Chapter 38
Thought Experiments in Science and in Science Education

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38.1 Introduction

When Albert Einstein was 16, he considered the following thought experiment. He imagined chasing after a beam of light with the velocity of c. He would then catch the light wave and be moving with it and the light wave would seem to be frozen. Einstein noted both his experiences and Maxwell's electromagnetic theory, which suggests that such a stationary wave does not exist. In addition, he noted that if an observer were to see him riding on a light wave with a velocity of c, Einstein himself would not be able to observe the velocity.

This example illustrates the essence of a thought experiment.[1] The thought experiment describes an imaginary, hypothetical situation. The thought experiment cannot always be performed as a physical experiment, in this particular case, because it is impossible for such a massive object (Einstein) to have the velocity of c. In several respects, however, the thought experiment resembles a physical experiment. Its premise of c as the velocity of light is an empirically measured theoretical result using Maxwell's theory of electromagnetism as a starting point. It rests on the hypothesis of riding a light wave, which inevitably fails as a result of the empirical observations and impossibilities contained in theories associated with physics.

The purpose of what follows in this chapter is to examine the role of thought experiments in science and science education. First, different definitions of the concept of thought experiment will be discussed. Second, it will be argued that TEs form an essential part of scientific methodology, a special case of scientific experimentation. Third, attention will be paid to the role played by TEs in the

[1] A scientific experiment can be either a thought experiment performed in thought or a physical experiment performed in the laboratory.

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development of scientific theories. Subsequently, attention will also be paid to the pedagogical benefits of the use of thought experiments in science learning and the reported studies on the use of thought experiments in science teaching. It will be argued that, as a result of the various benefits of TEs, their use should be increased in science teaching. Finally, our discussion will focus on the challenges posed by TEs in the teaching and learning of science.

38.2 Descriptions of the Concept of the Thought Experiment

Thought experiments have a long history, starting from the time of pre-Socratics (Rescher 1991; Brown and Fehige 2010). It has been argued that during the Middle Ages, thought experimenting was one of the main methods used in science (King 1991). In the seventeenth century, Galileo Galilei and Isaac Newton used thought experiments (TEs) as part of their scientific methodology.[2] The rise of relativity and quantum physics would not have been possible without thought experiments, and famous thought experimenters include Niels Bohr, Erwin Schrödinger, and Albert Einstein (Brown 1986; Matthews 1988; Zeilinger 1999).

Modern science philosophers and scientists have attempted to frame a general description of the concept of thought experiment (TE). Roy A. Sorensen (1992) sees TEs in a broad light: the only difference between an actual experiment and a thought experiment is that a thought experiment attempts to achieve its aim without the benefit of actual implementation. However, as Galili (2009) has criticised, Sorensen's definition of an experiment goes beyond the realm of science. According to Sorensen, a scientific experiment is "a procedure for answering or raising questions about the relationship between variables by varying one (or more) of them and tracking any response by the other or others". Galili states that physical experiments are based on certain theoretical assertions and this is how TEs are also used in science.

Sören Häggqvist (1996) claims that philosophers and scientists often see TEs as something different from "genuine", "actual", or "real" experiments but rather as or a species of experiments similar to "laboratory experiments" or "cyclotron experiments". He characterises a TE loosely as an experiment that aspires to test some hypothesis or theory: it is performed in thought, but paper or pencil, encyclopedias, or computers may also be used (Häggqvist 1996, p. 15).

According to Irvine (1991, pp. 158–159), TEs have to possess at least several, if not all, of the characteristics of a scientific experiment. This means that not all varieties of hypothetical reasoning concerning the natural world can be considered to be TEs. A TE has to bear a special relationship both to previous empirical observations and also to the background theory of TE. A thought experiment cannot ever

[2] See, e.g. Newton (1728), Newton (1863), Gendler (1998), Palmieri (2003), Palmier (2005), Hall (2000), and Norton (1991).

replace observations or a physical experiment because a thought experiment rests on auxiliary presuppositions considered to be true but whose failure changes the result of the thought experiment per se.

Nancy Nersessian's view of TEs differs slightly from the views presented above in that she sees a TE as a mental model that enables the dissemination of a possible physical event that is often unrealisable in one's imagination (Nersessian 1989, p. 175). Nersessian claims that Galilei, for instance, acted in this way in the case of his TE concerned with falling bodies. According to Nersessian (1992, p. 27), mental simulation is needed for a thought experiment to be both thought and experimental. The original scientific thought experiment is executed by a scientist who imagines a sequence of events and constructs a mental model. Then she/he constructs it in a narrative form in order to describe the thought experiment to others.[3]

Nersessian's view is fascinating because it makes a connection between thought experiments and mental models. On the other hand, the connection makes her definition somewhat complicated because there is no consensus about how individuals possess their knowledge. Is it in form of models (Nersessian 1989, 1992; Nersessian and Patton 2009), "in pieces" (di Sessa et al. 2004; diSessa and Sherin 1998; diSessa 2002), or as coherent and organised naive theories related to particular topics (Vosniadou 1994; Vosniadou et al. 2008)? Some researchers even think that a mental model is an individual's inner, private model that cannot be expressed exactly; when an individual presents his/her model to an audience, the model is not a mental model but *an expressed model* (Gilbert et al. 1998).

Having analysed several definitions of thought experiment, Igal Galili proposes the following definition: "Thought experiment is a set of hypothetico-deductive considerations regarding phenomena in the world of real objects, drawing on a certain theory (principle or view) that is used as a reference of validity" (Galili 2009, p. 12).

Galili's (2009) definition is not concerned with the reality existing outside scientific theories, and it also excludes a pure, formal analysis manipulating with theoretical entities without addressing the real objects. The definition includes scientific TEs that are part of the scientific process and excludes philosophical TEs. Even if we mostly agree with Galili's definition, we do not think that phenomena should be restricted to include only the world of real objects because that would exclude from the definition Maxwell's demon or hypothetical entities, for instance, whose existence cannot be verified. The definition of a thought experiment should also include a more explicit statement about its mental implementation. In sum, TEs are an essential part of scientific methodology, a special form of scientific experiments. Like other scientific experiments, they are based on a particular background theory. The main difference between physical experiments and TEs is that TEs are performed in thought. In addition, TEs can also be devised with hypothetical entities that have not yet been verified or cannot even be verified at all.

[3] Racher Cooper (2005) and Tamara Szabó Gendler (1998, 2004) are also supporters of this kind of mental model account.

38.3 The Role of Thought Experiments in Science

Ernst Mach and Pierre Duhem were the first to consider the value of thought experiments in science. According to Mach, thought experiments are needed because they precede physical experiments by preparing for their actual implementation (Mach 1976). Duhem's view is the opposite: he considered thought experiments useless because they cannot be presented in symbolic form and hence they cannot replace scientific experiments (Duhem 1990).

Mach (1976) stated that the possibility of a thought experiment rests on our mental images, which are more or less copies of facts. When reminiscing, we may even find new properties of the physical facts that we had not noticed previously. Our mental images are easier and faster to use than the physical facts. Thus, it can be said that thought experiments precede physical experiments and prepare for them. This means that every experimenter has to be aware of the details of the experiment before its actual implementation.

Mach thought that if thought experiments are reported sincerely, they will be true even if two thought experimenters report different sequences. In addition, errors can only occur when the results of thought experiments are compared with the physical reality. Sorensen (1992) argues that Mach's account overemphasises the subjectivity of a thought experiment. Sorensen considers that thought experiments can also be fallacious in their reporting phase.

Sorensen also argues that if a TE always precedes a physical experiment, the concept of the thought experiment has to be so wide that it covers "any kind of forethought about an experiment". He thinks that it is not normal in science to perform the full experiment in thought, but the mental processing is more like the planning stage of a physical experiment. We agree with Sorensen with regard to both of his arguments. Thought experiments conducted by two different thought experimenters can lead to different results in the first stage of TEs, and as often as not they cannot both be true. In addition, experimental scientists undoubtedly plan their physical experiments mentally, but these thoughts are frequently more like schemes of action rather than being full thought experiments.

Mach argues that in some cases, the result of a thought experiment can appear so sure and final that its implementation as a physical experiment may even seem unnecessary (Mach 1976). Duhem sees the role of thought experiments differently than Mach. He considered that thought experiments could not replace physical experiments and that they should be forbidden in science and in science teaching (Duhem 1990). Duhem alleged that only mathematical argument was precise and unambiguous, while the language of concrete observation is not: "The facts of experience, in all their native brutality, cannot be used in mathematical reasoning. To feed such reasoning they must be transformed and put into symbolic form". Duhem's view is sometimes termed sceptical objection (see Brown and Fehige 2010).

This kind of sceptical view of thought experiment is not common amongst science philosophers, but critical views of thought experiments can be found (see, e.g. Brown and Fehige 2010). Hull (1998, 2001) argues, for instance, that TEs are nothing but simple illustration and they end up persuading people; but TEs often contain deficiencies, such as incoherence and missing details. Norton (2004b) agrees with Hull over the fallibility of TEs. In addition, he claims that TEs are simply arguments, and hence they cannot offer any kind of special information that could not also be uncovered by conventional argumentation.

Cooper (2005) argues that thought experiments are needed for several reasons. Some thought experiments are practically possible to implement as physical experiments, but there may be sound reasons (ethical reasons, e.g. or the monetary expense of physical experiment) for performing them only in the mind. Other thought experiments may be impossible to implement as real experiments because they involve idealisations. Cooper (2005, p. 344) argues that Galileo's TE demonstrating that bodies continue moving with constant velocity in the absence of a force – a ball rolling in a frictionless U-bend – includes an idealisation. In science, the idealisations are often similar to the limiting case imposed by extrapolation of the results of the physical experiment. Other thought experiments may be impossible to implement as real experiments because they involve the violation of a physical law. According to Cooper, these TEs resemble the computer simulations that scientists run to discover how phenomena may behave if the laws of nature are slightly different. Cooper states that simulations and thought experiments that cannot be implemented as physical experiments can nevertheless be used as potential sources of knowledge in science.

Buzzoni (2009) claims that thought experiments and real-world experiments form a dialectical unity: without thought experiments there would be no real experiments because we would not know how to ask about their nature, and without real experiments we would not find answers to these questions. According to Galili (2009), thought experiments play a heuristic role. They are free from the constraints imposed by reality (heat, friction, etc.), and the thought experimenter can also forget the technical restrictions (equipment, costs, availability, etc.). In a sense, a person conducting a thought experiment mentally models theoretical physics (Peierls 1980).

From the above it follows that a thought experiment is a special case of scientific experiment that can precede a physical experiment and help the experimenter to conduct it. In some cases, a physical experiment may not be possible and TE may then be the only way to experiment. TEs can also be used to idealise complex physical situations and remove constraints imposed by reality. The physical experiment may either confirm the results of a TE or show that the TE was fallible; both types of TEs are important in constructing an understanding of scientific knowledge. This view of thought experiments can then be used as a starting point in science teaching.

38.4 The Epistemological Role of Thought Experiments in Science

If we approve of TEs as one special part of scientific methodology, we need also to discuss whether TEs play a special epistemic role in the knowledge construction processes of science. The theoretical framework of TEs is of great importance because it determines the image of the nature of science that TEs convey when used in science teaching.

There are two different views of the epistemological status of TEs. The argument-based view states that knowledge comes only via sensory experiences, while the intuition-based (Platonic) view argues that TEs provide information beyond our senses. The argument-based views rely on the idea that TEs can be reconstructed as arguments or that they function via their connection to arguments, so they are unable to provide more information than argumentation in general. On the other hand, the intuition-based view argues that a special group of TEs, Platonic thought experiments, go beyond our senses to acquire a priori information about nature.

38.4.1 Argument-Based Views

Argument-based views rely on the idea that TEs are unable to provide more information than argumentation in general. The supporters of the argument-based view do not mean that TEs are meaningless in science; rather, they are meaningless in an epistemological sense.

John Norton is probably the best-known supporter of the view that thought experiments are basically arguments. He thinks that TEs are not epistemic wonders, but they do tell us about our world using our normal epistemic resources[4] (Norton 1996, 2004a). Norton (1996, p. 339) has formulated his claim in a more precise form, referred to as a *Reconstruction Thesis*, as follows:

> *Reconstruction Thesis:* All thought experiments can be reconstructed as arguments based on tacit or explicit assumptions. Belief in the outcome-conclusion of the thought experiment is justified only insofar as the reconstructed argument can justify the conclusion.

TEs draw on hypothetical and counterfactual situations that essentially separate them from physical experiments (Norton 1991, 1996). These unnecessary particulars are needed for the experimental nature of thought experiments; without them, TEs would not be experimental. These particulars can be psychologically useful, but they are unnecessary for the thought experiment itself.

Norton claims that the epistemological potential of TEs is the same as that of argumentation, since every TE can be reconstructed as an argument (Norton 2004a, b). Because TEs do not involve new empirical data, they can only reorganise or generalise the old data (Norton 1991, p. 335). This prior knowledge, based on our previous experiences, can enter into thought experiments as assumptions. Hence, thought experiments are devices that reorganise or generalise these assumptions to achieve the result of the thought experiment. Norton regards these "devices" as arguments.

If the TE simply reorganises, it is a *deductive* argument or a *reductio ad absurdum* argument, where the particular conclusion follows deductively from the premises.

[4] Epistemic recourses are processes and tools that we use to decide that we know something or to create knowledge (Redish 2004, p. 31).

For instance, thermodynamics includes some powerful TEs because the first, second, and third laws of thermodynamics can be formulated as "assertions of impossibilities" (Norton 1991, p. 131). The first law can be expressed as an assertion as follows: "It is impossible to design a perpetual motion machine of the first kind, that is, a machine whose sole effect is to produce more energy than it consumes". Norton explains that consequences can be derived from the assertions included in a *reductio* argument, which then almost automatically becomes a thought experiment.

If the TE generalises on a wider scale, it is an *inductive* argument. This kind of TE includes an inductive step that frees the conclusion of its particulars. Norton (1991) suggests that Einstein's magnet and conductor and Einstein's elevator thought experiments belong to this class. According to Norton (1991, p. 137), Einstein's elevator can be constructed as arguments as follows:

1. In an opaque chest, an observer will see free bodies move identically in the case where the box is uniformly accelerated in a gravitation-free space and where the box is at rest in a homogenous gravitational field.
2. Inductive step: (a) the case is typical and will hold for all observable phenomena and (b) the presence of the chest and observer are inessential to the equivalence.
3. A uniformly accelerating frame in gravitation-free space and a frame at rest in a homogenous gravitational field are observationally identical but theoretically distinguished, which is self-contradictory.
4. The verifiability heuristic for theory construction (version 2[5]).
5. A uniformly accelerating frame in a gravitation-free space and a frame at rest in a homogenous gravitational field are the same thing (which becomes a postulate of a new theory).

According to Norton, the inductive step (2), which proceeds from a finite number of specific facts to a general conclusion, is quite problematic but "masked by the thought experiment format". He continues: "The extension from the motion of bodies in free fall to arbitrary processes is quite a leap, especially in view of the bizarre consequences that follow". Based on this example, it seems that constructing a thought experiment as arguments may also contain challenging phases that may not be unambiguous.

Brown and Fehige (2010) present three objections to Norton's claims. First, they consider Norton's view too vague. Second, they argue that Norton reaches far ahead of established facts: every real-world experiment can be represented as a thought experiment but nobody claims that thought experiments are unnecessary. Furthermore, Norton's view does not tell where the arguments come from. Brown and Fehige (2010) admit that a thought experiment can be an essential phase in the building of Nortonian reconstruction, but a thought experiment expressed as an argument loses its power. Arthur (1999) also disagrees with Norton by arguing that

[5] States of affairs that are not observationally distinct should not be distinguished by the theory (Norton 1991, p. 135).

if TEs are constructed as arguments, there will be an epistemic loss: the original thought experiment is not epistemically similar to the constructed arguments.

Nersessian (1992, p. 27) argues that a Nortonian reconstruction cannot be performed before the actual thought experiment has been executed. This means that TEs really have experimental power. By claiming that a TE contains particulars irrelevant to the conclusions, Norton fails also to see the constructive function of the narrative form in which thought experiments are presented.

Häggqvist (1996) claims that thought experiments are not arguments because something that is a process, an event, or a procedure cannot, by its nature, be an argument; TEs function, however, via their connection with arguments. He argues that thought experiments work in the same way as experiments in general, by affording premises for their associated arguments. For a successful experiment, the premises are true. Only arguments as truth-valued, linguistic entities matter when the truth-value of a scientific or philosophical theory or hypothesis is evaluated.

The argument-based view of TE as presented by Norton (1991, 1996, 2004a, b) seems to be problematic with regard to its potential use in science teaching. The reconstruction process, in particular, would be rather demanding for students because, in practice, students would already need to understand the original TE quite well in order to be able to perform the reconstruction. This does not mean that we do not appreciate the basic skills of scientific argumentation that constitute important learning goals in science education. The argument view may, however, be useful for science educators and science teachers in regarding the nature of the counterpoint of the argument-based view, i.e. Brown's destructive and constructive TEs, which will be examined next.

38.4.2 Brown's Destructive and Constructive TEs

James Robert Brown (1991) classified TEs according to their role in building scientific theories as destructive and constructive TEs. *A destructive TE* is an argument against a theory; it destroys or at least indicates serious problems in the particular theory. According to Brown, Einstein's chasing the light beam, presented in the introduction to this chapter, and Schrödinger's cat are examples of this kind of TE. Erwin Schrödinger presented a cat paradox where a cat in a box exists in a superposition of two states: dead and alive (Schrödinger 1935). His aim was to question the limitations and conceptual difficulties of quantum mechanics.

In contrast, *constructive* TEs break down into three further types: *direct*, *conjectural*, and *meditative* TEs. *A meditative TE* helps in the drawing of a conclusion from a specified, well-articulated theory. It may illustrate some counter-intuitive aspects of the theory, making it seem more satisfying, or it may act like a diagram in a geometrical proof that helps to support understanding, or even in the discovery of, the formal proof. Brown uses Maxwell's demon as an example of meditative TE.

The demon sits between the chambers of a gas vessel, which are filled with gas. The demon opens a trapdoor between the chambers by allowing the faster molecules to move to one side and the slower molecules to the other side. The TE shows that if this kind of demon existed, it would decrease the entropy of the gas system and cause a violation of the second law of thermodynamics. James Clerk Maxwell used this thought experiment to discuss the second law of thermodynamics at molecular level and to show that it possessed only statistical certainty (Schlesinger 1996; Radhakrishnamurty 2010). According to Schlesinger, Maxwell's intention was to use the demon to dramatise his claim concerning the statistical nature of thermodynamics.

A *conjectural TE* establishes some phenomenon and hypothesises a theory to explain the theory thereafter. The events of conjectural TEs have a presumed explanation. A *direct TE* begins with an unproblematic phenomenon and ends with a well-articulated theory. Brown considers Newton's bucket to be a prime example of a conjectural TE. Newton suggested that the existence of absolute space could be substantiated by hanging a bucket of water from a rope and spinning it. The concave shape of the water's surfaces caused Newton to assume that it was spinning with respect to something. Furthermore, according to Brown (1991), Stevin's inclined plane[6] and Einstein's elevator[7] belong to this class of TEs.

A small group of TEs are both destructive and constructive at the same time. These thought experiments are termed Platonic TEs (Brown 1991, p. 34). According to Brown (1991), in a few special cases we may go well beyond existing data to obtain a priori information about nature. Brown and Fehige (2010) explain that this information is a priori information about nature since, because the thought experiment does not contain new information, the conclusion does not draw on old data and it is not some sort of logical truth. This view of thought experiments can be further developed by combining a priori epistemology to recent views about the laws of nature, according to which laws consist of objectively existing relations between abstract entities. This view is, therefore, Platonic.

According to Brown, Galileo's free fall and the EPR (Einstein, Podolsky, Rosen) paradox may be regarded as examples of Platonic TEs. Brown argues that Galileo's free fall extinguished Aristotle's view and generated a new view, while EPR seriously challenged the Copenhagen interpretation and established the incompleteness of quantum mechanics. Brown and Fehige (2010) have characterised Brown's view as an intuition-based view.[8]

Galileo's free fall TE indeed revealed an inconsistency in the Aristotelian view, but it could not say anything about the actual descent of objects, which indeed fall at different rates of acceleration relative to the ground. According to McAllister (2004), Galileo's TE merely verified that if the rate of fall of simple and compound bodies was simply a function of their mass, then the rate of fall of bodies would be

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[6] Stevin's TE discusses the forces that are needed to keep a weight on an inclined plane (see, e.g. Gilbert and Reiner 2000).

[7] If a man is in a windowless elevator, he cannot tell whether the sensation of weight is due to gravity or acceleration.

[8] Intuition can be defined as a capacity for attaining direct knowledge or understanding without the apparent intrusion of rational thought or logical inference (Sadler-Smith and Shefy 2004).

independent of mass. This is an important point that needs to be grasped in physics education (Lehavi and Galili 2009). Hence, Galileo's free fall TE is not actually a Platonic TE. Furthermore, Albert Einstein, Boris Podolsky, and Nathan Rosen attempted to show that quantum mechanics is incomplete, but, instead, a definition of nonlocality was found (Einstein 1918). Quantum mechanics is, however, generally regarded as complete. Bokulich (2001) has discussed both the essence and also further modifications of EPR.

Our view is aligned with that of Arthur (1999), who does not agree with the epistemological power of Platonic TEs but thinks that TEs can go beyond arguments by offering an effortlessly understandable imaginative reconstruction of the phenomenon. According to Arthur (1999, p. 27), there are no pre-existing concepts but rather some sort of presentiment or intuition of them. This does not mean that such ideas would really exist and that we could not yet understand them. Rather, we have not succeeded in formulating them.

Norton (2004a) has questioned the reliability of the use of those TEs that are supposed to be "the glimpsing a Platonic world". Brown's counterargument is that even ordinary vision can be mistaken (1991, p. 65–66). Norton sees this differently: the TE that fails is simply an argument that contains an erroneous assumption. Brown's Platonism has also been criticised for not presenting criteria for good and poor thought experiments (Brown and Fehige 2010). Brown and Fehige argue that this objection will be weak if the intuitions do the work in thought experiments, since rationalists and empiricists do not have a theory of the validity of intuitions.

Brown's (1991) categorisation of TEs as constructive and destructive has already been used in the analysis of thought experiments in physics textbooks and popular physics books by Velentzas, Halkia, and Skordoulis (2007). When they analysed 25 books to discover how the 11 most essential thought experiments in the domains of relativity and quantum mechanics are presented, they found all of the thought experiments contained in the books to be constructive.

The use of Brown's categorisation shows that it has potential in science education. We believe that it could also be used in science teaching as a theoretical framework of thought experiments for understanding how scientific knowledge is constructed. In the following section, thought experiments are discussed from the perspective of science education.

38.5 Thought Experiments in Science Education

In the course of the past 10 years, there has been a slight increase in research activities related to thought experiments in science education, and thought experiments have received more attention in scientific discussions. Here we argue why and how TEs might be used in science teaching in supporting student learning and offering an authentic image of science. In addition, the possible challenges involved in the teaching and learning of TE will form part of the discussion.

38.5.1 Pedagogical Benefits of Thought Experiments

Ernst Mach was the first to realise that thought experiments might have a high didactical value (Mach 1976). He emphasised in particular the role played by students in thought experimenting (Matthews 1988, 1990). By using thought experiments as a teaching method, a teacher can keep students guessing. In addition, this method provides a significant support to the teacher in coming to know his/her students better. Some students are able to guess the next phase immediately, while some will present extraordinary guesses. Through thought experiments, students will learn to distinguish solvable from unsolvable concerns.

The use of TEs introduces an authentic image of the culture of science (Galili 2009; Reiner et al. 1995; Reiner and Gilbert 2008). TEs can be used to address the essential characteristics of physical theories (Galili 2009). They often employ representative models that eliminate technical details, errors, and impeding factors such as heat or friction. By introducing TEs before real experiments, students may develop an ability to appreciate real experiments and perceive the focus of the experiments, which is otherwise frequently difficult to see because of the sheer quantity of details. Naive observers' difficulties in differentiating between non-relevant and relevant details may impede them from finding out the aimed observations, results, and conclusions (see, e.g. Kozma and Russell 1997; McDermott 1993). Klassen (2006) believes that by devising their own thought experiments, students are mentally engaged in the concepts to be learned, and this, in turn, may help them to construct a deeper understanding of science. Nersessian (1992) claims that "the historical processes provide a model for learning activity itself" and may assist students in constructing representations of scientific theories. Social discussions of TEs may lead students to conceptual refinement and construction of reliable knowledge, as would be the case in science itself (Reiner and Gilbert 2008).

Reiner and Burko (2003) claim that both the TEs devised by physicists and also those formulated independently by students are important in the learning of physics. Scientifically correct TEs constructed by famous physicists enable students to familiarise themselves with the potential of TEs and to see them as a special mode of argumentation. In contrast, incorrect TEs prepare them for the existence of logical and conceptual stumbling stones, the temporary state of knowledge in physics, and the meaning of self- and peer criticism in the construction of physical knowledge. By working on thought experiments independently, students also work through the processes that underlie erroneous reasoning and learn to negotiate over the processes and conclusions with their peers in a relevant form of social interaction (Reiner et al. 1995). Procedures such as these all contribute to the clarification of concepts.

It has also been claimed that the use of TE in teaching stimulates students' interest (Lattery 2001; Velentzas et al. 2007; Velentzas and Halkia 2011) and helps their imaginations to develop (Galili 2009). By introducing situations that are impossible to reproduce despite the sophistication of the available equipment, TEs also become an irreplaceable tool of teaching. According to Galili (2009), this applies especially in the teaching of relativity and quantum physics, where real experiments are not widely used in the classroom, and the use of the multimedia often fails to promote enhanced understanding. Encouragement is also given to the use of thought experiments in teaching if the aim of the teaching is to activate students' cognitive processes with situations that would otherwise be beyond their everyday experiences (Velentzas and Halkia 2010).

38.5.2 The Use of Thought Experiments in Science Textbooks

It has been noted that in some domains of physics such as relativity and quantum mechanics, thought experiments are the main method of presenting the concepts in physics textbooks and popular physics books (Velentzas et al. 2007). Because science teachers often base their teaching on textbooks (Levitt 2002; Yore 1991), textbook studies are an important method for understanding the premises of science teachers' use of thought experiments. In addition, it would appear that studies concerned with teachers' use of TEs are still absent from in the literature.

The extent to which thought experiments are used in science textbooks and the ways in which they have been exploited have been studied by Gilbert and Reiner (2000) and Velentzas, Halkia, and Skordoulis (2007). Gilbert and Reiner's study focused on popular physics textbooks[9] while Velentzas and colleagues looked at both popular science books and physics textbooks.[10]

Gilbert and Reiner (2000) discovered that textbooks often miss opportunities to develop thought experiments suitable for teaching even though there were numerous suitable opportunities to do so. Thought experiments in textbooks frequently turn into thought simulations that lack two essential elements of thought experiments: recognition and approval of the imposed problem and conclusions based on the results. Instead of drawing on the six elements of TEs,[11] the textbook thought simulations typically consisted of the following parts:

i. Statement of the conclusion reached
ii. Creation of the imagined world
iii. Conflation of the design and running elements
iv. Statement of the results obtained, often with an optional restatement of the conclusions reached (Gilbert and Reiner 2000, p. 279)

[9] The books analysed were Breithaupt's *Understanding Physics for Advanced Level* and Ohanion's *Physics* and *Conceptual Physics* by Hewitt.

[10] The books were either written in Greek or translated into Greek from English. The study aimed at finding out how the books represented the 11 most essential thought experiments in the domains of relativity and quantum mechanics. A total of 25 books were included in the study.

[11] The six elements of a TE: (1) posing a question or a hypothesis, (2) creating an imaginary world, (3) designing the TE, (4) performing the TE mentally, (5) producing an outcome of the TE, and (6) drawing a conclusion.

According to Gilbert and Reiner (2000), this may be the result of the textbook writers not understanding the actual potential of using thought experiments. Indeed, thought experiments can be a successful way to enhance students' cognitive engagement, which is the key to developmental success. Thought experiments offer opportunities for creating new ontological entities, developing reasoning skills, and adopting epistemological engagements. These skills are claimed to be essential for gaining an understanding of physics (Driver et al. 1994). It might also be asked whether this kind of one-sided deductive approach to thought experiments is pedagogically valid.

Velentzas, Halkia, and Skordoulis (2007) observed that all of the thought experiments that they had found in the physics textbooks and popular physics books in their study were constructive. In addition, the authors had modernised numerous thought experiments: for example, Einstein's chest TE was examined in the form of a spaceship thought experiment. The authors had also invented thought experiments independently. The mathematical level of thought experiment was low and the terminology, language, and abstraction level were all modified to match their readers' perceived skills. The use of narratives was typical of the popular textbooks, whereas the other textbooks tended to avoid narratives by using scientific language and terminology.

38.5.3 Studies on the Use of Thought Experiments in Teaching

Thought experiments have been used in science teaching in different ways, and some of the possibilities have been reported. In the following we describe a few of these: using written tasks to help students to understand well-known TEs,[12] constructing historical physics experiments as thought experiments in narrative form (Klassen 2006), and students' own TEs in the context of experimental work (Reiner 1998).

Velentzas, Halkia, and Skordoulis (2007) used the famous TE known as Einstein's elevator thought experiment to introduce the concepts of the equivalence principle to 9th grade students. A group of six students studied the thought experiment as it was presented in a selected popular physics book[13] and replied to related questions, first individually and then as a group. The results indicate that the pupils achieved a reasonable understanding of the concepts. They were also surprisingly enthusiastic about performing the given task. The researchers supposed that this reaction may have been a consequence of the nonmathematical, narrative representation of the task. It seems, then, that popularised thought experiments can be used to inspire pupils in the case of concepts and principles that are discussed in greater depth later in the teaching process.

[12] See, e.g. Velentzas et al. (2007), Lattery (2001), Velentzas and Halkia (2011), and Velentzas and Halkia (2012).

[13] Stannard, R. (1991). *Black Hole and Uncle Albert*. London: Faber and Faber Ltd.

Velentzas and Halkia (2011, 2012) have also successfully used thought experiments as a teaching tool in physics teaching for upper secondary students. They studied the ways in which the uncertainty principle and the basic concepts of the theory of relativity could be taught to upper secondary school students. The uncertainty principle was introduced via Heisenberg's microscope thought experiment (Velentzas and Halkia 2011), while the theory of relativity was approached via Einstein's train and Einstein's elevator thought experiments (Velentzas and Halkia 2012). In the case of the uncertainty principle, the students were able to derive the uncertainty principle, and by the end of the teaching, they understood it as a general principle in nature (Velentzas and Halkia 2011). Furthermore, Einstein's TEs concerning relativity enabled students to realise situations related to the world beyond their everyday experiences and to gain a basic understanding of the theory of relativity (Velentzas and Halkia 2012).

Lattery (2001) used Galileo's TE Law of Chords (rates of descent along certain curves) as a basis for a student project at the university level. A group of three students discussed the TE and made predictions, following which they tested the predictions experimentally. Subsequently, they wrote a paper, prepared a poster, and made an oral presentation for their peers and the faculty concerned with the project. Lattery concludes that it offered a positive learning experience for the students themselves, for their peers, and for faculty in general.

Klassen (2006) argued that thought experiments could be expressed as stories. To test his hypothesis, he wrote a story about Benjamin Franklin's life and experiments in a form that invited students to render Franklin's experiments as thought experiments. He believed that this kind of narrative construction would help students to become mentally engaged in the concepts to be learned and that this, in turn, would them help to construct a more profound understanding of science. Even if a method of this kind seems to be rather interesting, its effectiveness should still be assessed scientifically by examining students' learning processes before further conclusions.

Reiner (1998) studied grade 11 students' self-devised thought experiments. A total of 12 students were given the following task. Using a computer-based simulator and hands-on equipment, they were required to design a periscope with a wide visual field. To solve the task, the students worked in groups of three. Analysis of the processes produced by one group showed that the students' thought experiments developed because of a collaborative problem-solving process in which the students used the computer system to validate potential events and results. The system helped the students to make their intentions visible to their peers and also to test hypothetical events. Furthermore, the four different student groups displayed a considerable variety of thought experiments, e.g. the logic and contexts that the students used and the conclusions that they drew varied considerably. It was also typical of the four groups that the students' thought experiments were partial and incomplete; they did not contain all three parts of the typical thought experiment: hypothesis, results, and conclusions. Reiner claims, however, that the results show that the thought experiments, which consisted of episodes, were general rather than random, even if they missed out one or two of the three parts. According to Reiner, a collaborative environment helps students to construct thought experiments as a shared construction that is based on individual students' contributions.

These examples of the implementation of thought experiments in teaching are illustrative; but in actual classroom teaching, some limitations may occur. Teachers need to take into account the fact that students' cognitive processes may lead to erroneous conclusions (Velentzas and Halkia 2011). In analysing some of the famous TEs of physics, Reiner and Burko (2003) have discovered cognitive processes that also lead to erroneous conclusions. At least three of this kind were found: strong *intuition* of a kind that induces the abandonment of theory-based reasoning, *incompleteness* of the basic assumption of the thought experiment, and *irrelevance* of the system's properties in the thought experiment.

Reiner and Burko (2003) claim that the processes that are characteristic of physical thinking are likely to be found in physics learning as well. The use of intuition instead of logical, theory-based reasoning is even stronger in the case of naive physics learners than amongst famous physicists in the history of physics. In addition, research has shown that students more often apply concrete, experiential knowledge rather than using logical reasoning (e.g. DiSessa 1993; Gilbert and Reiner 2000). The incompleteness of the students' TEs relates to the narrowness of the learners' physical world. Their readiness to conclude is insufficient because assumptions integrated into knowledge structures are partial instead of being comprehensive; the learners may not have sufficient knowledge of the physical world to make sense of the TE. Reiner and Burko (2003) argue that the use of TEs in physics learning is important, because it allows students to experience the destructive and constructive role of physical intuitions, incompleteness, and the importance of relevancy.

We agree with Reiner and Burko and Velentzas and Halkia (2011), who recommend the use of TEs in cases where the performance of a physical experiment is impossible, harmful, and dangerous or has nothing to offer in the end for the result. They also suggest the use of TEs in situations that require students to mentally surpass their everyday experiences.

In sum, thought experiments can be used in science teaching to help students to develop their conceptual understanding of science.[14] Thought experiments may increase students' interest in learning science[15] and to activate and support their thinking processes.[16] In addition, the construction of students' own thought experiments can be supported by creating a collaborative environment that enables students to construct thought experiment together with their peers (Reiner 1998). Students' erroneous conclusions should, however, be taken into account in teaching; they can be used as a basis for discussion about the destructive and constructive intuitions in thought experimenting (Reiner and Burko 2003).

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[14] See Galili (2009), Velentzas et al. (2007), and Velentzas and Halkia (2011, 2012).

[15] See, e.g. Gilbert and Reiner (2000), Velentzas et al. (2007), and Lattery (2001).

[16] See, e.g. Reiner and Burko (2003), Reiner and Gilbert (2008), and Velentzas and Halkia (2011, 2012).

38.6 Conclusion

This article has examined the role played by thought experiments in science and science education. It has been argued that TEs are a natural part of scientific methodology, a special type of scientific experimentation that may play either a constructive or a destructive role in the construction of scientific theories. The important role played by TEs in science should also be discussed in science teaching. In addition, TEs have been used in science education in various ways to foster the development of students' reasoning, mental modelling, and conceptual understanding; to teach them about the nature and processes of science; and to stimulate their interest in science. Thought experiments also provide opportunities for focusing on the epistemology and ontology of science in the teaching of science.

TEs are a special variety of scientific experiment that can, at its best, precede a physical experiment and help the experimenter in conducting it. In some cases, physical experimentation may not yet be possible and the TE can be the only way to experiment; TEs are free from the constraints imposed by the learning environment and by technical restrictions (Cooper 2005; Galili 2009). In addition, a physical experiment may be considered useless if it is unlikely to substantially improve understanding gained from a TE (Sorensen 1992). These statements also hold true in science education: TEs can be used as an effective tool for teaching. By performing a TE before the physical experiment per se, students may develop their ability to see the focus of the physical experiment (Galili 2009). At times, the experiment can only be made mentally as a TE for practical reasons: the school may not have certain equipment or the experiment is too laborious to be conducted during a lesson. In some cases, thought experimenting is the only way to experiment because the situation cannot be performed as a physical experiment, regardless of the sophistication of the equipment available (Galili 2009). TEs also frequently involve idealisations such as technical details, errors, and impeding factors such as heat or friction; these factors can be eliminated by using TEs (Cooper 2005; Galili 2009). This particular use of TEs in school teaching may already be more common than might be expected.

TEs in science can be fallible, but the mistakes can also teach important lessons that help scientists to develop scientific theories. For instance, erroneous conclusions in famous TEs can be explained in terms of three different cognitive processes: strong *intuition*, which induces the abandonment of theory-based reasoning; the *incompleteness* of the basic assumptions of thought experiment; and the *irrelevance* of the properties of the system in the thought experiment (Reiner and Burko 2003). This kind of erroneous reasoning is also likely in the case of students; teachers should also be prepared to take it into account in their teaching (Velentzas and Halkia 2011). Teachers should also be prepared to encourage students to experiment mentally. As Ozdemir's (2009) results have shown, even physics graduates may tend to think that mental simulations cannot be used correctly to explain the phenomena of physics. Hence, teachers should be ready to help their students to become more open-minded and to be undaunted by errors in their reasoning. Teachers need to help their students to gain an insight into the value of thought experiments in scientific reasoning since they may otherwise remain unaware of it (Reiner 2006).

Thought experiments can be used in science teaching to allow students to see that scientific intuitions can play both destructive and constructive roles. It has, however, been observed that authors of science textbooks and popular science books may be in the habit of using only constructive TEs (Velentzas et al. 2007). This rather one-sided use of TEs may bias the image of science that the books attempt to convey. If the authors of textbooks aim at conveying an image of the processes of science, then the use of TEs in textbooks should be carefully designed to include both destructive and constructive TEs.

It must also be emphasised that, when conceptually demanding thought experiments have been simplified for teaching a particular student group, it has been noted that thought experiments stimulate the students' interest (Velentzas et al. 2007). Our own approach tends to agree with that of other researchers who acknowledge that this use of TEs works well if the concepts are taught in greater detail at a later stage. Reconstruction of historical physical experiments as thought experiments has also been reported to enhance students' interest (Klassen 2006).

The role played by a skilful teacher is pivotal in the use of thought experiments in science teaching. Students' own thought experimenting needs to be supported by the teacher by means of the selection of suitable resources, the structuring of the learning activities, and guidance of the students' experimentation (Hennessy et al. 2007). A skilful teacher is able to observe instances of erroneous reasoning and knows how to guide students' learning processes in the right direction. To be able to evaluate thought experiments in science textbooks and also thought experiments implemented by students, a teacher should present or formulate the theoretical background and criteria for the elements of a TE. Gilbert and Reiner (2000, p. 268) provide a system of categorisation for thought experiments that appears to be promising for understanding the use of TEs in science teaching. The categorisation is briefly as follows. An *expressed thought experiment* is a TE that has been placed in the public domain by an individual or a group of researchers. A *consensus thought experiment* is a TE accepted by at least some of the scientific community and one that has been scientifically justified, that is, published in a scientific journal.

In addition, a *historical thought experiment* is a TE that has already been replaced in science but may still be used to explain particular phenomena economically. A *teaching thought experiment* contains "the criterion by the teacher (or, indeed, the taught) of the TE based on the situations familiar to or imaginable by the students, through which to develop an understanding of a given consensus TE". Gilbert and Reiner emphasise that all of the different types of TEs include the six elements of TEs described by Reiner (1998).

As Gilbert and Reiner (2000) point out, although different types of thought experiment exist in science, they all have a certain structure. Hence, thought experiments devised and conducted by students should also include these common elements in order to qualify as genuine thought experiments; if some of the elements are missing, then the exercise should be termed a thought simulation rather than a thought experiment (Gilbert and Reiner 2000). According to some studies, historical TEs have sometimes been modernised in textbooks to be more readily understandable (see, e.g. Velentzas et al. 2007). This reconstruction may, however, lead to another problem: textbooks do not always include all of the necessary elements of thought experiments, with the result that TEs that have been reduced as thought simulations will lead to loss of the necessary cognitive engagement (Gilbert and Reiner 2000). Such thought simulations may nevertheless be used to some extent in science teaching if the primary goal of the teaching is not the actual subject matter or to foster students' understanding of the processes of science but rather to stimulate the students' interest in the science per se. Naturally, it would be unreasonable to assume that, for instance, secondary students would be able to perform thought experiments as effectively as, say, university students. It is perhaps self-evident that the science teacher should have the freedom to decide just how accurate students' mentally performed experiments need to be for them to fulfil the criteria of a thought experiment.

Undoubtedly, TEs need to be considered carefully in the context of science teacher education, and in-service education would need to be organised for practicing teachers. Both pedagogical and subject-matter departments could introduce TEs to students as part of the history and philosophy of science teaching. In addition, many subject-matter courses, such as mechanics, thermodynamics, and quantum physics, offer good opportunities for the use of TEs in the teaching of subject matter. In this way, TEs could become better integrated into the knowledge structures of future science teachers, who could then use thought experiments flexibly in their own science teaching. As Matthews (1992, p. 28) suggests, "A historically and philosophically literate science teacher can assist students to grasp just how science captures, and does not capture, the real, subjective, lived world".

Systematic research into the use of TEs in science teaching is, however, definitely needed so that we can acquire further research-based, valid information on their effective use at various educational levels. In particular, the notion of a *teaching thought experiment* is interesting from the perspective of science teaching as conducted in schools. It would be interesting to discover the kind of TEs that teachers use and how they use them, and whether teachers use thought simulations (TSs) rather than TEs. It is likely that consensus and historical TEs are not widely used in teaching at secondary school level, but teaching TEs may nevertheless prove to be more common than is thought. Thus far, the groups participating in the studies have been small and they have varied from lower secondary school pupils to university students. In consequence, the results cannot be readily compared; and hence our recommendations for the use of TEs in teaching are inevitably still rather loosely based. Nevertheless, analysis of students' thought experiments has interesting possibilities that may help us to understand better the challenges posed by science learning. There is undoubtedly a need for further studies of how science teachers actually use TEs in their teaching. This gap in the literature deserves to be filled.

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