Thought experiments in physics theories of the 20th century: A tool for popularization and teaching in secondary education.[1]

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Introduction

The focus of this work is the thought experiments (TEs) -gedankenexperimente- in physics theories of the 20th century and the role they can play in secondary education. TEs have played an important role in the development of science because they were used by leading scientists for the formulation of innovative theories; for establishing the contradictions in already existing theories; for the modification of the old theories according to new findings, or even for their replacement with a new paradigm. TEs are experiments which are designed and performed mentally by the scientists when investigating a new physics topic. They utilize the imagination in setting up a "thought scenery" which usually refers to familiar situations, though the conventions they require go beyond daily experiences (Mach 1896/1976, Sorensen1992, Kuhn 1977). Several philosophers of science, such as Popper (1959/1999) and Brown (1991), have commented on the role of TEs in the route of science and have proposed various classifications.

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 2000). According to Reiner (1998), TEs in the classroom evolve "as a result of collaborative problem solving". In addition Matthews (1994) argues that TEs of the anticipatory type are very fruitful in science teaching, especially when students are first asked to anticipate the result of an experiment, and after performing the actual experiment, to find out if the result was in agreement with their predictions. This type of TEs can help students to express firstly their ideas and then to change them according to their findings (Helm at al. 1985).

In our days the approach to theories of science can be reached via a wide spectrum of sources in formal as well as in informal education (Wellington 1991). The sources of informal science education can be radio, television, newspapers, magazines, popular science, web pages and others. These 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 innovated TEs not only for the development of their theories, but also for their presentation and communication to the public. Popular books of science often use TEs to present physics theories of the 20th century. 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 this reason, it was considered that it would be of interest to investigate the presence of TEs in books popularizing science of the 20th century.

The present research is focused on the TEs (as they are presented in popular science books), which refer to the following topics:

- the uncertainty principle (quantum mechanics).
- the principle of equivalence (general theory of relativity).

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- the consequences of the principle of the constancy of speed of light on the concepts of time and space (special theory of relativity).

Specifically, the present work attempts to investigate:

- The way scientists use TEs as a tool to popularize the above topics.
- The possibility of using the TEs (as they are presented in popular science books referring to the above topics) for teaching the relative physics concepts to secondary school students.

Mode of inquiry

The research was carried out in two phases:

Phase A: The detection, the selection and the study of books popularizing science.

By searching the lists of Greek publishing companies, 72 Greek translated of mostly English books, which popularize science, were detected. 26 books out of them refer to the theory of relativity (special or general) and/or to the quantum theory. Among them, 13 were selected for study, based on the following criteria:

(i) They are popular worldwide.

(ii) Their writers are famous scientists.

(iii) They deal with issues which are related to the ones included in the program of study.

For each book, the TEs referring to the topics of interest were noted and finally the most popular ones among them were selected.

Then three passages from the above books were selected, one for each TE, to be used as teaching material. The choice of the relevant passages was based on:

- their extent (not too short or too lengthy)
- the narrative techniques they used to attract the reader
- the use of instructive tools (e.g. analogies, metaphors etc) for the presentation of complex concepts.
- the terminology used (not too technical).

Phase B: The experimental implementation.

Three teams of students were chosen who had not been taught the topics presented by each one of the selected TEs. Each team was composed of mixed ability students according to their performance in physics courses. A different TE was addressed to each team:

A) The TE on the uncertainty principle selected from Gamow's (1990) book, was administered to a team of five, 17 year old students (12^{th} grade)

B) The TE on the principle of equivalence selected from Stannard's (1991) book, was administered to a team of five, 14 year old students (9^{th} grade).

C) The TE on the consequences of constancy of speed of light selected from Landau's (1959) book, was administered to a team of five, 16 year old students (11^{th} grade).

Each TE was addressed to a different age group by the following criteria:

- The writer's aim to address a certain group age
- The background needed to understand the relevant text.

The students in each team were selected by their physics teachers according to their physics grades: outstanding - good - mediocre – weak.

Individual students in each team studied the selected passages referring to the specific TE, and then answered as a team to some questions aiming to assess their understanding on the physics concept related to the TE. To answer these questions, students had to argue on the matters emerging from the TE. The discussions were recorded and a qualitative research was carried out through a discourse analysis. The implementation lasted for two hours.

Results

Phase A

The study of the books led to the following results:

- TEs constitute the most common, almost unique tool used by the popularizers of scientific issues. Specifically TEs are used in 93% of the books referring to above mentioned topics of special and general relativity and of quantum mechanics.
- The TEs which are primarily used for the popularization of these three topics, are:

I) "the train of Einstein" for the consequences of the constancy of speed of light on the concept of space and time.

II) "the elevator of Einstein" for the principle of equivalence

III) "Heisenberg's microscope" for the uncertainty principle.

These TEs are presented, either as a variation or as simplified versions of the original TEs. For example, the elevator or the train, is usually represented as a spaceship which is equipped with mirrors, and instead of lightning, a flash.

The mathematical formalism, in Heisenberg's microscope, is omitted or simplified in comparison to the original TE (Heisenberg 1930/ 1949).

Phase B

The discourse analysis of students' dialogues and argumentation as well as the content analysis of the written tests, revealed the following main points:

- The engagement of students with the study of the specific TEs provoked their interest which proved to be much greater that their own teachers had anticipated. A strong argumentation developed between the students (in the team) when they were trying to answer the questions of the test. The discussion between students helped especially those students with low marks in physics, to understand the relevant concepts.
- The students seem to have reached a sufficient degree of comprehension of the relevant concepts after a careful reading of the passages referring to the TE. 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 (in all teams) seem to have comprehended the meaning of the passages of the books, though the younger students (team B) used less accurate terminology than the older ones (team A) who were more precise.
- In the cases where the TEs were either far from their experiences (e.g. Heisenberg's microscope) or where they were supported by their experiences (e.g. Einstein's elevator), students could follow the relative syllogisms and adopt the deduction of the corresponding theories. However, in the case where the TE contradicted students'

experiences, they found it difficult to follow the relevant syllogisms and accept the consequences these syllogisms lead to. For example, in the TE referring to the "train of Einstein", while students could explain sufficiently well the relativity of simultaneity, they could not explain the dilation of time. In the latter case, though they could not find a reasonable contradiction with the TE, they preferred to invent their own models or to "philosophize" in order to avoid accepting the TE's conclusion (that the two clocks, moving and motionless, work with different rhythms).

Conclusions and Implications

TEs constitute very powerful and (in certain cases) irreplaceable instructive tools for helping students to approach the principles of equivalence, of uncertainty as well as the consequences of the constancy of the speed of light.

The transformation made by famous scientists, of the historical TEs into forms accessible to the public, helped the popularization of difficult physics topics. The relevant popular science books contain reliable knowledge and utilize attractive communication techniques (e.g. the use of narrative style) to tell a science story. Thus, they can be used as an introduction to inform secondary school students about physics theories of the 20th century, or even to provide them with the necessary background to approach complex physics concepts (at a basic level). These texts are very helpful, especially for those students who have a poor physics knowledge background and find difficult to study physics in the formalistic way as presented in their textbooks. These TEs can constitute a rich source for the design of educational material, which physics teachers can use in their everyday teaching.

The teamwork in science classrooms proved quite fruitful in handling questions which demand the comprehension of scientific texts. The overall result of teamwork is enhanced especially when the team is composed of students with mixed background knowledge in physics. It seems that the inter-student communication in teamwork, allows students with poor physics knowledge to feel free to participate in the discussion and the relevant argumentation, thus improving their knowledge in the science issue under discussion.

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