

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 books popularizing physics - can be used as an introduction to familiarize secondary school students with physics theories of the 20th century. The study of textbooks and books popularizing physics theories showed that TEs constitute a powerful and irreplaceable tool for the writers of both types of books in order to present the theory of relativity and quantum mechanics. Furthermore, a pilot 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.

Introduction

TEs have played an important role in the course of science and several philosophers of science, such as Mach (1896/1976), Popper (1959/1999) and Kuhn (1977) have commented on this. A number of books have been published in which TEs are presented analyzed and categorized (Brown 1991, Sorensen 1992) and also a conference was organized about the role of TEs in science and philosophy (Pittsburgh 1986, a book edited by Horowitz T. , Massey G. 1991)

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).

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. Books that popularize science often use TEs to present, mainly, physics theories of the 20th century. This use contributes towards 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 these reasons, it was considered that it would be of interest to investigate the presence of TEs, which refer to the theory of relativity and to quantum mechanics, in books popularizing physics and in physics textbooks.

TEs in Science

TEs have played an important role in the development of science because they were used by leading 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 paradigm. For these reasons TEs such as Galileo's falling bodies (Galileo 1638/1914), Newton's bucket and cannon (Newton 1729/1962), 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), are very popular in the physicists community.

TEs are experiments which are designed and performed mentally by the scientists when investigating a new physics topic. According to Sorensen (1992) "TEs are designed without the intention of being performed". They use the imagination in setting up a "thought scenery" which usually refers to familiar situations, though the conventions they require go beyond daily experiences. In addition, 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 Mach (1896/1976) comments: "the law of inertia was discovered by abstraction; thought experiment and continuous variation have led to it"

According to Kuhn (1977), TEs assist scientists in arriving at laws and theories different from the ones they have held before. The new understanding produced by TEs is not an understanding of *nature* but rather of the scientist's *conceptual apparatus*. Unlike the discovery of new knowledge, the elimination of existing confusion does not seem to demand additional empirical data. For example, Galileo's TE of the two planes helped to reform the concept of speed. (Galileo 1633/1967).

CLASSIFICATION OF THE TEs

Various classifications have been proposed for the TEs. Popper (1959/1999) categorized TEs, according to their use, in

- (i) TEs that criticize existing theories (*critical use*)
- (ii) TEs that lead to innovations (*heuristic use*)
- (iii) TEs that function apologetically for a theory (*apologetic use*),

Another classification that appears in bibliography and is generally acceptable by researchers, is that of Brown (1991), who classified the TEs 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 and 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).

TEs in Science Education

The use of TEs in classroom practice familiarizes students with the methodology of science because activities can be included focusing on: the understanding of conceptual conventions; the strategies of enquiry used in science; the tools used in communicating the outcomes of such enquiry; and the role and mechanisms of collaborative work between scientists.

According to Gilbert and Reiner (2000a) "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)

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. This method is the best way for teachers to get to know their pupils way of thinking. Some will guess the most obvious likely thing, while others will surmise unusual and strange results. (Mach 1896/1976). 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 at 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, based on idealized situations characteristic of noteworthy TEs, to be reached. (Matthews 1994).

RESEARCHES CONCERNING THE USE OF TEs IN SCIENCE EDUCATION

Educational researches about the use of TEs in every day school practice have revealed that:

- (i) the results for student learning are positive when TEs are used as a basis for designing and organizing students project (Lattery 2001).
- (ii) TEs when conducted in the context of computer- based microworlds, are powerful tools for collaborative learning.(Rainer 1998)
- (iii) The potential uses of the various types of TEs in bringing about conceptual development were found not to be realized in a satisfactory degree in physics textbooks, though elements of a TE design are found to be integrated with other pedagogic devices such as 'thought simulations' (Gilbert, Rainer 2000a)
- (iv) Teachers feel that TEs are indispensable, when they teach physics laws which involve with 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 at al. 1985)
- (v) 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)

Famous scientists such as Einstein and Heisenberg used TEs for the foundation, the development, the critique and the popularization of the theories concerning the scientific revolution of the 20th century. Some of these TEs are used either as they were proposed by well known physicists or in several transformations as material for the teaching and the popularization of the theory of relativity and quantum mechanics.

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 and books popularizing physics and b) if the TEs which are included in popular science books can be used as an introduction to familiarize secondary school students with physics theories of the 20th century.

Mode of inquiry

The present research was carried out in three phases:

PHASE A: TRACING OF TEs IN THEIR ORIGINAL TEXTS

TEs which played an important role in the establishment and development of the theories of relativity and quantum mechanics, were traced to their original sources (texts) and they were classified according to Brown's classification (1991).

PHASE B: SELECTION AND STUDY OF TEXTBOOKS AND BOOKS POPULARIZING PHYSICS

By searching the lists of Greek publishing companies, fifteen books which popularize physics and ten physics textbooks were selected for study (appendix). All of them have been translated into Greek, mainly from English.

The choice of physics textbooks was based on the following criteria:

- They are written or translated in Greek and are addressed to students in the last year of secondary education or the first year of university.
- They contain the theory of relativity and quantum mechanics

The choice of books popularizing physics is based on the following criteria

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

The study of two types of books was 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).

PHASE C: EXPERIMENTAL IMPLEMENTATION

A pilot research was carried out to investigate if TEs - as they are presented in books popularizing science - can be used as an introduction to familiarize secondary school students with concepts of the physics theories of the 20th century.

The TE "Einstein's Elevator" on the principle of equivalence was selected from Stannard's (1991) book and was administered to a team of six 14 years old students (9th grade). The writer starts from a student's experience in a fun fair in order to present the principle of equivalence and 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.

Although the particular TE refers to complex concepts it was selected because it does not require mathematical formalism and has as a starting line situations that relate to the every day experiences of students.

The team was composed of mixed ability students according to their performance in physics courses. The students were selected by their physics teacher according to their grades in physics.

The choice of the relevant passage was based on:

- the background needed to understand the relevant text.
- its extent (not too short or too lengthy)
- the narrative techniques used to attract the reader
- the terminology used (not too typical).

Individual students studied the selected passage and then answered as a team to questions aiming at assessing their understanding of the physics concept relating to the TE. To answer these questions, students had to argue on the matters emerging from the TE. In the end the students were asked again to answer to some questions first individually and then as a team. The discussions were recorded and a qualitative analysis was carried out through a discourse analysis. The process lasted for two hours.

Results - Findings

PHASE A: TRACING OF TEs IN THEIR ORIGINAL TEXTS

By studying the primary texts of scientists who founded the theories of relativity and quantum mechanics, during the first half of the 20th century, eleven important TEs were detected. Seven of them referred to the theory of relativity and four to quantum mechanics. These TEs were classified according to Brown as they are presented in the following table

	Thought Experiment	Aim	According to Brown
1	Chasing a light beam (Einstein 1949/1979)	To reveal a problem in Maxwell's theory or in transformations of classical mechanics	Destructive
2	Magnet and conductor (Einstein 1905/1952)	To suggest that phenomena of electrodynamics posses no properties corresponding to the idea of absolute rest	Constructive-conjectural
3	Einstein's train (Einstein 1917/1961)	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 1905/1952)	To derive the formula $E=mc^2$	Constructive-Mediative
5	Two freely fluid bodies (Einstein 1916/1952)	To criticize the concept of Newtonian absolute space	Constructive-conjectural
6	Einstein's elevator (Einstein 1917/1961) (Einstein, Infeld 1938)	To establish the principle of equivalence and afterwards to predict the bending of light by the gravitational fields	Constructive-direct
7	Rotating circular disk (Einstein 1917/1961)	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)	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

PHASE B: SELECTION AND STUDY OF TEXTBOOKS AND BOOKS POPULARIZING PHYSICS

All books (popular and textbooks) studied, used TEs as a prime tool for presenting the relevant physics concepts. The physics textbooks had on average 4 TEs per book and all of them were mainly historical. The popular books which popularise physics had about 6 TEs per book, many of which were invented by the writers. Thus, the writers consider TEs as a powerful tool for the presentation of the physics theories of the 20th century.

TEs of the "constructive" type, according to Brown, are exclusively included in the textbooks and in 75% of the popular science books. The writers 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.

The writers of textbooks prefer to use TEs that are orientated towards the presentation of the corresponding topic of the curriculum and they do not use TEs which make the readers think deeply about the inner essence of the presented theories. For example the TE "Schrödinger's cat" is not reported in textbooks in contrast to the "Heisenberg's microscope". However, popular science books include to some extent TEs which help readers to think about the relevant concepts.

The TEs which are primarily used in textbooks are: "the train of Einstein" (90%), "the elevator of Einstein" (100%) and "Heisenberg's microscope" (70%). It is worthwhile 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).

The mathematical formalism as well as the language used in both types of books are modified depending on the background and age of the reader to whom they are addressed. For example, the mathematical formalism in Heisenberg's microscope is omitted or simplified in comparison with the original TE (Heisenberg 1930/1949).

By studying the texts of both types of books (textbooks and books popularizing physics), it is obvious that in the course of time, the presentation of TEs is modified according to advances in technology. For example the "elevator" of Einstein is updated from a "box", (Einstein 1917/1961) to a "spaceship".

PHASE C: EXPERIMENTAL IMPLEMENTATION

During the pilot research the discourse analysis of students' dialogues and the argumentation developed in these dialogues as well as the content analysis of the 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 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 textbooks, preferring the use of narration to tell the specific science "story".

The students seem to have reached a sufficient degree of comprehension of the relevant concepts after a careful reading of the passage. They all reacted equally well to the mental demands of the TE, despite their differences in school performances in physics courses. In most cases, mediocre students responded better than the outstanding ones, when answering a question.

In answering the questions, students seem to have comprehended the meaning of the passage of the book, though in some cases, they could not use the accurate scientific terminology. This is justifiable because students are only fourteen years old. Also, strong argumentation developed between the students (in the team) when they were trying to answer the questions. The discussion between students helped especially the students with low marks in physics to understand the relevant concepts

Furthermore, they were helped by the writer's strategy to start the science story from their experiences in the fun fair. During the discussion they recalled their experiences from the fun fair as well as from analogous every day experiences.

Comments and Conclusions

By studying the primary texts of the physicists who founded the theories of relativity and quantum mechanics it was obvious that TEs were used to a large extent by these scientists to present, develop and communicate their theories. TEs also seem to constitute irreplaceable material for the writers of physics textbooks and books popularizing physics in order to present the theories of the 20th century.

Textbook writers mainly use constructive- meditative or constructive- direct type of TEs to present the theories of relativity and quantum mechanics, but they mention historical experiments (e.g. the Michelson - Morley) or appropriate phenomena (e.g. photoelectric effect) and no TEs of destructive type in order to demonstrate the impasses of the 19th century physics theories. Also the textbook writers do not use constructive- conjectural type of TEs which make the readers think deeply of the relevant physics theories. In contrast, books popularizing physics include to a certain degree destructive as well as constructive-conjectural type of TEs. This can be attributed to the fact that the textbook writers focus on the curriculum while the writers of books popularizing physics do not have any limitations about the context and usually try to present the whole science story which will be interesting and attractive to their readers.

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 or the formula of contraction of length. The writers 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 the scene. This adjustment follows the technological advances of the time which every book is written.

Pilot research shows that narrative techniques used in popular science books to present 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 might be concluded that the 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 physics theories of the 20th century.

The present paper supports TEs 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.

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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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HEWITT P. (1985) *Conceptual physics* (5th edition)
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SERWAY R. (1990) *Physics for scientists and engineers*, (third edition)
SERWAY R., MOSES C., MOYER C., (1989) *Modern Physics*, Saunders College Publishing
YOUNG H. (1992) *University Physics* (8th edition) Addison- Wesley publishing company, USA
JOANNOY A., NTANOS G., PITTAS A., RAPTIS S., (1999) *Physics* (for 12th grade Greek students selecting science and technology orientation)

(B) Books popularizing physics

- BRUCE C. (1997), *The Einstein Paradox*.
DAVIES P. BROWN J. (1995), *The ghost in the atom*, Cambridge University Press.
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