloon because it is not attached to the bottom, due to its initial velocity and the charge of balloon attracts the aluminum sphere."

It seems that students' construction of explanatory models of events in an electrostatic demonstration of weightlessness is influenced by the moment at which this research was carried out. Primary-school students answered explanatory question a few months after they studied the topic of weightlessness and had (likely) an opportunity to perform a weightless demonstration with a plastic cup and water jet that does not flow out in free fall. Namely, two of five officially authorized physics textbooks suggest that students carry out that demonstrations and give an explanation why water does not flow out:

1. «Drill two small holes near the bottom o paper glass, and then fill the glass with water.
Water will flow out through the holes due its weight.
Repeat the experiment, in such a way that you drop the filled glass from a sufficiently big height. What do you observe now?
While the glass falls, the water doesn't flow out.
In the system that falls freely, the water is in the state of weightlessness» [42].

2. "Weigh plastic cup on a scale, and then fill it with water and weigh again. What do you conclude? Water exerts weight on the scale pan. Pour water in the plastic cup up to half and the drill a hole at its bottom, water will leak through the hole! Then repeat all the same and let the glass to fall! In falling the water does not come out from the cup, because it doesn't have weight." [43, p. 84]

From scientific point of view, the explanations given in the textbooks are rather superficial. Unfortunately, due to their linguistic simplicity, they are suitable for students' memorization and for short-time "transfer" to the other demonstrations.

Those high-school students, who eventually carried out the demonstration and saw the textbook explanation, forgot them and long-time "transfer" didn´t happen. They mentioned very rarely the textbook explanations "the sphere is in the state of weightlessness" or "the sphere does not have weight" in their explanations.

More frequently, a short-time "transfer" of the term "inertial force" is visible, because the moment in which the topic of "non-inertial reference frames" studied was nearer to the moment in which this research was carried out.

C. Causal coherency and argumentative structure of students' explanatory models

We also wanted to explore how coherent are students' explanatory models of the events in two related physical situations described above. Namely, the search of explanatory coherence is very important goal of science:

"…Theories in science must meet a very different set of criteria, such as ***parsimony*** (a preference for simpler solutions) and **explanatory coherence** (essentially how well any new theory provides explanations of phenomena that fit with observations and allow predictions or inferences about the past to be made). Moreover, the aim of science is to find a single coherent and comprehensive theory for a range of related phenomena. Multiple competing explanations are regarded as unsatisfactory and, if possible, the contradictions they contain must be resolved through more data, which enable either the selection of the best available explanation or the development of a new and more comprehensive theory for the phenomena in question" [2 emphasis added].

To get an initial insight into causal coherency of students' explanatory models, it is necessary to compare causal factors students used while answering ***both*** research questions:

1. Why aluminum sphere is motionless at the bottom of the plastic container, although the charged balloon attracts it by electrostatic force?

2. Why, during free fall, did the aluminum sphere get closer to the balloon?

Explanatory models are ***coherent*** if the same set of causal factors is used in both of them and the reasons are given why and how the change of one them leads to a change in behavior of aluminum sphere.

If different causal factors are used in physically related situations, then the explanatory models are ***incoherent***.

An important result in this part is that students, in almost all cases, were not able to formulate coherent explanatory models for both situations. Only a few of them got models that might be accepted, in the most generous evaluation, only as partially coherent. Here comes one example:

"**1.** Why aluminum sphere is motionless at the bottom of the plastic container, although the charged balloon attracts it by electrostatic force?

Regardless that electrostatic force acts on the sphere, it is not strong enough to attract the sphere toward the balloon.

2. Why, during free fall, did the aluminum sphere get closer to the balloon?"

During free fall, the aluminum sphere is in the state of weightlessness and the electrostatic sphere acts strongly enough to attracts the sphere towards the balloon".

To improve causal coherence, in the first situation the opposing action of gravitational force of the sphere should have been explicitly included. Doing so, it would not be necessary to invent a «magical change» of the strength of electrostatic force in free fall. The electrostatic force does not become stronger, but, during free fall, opposing gravitational force on the sphere was eliminated.

Many of students' explanatory models are explicitly causally incoherent:

Example 1 (Primary school)

«**1.** Why aluminum sphere is motionless at the bottom of the plastic container, although the charged balloon attracts it by electrostatic force?

Balloon will no attract aluminum sphere because *they are distant*. (Comment: *Distance* as causal factor)

2. Why, during free fall, did the aluminum sphere get closer to the balloon?

Due to free fall, aluminum sphere is in the *state of weightlessness* and because of it (the sphere) is attracted toward the balloon. (Comment: *state of weightlessness* as causal factor) ».

Example 2 (Primary school)

«**1.** Why aluminum sphere is motionless at the bottom of the plastic container, although the charged balloon attracts it by electrostatic force?

Because *it is the container*. (Comment: Position of the sphere as causal factor)

2. Why, during free fall, did the aluminum sphere get closer to the balloon?

Because *it is charged*. (Comment: Charge of the sphere as causal factor) ».

Example 3 (High school)

«**1.** Why aluminum sphere is motionless at the bottom of the plastic container, although the charged balloon attracts it by electrostatic force?

The *distance* too big. (Comment: Distance as causal factor)

2. Why, during free fall, did the aluminum sphere get closer to the balloon?

Inertial force. (Comment: Inertial force as causal factor) ».

Example 4 (High school)

«**1.** Why aluminum sphere is motionless at the bottom of the plastic container, although the charged balloon attracts it by electrostatic force?

Due to the *Earth's gravity*. (Comment: Earth's gravity as causal factor)

2. Why, during free fall, did the aluminum sphere get closer to the balloon?

Because of the *balloon's charge*. (Comment: Charge of the balloon as causal factor) »

It was noted that some students have an intuitive notion of coherence criterion. These students structured their explanatory models in the way that they formally coherent.

Nevertheless, their conceptual content is partially or completely wrong.

Here come two examples:

Example 1 (primary school)

«**1.** Why aluminum sphere is motionless at the bottom of the plastic container, although the charged balloon attracts it by electrostatic force?

Balloon does not have strength to attract the foil because they are at *too big distance*. (Comment: Balloon's attractive force and distance as a basic causal factors).

2. Why, during free fall, did the aluminum sphere get closer to the balloon?

Because, during free fall, the balloon gets more and more inflated and the attraction of the sphere happens. (Comment: *ad hoc* invented «self-inflating balloon» makes the *distance* between the balloon and the foil smaller and balloon's attractive force becomes strong enough to attract the sphere. Attractive force and distance are still basic causal factors. It is incorrect to suppose that a balloon can be self-inflated).

Example 2 (high school)

«**1.** Why aluminum sphere is motionless at the bottom of the plastic container, although the charged balloon attracts it by electrostatic force?

Due to *gravitation*, it has not enough force to get closer to the balloon. (Comment: Gravitation and electrostatic force as causal factors).

2. Why, during free fall, did the aluminum sphere get closer to the balloon?

Gravitation force becomes weaker and they start to get nearer. (Comment: Weaker gravitation force and unchanged electrostatic force are again causal factors. It is wrong to suppose that gravitation force becomes weaker. It is either constant in the reference frame attached to the ground or it is zero in the reference frame attached to the falling container.)

As was shown above, many students' explanations are rather short having only a few words. Consequently, they do not reveal any argumentative structure.

V. CONCLUSIONS AND IMPLICATIONS FOR TEACHING AND LEARNING

As far as we know, *this is the first research report that brings the results of real students' performances in paper-and-pencil explanatory tasks related to a demonstration of free-fall weightlessness*. These results show that in such tasks students face big conceptual difficulties leading them to formulate various alternative explanations of the events happening in stationary and in free-fall situations. Other studies, that report that the students explored actively three [18] or, even, five [44] different free-fall demonstrations of weightlessness, do not say a single word about how students did perform and which conceptual difficulties and alternative conceptions they did reveal.

This initial study has various limitations. The first one is that students neither performed the demonstration in question nor watched a video recording of it. Instead, they could learn about the events in free fall looking at the set of three photos (Figure 4). The second one is that students only had to provide a written verbal answer. If they were asked to complement their answers with a drawing (for example, a free-body diagram), we would very likely get a better insight into fine details of their causal reasoning. The third limitation is that we have only collected students' individual answers.

Nevertheless, all these limitations can be easily eliminated in carefully designed classroom implementations of active learning sequences for the topic of weightlessness. These sequences should contain, at least, three different demonstrations of free-fall weightlessness to offer students more opportunities to construct, through individual and collective efforts, a robust understanding of different physical events happening in systems that fall freely.

Teachers should discuss and co-evaluate with students "causal coherency" of different explanatory models they propose. Students also need a scaffolding help related to basic "argumentative structure" of scientific explanations, consisting of three elements: claim, evidence and reasoning [45].

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