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ARTICLE

Exploring How Students Construct Collaborative Thought Experiments During Physics Problem-Solving Activities

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Abstract
Thought experiments are personal and tacit processes of experimentation that scientists perform within their own imagery in formulating new theories or refuting existing theories. However, by viewing learning as a social process, this study aims to show that thought experiments can also be constructed collaboratively and to present a detailed mechanism of how thought experiments occur as a collective activity. The paper presents a study involving 12 students divided into 3 groups. The physics problem-solving activities were used to set the necessary conditions for observing the processes of students in constructing collaborative thought experiments. The results show that while solving physics problems, students design, share, rethink, and evaluate their thought experiments. This indicates that thought experiments can be constructed in a collaborative context even though the thought experiments are mostly individual in nature. In the process of constructing collaborative thought experiments, the students carried out five activities: visualizing imaginary worlds, performing experiments, describing the results, sharing and evaluating experiments, and drawing conclusions. We refer to these activities as the steps of collaborative thought experiments. In the process of evaluating thought experiments, four evaluation sources were then identified: conceptual understanding, past–daily experience, logical reasoning, and conceptual–logical inference. Based on these results, we discuss the importance and implication of collaborative thought experiments to both current and future physics teachers.

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1 Introduction

Thought experiments (TEs) have attracted the attention of many researchers in not only history and philosophy of science but also science education. Throughout the history of science, there have been several exemplary cases where scientists used TEs either to formulate a new theory or to refute an existing theory. For example, at the beginning of his paper "On the Electrodynamics of Moving Bodies" (1905), Einstein used a TE involving magnet and conductor to describe the concept of relative motion. Using this TE about magnet and conductor, Einstein then raised the status of the principle of relativity to become a postulate and introduced another postulate: the speed of light is constant in all inertial frames (Einstein 1905). In the physics community, there were several popular TEs, such as Galileo's free-falling body (Galileo 1638/1914), Newton's bucket and cannon (Newton 1687/1962), Maxwell's demon (Maxwell 1871/2001), Einstein's magnet and conductor (Einstein 1905), and Schrodinger's cat (Schrödinger 1935). These are just a few examples that illustrate the important role of TEs in developing scientific theories.

Concerning science education, some studies have investigated the contribution of TEs to science teaching and learning. Mach (1905/1976) argued that by using TEs as a teaching method, students could learn to guess which problems can be solved and which cannot. Other studies have shown that the use of TEs can inspire students to provide a rich source for their ideas (Lattery 2001) and develop students' intuition (Georgiou 2005). Teaching TEs is always related to the history and philosophy of science. Therefore, the inclusion of TEs is important in teaching science because they can familiarize students with the culture of science (Reiner 1998; Galili 2009), and as imagination tools to investigate the nature of science (Brown 2006; Sorensen 2016). The integration of TEs into the subject matter will also be useful for pre- and in-service teachers, who can then see the possibility of using TEs in teaching science in schools. Klassen (2006) believed that by designing their own TEs, students are mentally involved in constructing concepts, and in turn, they will understand scientific concepts more deeply. The use of the history of TEs as a tool in teaching modern physics can help develop students' syllogistic abilities and help them to imagine situations outside of everyday experience (Velentzas and Halkia 2013). In order to understand how TEs have been presented in high school physics textbooks, some researchers have examined textbooks and evaluated whether TEs are necessary as an introduction in teaching physics (Gilbert and Reiner 2000; Velentzas et al. 2007; Bancong and Song 2018). All of these concerns point to the importance of TEs in the teaching and learning of science.

Despite this consensus on the importance of TEs for science teaching and learning, several studies have also shown that most science teachers and students have difficulties in designing and doing TEs (e.g., Reiner and Burko 2003; Asikainen and Hirvonen 2014; Kösem and Özdemir 2014). Even when students visualize the imaginary world appropriately and design and run experiments in their heads structurally, they may still draw erroneous conclusions from the TEs (Reiner and Burko 2003). Norton (2004) and Brown (2006) also showed that TEs could and often do produce the wrong results even though they can provide useful results in the development of scientific theory. Recommendations to physics teachers on how to apply TEs in meaningful ways and how to help students find effective thinking procedures in running TEs are still rare. Reiner (1998) has proposed using computer simulation when teaching TEs, but some researchers (e.g., Galili 2009) have refuted this strategy because most TE simulation often fails, suffering superficial and conceptually irrelevant contents. Although Velentzas and Halkia (2013) had reported positive results when they implemented Einstein's historical TE of the elevator and TE of the train for teaching the basics of relativity, it was being not enough. There is still much work to be done to identify the better strategies for teaching TEs.

According to Reiner (1988), TEs are more easily constructed in a collaborative manner, where the number of students' contributions can lead to a complete TE. This might provide us an insight into teaching TEs in collaborative learning. However, how TEs are constructed collaboratively, how students share and negotiate meaning during constructing TEs in collaborative learning, and how students validate the results of TEs are not clearly explained either by Reiner (1988) or in subsequent studies. After all, most philosophers and historians are viewing TEs as a private and tacit process of experimentation with personal imagery, which is difficult to represent and communicate. For example, Brown (1991) argued that TEs are experiments that are designed and run in the mind of a thought experimenter and are difficult to implement as real experiments. They are based on logical derivation and knowledge of individual experience (Kuhn 1977) and only occur in a person's mind, which is observed using the mind's eye (Sorensen 1992). So, the fundamental questions in order to teach TEs in a collaborative way are as follows: Can a TE, which is often built by individual scientists (Kuhn 1977; Brown 1991; Sorensen 1992), be shared and communicated with other members in group learning? Can two thought experimenters perform the same TE and reach the same conclusion? Can a TE be replicated, reworked, and even retooled by different thought experimenters? The challenge in trying to answer these questions is that there is no consensus on what exactly TEs are. Are TEs *experiments* (e.g., Mach 1905/1976; Kuhn 1977; Brown 1991; Sorensen 1992; Höggqvist 2009; Galili 2009; Buzzoni 2008, 2013, 2019), *arguments* (Norton 1991, 1996, 2004), *mental model* (Nersessian 1992; Miščević 1992; Cooper 2005), *fiction* (Ichikawa and Jarvis 2009; Elgin 2014), or something else?

2 Literature Review

2.1 The Meaning of Thought Experiment

The concept of TE, a direct translation of the German term *Gedankenexperimente*, has been widely discussed in the philosophy of science since Ernst Mach (1838–1916). Mach was considered as the first to introduce this term into active use (Matthews 1988; Galili 2009), even though some researchers have argued that the term TE had already been used by Danish physicist Hans Christian Ørsted in 1811 (Witt-Hansen 1976; Klassen 2006). In his paper "On Thought Experiments" (1905/1976), Mach argued, "besides physical experiments there are others that are extensively used at a higher intellectual level, namely thought experiments. The planner, the builder of castles in the air, the novelist, the author of social and technological utopias is experimenting with thoughts" (p. 136). Mach (1905/1976) emphasized the values of TEs as techniques for professional inquiry and for guessing the results of laboratory experiments.

Even though a large number of studies have been carried out in a variety of areas such as philosophy, history, and education that have contributed to the TE literature, a consensus has still not been reached on the exact definition of TEs. According to one of the most cited definitions (Brown 1991), TE is an experiment in the laboratory of mind that involves mental manipulations, is not the mere consequence of a theory-based calculation, and is often impossible to be implemented in the real laboratory. Like Brown (1991) and others (including Mach 1905/1976; Kuhn 1977; Bishop 1999; Bokulich 2001; Höggqvist 2009; Galili 2009; Buzzoni 2008, 2013, 2019), Sorensen (1992) viewed TEs as being on a continuum with real experiments (REs). Sorensen (1992) argued that TEs as specail cases of REs that they can achieve the aim of REs without physically executing them but instead mentally simulating them and be observed with mind's eye. TEs can teach us anything that was not known beforehand, and they are based on logical derivation and knowledge of individual experience (Kuhn 1977). Bokulich (2001) argued that because TEs are important tools for testing and evaluating the internal consistency, external coherence, and simplicity of scientific theories, they are the same as REs. Marco Buzzoni, in his efforts through a Kantian point of view (e.g., Buzzoni 2013, 2019), claimed that TEs and REs are identical in principle, and at least in science, one is impossible without the other. Simply, he argued, "(empirical) TEs without REs are empty; REs without TEs are blind" (Buzzoni 2013 p. 100).

John Norton, in a number of his works (1991; 1996; 2004), has been trying to convince us that TEs are nothing but arguments disguised in picturesque. For example, by analyzing several TEs in Einstein's work, Norton (1991) claimed that TEs are merely beautiful arguments because TEs do not involve new empirical data but only reorganize or generalize the old data. To further support his contention that TEs are merely arguments, Norton (1996) then outlined the epistemological of TEs by giving some well-known examples of TEs, such as Galileo's free-falling body and Newton's bucket. In 2004, Norton illustrated a number of TEs that produced erroneous results, which indicated that TEs were just ordinary arguments, as he said, "thought experiments in science are merely picturesque argumentation. I support this view in various ways, including the claim that it follows from the fact that thought experiments can err but can still be used reliably" (Norton 2004 p. 1139). However, some philosophers have criticized Norton's ideas because TEs consist of processes and procedures that are parallel to REs, and two or more different arguments can be generated from one TE (see Bishop 1999; Brown 1991; Höggqvist 2009; Stuart 2016).

Some scholars also viewed TEs as fiction (e.g., Ichikawa and Jarvis 2009; Elgin 2014). Elgin (2014) claimed that because the function of literary fiction is similar to the TEs, as both have narrative structures by imagining the scenario of events from the beginning, middle, and end, TEs are literary fiction. However, in our view, TEs must be logically and conceptually coherent, unlike fiction which often presents unreasonable discourse (Dohrn 2016). TEs, unlike literary fictions, are used to make arguments and are presented in the strongly allegorical terms (Egan 2016). TEs are also not arbitrary acts and think of strange irrational realities, such as when hallucinating. But they are structured acts of imagination based on theories (Reiner and Gilbert 2000; Galili 2009) as well as previous experiences (Nersessian 1992; Reiner and Gilbert 2000) to achieve certain goals.

Others (such as Nersessian 1992; Miščević 1992; Cooper 2005) claimed that TEs are mental model-based reasoning. Nersessian (1992) said:

> While I agree with Norton that thought experiments can often be reconstructed as arguments, the [mental] modeling function [of the thought experiment] cannot be supplanted by an argument … On my view, thought experimenting is a complex form of reasoning that integrates various forms of information - propositions, models, and equations - into dynamic mental models (p. 297).

The mental model in TEs consists of a set of propositions that describe the situation. Cooper (2005) said, "One thought experimenter will be able to visualize a situation, another will use a scrawled diagram, and a third will need to use concrete objects to represent the actors. All three model the situation" (p. 338). Nersessian (1992) has also told us the mental model in constructing TE as a "structural analog of the situation described" (p. 297). However, the mental model presented by Nersessian (1992) and Miščević (1992) is limited to simulating real-world phenomena. In contrast, Cooper (2005) viewed that the phenomenon being modeled is not limited by the real world, as the thought experimenters can create their own world model in which some laws of nature are suspended or changed.

Reiner and Gilbert (2000) tried to incorporate experimentalist views with mental models. They defined TEs as reasoning processes that represent the model of an event and start out in the mind of an individual. We support their opinion that TEs consist of two aspects: thought and experiment (Reiner and Gilbert 2000). The thought aspect involves modeling an imaginary world that is related to theories and experiences of thought experimenter, while the experiment aspect refers to experimental activities in the real world, such as manipulating variables and objects. Galili (2009) also said that TEs consist of experiments and thought activities. However, he limited the activity of thought which only deals with theory without experience. In our previous study (Bancong and Song 2020), however, we have identified that bodily knowledge, in the sense of experience, is one of the factors that trigger students to perform TEs while solving physics problems. Both Nersessian (1992) and Reiner and Gilbert (2000) also agreed that the use of imagery in a TE enables the thought experimenter to accesses body knowledge (non-explicit knowledge), in the sense of experience, that acts as the basis for generating new states of knowing.

2.2 The Steps of Conducting Thought Experiments

As mentioned earlier, we view TEs as a continuum of REs based on the mental model activity. Like REs, TEs are not random and undisciplined activities, but they operate on structured imagination. According to Reiner (1998), the structure of TEs is divided into five stages. First, thought experimenters construct an imaginary world and describe the features of the world they imagined, such as objects, rules, and conditions. Second, thought experimenters set the hypotheses to be used, such as using scientific theory. Third, thought experimenters design and conduct an experiment in their minds. Fourth, thought experimenters describe the results of carrying out the experiment, and, fifth, thought experimenters draw conclusions. In 2003, Reiner and Burko proposed five stages of TEs by swapping the first two stages before: thought experimenters (a) propose general assumptions, (b) describe the feature of imaginary world, (c) perform the experiments, (d) describe the results, and (e) draw conclusions. Brown (2006) also argued that TEs are carried out in a laboratory of the mind and have at least three steps: Thought experimenters (a) visualize the situation, (b) carry out an experiment, and (c) describe the results. Both of them proposed several similar structures of TEs: visualize imaginary worlds, performance experiments, and describe the results.

However, there is an inconsistency of the first two steps of TEs proposed by Reiner (1998) and Reiner and Burko (2003) that whether or not the thought experimenter sets hypothesis after describing the imaginary world. In addition, we think that something is missing from the previous TE steps. If we see TEs as a kind of experiment that depends on the epistemic force of their results, what is the validity of the results obtained? Brown (2006) also realized that each

TEs required background information just as REs do. However, he did not mention clearly what kind of this information was (whether theories, experience, intuition, or something else) and at what stage was to apply it. We therefore think that the previous TE steps lose the validation or evaluation steps before drawing conclusions.

2.3 Collaborative Learning and Collaborative Thought Experiment

Bokulich and Frappier (2017) argued that if TEs are a continuum of REs, then a TE can be replicated and rethought like a RE. This opens the discourse to construct TEs collaboratively. However, the challenge for philosophers and educators is whether the TEs can be constructed together so that they reach the same conclusions? To answer this challenge, we look at the social constructivism theory. In the field of education, learning is sometimes viewed as a social process (Vygotsky 1978) that includes participation in a community of practice (Lave and Wenger 1991). The concept of collaborative learning is based on social constructionism (Roschelle and Teasley 1995; Dillenbourg 1999), which views knowledge more as a property created by a group of students who share practices rather than the idea that knowledge is a cognitive residue in the head of an individual student (Lave and Wenger 1991; Hennessy 1993). Collaborative learning is rooted in the concept of the proximal development zone that was put forward by Vygotsky. In that concept, Vygotsky (1978) emphasized the importance of learning through communication and interaction with other people rather than learning independently. In collaborative learning, participants take advantage of each other's resources and skills, for example, asking each other, validating ideas with each other, and supporting and clarifying ideas with each other (Dillenbourg 1999; Chiu 2000).

Collaborative learning differs from cooperative learning, where it requires the mutual involvement of all participants as a mutual effort to solve problems, while cooperative learning requires individuals to take responsibility for certain parts and then coordinate their respective parts together (Dillenbourg 1999; Roschelle and Teasley 1995). Therefore, cooperative learning is usually used for children because it is used to understand the basics of knowledge, while collaborative learning applies to adults or university students because it involves a negotiation process (Bruffee 1995). Several studies have shown that collaborative activity in which students have to manage without teacher support shows remarkable success in learning (e.g., Roschelle 1992; Roschelle and Teasley 1995; Hausmann et al. 2004; Gijlers and Jong 2013). That is in contrast with cooperative problem-solving, in which students are supported by teacher guidance (Heller et al. 1992; Matthews et al. 1995). According to Dillenbourg (1999), there are three interactions as collaborative activities. First, the activity must reflect sufficient interaction between group members. Second, there is an activity to do something together. Third, there is an activity of negotiation of meaning.

Therefore, by looking at TEs as a continuum of REs using mental model activities, this study aims to show that TEs can be constructed collaboratively and to present a detailed mechanism of how TEs occur as a collective activity. The concept of collaboration was used in this study. We will refer to the TEs that are co-constructed by students as collaborative TEs. Although TEs are scientists' personal and tacit processes of experimentation in constructing a scientific theory, we think that they have the possibility of being replicated, rethought, and evaluated with other students in a group setting. When students are given the opportunity to work together to solve meaningful problems, we believe that they will perform TEs and then share them with their group members to be polished and validated as a collective effort to achieve mutual understanding. So, the research questions were as follows:

(1) Can TEs done by one student be shared and evaluated with other students in their group?
(2) What are the steps of collaborative TEs during physics problem-solving activities?
(3) How do students validate the results of TEs during physics problem-solving activities?

3 Methods

3.1 Context

The main purpose of this study is to get as much information as possible about how students construct collaborative TEs. Some related literature has argued that TEs are cognitive tools for both students and experts when they are working on problems (e.g., Mach 1905/1976; Reiner 1998; Reiner and Gilbert 2000; Clement 2009). Mach (1905/1976) emphasized the values of TEs as logical devices for guessing which problems can be solved and which cannot. Therefore, physics problem-solving activities were used to set the necessary conditions for observing the processes of students in constructing collaborative TEs. During the problem-solving sessions, we carefully observed the activities and interactions that occurred between students in each group. The selection of the problems used in this study was based on the following criteria: They must (1) trigger and activate the imaginary world of students, (2) not require advance algebraic calculation, (3) be related to situations in everyday life, and (4) be interesting for students.

Some researchers who deal with the topic of TEs (e.g., Georgiou 2005; Kösem and Özdemir 2014) have adapted physics problems from Epstein's (1995) book entitled *Thinking Physics Is Gedanken Physics* when investigating the processes of students' TEs while solving a physics problem. The book contains a series of physics problems that can trigger and activate the imaginary world of students to enable them to perform TEs while solving problems. Therefore, in this study, we adopted physics problems from Epstein (1995) and modified the language to be simple and easily understood by students. The potential problems were discussed and then piloted with some students to check whether or not they encourage students to do TEs. After being piloted and discussed again, the number of potential problems was reduced from 12 to 5 according to their effectiveness in stimulating and triggering students to perform TEs.

3.2 Participants

There were 12 voluntary participants in this study. They were pre- and in-service physics teachers at three different universities: Unismuh, UNM, and Unhas. All of these universities are located in Makassar, Indonesia. There were six master's students and six undergraduate students. In order to capture the variation of the collaborative TE processes in-depth and in details, the participants were divided into three small groups according to the level of education. Each group consisted of four participants. These groups were named as master's student group, mixed student group, and undergraduate student group.

As this study involved human participants, the Institutional Review Board (IRB) of Seoul National University monitored all procedures, including recruitment of participants, consent form for the participants, data collection, and analysis. This study received IRB approval (No.1811/003-015). Following the guidelines for conducting an ethical study, we used the code for all participants. Detailed information about participants is presented in Table 1.

Table 1 Overview of participants in each group

Group	Members	Gender	Age	Student Level
1	H1	Female	28	Third semester (master's candidate)
	H2	Female	24	Third semester (master's candidate)
	H3	Female	24	Third semester (master's candidate)
	H4	Female	23	Third semester (master's candidate)
2	M1	Male	24	Third semester (master's candidate)
	M2	Male	23	Third semester (master's candidate)
	M3	Female	21	Seventh semester (undergraduate)
	M4	Female	20	Seventh semester (undergraduate)
3	L1	Female	21	Seventh semester (undergraduate)
	L2	Female	21	Seventh semester (undergraduate)
	L3	Female	21	Seventh semester (undergraduate)
	L4	Male	21	Seventh semester (undergraduate)

The aim of gathering data from group 1 was to observe the processes of TEs for a kind of expert. In this study, we chose physics problems related to the fundamental physics laws on classical mechanics designed for first-year university students, with the assumption that the expertise of master's students on this topic is higher than that of undergraduate students. The criteria for selecting participants for group 1 were (1) being a graduate student majoring in physics or physics education and (2) receiving their undergraduate education from a teacher-training university. On the other hand, group 3 consists of undergraduate students. The criteria for selecting participants in this group were (1) being a pre-service physics teacher at a teacher-training university and (2) having not yet passed or taken the exam qualification as the main requirement for graduation. Group 2 was a combination of master's students and undergraduate students. It was set to observe the interaction that might occur between the master's students and undergraduate students in constructing TEs.

3.3 Data Collection

For the data collection, group observation, interviews, and field notes were the primary methods for collecting the data. Small-group physics problem-solving activities was used to set the necessary conditions for observing the processes of collaborative TEs. Audio and video of the three small groups' activities were recorded. The group observation and interview were conducted in the physics meeting room and physics lab at a university in Indonesia.

First, we presented the physics problems and provided a blank piece of paper to each group member to be used to write and/or to draw their thoughts during the physics problem-solving activity. During problem-solving activities, we carefully observed the activities and interactions that took place among participants in each group, focusing particularly on identifying the processes of collaborative TEs that occurred while solving physics problems. For each group, observation and recording were carried out five times, once for each of the five physics problems available. In addition, in order to understand students' thinking, we used questions at particular instants during physics problem-solving activities, asking them what they thought about something or why they thought something? For triangulation, we also collected data regarding the notes written and drawn freely by the participants.

3.4 Data Analysis

3.4.1 Identifying the TEs

The main data sources for analysis in this study were the transcripts of the audio and video recordings from each group during physics problem-solving activities. The data processing for selecting TE episodes was as follows. First, all conversations made by students during solving problems were transcribed. Second, based on what had been identified as the TEs from the transcripts of physics problem-solving activities, audio and video recordings were reviewed to identify the TEs in detail. When we identified discourses that appeared to be a TE, we watched and listened to the video carefully several times. Third, the selected TE episodes in the second step were cross-checked with observation notes and students' notes. In addition, we checked carefully whether there were any missed TE episodes from the second step by watching and listening to the video repeatedly.

As mentioned earlier, Reiner (1988), Reiner and Burko (2003), and Brown (2006) proposed several similar structures of TEs: visualizing imaginary worlds, performing experiments, and describing the results. In order to identify the visualization of TEs, the framework for "imagery-related observation indicators" provided by Clement (2009) was used in this study. These indicators are presented in Table 2.

The following is an example of how TE processes performed by a participant were detected.

R[a] OK. Let us start from the first question … Now, imagine the possible effect of the accumulating rainwater on the trolley's speed as shown in the figure [Fig. 1]. What do you think?

[…]

H2 But there is rain, which means there is an external force, automatically, the trolley will definitely stop. For example, [1]suppose that I push this trolley while it is raining. [2]I push this trolley forward to roll on a straight road and the rain falls down vertically and hits it, so [3]the mass of this trolley will increase, so there is an external force, which means that the trolley will automatically stop at a certain time on the condition that the rainwater is being collected in the trolley.

1 = visualize imaginary world; 2 = perform experiment; 3 = describe the results

[a]R stands for researcher

In this episode, the words *suppose that* were coded as an imagery indicator. It was the sign that H2 was starting to visualize a TE. As expected, H2 visualized pushing the trolley and showed that by putting her hand on the trolley image on the given question. After the visualization step, H2 then performed an experiment in her mind and described the results.

Table 2 List of imagery-related observation indicators

No	Categories	Details
1	Imagery reports	The subject says "imagining," "seeing," "feeling," "suppose that," "if," "think that" (or experiencing any other sensation)
2	Hand motions	The subject describes the object, force, location or dynamic event while moving his/her hand
3	Analogy	The subject uses a personal analogy by referring to an analogous situation involving body forces

3.4.2 Coding for Evaluation Resources

Reiner and Gilbert (2000) stated that TEs draw on three epistemological resources: conceptual–logical inferences, visual imagery, and bodily-motor experience. Kösem and Özdemir (2014) argued that there are three resources used by students during TE processes: observed/experienced fact, intuitive principles, and scientific theory. Some researchers (e.g., Fournier 1995; Schwandt 1997) have emphasized the use of general logic in evaluating arguments or assumptions that occur in collaborative learning. According to Fournier (1995), general logic covers all fields in evaluation, which is the basic reasoning that specifically determines the meaning of activities.

Therefore, in this study, each evaluating moment identified during students' evaluation of their TEs was analyzed based on several evaluation resources explained above. The dialog excerpt below shows an example of coding for the evaluation resources used by a student to validate the results of their TE. This dialog is a continuation of the dialog described previously.

[…]
H4 Ooo, it will stop, why?
H2 Yes … Because if there is no external force action, it will continue to move. But if, for example, there is an external force, it will stop at a certain time.
Code: Newton's law
Categories: conceptual understanding

For the reliability of the analysis in this study, member checking was done (Miles and Huberman 1994). We and two other science education experts recursively categorized the processes of the TEs and compared them with other groups. For better reliability, the discourses were further analyzed by listening to the audio recording together with the transcript, participants' notes, and our observation notes. The process of data triangulation was carried out, and the valid data was obtained. We discussed the discourses until reaching an agreement. We also provided opportunities for participants to check whether our interpretation was distorted or not in order to improve the reliability of data analysis.

4 Results and Discussion

4.1 Collaborative TEs as Social Construction of Knowledge

The data analysis shows that while solving physics problems, students designed, shared, rethought, and evaluated their TEs in group work. This indicates that TEs can be constructed in a collaborative way, even though they are mostly individual in nature. In the process of sharing and evaluating TEs, there are activities where knowledge is constructed socially. The following is an example that was taken from the transcript of a problem-solving session in group 1 working on Problem 1, asking the possible effects of rain collecting in a trolley while the trolley was moving, as shown in Fig. 1.

R	OK. Let us start from the first question … Now, imagine the possible effect of the accumulating rainwater on the trolley's speed as shown in the figure [Fig. 1]. What do you think?	1
H4	Is the path a straight line?	2
H1	Is it pushed like this [while pushing the cellphone]?	3
R	Yes, the path is a straight line. Yes, it is pushed.	4

[…]
H1 So, I think that there is no external force and no friction. 5
H4 Aaa, external force. 6
H2 What is the effect? 7
H1 It will move continuously [It will never stop moving]. 8
H2 But there is rain, which means there is an external force, automatically, the trolley will definitely stop. For example, suppose that I push this trolley while it is raining. I push this trolley forward to roll on a straight road and the rain falls down vertically and hits it, so the mass of this trolley will increase, so there is an external force, which means that the trolley will automatically stop at a certain time on the condition that the rainwater is being collected in the trolley. 9
[…]
H4 Ooo, it will stop, why? 10
H2 Yes … Because if there is no external force action, it will continue to move. But if, for example, there is an external force, it will stop at a certain time. 11
H1 Yes, I agree [H1 agrees with H2] … 12
H3 Stop? [H3 asks H2] 13
H2 Yeah. It will stop. Over time, surely. 14
[…]
H1 Wait, the question here is will the accumulated rain affect the motion of the trolley? 15
H2 It will affect it. If, for example, the mass increases, the speed decreases … That is the effect. 16
[…]
H4 Wait, if forces, not, kinetic energy [while writing a formula] 17
H2 $Ek = 1/2mv^2$ 18
H1 Because of the mass increase. 19
H3 Yes, the mass increases. 20
[…]
H1 The speed is decreasing, right? Because initially the mass is small and the speed is higher, then the mass increases, so that means … 21
H3 So, it has an effect. 22
H1 Yes, it has an effect, the trolley will stop. 23
H4 Yes, at first it rolls continuously then this [indicates trolley] will be filled with water. Over time the speed becomes slower and slower, until maybe it stops. 24
H2 Yes, the trolley will become slower and will stop. 25
H1 That is right. 26

As can be seen in the transcript above, before H2 started to visualize a TE, the participants first actively involved themselves in understanding the problem. At the beginning of the

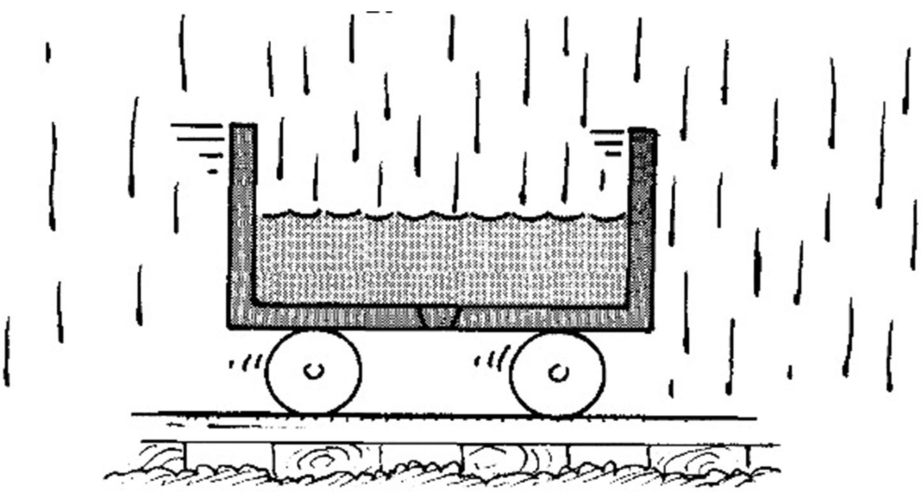

Fig. 1 Accumulating rainwater in the trolley in Problem 1

discourse, H1 and H4 asked the researcher to clarify the problem (lines 2–3). After that, H1 assumed that there was neither external force nor friction force acting on the trolley (line 5). H4 supported the assumption being built by H1 by saying, “Aaa, external force” (line 6). However, H2 asked H1 and H4 what the effect of the external forces is. H1 then responded that the absence of external forces would allow the trolley to move continuously (lines 7–8). In other words, H1 assumed that there is no effect of the accumulating rainwater on the trolley’s speed. Suddenly, H2 rejected the assumption built by H1 and H4, saying that rain hit the trolley, meaning that there is an external force acting on the trolley (line 9). Due to the external force acting on the trolley, it will not move continuously, but it will stop at a certain time. H2 then began to visualize a TE in order to explain her assumption.

The words *suppose that* (line 9) were coded as an indicator of visualization. This indicated that H2 started to visualize a TE. As expected, she visualized pushing the trolley and showed that by putting one of her hands on the trolley image on the given question. She then performed an experiment in her mind and described the results (line 9). By using her mind’s eye, H2 saw that raindrops hit the trolley and collected there, causing the mass of the trolley to increase (mass of trolley + rainwater collected). H2 then shared her TE to group members so that it could be run and evaluated together. In such situations, there was a process of further discussion by students in their groups in order to construct and continuously reconstruct knowledge. This knowledge grows through the intense communication among students in the group. During evaluating a TE, all students are engaged in the discussion by asking and answering questions, supporting and clarifying arguments, providing equations, and so on (line 10–21). They also validate the result of their TE using several evaluation resources. For example, H2 validated the result of the TE using Newton’s first law (line 11), and H1 used conceptual–logical inference (line 21). This process was done continuously until they reached a conclusion as a collective agreement (lines 22–26).

The transcript piece below is another example of collaborative TEs. The transcript was taken from the transcript of a problem-solving session in group 3 working on Problem 2, asking about which scientist can detect her motion in the space, the scientist who is in the straight-moving box, or the one in the smoothly spinning box as shown in Fig. 2.

R We continue on to Problem 2 [the researcher then reads the question]. So, what do you think about this problem? Which scientist can detect her motion? 1

[…]

L1 Ok. Suppose that, if I were in the box that is moving straight ahead, then I drop a coin or a pen into the glass, and there is no gravity, then if I move forward, the pen I drop will be left behind. 2

[This photo shows L1 did a TE by imagining herself isolated in a smooth moving box that follows a straight line through space and then drops her pen into a glass].

L4	Yes, that will happen if there is no gravity. How if the gravity exists? The coins will go into the glass, right?	3
P	[All participants are silent while thinking].	4
L1	As long as the speed [of the box] is constant.	5
L4	Oo, yes, remember when we were traveling by train and dropped something. When the track was straight and the train moved constantly, it will fall down. won't it? It is similar to that.	6
L2	So, I think the scientist in the spinning box will feel if she is moving because if we drop the pen.	7
L3	Yes, the pen will fall randomly [it will not fall straight down].	8
	[…]	
L4	Aha, imagine when we are inside a train with high speed and constant. For example, on a train which is moving straight forward and the wall is dark [we cannot see outside]. At that time, we do not know whether we are moving or not. If we drop a coin into a glass, the coin will surely go into the glass, right? If, for instance, we are on spinning, like a propeller, and we try to drop a coin [into a glass], then it will be more difficult to drop the coin right into the glass, right?	9
L3	Yes, the logic is like that.	10
L4	Aa, so, it will be harder to put the coin into a glass when the box is spinning rather than when it is moving straight forward. Therefore, in my opinion, the scientist who can feel that she is moving is the one inside the spinning box.	11
L2	Yes, I think so.	12
R	How about you, L1?	13
L1	Yeah, I agree with them [while smiling].	14

As seen in the transcript above, while solving Problem 2, group 3 conducted a collaborative TE. The words *suppose that* (line 2) were coded as an indicator of visualization, which indicated that L1 started to visualized a TE. As expected, she visualized herself in a box that moves straight ahead. She then performed an experiment in her mind and described the results (line 2). By using her mind's eye, L1 saw that the pen she dropped while the box moved straight ahead would not fall down but will be left behind. L1 then shared her TE with the group members so that it could be run and evaluated together.

During the evaluation of TE, L4 agreed with the results of L1's TE in the condition that there is no gravity in the box, but if gravity exists in the box, then the results will be different. L1 then responded by saying that the coin will fall down into the glass if there is gravity in the box, with the condition of the box moving at a constant speed. After students discussed for a while, L4 then did

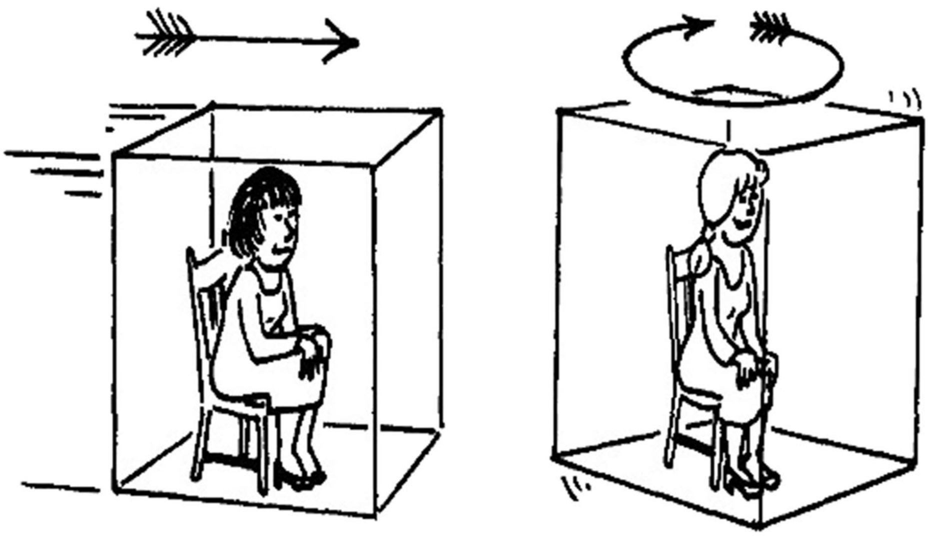

Fig. 2 Detecting motion in space in Problem 2

another TE by visualizing himself in a super-fast train that moves straight at a constant speed (line 9). He then performed an experiment and saw with his mind's eye that the coin he had dropped fell right inside the glass. He then imagined that when he was above the propeller (something moving around) and was dropping a coin, the coin he dropped was very difficult to get into the glass. L4 then shared his TE to be run and evaluated by other students until they reached the conclusion that a scientist who is completely isolated inside a smoothly moving box that travels a straight line will not feel that she is moving (lines 11–14). This activity shows that a TE can be shared, rethought, evaluated, retooled, and even two or more thought experimenters can reach the same conclusions from a TE. Therefore, based on this study, a collaborative TE is defined as activities of visualizing imaginary worlds in which experiments are designed and generated by one or more individuals in their own mind laboratories then shared with group members to be run and evaluated together as collective efforts to reach conclusions.

Figure 3 shows an illustration of the collaborative TE that occurred when group 1 was responding to Problem 1. As can be seen, collaborative TE begins with one student generating a TE then sharing it with the group members. The members of the group then run and evaluate the TE as suggested by its producer. In the processes of evaluating TE, all students are engaged in discussion by asking and answering questions, supporting and clarifying arguments, providing equations, validating the results of TE, and so on. This process was done continuously until they reached mutual understanding and found strong evidence to support their TE. According to Dillenbourg (1999) and Chiu (2000), collaborative activities are characterized by the activity of negotiating meaning and utilizing each other's resources and skills, for example, asking each other, validating ideas with each other, and supporting and clarifying ideas with each other. In short, because all of the students in collaborative TEs are actively involved in constructing and reconstructing knowledge through a negotiation process by asking and answering questions, supporting arguments, clarifying claims, validating the results of TE, and so on, collaborative TEs are considered a process of socially constructing knowledge.

Based on data analysis, while solving physics problems, all students performed a TE at least once. As seen in Table 3, the number of TEs performed by students does not vary much between groups. The number of TEs performed by group 1 is eight, while group 2 and group 3 performed them seven and nine times, respectively. The TEs occurred suddenly as a reaction to problems faced by students. If a problem stimulated students to perform a TE, students did as many as possible. Table 3 shows that for the first problem, only one TE was produced by each group, while for the second problem, groups 1 and 3 each produced three TEs, and group 2 produced two TEs. Unlike REs, students' TEs are spontaneously produced and without plans, precedent, and elegant designs beforehand. This may indicate that TEs are natural processes in physics learning in the sense that because they occur suddenly as a reaction to a problem, they do not need a priori design.

4.2 The Steps of Collaborative TEs

Based on the data analysis, there are five steps of collaborative TEs that occur during problem-solving activities. In the following section, details about each step are presented.

4.2.1 Visualizing Imaginary Worlds

As mentioned earlier, visualization is the first step in conducting TEs. The following is an example of a visualization that was taken from the transcripts of the problem-solving session with group 1 when they responded to Problem 1.

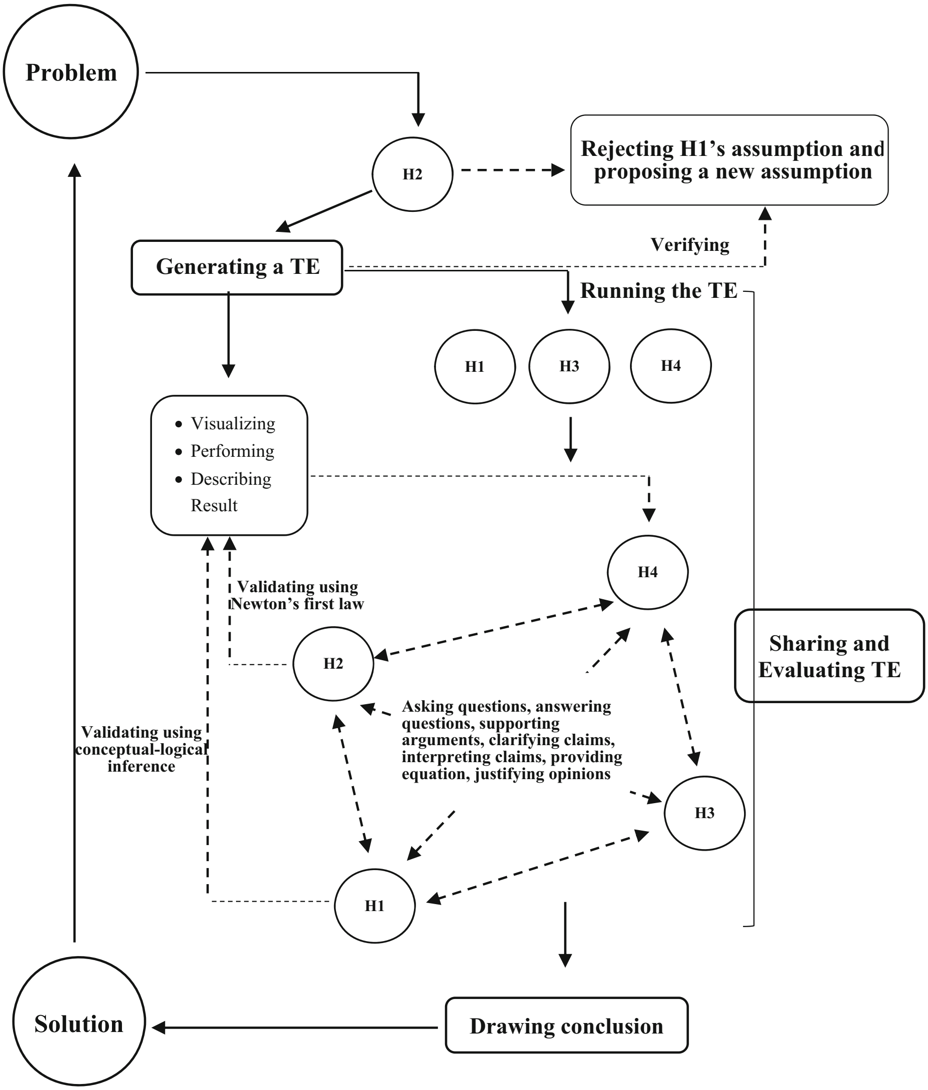

Fig. 3 Illustration of the collaborative TE that occurred when group 1 was responding to Problem 1

Table 3 Frequency distribution of the TE use while solving physics problems

Participant	Problem (P)					Total
	P1	P2	P3	P4	P5	
Group 1	*	***	*	*	**	8
Group 2	*	**	*	**	*	7
Group 3	*	***	**	*	**	9

H2 But there is rain, which means there is an external force, automatically, the trolley will definitely stop. For example, *suppose that* I push this trolley while it is raining. I push this trolley forward to roll on a straight road and the rain falls down vertically and hits it, so the mass of this trolley will increase, so there is an external force, which means that the trolley will automatically stop at a certain time on the condition that the rainwater is being collected in the trolley.

In the transcript excerpt above, the words *suppose that* were coded as an imagery indicator. This indicated that H2 started to visualize a TE. Besides using the imagery reports (suppose that), H2 also used hand motions indicators. As seen, she visualized an imaginary world by pushing the trolley and showed that by putting her hand on the trolley image on the given question. Another example can be seen when group 3 responded to Problem 2 (see Fig. 2), as shown in the transcript excerpt below.

R We continue on to Problem 2 … So, what do you think about this problem? Which scientist can detect her motion?

[…]

L4 Aha, *imagine when* we are inside a train with high speed and constant. For example, on a train which is moving straight forward and the wall is dark [we cannot see outside]. At that time, we do not know whether we are moving or not. If we drop a coin into a glass, the coin will surely go into the glass, right? If, for instance, we are on spinning, like a propeller, and we try to drop a coin [into a glass], then it will be more difficult to drop the coin right into the glass, right?

In this episode, the words *imagine when* were coded as an imagery indicator, which indicates that L4 started to visualize a TE. As expected, L4 visualize an imaginary world by manipulating the object (in the problem given, the object is a scientist in a box, while in L4's TE, the objects are a train, a glass, and a coin). L4 then constructs a situation where he is on a fast train moving at a constant speed on a straight road with no turns. Also, the train has no windows, so outside the train cannot be seen. With this situation, L4 then did an experiment, dropping a coin into a glass and seeing that the coin fell right into the glass.

4.2.2 Performing Experiments

After the visualization step, students begin to design and run experiments in their minds. As we can see in the transcript earlier, when group 1 was responding to Problem 1, H2 performed a TE to explain that the trolley will stop because there is an external force that influences it. First, she imagined pushing the trolley forward to roll on a straight road. As the trolley rolls, rain falls down vertically and hits the trolley. She then observed its motion and velocity in her mind's eye. In her observation, H2 saw that raindrops hit the trolley and were accumulated in the trolley, causing the mass of the trolley to increase (mass of trolley + rainwater collected).

This is an example of the performance of a TE, where students seem to do a real experiment in the real world. In both real and thought experiments, we can design objects, and related variables then let them run while observing the results. However, in TEs, there is no empirical data obtained. This does not mean, however, that TEs are completely unrelated to the real world. Rather, in some cases, TEs need to be supported by other empirical observations relevant to the issues of the TE. Idealization also is a significant dimension of TEs. To remove the technical or manipulative complexity when designing TEs, ideal conditions are necessarily needed. As Galili (2009) said, a "TE often makes it through simplified but representative models which keep the focus on the essential aspects of the subject, eliminating technical details, experimental errors and ruling out the impeding factors of a real experiment (heat, friction, etc.)" (p. 19).

4.2.3 Describing the Results

Again, when group 1 was working on Problem 1, H2 says, “the mass of this trolley will increase, so there is an external force, this means that the trolley will automatically stop at a certain time.” Based on this episode, the result of H2’s TE is that the mass of the trolley will increase and will stop at a certain time. H2 imagined that there is a force acting on the trolley, either by the interaction between rainwater and the wall and floor of the trolley or because of the accumulation of mass from the collected rainwater. These factors will make the trolley stop at a certain time.

After performing the TE, H2 then believed that the trolley she pushes through the rain would stop over time. This belief was obtained after carrying out the process of mental model activity herself. This kind of belief or knowledge seems to be tacit knowledge. Sternberg (1999) and Nonaka and Takeuchi (1995) argued that tacit knowledge is a personal knowledge of mental models that individuals follow in certain situations. Therefore, we think that the results of TEs are in the form of tacit knowledge, which is a belief or personal knowledge that thought experimenter holds after carrying out a TE. However, when this tacit knowledge is then evaluated using either conceptual understanding or experience or logical reasoning, it will become a new knowledge for students to understand the real world. The new knowledge produced in TE is a derivative of the particular theory or experience applied in the TE. Therefore, the results of TEs are useful for providing a new state of understanding of real-world situations.

> By using images of a visual nature, and images of bodily experience, the thought experimenter accesses tacit knowledge, which the person is not necessarily aware of, and of which only a small portion can be articulated in a verbal manner. Such tacit knowledge, when coupled with logical processes [evaluation tool] in a TE, is unconsciously recruited to generate new knowledge (Reiner and Gilbert 2000 p. 502).

4.2.4 Sharing and Evaluating Experiments

After declaring the result of her TE, H2 then shared it with all the members of the group. The members then ran this H2’s TE and tried to evaluate its process and results. As can be seen in the script earlier when group 1 was responding to Problem 1, there is a process of evaluating the results of the TE generated by H2. She tried to defend her argument that falling rainwater will affect the trolley’s speed using Newton’s first law, which states that an object will remain at rest or in uniform motion in a straight line unless acted upon by an external force.

H1 also evaluated the results of this TE by using conceptual–logical inference. By using the kinetic energy equation written by H4, $Ek = 1/2mv^2$, H1 then used her logic. If, initially, the mass of a trolley is a small and it is moving at high speed, then when the mass increases due to the accumulated rainwater in the trolley, logically, its speed should decrease. Here, H1 used logic along with the kinetic energy equation (initial Ek = final Ek). This is the process of evaluating a TE, where students tried to support their TE using various evaluation sources.

The following transcript is another example of how the students use past experience when evaluating the results of TEs. The transcript is from group 3 responding to Problem 5. The problem was asking: “Imagine a U-shaped magnet fixed in front of car as shown in Figure 4. Will hanging another U-shaped magnet facing it at opposite pole make the car move? Why or why not?”

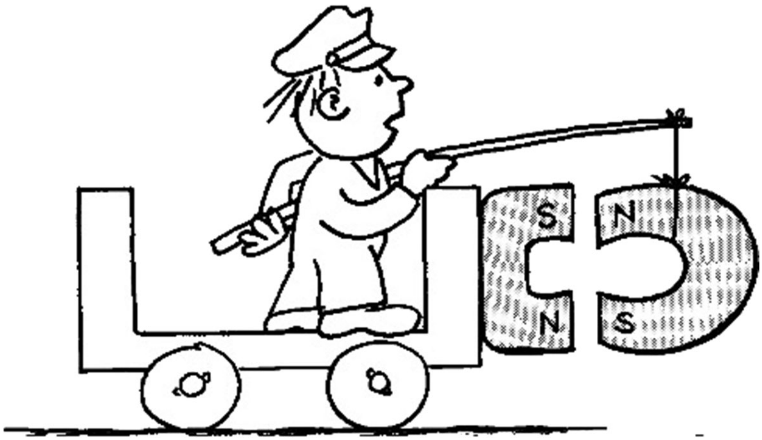

Fig. 4 Magnets on the car in Problem 5

L2 In my opinion, the car will move. *Imagine that* there is a magnet here [pointing to the car] and in front of it there is also a magnet. Hence, if I am in the car with a magnet fixed in front of it, and I hold another magnet like in the picture from the given problem, then the car will move in any direction from the magnet in front of it [L2 uses hand to demonstrate].

L3 I think that they will pull each other, right?

L2 No, this car will follow the hanging magnet's direction. I have seen cartoon movie scenes like that. In order for the car to stop, the magnet which is hung must be lifted upward.

In the transcript excerpt above, the words *imagine that* were coded as an imagery indicator, which indicates that L2 started to visualize a TE. As seen, she visualized an imaginary world by imaging herself in the car with a magnet fixed in front of it and brought another magnet closer to magnet attached to the car. L2 assumed that the car on which the magnet was hung would move in the direction of the magnet being hung because it is based on her experience of watching cartoons. In a movie, she saw a magnet that was hung on a car, which is similar to the problem given. The car could only stop when the magnet hanging in front of it was lifted up. Therefore, L2 evaluated the results of the TE using her past experience. In the upcoming section, the evaluation resources used by students in evaluating the TEs will be presented in detail.

4.2.5 Drawing Conclusions

The conclusion is the final process of a collaborative TE. It is an agreement or a decision made after considering all the information through the negotiation of meaning. The new knowledge that has been gained by a thought experimenter going through a series of image manipulations and then evaluated by members in a group is located in this step. This new knowledge is then applied by students to real-world situations.

In the example above, it can be seen that all group members drew the same conclusion that the trolley pushed by H2 passing through the rain will stop at a certain time. This indicates that two or more thought experimenters who are performing the same TE can reach the same conclusion. The conclusion generated through this collaborative TE is then applied to the physics problem. The students then set a solution to the physics problem given that there is a possible effect of rain accumulating in the trolley while the trolley is moving. Table 4 shows a summary of the episode when group 1 was responding to Problem 1.

Table 4 Summary of the phases of the collaborative TE by group 1 on Problem 1

Phase of the collaborative TE	Evidence from the episode
Visualize an imaginary world	• "Suppose that" • Hand motion 
Perform an experiment	I push this trolley while it is raining. I push this trolley forward to roll on a straight road and the rain falls down vertically and hits it.
Describe a result	So the mass of this trolley will increase … Which means that the trolley will automatically stop at a certain time.
Share and evaluate an experiment	• Because if there is no external force action, it will continue to move. But if, for example, there is an external force, it will stop at a certain time. • The speed is decreasing, right? Because initially the mass is small and the speed is higher, then the mass increases …
Draw a conclusion	• Yes, it has an effect, the trolley will stop. • Yes, at first it rolls continuously then … becomes slower and slower, until maybe it stops • Yes, the trolley will become slower and will stop. • That is right.

4.3 Sources of TE Evaluation

Based on the data analysis, four sources of the evaluation were identified: conceptual understanding, past–daily experience, logical reasoning, and conceptual–logical inference.

Table 5 Evaluation resources used by students during collaborative TEs processes

Type of validation	Group/problem (P)															Total
	Group 1					Group 2					Group 3					
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	
Conceptual understanding	*							*		*				*		4
Past–daily experience		*			*		**	*	**		*	*	*	*	**	13
Logical reasoning		*		*	*	*				*		*	*	*	*	9
Conceptual–logical inference	*		*	**					*					*		6

An overview of the variation in evaluation resources used by students while constructing the collaborative TEs is presented in Table 5.

As can be seen, all groups used the four sources of evaluation in constructing collaborative TEs at least once. Past–daily experience and logical reasoning were the most frequently used by students. Group 3, whose members were all undergraduate students, tended to evaluate their TEs by first connecting with their experience or using logical reasoning. Group 1, however, whose group members were master's students, looked for scientific concepts or physics laws first and then combined them with logic.

In addition, the results of TEs can be evaluated more than once. There were several episodes in this study where students in a group evaluated the results of their TEs using conceptual understanding then proceeded with the past–daily experience. During the evaluation of their TEs, students were involved in the process of negotiation of meaning. This process was done continuously until they found strong evidence that supported the truth of their tacit knowledge. In fact, when they failed to provide evidence of the resulting tacit knowledge, they did not hesitate to redesign their TEs. The following section will discuss each category of the evaluation resources in detail.

4.3.1 Conceptual Understanding

During the evaluation of TEs, some students used conceptual understanding that refers to physics concepts, physics equations, and laws such as Newton's law. Below is an example of how students used conceptual understanding to evaluate the results of their TE. This example is taken from the transcripts of the problem-solving session with group 2 when they were responding to Problem 3, which asked the path of the ball after it exits at 2 as shown in Fig. 5. As they were trying to solve the problem, M1 performed a TE, stating that "if, for example, the ball is suspended and is rotating above [while demonstrating it with his hand] then is suddenly released, apparently the ball is pointing out like B". This TE was then shared and evaluated by the other group members. After discussing it for a while, M1 then evaluated the result of his TE using scientific theory, as shown below.

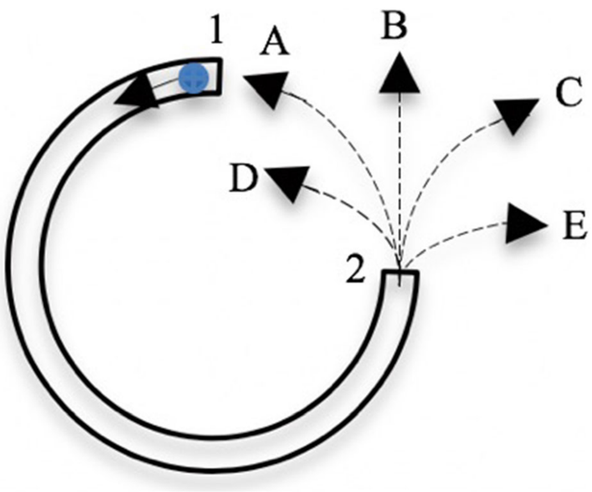

Fig. 5 Path of the ball in Problem 3

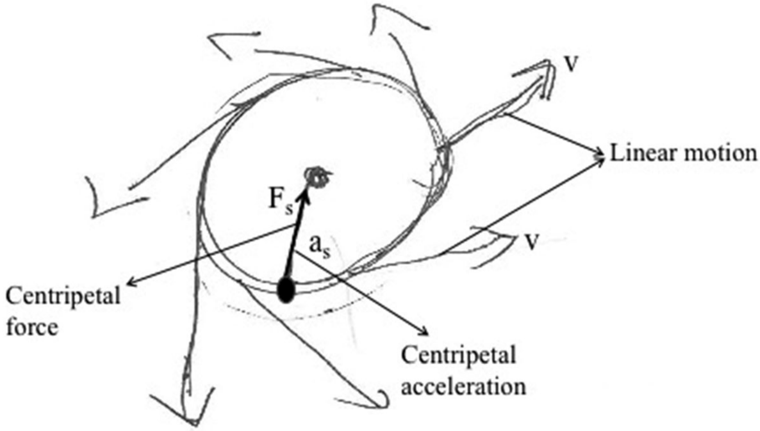

Fig. 6 Direction of velocity drawn by a student in Problem 3

M1	Yes, the direction of the velocity is always like that. Its direction is always perpendicular to radial acceleration. It can move in a circular motion because there is force given, centripetal force, but, the vector of its velocity is always pointing in the direction of motion. Like this [Fig. 6]

In the transcript excerpt above, M1 used the concept of circular motion to validate the results of the TE he ran. He believed that the ball would be thrown out perpendicularly because this is a characteristic of the velocity vector: The vector of velocity is always pointing to the direction of motion, while the vector of acceleration is directed to the center of the circle. Thus, the vector of velocity and radial acceleration is perpendicular to each point of the path for uniform circular motion. Then, he added that an object that moves in a circular motion must have force given to it to maintain its motion in a circle. This force is called centripetal force and is always directed to the center of a circle. M1 presented his argument while drawing a circular path accompanied by the direction of linear velocity, angular acceleration, and centripetal force experienced by objects while in the trajectory, as seen in the transcript excerpt above (with a description added by the authors).

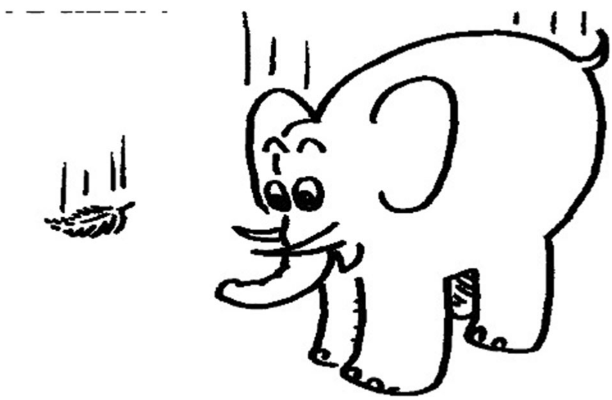

Fig. 7 Feather and elephant in Problem 4

4.3.2 Past–Daily Experience

Some students used their experience when evaluating the results of the TEs. This experience manifests as facts remembered from past experience or the students' daily activities. The following transcript excerpt is an example of how the students use daily experience when evaluating the results of TEs. While group 2 responded to Problem 4, asking about which encounters the greatest air resistance force between an elephant and a feather when falling from a high tree as shown in Fig. 7, M1 did a TE by saying "for example, if I drop a plane from a certain height, the air that passes by the plane will be chaotic. This means that the plane has a huge friction force. But if I drop chicken feathers instead, the air around it is not too chaotic". M1 then shared his TE to all the members of the group. After discussing it for a while, M1 evaluated the results of the TE as shown below.

M1 This is based on my daily experience when I ride my motorcycle. When I am behind a truck, I feel that the air flow I pass through is more chaotic than the air flow that occurs from a small car. That is my experience.

Based on the transcript excerpt above, M1 used his daily experience to evaluate the TE he carried out. He used his experience when riding a motorcycle and riding behind small cars and trucks. From his experience, M1 feels that the air flow around a truck is more chaotic than a small car. Therefore, M1 believed that if he dropped a plane (substituted for an elephant) and chicken feather from a certain height, the plane would experience a force of air resistance that would be greater than the chicken feathers. In M1's mind, because he felt that the air currents around the truck were more chaotic than those around the small car, the air currents around the plane that he dropped at a certain height must also be more chaotic than those around the chicken feathers. This indicates that the airplane has a greater air resistance force than the chicken feathers.

4.3.3 Logical Reasoning

Another resource used by the students during the evaluation of TEs is logical reasoning. Logical reasoning is different from conceptual–logical inference, as there is no use of theory or law or physical principles. The logic that students build on in this source is only in the form of personal assumptions or perceptions. This assumption is logical, however, so it can support the argument they are building. Here is an example of using logical reasoning in evaluating the results of TEs, which we took from the group 3 transcript excerpt when responding to Problem 5 (see Fig. 4).

L3 Suppose that this magnet is not tied to a rope, for instance, it is tied to a truck or something else because these supporting things are small [rope and stick].

L4 But still, there is a possibility, though very little, that the car will move

[…]

L3 No, suppose that these two magnets are tied together on a rope, they might be moving and pulling each other. Yet here the situation is different, one magnet is attached to the car and the other is tied to a rope. I do not think it's logical that the car will move.

While solving Problem 5, L2 carried out a TE by imagining herself being on a magnet-mounted car in front of her. Then she brought another magnet, which was hanging, to the car. She sensed that the car would move closer to the hanging magnet wherever the magnet was. However, L3 rejected the result of L2's TE because she considered it illogical. L3 believed that the car could not be attracted by the hanging magnet because it was only bound by a rope. She assumed that if the two magnets were tied together on a rope, then they might be pulling each other. However, if one magnet is affixed to the car and the other is tied to the rope and then brought to the car, it made no sense that the car would move. This is the logical reasoning built by L3 in evaluating the results of the TE. It was not based on a theory, a principle, or a law of physics. It was only a personal assumption, but it is enough to convince thought experimenters to support or reject the tacit knowledge they evaluated.

4.3.4 Conceptual–Logical Inference

The last source of evaluation used by the students during the evaluation of TEs was coded as conceptual–logical inference. It is a source of evaluation that combines laws, principles, or concepts of physics with logical manipulation. The transcript excerpt below is an example of how students used conceptual–logical inference in evaluating the results of their TE. This example was taken from group 1 when responding to Problem 1.

H2	$Ek = 1/2mv^2$
H1	Because the mass increases.
H3	Yes, the mass increases.
	[…]
H1	The speed is decreasing, right? Because initially the mass is small and the speed is higher, then the mass increases …

As seen in the transcript above, H1 used conceptual–logical inference in evaluating the TE in their group. First, H1 used the kinetic energy equation, $Ek = 1/2mv^2$, as stated by H2. She then used logic with the equation (initial Ek = final Ek). H1 believed that if initially the mass of the trolley was small and it had a high speed, then when the mass of the trolley increased as a result of the rainwater that was contained in it, logically the trolley speed should decrease and the trolley would even eventually stop. Here, H1 used logic along with the kinetic energy equation.

5 Summary and Implications

This study has shown that while solving physics problems, students designed, shared, rethought, and evaluated their TEs. Therefore, it can be concluded that TEs can be constructed in a collaborative way even though the TEs are scientists' personal and tacit processes of experimentation in constructing a scientific theory. The activities of visualizing imaginary worlds in which experiments are designed and generated by one or more individuals in their own mind laboratories and then shared them with group members to be run and evaluated together as collective efforts to reach conclusions are defined as collaborative TEs. There are five steps in conducting collaborative TEs: visualizing imaginary worlds, performing experiments, describing the results, sharing and evaluating experiments, and drawing conclusions. In order to validate the results of TEs, the students used four evaluation resources: conceptual understanding, past–daily experience, logical reasoning, and conceptual–logical inference.

Because a TE can be communicated, replicated, rethought, and constructed collaboratively, we view TEs as a continuum of REs based on the mental model activity. Like REs, TEs are not random and undisciplined activities, but they operate on structured imagination. We support the opinion that TEs consist of two aspects: thought and experiment (Reiner and Gilbert 2000;

Galili 2009). The thought aspect involves modeling an imaginary world that is related to theories and experiences of the thought experimenter, while the experiment aspect refers to experimental activities in the real world. The results of this study also support argument in the literature that TEs are a cognitive tool that both experts and students can use to work on problems (e.g., Mach 1905/1976; Reiner 1998; Reiner and Gilbert 2000; Clement 2009). All groups—regardless of their members whose all undergraduate students, master's students, or a mixture of both—were able to carry out experiments in mind. When students are given the opportunity to work together to solve meaningful problems, they will perform TEs and then share them with their group members to be polished and validated as a collective effort to achieve mutual understanding. Collaborative TEs allow students to progress beyond what they would have been able to learn alone by sharing mental models and observing the thought processes of others. Because all of the students in collaborative TEs are actively involved in constructing and reconstructing knowledge through a negotiation process, whether by asking questions, supporting arguments, clarifying claims, or validating the results, collaborative TEs are considered the process of socially constructing knowledge. Therefore, TEs are a tool for both the personal and social construction of knowledge.

Although we agree with Reiner (1998) that TEs are more easily constructed in a collaborative way in which the number of students' contributions can lead to the complexity of TEs, some of Reiner's TEs stages did not match with our results. Reiner (1988) analyzed the processes of students in constructing TE while solving physics problems collaboratively and proposed five steps of TE: visualization, hypothesis, experiment, result, and conclusion. In our study, we did not see students proposing hypotheses or general assumptions after the visualization step. When the problem was given, the students visualized the imaginary world and directly performed experiments without setting hypotheses. In this situation, they used TEs to predict the solution to the problem given. There were also some students who proposed hypotheses or general assumptions first and then visualized the imaginary worlds as the first step in constructing TEs. In this situation, the students constructed TEs to determine whether the hypotheses or assumptions were true or false. In addition, after students described the results of TEs, they shared their TE to be run and evaluated together by other members. During sharing and evaluating TEs, students were involved in the process of negotiation of meaning that is the hallmark of collaboration (Bruffee 1995; Dillenbourg 1999; Chiu 2000) before they drew conclusions. Therefore, based on this study, we proposed five stages in constructing TEs in a collaborative setting: visualizing imaginary worlds, performing experiments, describing the results, sharing and evaluating experiments, and drawing conclusions.

There is some evidence that students evaluate not only the results but also the processes of TEs. They do this evaluation activity continuously until they get strong evidence to support the truth of the tacit knowledge they have obtained. In fact, when the process of a TE is invalid according to thought experimenters, they are not reluctant to redesign a new TE. But when the results of TEs were invalid, the students corrected the results without trying to redesign new TEs. Therefore, in the evaluation of TEs, both the process and the results were checked. This indicates that TE can be replicated, reworked, and even retooled by different thought experimenters. Figure 8 illustrates the process of new knowledge obtained through collaborative TEs.

Some literature emphasized the important role of philosophy and history of science for science teaching. For example, according to Matthews (2014), a rich understanding of history and philosophy of science can well contribute to teaching science by

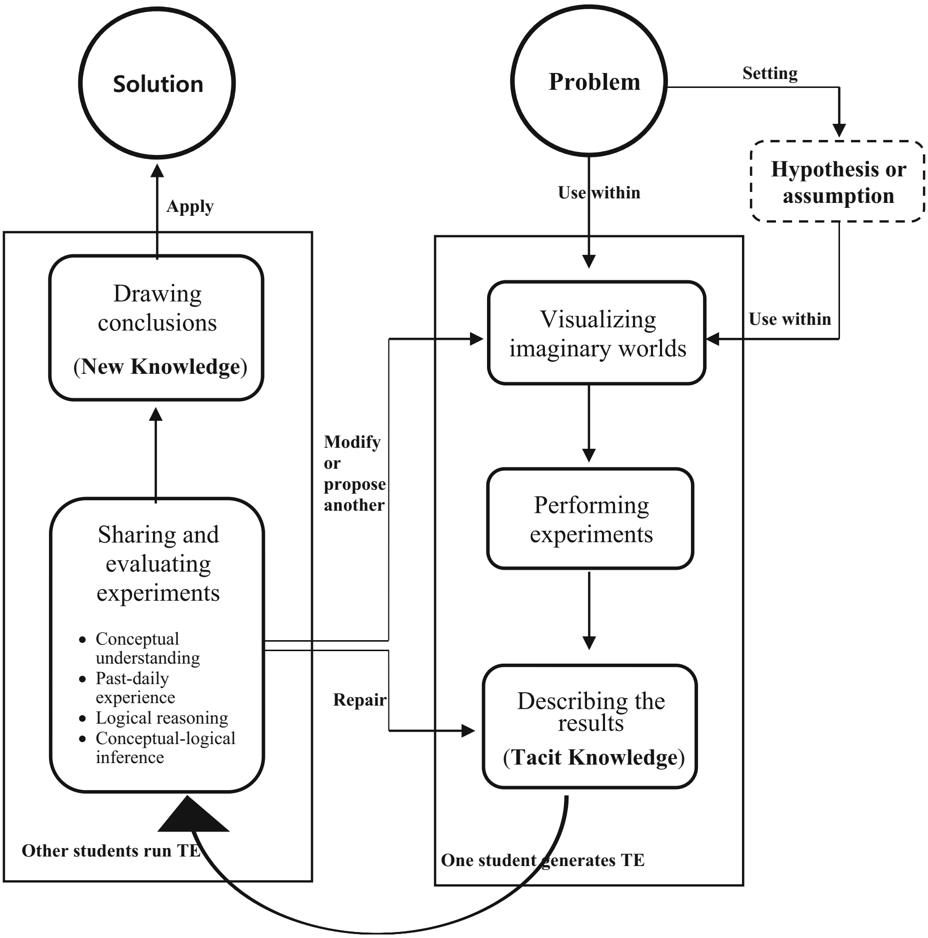

Fig. 8 Process of new knowledge obtained through collaborative TEs

understanding what material should be taught and how to place the topics and concepts in our teaching. Because of its essential role, especially in teaching physics, Levrini (2014) suggested a collaboration between educators, historians, and philosophers of physics for making the historical and epistemological roots of teaching physics more explicitly. Teaching TEs often belong to the history and philosophy of physics. The history of physics offers various examples in which physicists used TEs either to formulate new theories or to refute the existing theories. As the most representative example, Galileo had used TE of free-falling body to refute the gravitational theory of Aristotle (Galileo 1638/1914), or Newton used the TE of cannonball to support his hypothesis that the force of gravity was universal and it was the main force of planetary motion (Newton 1687/1962). Therefore, the inclusion of TEs is important in the process of teaching physics in schools because they introduce students into the culture of science (Reiner 1998; Galili 2009), are part of accepted scientific practice (Nersessian 1992; Sorensen 1992), and are useful as tools of imagination for investigating the nature of science (Brown 2006; Sorensen 2016).

Based on this study, we would recommend that collaborative TEs be introduced to both current and future physics teachers as a useful tool for teaching TEs to students at school for three reasons. First, because TEs can produce both correct and incorrect results in the development of a scientific theory (Reiner and Burko 2003; Norton 2004; Brown 2006), the communication and peer interaction in collaborative TEs have a great potential to correct both the process and the results in order to reach the correct conclusions. Second, because TEs are mental model activities that are mostly carried out in the minds of individuals (e.g., Kuhn 1977; Sorensen 1992; Nersessian 1992), some students have difficulty in constructing TEs independently (Kösem and Özdemir 2014). With collaborative TEs, students who have difficulties will be helped by other students in constructing TEs. Third, the stage of sharing and evaluating TEs may help each individual student to develop their own understanding and also bring them closer to scientific argumentation. Over the past decade, scientific argumentation has received serious attention from science educators around the world as a core competency in schools (Erduran et al. 2015).

The results of this study were only from small numbers of students who do not represent the experiences of all students. Therefore, further research is needed to support these results by implementing collaborative TEs. If more practical studies are carried out using a large number of students, including high school students, the results of this present study can be further supported. There are various possibilities for including TEs in subject matter related to physics, such as mechanics, thermodynamics, and relativity (Asikainen and Hirvonen 2014; Velentzas and Halkia 2013). This kind of integration into the subject matter will be useful for pre- and in-service physics teachers, who can then see the possibility of using collaborative TEs in teaching physics at school. In addition, physics teachers who participate in teacher education programs, such as tutoring teachers in teaching practice schools, should be offered in-service training related to collaborative TEs. These teachers could then include TEs in their own teaching. Future physics teachers can be supported through continuous professional development efforts to incorporate TE in their physics teaching.

Compliance with Ethical Standards

The Institutional Review Board (IRB) of Seoul National University monitored all procedures, including recruitment of participants, consent form for the participants, data collection, and analysis. This study received IRB approval (No.1811/003-015). Following the guidelines for conducting an ethical study, we used the code for all participants.

Compliance with ethical standards The authors declare that they have no conflict of interest.

References

Asikainen, M. A., & Hirvonen, P. E. (2014). Probing pre- and in-service physics teachers' knowledge using the double-slit thought experiment. *Science & Education, 23*(9), 1811–1833.

Bancong, H., & Song, J. (2018). Do physics textbooks present the ideas of thought experiments?: a case in Indonesia. *Jurnal Pendidikan IPA Indonesia, 7*(1), 25–33.

Bancong, H., & Song, J. (2020). Factors triggering thought experiments in small group physics problemsolving activities. *New Physics: Sae Mulli, 70*(5), 466–480. https://doi.org/10.3938/NPSM.70.466

Bishop, M. A. (1999). Why thought experiments are not arguments. *Philosophy of Science, 66*(4), 534–541.

Bokulich, A. (2001). Rethinking thought experiments. *Perspectives on Science, 9*(3), 285–307.
Bokulich, A., & Frappier, M. (2017). On the identity of thought experiments: thought experiments rethought. In M. T. Stuart, Y. Fehige, & J. R. Brown (Eds.), *The routledge companion to thought experiments* (pp. 545–557). London: Routledge.
Brown, J. R. (1991). *The laboratory of the mind: thought experiments in the natural sciences*. New York: Routledge.
Brown, J. R. (2006). The promise and perils of thought experiments. *Interchange, 37*(1–2), 63–75.
Bruffee, K. A. (1995). Sharing our toys: cooperative learning versus collaborative learning. *Change: The Magazine of Higher Learning, 27*(1), 12–18.
Buzzoni, M. (2008). *Thought experiment in the natural sciences. An operational and reflective-transcendental conception*. Würzburg: Königshausen+Neumann.
Buzzoni, M. (2013). On thought experiments and the Kantian a priori in the natural sciences: a reply to Yiftach J H. Fehige. *Epistemologia, 36*(2), 277–293.
Buzzoni, M. (2019). Thought experiments in philosophy: a Neo-Kantian and experimentalist point of view. *Topoi, 38*(4), 771–779.
Chiu, M. M. (2000). Group problem-solving processes: social interactions and individual actions. *Journal for the Theory of Social Behavior, 30*(1), 26–49.
Clement, J. J. (2009). The role of imagistic simulation in scientific thought experiments. *Topics in Cognitive Science, 1*(4), 686–710.
Cooper, R. (2005). Thought experiments. *Metaphilosophy, 36*(3), 328–347.
Dillenbourg, P. (1999). What do you mean by collaborative learning? In P. Dillenbourg (Ed.), *Collaborative learning: cognitive and computational approaches* (pp. 1–19). Oxford: Elsevier.
Dohrn, D. (2016). Fiction and thought experiment-a case study. *Teorema: Revista Internacional de Filosofía, 35*(3), 185–199.
Egan, D. (2016). Literature and thought experiments. *The Journal of Aesthetics and Art Criticism, 74*(2), 139–150.
Einstein, A. (1905). On the electrodynamics of moving bodies. *Annalen der Physik, 17*, 891–921.
Elgin, C. Z. (2014). Fiction as thought experiment. *Perspectives on Science, 22*(2), 221–241.
Epstein, L. C. (1995). *Thinking physics is gedanken physics*. San Francisco: Insight Press.
Erduran, S., Ozdem, Y., & Park, J. Y. (2015). Research trends on argumentation in science education: a journal content analysis from 1998–2014. *International Journal of STEM Education, 2*(5), 1–12.
Fournier, D. M. (1995). Establishing evaluative conclusions: a distinction between general and working logic. *New Directions for Evaluation, 68*, 15–32.
Galileo, G. (1638/1914). *Dialogues concerning two new sciences. (H. Crew, & A. d. Salvio, Trans)*. New York: MacMillan.
Galili, I. (2009). Thought experiments: determining their meaning. *Science & Education, 18*(1), 1–23.
Georgiou, A. (2005). Thought experiments in physics problem-solving: on intuition and imagistic simulation (Master's Thesis). Cambridge: University of Cambridge.
Gijlers, H., & Jong, T. d. (2013). Using concept maps to facilitate collaborative simulation-based inquiry learning. *Journal of the Learning Sciences, 22*(3), 340–374.
Gilbert, J. K., & Reiner, M. (2000). Thought experiments in science education: potential and current realization. *International Journal of Science Education, 22*(3), 265–283.
Hausmann, R. G., Chi, M. T., & Roy, M. (2004). Learning from collaborative problem solving: an analysis of three hypothesized mechanisms. In K. D. Forbus, D. Gentner, & T. Regier (Eds.), *Proceedings of the 26th annual conference of the cognitive science society* (pp. 547–552). Mahwah: Erlbaum.
Heller, P., Keith, R., & Anderson, S. (1992). Teaching problem solving through cooperative grouping. Part 1: group versus individual problem solving. *American Journal of Physics, 60*(7), 627–636.
Hennessy, S. (1993). Situated cognition and cognitive apprenticeship: implications for classroom learning. *Studies in Science Education, 22*(1), 1–41.
Höggqvist, S. (2009). A model for thought experiments. *Canadian Journal of Philosophy, 39*(1), 55–76.
Ichikawa, J., & Jarvis, B. (2009). Thought-experiment intuitions and truth in fiction. *Philosophical Studies, 142*, 221–246.
Klassen, S. (2006). The science thought experiment: how might it be used profitably in the classroom? *Interchange, 37*(1–2), 77–96.
Kösem, Ş. D., & Özdemir, Ö. F. (2014). The nature and role of thought experiments in solving conceptual physics problems. *Science & Education, 23*(4), 865–895.
Kuhn, T. (1977). A function for thought experiments. In T. Khun (Ed.), *The essential tension: selected studies in scientific tradition and change* (pp. 240–265). Chicago: University of Chicago Press.

Lattery, M. J. (2001). Thought experiments in physics education: a simple and practical example. *Science & Education, 10*(5), 485–492.
Lave, J., & Wenger, E. (1991). *Situated learning: legitimate peripheral participation*. Cambridge, England: Cambridge University Press.
Levrini, O. (2014). The role of history and philosophy in research on teaching and learning of relativity. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 157–181). Dordrecht: Springer.
Mach, E. (1905/1976). On thought experiments. In T. J. McCormack & P. Foulkes (Eds.), *In his Knowledge and error* (pp. 134–147). Dordrecht: Vienna Circle Collection.
Matthews, R. S., Cooper, J. L., Davidson, N., & Hawkes, P. (1995). Building bridges between cooperative and collaborative learning. *Change: The Magazine of Higher Learning, 27*(4), 35–40.
Matthews, M. R. (1988). Ernst Mach and thought experiments in science education. *Research in Science Education, 18*, 251–257.
Matthews, M. R. (2014). *International handbook of research in history, philosophy and science teaching*. Dordrecht: Springer.
Maxwell, J. (1871/2001). *Theory of heat*. New York: Dover.
Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: an expanded sourcebook*. Thousand Oaks: Sage publications.
Miščević, N. (1992). Mental models and thought experiments. *International Studies in the Philosophy of Science, 6*(3), 215–226.
Nersessian, N. J. (1992). In the theoretician's laboratory: thought experimenting as mental modeling. *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association, 1992*(2), 291–301.
Newton, I. (1687/1962). *Mathematical principles of natural philosophy and his system of the world*. Berkeley: University of California Press.
Nonaka, I., & Takeuchi, H. (1995). *The knowledge-creating company: how Japanese companies create the dynamics of innovation*. Oxford: Oxford University Press.
Norton, J. D. (1991). Thought experiments in Einstein's work. In T. Horowitz & G. Massey (Eds.), *Thought experiments in science and philosophy* (pp. 129–148). Savage: Rowman and Littlefield.
Norton, J. D. (1996). Are thought experiments just what you thought? *Canadian Journal of Philosophy, 26*(3), 333–366.
Norton, J. D. (2004). On thought experiments: is there more to the argument? *Philosophy of Science, 71*(5), 1139–1151.
Reiner, M. (1998). Thought experiments and collaborative learning in physics. *International Journal of Science Education, 20*(9), 1043–1058.
Reiner, M., & Burko, L. M. (2003). On the limitations of thought experiments in physics and the consequences for physics education. *Science & Education, 2*(4), 365–385.
Reiner, M., & Gilbert, J. (2000). Epistemological resources for thought experimentation in science learning. *International Journal of Science Education, 22*(5), 489–506.
Roschelle, J. (1992). Learning by collaborating: convergent conceptual change. *Journal of the Learning Sciences, 2*(3), 235–276.
Roschelle, J., & Teasley, S. D. (1995). The construction of shared knowledge in collaborative problem solving. In C. O'Malley (Ed.), *Computer supported collaborative learning: NATO ASI series* (128th ed., pp. 69–97). Berlin: Springer.
Schrödinger, E. (1935). Die gegenwärtige Situation in der Quantenmechanik (The present situation in quantum mechanics). *Naturwissenschaften, 23*(48), 807–812.
Schwandt, T. A. (1997). Evaluation as practical hermeneutics. *Evaluation, 3*(1), 69–83.
Sorensen, R. (1992). *Thought experiments*. New York: Oxford University Press.
Sorensen, R. (2016). Thought experiment and imagination. In A. Kind (Ed.), *The routledge handbook of philosophy of imagination* (pp. 420–436). London: Routledge.
Sternberg, R. J. (1999). What do we know about tacit knowledge? Making the tacit become explicit. In R. J. Sternberg & J. A. Horvath (Eds.), *Tacit knowledge in professional practice: researcher and practitioner* (pp. 231–236). London: Lawrence Erlbaum Associates.
Stuart, M. T. (2016). Norton and the logic of thought experiments. *Axiomathes, 26*, 451–466.
Velentzas, A., & Halkia, K. (2013). The use of thought experiments in teaching physics to upper secondary-level students: two examples from the theory of relativity. *International Journal of Science Education, 35*(18), 3026–3049.
Velentzas, A., Halkia, K., & Skordoulis, C. (2007). Thought experiments in the theory of relativity and in quantum mechanics: their presence in textbooks and in popular science books. *Science & Education, 16*(3–5), 353–370.

Vygotsky, L. S. (1978). Mind in society: the development of higher psychological processes. (M. Cole, V. John-Steiner, S. Scribner, & E. Souberman, Eds. and trans.), Cambridge: Harvard University Press.

Witt-Hansen, J. (1976). HC Ørsted, Immanuel Kant and the thought experiment. In *Danish Yearbook of Philosophy* (Vol. 13, pp. 48-65). Copenhagen, Denmark: Museum Tusculanum Press.