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Thought Experiments in the Theory of Relativity and in Quantum Mechanics: Their Presence in Textbooks and in Popular Science Books

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Abstract. This work investigates the presence of Thought Experiments (TEs) which refer to the theory of relativity and to quantum mechanics in physics textbooks and in books popularizing physics theories. A further point of investigation is whether TEs – as presented in popular physics books – can be used as an introduction to familiarize secondary school students with physics theories of the 20th century. The study of textbooks and popular physics books showed that authors of both types of books consider TEs as an important tool when presenting the theory of relativity and quantum mechanics. Furthermore, a qualitative research conducted in secondary education revealed that the historical TEs which were transformed into forms accessible to the public could trigger students' interest and act as educational material to familiarize them with concepts and principles of the 20th century physics.

Key words: thought experiments, relativity, quantum mechanics, textbooks, popular physics books

1. Introduction

Thought experiments (TEs) are an integral part of scientific thought. They constitute one of the conceptual tools by which scientists study the physical world. Thus, in science education, it is of importance to help students become acquainted with them and with their role in science. In this way they will become familiar with one of the key-tools of scientific thought and they may understand better the abstract concepts of the physics theories of the 20th century.

Many people (scientists, philosophers, etc.) have worked on TEs, trying to establish their role in science and to investigate their function in the process of scientific thinking. Most of them prefer to define TEs in a descriptive manner, rather than to give a rigorous definition. Mach (1896/1976), was the first to identify TEs as one of the ways of scientific thinking: "Besides physical experiments there are others that are extensively used at a higher intellectual level, namely TEs (Gedankenexperiment)".

According to Brown (1991) TEs are experiments which are designed and "performed in the laboratory of the mind", while according to Sorensen (1992) TEs are experiments which are designed by scientists "without the intention of being performed". In addition, Gendler (2000) states that to perform a TE is "to reason about an imaginary scenario with the aim of confirming or disconfirming some hypothesis or theory" and according to Gilbert and Reiner (2000b): "TEs are reasoning processes that are based on 'results' of an experiment carried out in thought".

A number of philosophers, too, have studied the role of TEs in the course of science. Among them, Kuhn (1977) comments that TEs have played "a critically important role in the development of science" and "the historian, at least, must recognize them as an occasionally potent tool for increasing man's understanding of nature".

Trying to understand TEs' function in science better, a number of researchers have analyzed and classified TEs and have determined their characteristics so that the role and significance of TEs may be more comprehensible (e.g. Brown 1991; Sorensen 1992). In addition a conference was organized about the role of TEs in science and philosophy in Pittsburgh 1986. (Horowitz and Massey 1991).

Some research has been done on exploring the role of TEs in science education. It seems that TEs are useful tools not only for scientists but also for science teachers since they may help the mental development of students considerably. This is because some characteristics that are required of the mental experimenter such as "imagination, hypothesizing and creative thinking" are also characteristics of science teaching (Matthews 1994). TEs could prove to be powerful tools for science teaching since they develop students' creative thinking and imagination, while helping them to formulate predictions and hypotheses, and reach reliable conclusions. Moreover, since TEs have a particular role in the history of science they familiarize students with the methodology of science (Gilbert and Reiner 2000a).

A question that arises is how the scientific knowledge could be transformed into school or public knowledge. Nowadays, theories of science can be approached via a wide spectrum of formal as well as informal sources of knowledge (Wellington 1991). The informal science sources are easily accessible to students, to their teachers and to the public in general (Halkia 2003). Leading scientists (such as Einstein) have designed TEs not only for the development of their theories, but also for their presentation and communication to the public. Well known scientists (e.g. Gamow 1966, 1990; Landau and Rumer 1959) wrote popular science books, where they often use TEs to present, mainly, physics theories of the 20th century. This use contributes towards an understanding as well as creating a positive attitude to science. As Stannard (2001) comments "an early familiarity with these topics appears to be effective in attracting young people to take serious interest in physics in general". For example, Roger Penrose in his preface to a new edition of Gamow's book "*Mr Tompkins in paperback*" (1990) states that this particular book, which he read when he was a teenager, inspired him to delve into the magic of physics for the rest of his life. Therefore, popular science books may help younger students to understand physics theories of the 20th century so that later, when they have acquired the appropriate background in mathematics, can study them in depth.

Thus the focus of this work is to investigate (a) the way the TEs, which refer to the theory of relativity and quantum mechanics, are presented in textbooks (TBs) and popular physics books (PBs) and (b) if the historical TEs which were transformed into forms accessible to the public could trigger students' interest and act as educational material to familiarize them with physics theories of the 20th century.

2. TEs in Science

TEs played an important role during the scientific revolutions of the 17th and 20th century, and they still play an important role in modern physics. "This role stems, mostly, from contemporary physics in regimes unreachable by current experiments, such as Planck-scale physics or black-hole interiors" (Reiner and Burko 2003). Examples of well known TEs, in the community of physicists, are Galileo's falling bodies (Galileo 1638/1914), Newton's bucket and cannon (Newton 1729/1962a, b), Einstein's elevator (Einstein and Infeld 1938), Maxwell's demon (Maxwell 1871/2001), Heisenberg's γ-ray microscope (Heisenberg 1930/1949), Schrödinger's cat (Schrödinger 1935/1983), the E.P.R. experiment (Einstein et al. 1935) etc.

TEs were used by famous scientists for the formulation of innovative theories, the establishment of contradictions in already existing theories, the modification of the old theories according to new findings, or even for their replacement with a new theory. Specifically, according to Popper (1959/1999) the possible uses of TEs are:

(i) *critical use* (TEs criticize existing theories)
(ii) *heuristic use* (TEs lead to innovations)
(iii) *apologetic use* (TEs used as arguments in a defensive or apologetic mood)

TEs are designed and performed mentally by the scientists when investigating a physics topic. They use the imagination in setting up "thought scenery" which usually refers to familiar situations, though the conventions they require go beyond daily experiences. According to Mach (1896/1976), in TEs there is an important process of mentally diminishing one or several conditions to zero that quantitatively affect the result so that the influence of the remaining factors alone could be studied. As he has stated "the law of inertia was discovered by abstraction; thought experiment and continuous variation have led to it". Also Sorensen (1992) comments: "TEs evolved from ordinary experiments by a process of attenuation". The idealization, according to Koyre (1968), is required for the "mathematical approach to nature" which is carried out in the mind, so TEs "close the gap between empirical fact and theoretical concept". This function of TEs is essential to scientific thinking and demonstrates the synthetic nature of scientific knowledge (Koyre 1968).

Nersessian proposes that "thought experimenting is a form of 'simulative model-based reasoning'. That is, thought experimenters reason by manipulating mental models of the situation depicted in the thought experimental narrative". TEs differ from logical arguments and other forms of propositional reasoning. Reasoning by means of a TE "involves constructing and making inferences from a mental simulation". In a TE the scientist constructs a dynamical model in his/her mind and imagines a sequence of events and processes and infers outcomes. Then the scientist "constructs a narrative to describe the setting and sequence in order to communicate" the TE to others (Nersessian 1993).

Differences and similarities exist between TEs and ordinary experiments. TEs, like ordinary experiments, are driven by theory and aim at the establishment, testing, and application of theory. Also, both types of experiments are presented for evaluation by the scientific community in similar ways, for example at conferences, in journals etc. and they often have unanticipated consequences (Gilbert and Reiner 2000a). Although "in their initial stages, all experiments are TEs" (Miller 1996), TEs have some differences from ordinary experiments. TEs usually require a thought experimenter but ordinary experiments, especially in our days, are performed by a team of scientists and technicians. Also, contrary to ordinary experiments, TEs do not involve real apparatus so it is impossible for any damage to take place, or the results to be misquoted by an extraneous factor. In addition, during the performance of a TE the experimenter does not take quantitative measurements (Sorensen 1992).

From the above it follows that TEs

- do not include real apparatus and therefore the experimenter does not take into account the practical limitations of laboratory experiments;
- refer usually to conditions that go beyond every day experiences;
- use the form of narration (story telling) to be presented;
- demand the use of imagination and reasonable thinking;
- are integral part of a science theory and help towards the understanding of science theory.

3. Classification of the TEs

For a better analysis of TEs and the understanding of their role within the framework of science various classifications have been proposed.

Norton (1991), who maintains that TEs are reconstructed as arguments, classifies TEs as

– *type I*, which are deductive arguments (whether in support of a theory or a reductio ad absurdum of it), and
– *type II*, which involve some sort of inductive inference.

Sorensen (1992) classifies TEs in accordance with "three reasons for inaction".

(i) *Unimprovables* (thinking about the procedure answers the question; the thought renders the action superfluous).
(ii) *Unaffordables* (the reason for inaction is that the gains are outweighed by the losses).
(iii) *Impossibles* (TEs whose execution is theoretically possible but impossible in practice).

Another classification, that appears in bibliography and is used in the present work, is that of Brown (1991), who classified the TEs according to their use as

(a) *Destructive TEs*: They destroy or at least pose serious problems to a theory (e.g. Schrödinger's cat);
(b) *Constructive TEs*: They aim at establishing a positive result and are divided into the following categories:
(b1) *Mediative TEs*: They facilitate a conclusion drawn from a specific, well-articulated theory. (e.g. Maxwell's demon);
(b2) *Conjectural TEs*: Their point is to establish some (thought-experimental) phenomenon; the scientist then hypothesize a theory to explain that phenomenon" (e.g. Newton's bucket);
(b3) *Direct TEs*: They do not start from a well articulated theory but they end with one (e.g. Stevin's inclined planes);
(c) *Platonic TEs*: They are simultaneously destructive (a) and constructive-direct (b3) (e.g. Galileo's falling bodies).

The *critical* and the *heuristic* uses of TEs, according to Popper (1959/1999), correspond to Brown's (1991) *destructive* and *constructive* types of TEs.

4. TEs in Science Education

TEs besides the significant role they played in the development of science could be proved important educational tools as well. In TEs, situations they do not take place in every day life (e.g. big distances, high speeds, excessive temperature, powerful fields etc) usually are described. Also, the thought experimenters have to imagine and to predict borderline situations and arrive at conclusions on the basis of certain hypotheses. Consequently, the use of TEs in the classroom requires that students use their imagination, develop their critical thinking, make hypotheses, exchange views with their classmates and infer outcomes.

According to Gilbert and Reiner (2000a), the use of TEs in classroom practice familiarizes students with the methodology of science, because activities can be designed, which focus: "on an understanding of conceptual conventions, on the strategies of enquiry used in science, on the tools used in communication of the outcomes of such enquiry, and on the role and mechanisms of collaborative work between scientists. Students will be encouraged to develop the thought processes involved in creating new facts, producing new explanations, and justifying those facts and explanations to the science community". In addition, TEs carried out in the classroom, in contrast to those performed by scientists, evolve as a result of collaborative problem solving where each of the participants contributes a different aspect (Reiner 1998). Therefore, the use of TEs in the classroom may help students to be familiar with aspects of scientific thinking and to understand the science concepts and theories.

According to Matthews (1994), there is also didactic value in asking students to mentally anticipate the result of an experiment. This process engages the mind, and reveals what a student believes about the relevant concepts being investigated. Such method is the best way for teachers to get to know their students' way of thinking. Then, if the relevant experiment is actually performed, it will arouse students' dissatisfaction with their existing conceptions. Thus, the area of conceptual change "is an obvious one for the utilization of this type of TEs" (Helm et al. 1985).

Situations that are usually described in a TE exist only in a world of abstraction, so they cannot be repeated in reality. Consequently, the use of computers can facilitate the use of TEs in the classroom. Computers remove practical obstacles in order to formulate and test hypotheses, and they allow conclusions to be reached based on idealized situations characteristic of noteworthy TEs (Matthews 1994).

Research in science education about the use of TEs in every day school practice has revealed that:

(i) the results for student learning are positive, when TEs are used by the teacher as a basis for designing and organizing students projects (Lattery 2001);
(ii) TEs when conducted in the context of computer-based microworlds, are powerful tools for collaborative learning (Reiner 1998);

(iii) Teachers feel that TEs are indispensable, when they teach physics laws which involve abstract and concise formulations (e.g. theory of special relativity) because they feel that TEs give them some chance to build bridges between students' knowledge and everyday experience and the new or modified concepts and principles which have to be learned (Helm et al. 1985);
(iv) TEs are powerful educational tools because students use their imagination which "is structured, goal-oriented, based on prior experiential imagery and internally coherent" (Gilbert and Reiner 2000b).

5. Mode of inquiry

The present research was carried out in three phases:

5.1. PHASE A: TRACING TES IN THEIR ORIGINAL TEXTS AND CLASSIFYING THEM

Initially, TEs referring to the theory of relativity and quantum mechanics from Brown (1991), Sorensen (1992) and Horowitz and Massey (1991) have been recorded. These historical TEs were traced to their original sources (texts) and then they were classified according to Brown's classification (1991). These texts were used in the research as a reference point for the investigation of the way TEs in TBs and in popular PBs are presented. Brown's classification was used because the categorization of TEs is based on their use, which is convenient for the present research. This view is shared by others researchers in science education. For example, according to Nersessian (1993), Brown's taxonomy of TEs "provides a useful classification schema" and "each of these types of TEs has the potential to contribute to science education" (Gilbert and Reiner 2000a).

The classification of TEs was made by the following procedure:

(i) The TEs which have already been classified clearly by Brown (as examples of each category) were kept in the same category;
(ii) The remaining TEs were classified with the help of a panel of four judges (physicist researchers in the field of history of science). They were given Brown's classification and the TEs and they were asked to classify them. The category of each TE was recorded only if at least three out of four judges shared the same view. If different, a discussion would follow in order to agree on classifying a TE, by placing it in a specific category.

5.2. PHASE B: SELECTION AND STUDY OF TBS AND POPULAR PBS

By searching the lists of Greek publishing houses, fifteen popular PBs and ten physics TBs were selected for study (Appendix). All of them have been translated into Greek, mainly from English.

The selection of physics TBs was based on the following criteria:

- They are written or translated into Greek and are addressed to students of the last year of secondary education or the first year of university;
- They have chapters referring to the theory of relativity (special or general) and quantum mechanics.

The selection of popular PBs is based on the following criteria:

- They are popular worldwide;
- Their writers are famous physicists;
- They refer to the theory of relativity (special or general) and/or to quantum mechanics.

The study of the two types of books aimed at:

- the detection of the TEs used, and
- the analysis of the way they are presented (the terminology, the level of abstraction, the strategies of transforming science knowledge into public or school knowledge, the narrative techniques and the instructive tools used).

According to Reiner and Burko (2003) a reasonable rule of thumb to identify a TE may be to see whether the following question can be asked: "Imagine that a physical system consists of A. What happens if B". This rule is followed in this work in order to identify a TE. Specifically, a TE is identified when a physical system is described (usually with paradoxes according to every day experience) and a question is placed. Afterwards, the experimenter, based on a theory, mentally predicts events that happen to the system in order to answer the question.

5.3. PHASE C: EXPERIMENTAL IMPLEMENTATION

A qualitative research was carried out to investigate if the TE "Einstein's Elevator" – as it is presented in popular physics books – can be used as an introduction to familiarize secondary school students with concepts related to the principle of equivalence.

The sample was a team of six 14-year-old students (9th grade). The students were selected by their physics teacher so that the team was composed of mixed ability students. Their preexisting knowledge on the subject was limited to the concept of acceleration and Newton's laws in one dimension.

The research instrument was a worksheet based on a popular physics book. This was done because the TBs studied in the present research are addressed to university students or to students of the last year of secondary education, whereas the popular PBs are addressed to the public or to junior high school students. The popular physics book used was Stannard's book *"Black hole and Uncle Albert"* (1991). The particular TE

(''Einstein's Elevator'') was selected because the findings of phase B showed that this TE was used by the majority of the writers (in TBs and in popular PBs). The choice of the relevant passage was based on:

– the students background knowledge necessary to understand the relevant text;
– its extent (not too short nor too lengthy);
– the use of narrative codes to attract the reader;
– the terminology used (not too scholastic and unfamiliar to students).

In the passage used, the author starts from a student's experience in an amusement park in order to present the principle of equivalence. He continues his story with the performance of the TE, putting the student in a spaceship (not in an elevator) travelling in space far away from the gravitation field created by stars.

Students had to study partially the selected passage and then to answer, as a team, to questions aiming at assessing their understanding of the physics concept relating to the TE (key concepts, inference). To answer these questions, students had to argue on the matters emerging from the TE. At the end students had to answer to an evaluation worksheet consisting of two parts. In the first part they had to answer individually and in the second as a team. The discussions were recorded and discourse analysis was made. The process lasted for two hours.

6. Results – Findings

6.1. PHASE A: TRACING TES IN THEIR ORIGINAL TEXTS AND CLASSIFYING THEM

From the research, eleven key-TEs for the development of the theory of relativity and for the development of the quantum mechanics were detected. These were invented by the scientists who founded the above theories, during the first half of the 20th century. These TEs, classified in accordance with Brown's classification, are presented in the following table.

	Thought Experiment	Aim	According to Brown
1	Chasing a light beam (Einstein 1949/1979, p. 53)	To reveal a problem in Maxwell's theory or in transformations of classical mechanics	Destructive
2	Magnet and conductor (Einstein 1905/1952a, pp. 37–38)	To suggest that phenomena of electrodynamics posses no properties corresponding to the idea of absolute rest	Constructive–Conjectural

	Thought Experiment	Aim	According to Brown
3	Einstein's train (Einstein 1917/1961, chapter IX)	To find the consequences of constancy of speed of light (relativity of simultaneity, time dilation, length contraction)	Constructive–Mediative
4	Body that emits light (Einstein 1905/1952b, pp. 69–71)	To derive the formula $E=mc^2$	Constructive–Mediative
5	Two freely fluid bodies (Einstein 1916/1952, pp. 112–114)	To criticize the concept of Newtonian absolute space	Constructive–Conjectural
6	Einstein's elevator (Einstein 1917/1961, chapters XX, XXII) (Einstein and Infeld 1938)	To establish the principle of equivalence and afterwards to predict the deflection of light by the gravitational fields	Constructive–Direct
7	Rotating circular disk (Einstein 1917/1961, chapter XXIII)	To find the consequences of the principle of equivalence (time dilation, the need for a new geometry)	Constructive–Mediative
8	Heisenberg's microscope (Heisenberg 1930/1949, pp. 20–24)	To produce the uncertainty principle	Constructive–Direct
9	Schrödinger's cat (Schrödinger 1935/1983)	To undermine the Copenhagen interpretation	Destructive
10	E.P.R. (Einstein et al. 1935)	To undermine the uncertainty principle and to establish the incompleteness of quantum mechanics	Platonic
11	Box with light and clock (Bohr 1949)	To undermine the uncertainty principle	Destructive

6.2. PHASE B: SELECTION AND STUDY OF TBS AND POPULAR PBS

The physics TBs and popular PBs studied, used TEs as a prime tool for presenting the relevant physics concepts. Specifically the books to a large extent, use TEs in order to

(i) present the relativity of simultaneity (100% TBs, 100% PBs), the dilation of time and the contraction of length (90% TBs, 70% PBs), (special theory of relativity).
(ii) introduce the principle of equivalence and prove the deflection of light in the gravitational fields (100% TBs, 100% PBs), (general theory of relativity).
(iii) present the uncertainty principle (80% TBs, 86% PBs), (quantum mechanics).

Thus, the authors of these books (both TBs and popular PBs) consider TEs as a very important tool for the presentation of the above theories of physics, because they use TEs exclusively (or almost exclusively) in order to present them.

TEs of the "constructive" type, according to Brown's classification, are exclusively included in the TBs and in 75% of the popular science books. Textbook authors seem to prefer to report mainly real experiments (e.g. the Michelson–Morley experiment) and not "destructive" TEs (e.g. the Einstein's TEs "chasing a light beam"), to comment on the "anomalies" in the theories of the 19th century. This may be an indication that the textbook authors believe that it would be educationally more beneficial to present the starting point of a physics theory according to the problems that the scientific community had to solve and not from the way of individual scientists' thinking. Also, textbooks' authors seem to prefer to use TEs that are orientated towards the presentation of the corresponding topic and they do not use TEs, which demand deep thought about the presented theories. For example the TE "Schrödinger's cat" is not reported in TBs in contrast to the "Heisenberg's microscope".

The TEs primarily used in TBs are: "the train of Einstein" (90%), "the elevator of Einstein" (100%) and "Heisenberg's microscope" (70%). It is worth mentioning that 90% of the textbook writers use the form of TE to derive the formula of dilation of time, (and not the Lorentz transformations), which indicates that they consider it educationally more fruitful.

By studying the texts of both types of books (TBs and popular PBs), it is obvious that in the course of time, the presentation of TEs is modified in accordance with the advances in technology. For example the "elevator" of Einstein is updated from a "chest", (Einstein 1917/1961) to a "spaceship". This presumably happens because they want to make the story-telling more attractive (up to date) to the reader. This modification does not affect the meaning of the relevant theory, since it does not affect the argument of the TE. The TBs use exclusively historical TEs and they use simple descriptions to present the corresponding theory. Popular PBs use historical TEs which have been transformed and even other TEs invented by the writers. For example, Gamow (1990) presents the uncertainty principle both with TE based on the known TE Heisenberg's γ-ray microscope making modifications and with TE invented by him using a mechanical method. In both types of books, TEs are used as a methodological tool for the presentation of some theories, but the writers of popular PBs also use them as a tool to make the text more interesting, motivating the reader, for example, to visit a world of two dimensions or a quantum jungle (Stannard 1991; Gamow 1990).

Generally, the TEs used from both types of books do not demand complex mathematical formalism. In TBs, the mathematical formalism used for TEs is significantly simpler than the one used for other topics in the same books. In popular PBs, the mathematical formalism does not exceed simple algebra's or geometry's formulas. The most complex mathematical formula used is that of the Pythagorean Theorem. For example, the mathematical formalism in Heisenberg's microscope is omitted or simplified in comparison with the original TE (Heisenberg 1930/1949).

The terminology, the level of abstraction as well as the language used in books that popularize physics are modified depending on the background and age of the reader to whom they are addressed. For example, Einstein in his book "*Relativity: The special and the general theory*. *A popular exposition*" (1917/1961), which is addressed to high school graduates, considers the concept of acceleration and its relation to force as granted. The language he uses is similar to that of TBs but it is more descriptive and friendlier to the untrained reader. For example:

> To the middle of the lid of the chest is fixed externally a hook with rope attached, and now a "being" (what kind of a being is immaterial to us) begins pulling at this with a constant force. The chest together with the observer then begins to move "upwards" with a uniformly accelerated motion.

On the other hand, Stannard in his book "*Black hole and Uncle Albert*" (1991), which is addressed to younger students, explains the concept of acceleration and his language is by far simpler than that of the TBs that were studied. For example:

> ...when you accelerate – when you go faster and faster in an upward direction – as you did coming out of that big drop – it's like adding extra gravity...

Popular science books usually embody TEs in a broader framework of story-telling. This story telling could be of two kinds. (a) The writer directly presents theories of science using descriptions that are based on everyday experience of the readers (e.g. Einstein 1917/1961; Landau and Rumer 1959) and (b) the writer creates heroes who reveal the laws of nature within the framework of a story using techniques common to novelists (e.g. Gamow 1990; Stannard1991). In the former case, the writer invites the readers to perform the TEs, whereas in the latter the TEs are performed by the heroes of the novel.

In the studied TBs the authors avoid to use extensive narration instead they try to be in agreement with the science code and they use similar language and terminology. This is due perhaps to the fact that the studied TBs (Hewitt book is an exception) address themselves to readers who have sufficient mathematical background and their thinking can be characterized by abstraction (last grade of secondary education or first year of university).

6.3. PHASE C: EXPERIMENTAL IMPLEMENTATION

The discourse analysis and the content analysis of students written answers, revealed the following main points:

The engagement of students in handling the specific TE provoked their interest which proved to be much greater than that which their own teacher had anticipated. For example, the students did not want to have a break during the experimental implementation which lasted for two hours, even though these hours were the last two hours of their daily school program. Moreover, they wanted to keep copies of the passage of the book which referred to the TE. The students' interest may have been triggered by the communication techniques used in the passage, which avoid the mathematical formalism used in science TBs, preferring the use of narration to tell the specific science "story", being in accordance with the mental skill of their age.

The students seem to have reached a sufficient degree of comprehension of the relevant concepts. They all reacted equally well to the mental demands of the TE, despite their differences in school performances in physics courses. In some cases, when answering a question, students with average grades responded better than the students with high grades. Furthermore, students were helped by the writer's strategy to start the science story from their experiences in an amusement park. During the discussion they recalled their experiences of an amusement park, as well as from analogous every day experiences. Thus, students starting with the experience of feeling heavier inside a booth that is accelerated upwards or lighter when the booth is accelerated downwards managed (with the help of the TE) to imagine what would happen in cases where the booth

(i) falls freely on the Earth's gravitational field
(ii) is in an area far away from any other body
(iii) is propelled by rockets in this area.

Specifically, the students were given drawings with an astronaut in a capsule in different positions in every case and they were asked to comment on "what does the astronaut feel" and what would happen to a book that would drops from his hand. There follows a characteristic part of dialogue, among students P, K, A (initial letters of names) concerning case (iii):

> P. I believe that the book will move ... in all cases it will move to a direction (the capsule in the drawing has four different orientations).
> K. Yes ... in the opposite direction than that the rockets pull the capsule.
> A. Yes I agree... the book will always move to the floor because the rockets propel from the floor to the ceiling ... in the space what is left, right, up and down has no meaning.
> K. Rightly so, we read in the text that the pencil that left the table went to the floor.

The students seem to have comprehended the meaning of the book's passage after a careful reading, though in some cases, they could not use the accurate scientific terminology. This is justifiable because the students were only 14-years-old. For example, the description concerning the deflection of the light within the accelerated capsule was comprehended at the first reading. Then they managed to follow the hero's thinking about the consequence that the application of the principle of equivalence would have in this case. Specifically, students were given a drawing without text, where the deflection of the light of a star whose rays pass very close to the Sun was visible and they were asked to interpret it on the basis of the text. Strong argumentation developed between the students (in the team) when they were trying to answer the question. Without intervention in the discussion, the students finally arrived at the right interpretation going back to the point of the text where it was said that the defection of the light can be observed in gravitational fields more powerful than that of the Earth. A characteristic part of dialogue follows:

G. The beam does not continue straight because of the gravity of the Earth.

J. I do not think so, this would be happen if the Earth had huge gravity... Uncle Albert in the text said that the Earth does not have so much gravity that we may notice that the light curves...

K. I believe that the beam is attracted by the Sun ... it is enormous compared to the Earth... (the student means much more powerful gravitational field)

A. Yes, I think so... if the Sun did not exist the beam would not meet the Earth.

7. Comments and Conclusions

From the study it was obvious that TEs were used to a large extent by physicists who introduced the theories of relativity and quantum mechanics in order to present, develop and communicate their theories. TEs also seem to constitute irreplaceable material for the writers of physics textbooks and popular PBs in order to present the theories of the 20th century.

The TEs which were initially used by the scientists to popularize their theories were adopted by the physicists who wrote textbooks adapting the language and the mathematical formalism appropriately as well as extending their use. For example the use of TE "the train of Einstein" was extended and showed not only the relativity of simultaneity but also the formula of dilation of time and/or the formula of contraction of length. The authors of both types of books do not only adjust the language and the mathematical formalism of the TEs but also the "props" used to set up the scene. This adjustment follows the technological advances of the times when every book is written. Furthermore, the writers of popular physics books, unlike the writers of textbooks do not use TEs exclusively as a methodological tool for the presentation of both 20th century theories but also they use them as a tool to make the text more interesting to the reader.

Research shows that narrative techniques used in popular science books when presenting TEs, proved to be very attractive to secondary school students. The students seemed to enjoy the story and get involved in its plot while trying to understand the relevant concepts. Thus, it may be concluded that TEs which were transformed into forms accessible to the public could trigger students' interest and act as educational material to acquaint them with concepts and principles of the physics theories of the 20th century which at a later time they will study in depth. Of course much additional work remains to be done before a final conclusion can be reached.

The present paper argues that TEs could be used as tools not only of thought but also of communication and of education, since they can help to transform scientific knowledge into school or public knowledge.

Appendix

Books that were studied in the phase B of the present research

(A) TEXTBOOKS

Eisberg, R.: 1961, *Fundamentals of Modern Physics*, Hardcover

Ford, K.: 1974, *Classical and Modern Physics* (volume 3) John Wiley and sons, New York.

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