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Exploring the Processes and Factors of 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 sought to investigate whether thought experiments can be constructed in collaborative ways. In particular, this study explores how students construct thought experiments in collaborative learning and identify the factors that influence students during those processes.

There were 12 voluntary participants in this study, six master's students, and six undergraduate students in three universities in Makassar, Indonesia. The participants were divided into three groups, so that each group consisted of four students. The physics problem-solving activities were used to set the necessary environments for observing the processes and factors that influenced students when constructing collaborative thought experiments. Audio and video of the three group activities were recorded as the source of data. The group observation was conducted in the physics meeting room and physics lab at the Muhammadiyah University of Makassar, Indonesia. In order to ensure the validity of data, the notes that were written and drawn freely by the students while solving the problems and researcher' observation notes were also collected as the sources of the data.

The results show that while solving physics problems, students construct, share, and evaluate their thought experiments. This indicates that thought experiments can be designed and constructed in a collaborative manner, even though the thought experiments are mostly individual in nature. Based on the results, collaborative thought experiments are defined as 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. 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. I refer to these activities as the steps of collaborative thought experiments.

There are three purposes of students' thought experiments: prediction, verification, and explanation. In prediction, when problems were given, students directly visualized the imaginary world and then designed and ran thought experiments to predict the solution to the problems given. In verification, students first proposed hypotheses or assumptions and then designed and ran thought experiments to determine whether the hypotheses or assumptions were true or false. In explanation, students designed and ran thought experiments as a tool to provide further explanation about their hypotheses.

The results also show that the students validate the results of thought experiments using four evaluation resources. Firstly, some students used conceptual understanding that refers to physics concepts, physics equations, and laws such as Newton's law. Secondly, students used their specific experience. Past and daily experiences such as watching movies, playing ball, and traveling by motorcycle or train are examples used by the students when evaluating their TEs. Thirdly, students used logical reasoning in the form of personal assumptions or perceptions. Although this source is only a personal assumption or perception, it is enough to convince thought experimenters to support or reject the tacit knowledge they evaluated. Lastly, students used conceptual-logical inference that combines laws, principles, or concepts of physics with logical manipulation.

This study identifies five factors that can encourage students to visualize imaginary worlds as an initial step in constructing collaborative thought experiments: conflicting ideas, the similarity of ideas, the guidance and support from more experienced people, students' bodily knowledge, and students' imaginary visual knowledge. This indicates that thought experiments can occur not only because of students' personal knowledge (bodily knowledge and imaginary visual knowledge) but also because of interaction among students in a group to solve problems. Conflicting ideas between students in understanding problems would encourage them to broaden their perspectives, leading them to perform thought experiments in order to support their ideas and simultaneously refute the ideas of their fellow group members. Likewise, sharing similar ideas can lead to students responding to and supporting each other, and performing thought experiments in order to further support their assumptions. In addition, this study also shows that thought experiments could arise when master's students provide support and guidance for undergraduate students.

Furthermore, there are four factors that are considered to influence students in the process of sharing and evaluating thought experiments: validation of concerns, understanding, logical arguments, and conflicting evidence. The absence of evidence to validate the results of thought experiments during the evaluation process leads to the failure of the thought experiments. Likewise, a misunderstanding between students in understanding the evidence presented by others or the argument being built illogically can lead to the failure of the thought experiments. Also, when the evidence obtained through life experience contradicts with other evidence presented by others, students will try to maintain their beliefs to reach conclusions.

Based on this study, I would recommend that collaborative thought experiments be introduced to both current and future physics teachers as a useful tool for teaching physics at school for several reasons. First, the communication and peer interaction in collaborative thought experiments have a great potential to correct both the process and the results in order to reach the reliable conclusions of thought experiments. Second, with collaborative thought experiments, students who have difficulties will be

helped by other students in constructing thought experiments. Third, collaborative thought experiments can also improve social interactions and support diversity. Fourth, collaborative thought experiments might bring students closer to scientific argumentation through the interpretation of ideas and evaluating each other's thoughts and views. Lastly, through collaborative thought experiments, students clarify each other's ideas, views, and opinions through discussion forums before making conclusions. Therefore, collaborative thought experiments might nurture students' critical thinking and creative thinking skills.

Keywords: Collaborative, factors, physics teacher, problem-solving, processes, thought experiments

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Chapter 1. Introduction

1.1. Background of study

Scientific inquiry has been considered as one of the main goals in science education since the 1960s (National Research Council [NRC], 2000). Scientific inquiry was originally used as an effort to involve students in thinking processes and activities similar to those practiced by scientists (NRC, 2000; Hofstein & Lunetta, 2004; Bell et al., 2010; Lederman & Lederman, 2012). Although only a small proportion of students will go to be scientists (Yager, 1996), familiarizing students with the practices of knowledge-building as practiced by scientists is one of the cores of science teaching (Atkins & Helms, 1993; Roth 1995). Students, like real scientists, must study the natural world, make their own observations, and provide explanations based on evidence of their own work (NRC, 2000; Bell et al., 2010; Lederman & Lederman, 2012). Through scientific inquiry, students will be encouraged to develop the thought processes involved in creating facts, generating new explanations, and justifying facts (Bell et al., 2010; Reiner & Gilbert, 2000).

There are two types of experiments that are used to justify facts: real experiments and thought experiments (TEs) (Mach, 1976; Kuhn, 1977; Brown, 1991; Sorenson, 1992; Reiner, 1998). Real experiments have been widely accepted by science educators as a learning tool and are well integrated into the curriculum. On the other hand, TEs still receive less attention even though they are inherently embedded in the culture of science (Reiner, 1998; Galili, 2009). Real experiments cannot replace the role of TEs because TEs allow situations that are impossible to be reproduced by real experiments regardless of the sophistication of the equipment (Cooper, 2005; Galili, 2009). TEs also idealize the conditions of real experiments with complex technical details, experimental errors, and inhibiting factors (heat, friction, etc.) (Cooper 2005; Galili, 2009). In addition, TEs are indispensable in teaching modern physics: the relativity theories and quantum mechanics, where real experiments are practically difficult to be implemented in regular classroom activities, and multimedia tools very often fail (Galili, 2009).

TEs, as the scientific methodology (Mach, 1976; Reiner, 1998; Asikainen & Hirvonen, 2014b), play a special epistemic role in constructing scientific theories. 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 principle of light (Einstein, 1905). TEs existed not only in the era of physics evolution but long times before that Galileo had used TE of free-falling body to refute the gravitational theory of Aristotle (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). 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), Einstein's train (Einstein, 1905), and Schrödinger'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 (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 familiarise students with the culture of science (Reiner, 1998; Galili, 2009), inspire students to provide a rich source for their ideas (Lattery, 2001), and develop students' intuition (Georgiou, 2005; Tortop, 2016). TEs can also expose students' hidden reasoning (Clement, 2009; Kösem & Özdemir, 2014), promote imagistic simulation (Stephens & Clement, 2012) and help students' imagination to develop (Galili, 2009). 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 learning tool in teaching modern physics can help develop students' syllogistic abilities and help them to imagine situations outside of everyday experience (Velentzas & 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 & Reiner, 2000; Velentzas et al., 2007; Bancong & 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 & Burko, 2003; Asikainen & Hirvonen, 2014a; Kösem & 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 & 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. However, some researchers (e.g., Galili, 2009) have refuted this strategy because most TEs simulation often fails, suffering superficial, and conceptually irrelevant content. Klassen (2006) advised physics teachers to use a narrative technique and rewrite the TEs in a story format. This kind of solution, however, in which the students just rewrite TEs in the form of narrative, is unlikely to develop students' imaginative abilities in constructing TEs. Velentzas and Halkia (2011; 2013) reported positive results when they implemented Heisenberg’s historical TE of the microscope as a learning tool in teaching the “uncertainty principle” to high school students, and Einstein's historical TE of the elevator and TE of the train for teaching the basics of relativity. They claimed that historical TEs have great potential as learning tools to teach physics topics that demand concepts. However, that was being not enough. Asikainen and Hirvonen (2014b) argued that so far, the researchers participating in this study are still small, and therefore recommendations on how to implement the TEs in teaching science are very necessary.

Reiner (1988) analyzed the processes of students in constructing TEs while they were working on the problem in a collaborative setting and proposed five stages of TEs: visualization, hypothesis, experiment, results, and conclusions. She then argued that TEs are more easily constructed in a collaborative manner where the number of students' contributions can lead to a complete TE. However, how TEs are constructed collaboratively, how students share and negotiate meaning during constructing TEs in collaborative learning, and how students validate the knowledge generated from TEs are not clearly explained either by Reiner (1988) or subsequent studies. In addition, the steps of TEs proposed by Reiner (1988) did not reflect the existence of collaborative activities.

In addition, in the field of science education, there has been little research concerning the factors that influence students in constructing TEs. Although Reiner and Burko (2013) have analyzed and released several factors that are likely to influence students in doing TEs—intuition, incompleteness, and irrelevancy—they focused on TEs built by individual students. Likewise, Asikainen and Hirvonen (2014a) explored the ability of individual physics teachers to understand the double-slit TE. How TEs are constructed by students in group learning and what factors influence students during the processes have not yet received serious attention from researchers.

So far, there are still some questions that have not been answered clearly, such as how to teach TEs appropriately especially in collaborative learning, and whether TEs, which are often built by individual scientists (Kuhn, 1977; Brown, 1991; Sorensen, 1992), can be shared and communicated with other members in group learning. Previous studies have focused more on the TEs' processes at the individual level rather than in groups (e.g., Georgiou, 2005; Clement, 2009; Asikainen & Hirvonen, 2014a; Bademci & Sari, 2014; Kösem & Özdemir, 2014). This is likely due to most philosophers and historians 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).

However, in another perspective, learning is viewed as a social process (Vygotsky, 1978) that includes participation in a community of practice (Lave & Wenger, 1991; Wenger, 1998). The Vygotskian view of learning (Vygotsky, 1978) asserts that meaning is constructed through continuous negotiations within the social environment. The concept of collaborative learning is based on social constructionism (Roschelle & 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 & Wenger, 1991; Hennessy, 1993). 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).

Several studies in science education have shown that students who worked collaboratively performed significantly better than those who worked alone (e.g., Chang & Mao, 1999; Hofstein & Lunetta, 2004; Sampson & Clark, 2009; Bell et al., 2010; Gijlers & Jong, 2013). In collaborative learning inquiry, students are provided the opportunity to share and discuss ideas, clarify and justify their perspectives, and continuously refine one another's ideas by comparing multiple points of view (Sampson & Clark, 2009; Gijlers & Jong, 2013). Collaborative inquiry learning was superior in promoting students' achievement and attitudes toward science because it allows students to share information, to utilize various inquiry processes, and to reflect on their inferences through small group activities (Chang & Mao, 1999; Bell et al., 2010).

Therefore, the concept of collaboration was used in this study to analyze the TEs that are co-constructed by students. Although TEs are scientists' personal and tacit processes of experimentation in constructing a scientific theory, I think that they have the possibility of being communicated with other students in a group setting. When students are given the opportunity to work together to solve meaningful problems, I 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. From this perspective, communication with other members in constructing TEs can be possible.

1.2. Purposes of the study

In particular, there is limited study on TEs in relation to collaborative learning. Previous studies have focused more on the TEs' processes at the individual level rather than in groups. Although Reiner (1998) argued that TEs are more easily constructed in a collaborative manner, how TEs are constructed collaboratively are not clearly explained either by Reiner (1988) or subsequent studies. In addition, the steps of TEs proposed by Reiner (1988)—visualization, hypothesis, experiment, results, and conclusions—did not reflect the existence of collaborative activities. Brown (2006) also proposed three steps of TEs: (a) visualize a situation, (b) carry out an operation, and (c) describe the result. Both Reiner (1998) and Brown (2006) focused on TEs steps of an individual perspective while ignoring aspects of the group. Therefore, there is still a limited understanding of how students are involved in the process of constructing TEs in group learning, how students share and negotiate meaning during constructing TEs, how students validate the knowledge generated from TEs, and what factors influence students in constructing TEs in group learning.

The main focus of this study, therefore, is to investigate whether TEs can be constructed in a collaborative manner. If so, I will further explore how students construct TEs in collaborative learning and identify the factors that influence students during those processes. I will refer to TEs that are co-constructed by students in group learning as collaborative TEs. I believe that collaborative TEs are superior to individual TEs because, in a collaborative TE, students have the opportunity to share and discuss ideas, criticize, and evaluate ideas with each other from various perspectives. Therefore, collaborative TEs provide many benefits for students because students can access various types of experiences, resources, and understanding. With collaborative TEs, students can learn something new from others, and also learn to respect different perspectives. In addition, because TEs are mental models activities that are carried out mostly in the minds of individuals (Nersessian, 1992; Gilbert & Reiner, 2000), some students have difficulty in constructing TEs independently (Kösem & Özdemir, 2014). With collaborative TEs, students who have difficulties or students who have less capacity will be helped by other students in constructing TEs. Collaborative TEs can also provide self-confidence for students. When students work as a team, they receive support from each other so that they will gain confidence. It will be shown some evidence in this study (Chapter 5) where collaborative TEs arise because of the support and guidance from fellow group members. Therefore, in collaborative learning, students who feel ashamed to express their ideas will be helped by other students.

I also suggest the importance of including collaborative TEs as part of the physics teaching strategy for several reasons. First, because TEs can produce both correct and incorrect results (Reiner & 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 reliable conclusions. Collaborative TEs can improve social interactions and support diversity because, in collaborative TEs, students must work together in a group with different backgrounds, experiences, cultures, and knowledge. They will hear different opinions and learn more about different cultures. When students spend time together to work, they will learn how to relate to each other. They also make friendships by getting to know each other, thereby increasing morale and group performance. Also, through collaborative TEs, students clarify each other's ideas, views, and opinions through discussion forums before making conclusions. This can nurture students' critical thinking skills. Collaborative TEs could also bring students closer to scientific argumentation through the interpretation of ideas and evaluating each other's thoughts and views. Therefore, to achieve these goals, two broad research questions and sub-questions were used to guide my data collection and analysis as follows:

1. How do collaborative TEs occur in physics problem-solving activities?
   - What is the meaning of collaborative TEs?
   - What are the steps of collaborative TEs?
   - What are the students' purposes in conducting TEs?
   - How do students validate the results of TEs?
2. What factors influence students in constructing collaborative TEs?
   - What factors influence students in visualizing TEs?
   - What factors influence students in sharing and evaluating TEs?

1.3. Synopsis

This dissertation has two chapters of research findings.

Chapter 4. Processes of Collaborative Thought Experiments

This chapter explores how students construct TEs in a collaborative manner during physics problem-solving activities. The concept of collaborative learning (Vygotsky, 1978; Lave & Wenger, 1991; Hennessy, 1993; Wenger, 1998; Dillenbourgh, 1995; Chiu, 2000) was used in this study to analyze the TEs that are co-constructed by students. The findings in this chapter describe the meaning of collaborative TEs and the five activities that the students carried out in constructing collaborative TEs. I refer to these activities as the steps of collaborative TEs. This chapter also describes the purposes of students in conducting TEs and the evaluation resources used by students in validating their TEs. In the last part of this chapter, I illustrate the process of new knowledge obtained through collaborative TEs during physics problem-solving activities.

Chapter 5. Factors Influencing Collaborative Thought Experiments

This chapter identifies the factors that influence students when constructing collaborative TEs. Some related literature has emphasized that visualization is the main feature of TEs (Gooding, 1992; Reiner, 1998; Gendler, 2004; Brown, 2006), and the first step in the TE process (Reiner, 1998; Brown, 2006). Therefore, in order to identify the factors that trigger the emergence of collaborative TEs when students interact with each other in their groups to solve problems, first of all, I located the process of visualization. As a result, five conditions were identified as factors that can encourage students to visualize TEs as an initial step of collaborative TEs. These five factors are explained in this chapter in detail. This chapter also describes four factors that are considered to influence students in the process of sharing and evaluating TEs. I think that understanding the factors that influence students in constructing collaborative TEs can give us not only a clear understanding of how students do TEs in detail but also can generate information about how to help students to improve their TEs. In the last part of this chapter, I illustrate the factors that influence students in constructing collaborative TEs.

After these two chapters of findings, Chapter 6 provides conclusions and implications of collaborative TEs to both current and future physics teachers. The limitation of this study and suggestions for future research are also provided.

1.4. Definitions of terms

- Thought experiment (TE) is an activity of visualizing an imaginary world in which experiments will be designed and run in the head of an individual, and then the results of the carrying out the experiment are described.

- Collaborative TE is 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.
- Tacit knowledge is a personal belief or personal knowledge of thought experimenter after generating the TE. In this study, I refer to the results of TE as tacit knowledge.

Chapter 2. Theoretical Framework and Literature Review

2.1. Thought experiments

2.1.1. Definition of thought experiments

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 thought experiment (TE) literature by examining their significance, function, and role in learning and teaching. Nevertheless, a consensus has still not been reached on the exact definition of a TE. As Brown (2006) said:

> *We know thought experiments when we see them. But there is no point in trying to define thought experiment any more than there is in trying to define loyalty, religion, or a meaningful life. With luck we may someday be able to describe them in a sufficiently precise way to call it a definition. But that day is a long way off* (p. 63).

The term TE, a direct translation of the German term *Gedankenexperimente*, has been widely discussed in the philosophy of science since Ernst Mach (1838-1916). Even though some researchers have argued that the term had already been used by Danish physicist Hans Christian Ørsted in 1811 (Witt-Hansen, 1976; Klassen, 2006), Mach was considered as the first to introduce this construct into active use, particularly in education (Matthews, 1988; Galili, 2009). In his paper "On Thought Experiments" (1976), Mach said:

> *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 (1976) emphasized the values of TEs as techniques for professional inquiry and for guessing the results of laboratory experiments.

Although scientists did not use the term TE when describing a theory or discussing it with others, in fact, they often use it with other expressions. For example, Bohr (1949) used the words "pseudo-realistic style" and "devices proposed by Einstein" when discussing Einstein's TEs. In *the Evolution of Physics*, Einstein and Infeld (1938) used the term "idealized experiment" to describe the TE as they said, "we recognized the importance of the idealized experiment created by thought . . . Although these may sound very fantastic, they will, nevertheless, help us to understand as much about relativity as is possible by our simple methods" (p. 226). Galili (2009) claimed that because scientists consider TE so obvious, they refrained from defining TE even though they often use it in different expressions.

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. Brown (1991) then classified TEs into three types: destructive, constructive, and platonic. By supporting Brown's argument, Sorensen (1992) argued that TEs are mentally simulating in an individual's mind and be observed with the 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). In Kuhn's account, TEs act to trigger scientists' memories of anomalies that they had seen before but so far ignored. Therefore, in Kuhn's view, the new knowledge gained in a TE is not really new, but instead of the remembered knowledge.

Some authors claimed that TEs are mental model-based reasoning (Nersessian, 1992; Miščević, 1992, Coper, 2005). 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).

Miščević (1992) also argued that performing a TE consists of constructing a mental model and reasoning on it. It explains the nature of data and points to the skill employed in manipulating the items in the model. Coper (2005) viewed TEs as activities to construct a model used a series of "what if" questions:

> *Thought experiments present us with a series of "what if" questions. For example, we may seek to discover what would happen if there were no friction, or what would happen if people split like amoebas. In performing a thought experiment we temporarily adjust our worldview in order to construct a model in accord with the answers to these ''what if'' questions* (p. 336).

The mental model in TEs consists of a set of propositions that describe the situation. Coper (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) also tells us that 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, Coper (2005) viewed that the modeled phenomena do not limit 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) defined TEs as "reasoning processes that are based on results of an experiment carried out in thought" (p. 489). In Reiner and Gilbert's view, a TE consists of two aspects: thought and experiment. The thought aspect involves creating an imaginary world that can be reconstructed and reorganized but is limited by the intentions of the thought experimenter. The construction created is, therefore, related to the knowledge and experience of the thought experimenter. In the experiment aspect, it refers to experimental activities in the real world, such as manipulating variables to achieve coherence with the theory being tested. Both Nersessian (1992) and Reiner and Gilbert (2000) agreed that the use of imagery in a TE enables the thought experimenter to access tacit knowledge (non-explicit knowledge) that acts as the basis for generating new states of knowing.

Others, such as Norton (1996), do not accept claims that TEs provide some new and even mysterious ways to arrive at knowledge. Norton (1991, 1996) believed that TEs are merely beautiful arguments for denying or creating a new theory and that they should be classified into two parts: deductive and inductive arguments. According to Norton (1996), if a TE is merely reorganized, it is a deductive argument where the specific conclusion follows deductively from the premises, but if a TE is generalized on a more extensive scale, it is an inductive argument.

Some literature also typically describes TEs in terms of their function. For example, Sorensen (1992) viewed TEs as limiting cases of real experiments that can achieve the aim of real experiments without actually executing them but instead mentally simulating them in mind. After analyzing the relevant episode of TEs throughout the history of physics, Galili (2009) claimed that TEs are logical devices for scientists not only for developing scientific theories but also for clarifying, and criticizing existing theories. Similarly, Stephens and Clement (2012) argued that TEs are activities that can be used to evaluate scientific concepts, models, and theories and even to predict aspects of a concrete system.

Therefore, based on these explanations, it can be drawn a common thread that TE is an experimental activity carried out in the mind of individuals with personal imagery that is usually used by scientists in formulating new theories, supporting or refuting existing theories. In doing a TE, reasoning plays an important role, and it allows the thought experimenter to produce new knowledge.

2.1.2. Thought experiments and real experiments

According to Irvine (1991), there are five similarities between TEs and real experiments (REs). First, the assumptions of both REs and most TEs should be independently confirmed by empirical observations. Second, they should have a reasonably developed background theory. Third, they should have a bearing on how to answer the question. Fourth, they should have independently isolated variables. Last, the results of both TEs and REs should have consequents for the background theory.

Reiner and Gilbert (2000) also classified the similarities between REs and TEs. First, they are about constructing or testing of a theory. Second, the results of both TEs and REs may be shared with a scientific community. Third, both TEs and REs may have unpredicted additional consequences. Galili (2009) argued that TEs, like in the real laboratory, present the basic theory needed for each experimental activity. Skipping TEs and going directly to REs often removes the meaning and value for students (e.g., as a tool for guessing the results). Therefore, according to Galili (2009), TEs are effectively used for students before conducting experiments in a real laboratory.

On the other hand, according to Irvine (1991), the differences between TEs and REs are: (1) TEs do not involve the physical environment; (2) High cost and lack of equipment can be a problem for REs but not for TEs; (3) REs depend on actual intervention in nature while TEs depend on argument based upon hypothetical premises. In a similar sense, Reiner and Gilbert (2000) claimed five differences between TEs and REs. First, TEs are conducted mentally. Second, TEs require one mental experimenter, while REs generally require a group of scientists. Third, the designer and the experimenter are the same person in TEs, but REs generally have separate designers and experimenters. Fourth, TEs do not involve luck or chance factor in determining the outcome, however, REs may have as problems about reproducibility can be attributed to chance factor. Last, because TEs are conducted in mind, they cannot cause personal and social harm.

Others, such as Galili (2009) argued that TEs are often made simpler by removing technical details and setting aside the inhibiting factors of a RE such as heat and friction, but the representative model remains to focus on the important aspects of the subject. Similarly, Park et al. (2001) argued that ideal conditions are needed when designing TEs to eliminate technical or manipulative complexity of TEs and to simplify the experimental context. They also said that TEs start from well-known and familiar existing theories, in which no empirical data is produced, and reasoning plays an important role in drawing conclusions. TEs never performed other than in mind (Brown, 1991; Sorensen, 1992), and are observed only with the mind's eye (Sorensen, 1992).

Nersessian (1992) released specific features of TEs related to her understanding: TEs as a species of simulative model-based reasoning. First, TEs are presented in the form of a narrative that has the character of a simulation. Second, when the TEs are presented to the public, they are in polished form. Third, the narrative of TEs illustrates an abstraction. For example, certain features of objects in real-world experiments are not included, such as the color of the stone and the physical characteristics of the observer. A diagram of the difference between TEs and REs can be seen in Figure 2.1.

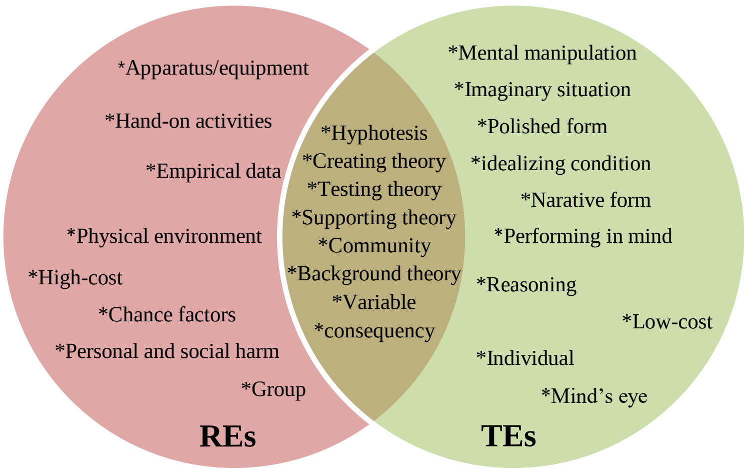


Figure 2.1. Diagram of the difference between REs and TEs

2.1.3. Steps of conducting thought experiments

Generally, the structure of TEs is divided into five stages, and each stage includes different activities (Reiner, 1998). First, thought experimenters construct an imaginary world and describe the features of the world they imagined, such as objects, rules, and conditions. The main focus in this stage is to become familiar with the objects, conditions, and events in the imaginary world in formulating the physical model to be used. Second, thought experimenters set the hypotheses or general assumptions to be used, such as using scientific theory. This phase includes the process of translating problems and proposing hypotheses that can be tested. Third, thought experimenters design and conduct an experiment in their minds. Fourth, thought experimenters describe the results of the carrying out the experiment, and, fifth, thought experimenters draw conclusions.

Brown (2006) analyzed several TEs carried out by scientists, such as Galileo's free-falling body, Newton's bucket, Stevin's problem in statics, and Einstein's chasing a light beam, claiming that TEs have at least three structures: (a) visualize the situation, (b) carry out experiments, and (c) describe the results. For example, according to Maxwell's theory of electrodynamics, light is an oscillation in the electromagnetic field. The theory said that the speed of the light wave in the medium along the axes x, y, and z both the propagation and the electric displacements direction will always be the same even though the values of k and μ were different

(Maxwell, 1865). That is, light always travels at a constant velocity in any directions in the medium with respect to the ether. This theory produced a paradox for Einstein since the age of 16 years, as he said:

> *A paradox upon which I had already hit at the age of sixteen: If I pursue a beam of light with the velocity c (velocity of light in a vacuum), I should observe such a beam of light as an electromagnetic field at rest though spatially oscillating. There seems to be no such thing, however, neither on the basis of experience nor according to Maxwell's equations* (Einstein, 1949, p. 53).

According to Brown (2006), there are three components visible in this TE. First, Einstein visualized the situation by chasing a beam of light traveling at speed c. Second, while chasing the beam of light, Einstein then observed the state of the light beam, whether stationary or moving with speed c. Third, Einstein then described the results of his observations, which saw a beam of light like an electromagnetic field that looked static despite spatially oscillating. This TE shows that the speed of light is not always the same as c. Einstein assumed that the speed of light would be 0 when he was able to catch the beam of light. Similarly, water skiers or runners on the beach will see stationary water waves when moving together, as Brown said:

> *When he was only 16, Einstein wondered what it would be like to run so fast as to be able to catch up to the front of a beam of light. Perhaps it would be like running toward the shore from the end of a pier stretched out into the ocean with a wave coming in alongside. There*

would be a hump in the water that remains stationary with respect to the runner (Brown, 2006, p. 67).

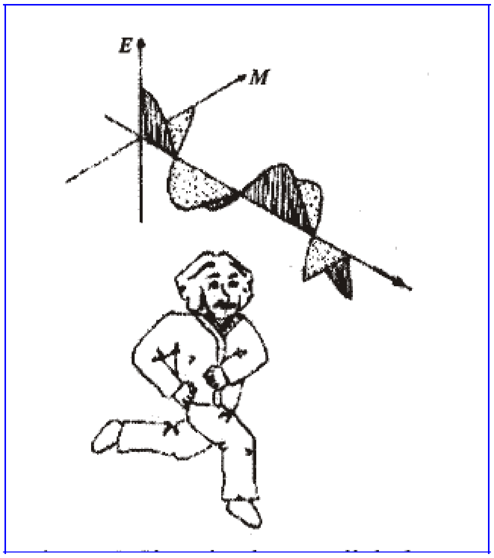


Figure 2.2. Einstein chases a light beam (Brown, 2006, p. 67)

Based on the above explanations, in order to distinguish it from collaborative TE, TE is defined as a structured process of visualizing an imaginary world where experiments will be designed and run in the head of an individual, and then the results of conducting experiments are explained. Therefore, there are three activities are used to detect the TE carried out by students in this study: visualizing the imaginary world, performing experiments, and describing the results.

2.2. The concepts of collaboration

2.2.1. Collaborative learning

In the field of education, learning is sometimes viewed as a social process (Vygotsky, 1978) that includes participation in a community of practice (Lave & Wenger, 1991; Wenger, 1998). The concept of collaborative learning is based on social constructionism (Roschelle & 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 & Wenger, 1991; Hennessy, 1993).

In the most general sense, collaboration is claimed to occur when two or more people work together to solve a task or problem. The Oxford Dictionary of English provides the definition of the word "Collaborative" as the action of working with someone to produce something (Stevenson, 2010). Similarly, Smith and MacGregor (1992) said that collaborative learning could occur when two students or more work together in a group for sharing understanding, finding solutions or making a product. In this sense, collaboration involves at least two people who work together to achieve a goal.

Collaborative learning is rooted in the concept of the proximal development zone that was put forward by Vygotsky. The Vygotskian view of learning (Vygotsky, 1978) asserts that meaning is constructed through continuous negotiations within the social environment. 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, evaluating ideas with each other, and monitoring each other's work (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 (Dillenbourgh, 1995; Roschelle & Teasley, 1995). 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). Cooperative learning refers to a specific classroom technique that fosters student interdependence while collaborative learning has a philosophical social constructivist basis, which views learning as a construct of knowledge in a social context (Oxford, 1997).

According to Dillenbourg (1999), there are three interaction characteristics as collaborative activities. The first and most prominent criterion is that collaborative situations must reflect sufficient interactions among participants. The second criterion is that there is an activity to do something together. The last criterion is that there is an activity of negotiation of meaning. Therefore, the structure of collaborative dialogue is more complex than, for example, tutoring dialogue. Members in collaborative learning debate each other's point of view, justifying their claims, and trying to convince their opinions to other members (Dillenbourg, 1999).

The negotiation process is a central feature of collaborative learning (Dillenbourg, 1999). Negotiation of meaning is a dynamic and unique process formed by several elements. It came up with a history (experience) manifested in a particular context, as Wenger (1998) argued that negotiation of meaning is an active process of producing meaning that is both dynamics and historical, contextual, and unique. Wenger (1998) said that the negotiation of meaning involved the interaction of participation and reification in the act of processing the claims. As a form of participation, participants contribute to the negotiation of meaning by becoming members of the group and sharing their social experiences from their lives. Meanwhile, in reification, participants produce claims that have been fixed in their form.

2.2.2. Benefits of collaborative learning

Several studies have demonstrated that students who worked collaboratively have better performance than those who worked alone in inquiry learning (e.g., Chang & Mao, 1999; Hofstein & Lunetta, 2004; Sampson & Clark, 2009; Bell et al., 2010; Gijlers & Jong, 2013). Chang & Mao (1999) claimed that collaborative inquiry learning was superior in promoting students' achievement and attitudes toward science because it allowed students to plan their own investigations, to share information with group members, and to reflect on their inferences through discussion activities. Likewise, Hofstein & Lunetta (2004) argued that the inquiry group was superior to individual learning because this approach encouraged students to work collaboratively in small groups, and therefore, they discussed ideas and utilized resources and skills with each other.

A number of science educators have suggested that students work collaboratively when they make scientific arguments to be more productive (e.g., Sampson & Clark, 2009; Lazarou et al., 2017). Sampson & Clark (2009) investigated the impact of collaboration on students' scientific argumentation, claiming that the students who worked in groups produced better scientific argumentation than those who worked alone. The study showed that collaborative learning could help students learn not only the content but also the practice of scientific argumentation when they engaged in problems that require evaluation of alternative explanations (Sampson & Clark, 2009).

Gijlers & Jong (2013) analyzed the effects of shared concept mapping assignments on high school students' learning in a collaborative-based inquiry. The regression analysis showed that there was a positive relationship between collaborative-based inquiry and learning outcomes for both intuitive and structural knowledge. The positive effect of collaboration can be explained by the fact that the involvement of all students in collaborative learning allowed them to talk about their own understanding and ideas

(Gijlers & Jong, 2013). During collaborative inquiry learning, students were invited to share their plans and ideas with their partners, meaning that when students worked collaboratively, they needed to externalize their ideas and provided arguments and explanations so that their partners can understand and evaluate their ideas (Gijlers & Jong, 2013).

Bell et al. (2010) suggested the use of computerized tools to support students' collaborative learning. They claimed that computerized tools have a positive effect on students' motivation during collaborative inquiry learning for two reasons. First, the computerized tools can help students to focus on the learning process. In other words, computers may support students in planning investigations or constructing knowledge such as calculating, visualizing data, retrieving, and storing information. Second, with computers, students can access information and instructions through the interface on their own initiative and do not have to depend on the teacher. Others, such as Ucan and Webb (2015), emphasized the importance of using the regulatory process during collaborative inquiry learning. They claimed that the co-regulation of the metacognitive processes stimulated students to ponder and clarify their thinking, as well as facilitated the construction of new scientific understanding. Furthermore, shared regulations of the metacognitive processes helped students to build a shared understanding, clarify and justify their shared perspective, and maintain the ongoing co-construction of knowledge.

In sum, the concept of collaboration was used in this study to analyze the TEs that are co-constructed by students. Although TEs are scientists' personal and tacit processes of experimentation in constructing the scientific theories, I think that TEs have the possibility of being communicated with other students in a group setting. When students are given the opportunity to work together to solve meaningful problems, I 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. From this perspective, communication with other members in constructing TEs can be possible.

I will refer to collaborative TEs as activities in which one or more individuals visualize the imaginary worlds in which experiments will be designed and generated in their own mind laboratories and then shared them with group members to be run and evaluated as a collective effort to reach conclusions. I strongly believe that collaborative TEs are superior to individual TEs because, in collaborative TEs, students have the opportunity to share and discuss ideas, criticize and evaluate ideas with each other from various perspectives so that the TEs are generated as cumulative thoughts of all group members. Therefore, collaborative TEs are believed to provide many benefits for students because students can access various types of experiences, resources, and understanding. Collaborative TEs can also provide self-confidence for students because when students work as a team, they will receive support from each other so that they will gain confidence.

Collaborative TEs are, therefore, important as a strategy for teaching physics because the communication and peer interaction in collaborative TEs have great potential to correct both the process and the results in order to reach reliable conclusions. Collaborative TEs can also improve students' social interactions and support diversity. In collaborative TEs, students must work together in a group with different backgrounds, experiences, cultures, and knowledge. They will hear different opinions and learn more about different cultures. When students spend time together to work, they will learn how to relate to each other. They also make friendships by getting to know each other, thereby increasing morale and group performance. Also, through collaborative TEs, students clarify each other's ideas, views, and opinions through discussion forums before making conclusions. Therefore, this can nurture students' critical thinking skills. Collaborative TEs can also bring students closer to scientific argumentation through the interpretation and evaluation of ideas, thoughts, and views among students.

2.3. Previous studies

2.3.1. Studies on the role of thought experiments in science

Brown (1991) classified TEs according to their role in constructing scientific theories as destructive, constructive, and platonic TEs. Destructive TE is a type of TEs that aims to destroy a theory or at least show a serious problem for a scientific theory. Schrödinger's cat is an example of this kind of TE. Erwin Schrödinger presented a cat in a box in a superposition of two states: dead or alive (Schrödinger, 1935), which aimed to question the limitations and conceptual difficulties of quantum mechanics. In contrast, constructive TE aims to support or construct scientific theory, such as Maxwell's demon and Einstein's elevator. Brown (1991) then divided constructive TE into three further types: direct, conjectural, and mediative TE. Platonic TE is a small class of TEs that simultaneously refute an existing theory and produce a new theory. TE of Galileo's free-falling body is an example that refuted Aristotle's view that heavier objects fall faster and simultaneously established the new idea that all objects fall at the same speed. The taxonomy of TEs is shown in Figure 2.3.

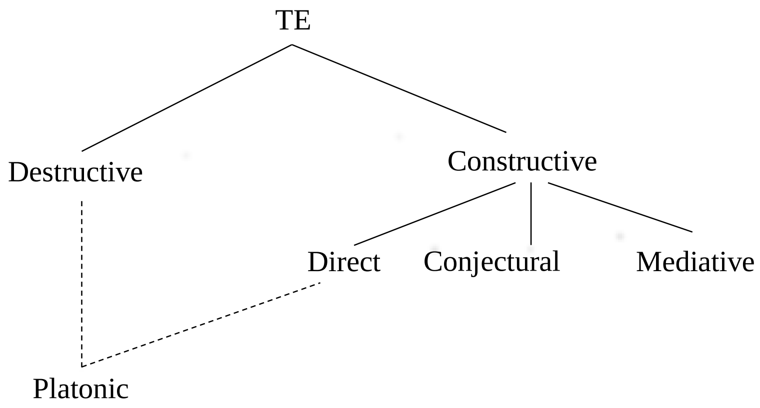


Figure 2.3. Taxonomy of TEs (Brown, 1991, p. 33)

Norton is a philosopher who, in many of his works, has been trying to convince us that TEs are just beautiful arguments to support or reject scientific theories. 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. According to Norton (1991, p. 137), TE of 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). Therefore

(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).

In order to support his assumption that TEs are just beautiful arguments, Norton (1996) 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 2014, Norton then illustrated several TEs that produced erroneous results, which indicated that TEs are just ordinary arguments, disguised in some vivid picturesque or narrative form. Norton (2014) said that “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” (p. 1139).

Park et al. (2001) analyzed the thinking processes of several TEs, including TE of Galileo’s free-falling body, TE of Leibniz’s vis viva, TE of Newton’s bucket, and TE of Schrödinger’s cat. Based on the analysis, they illustrated three functions of TEs: falsifying existing knowledge, manifesting existing knowledge, and inventing new knowledge. They also described some of the characteristics of TEs, such as idealizing the situation, starting with a well-known theory, no producing empirical data, and reasoning playing an important role.

Reiner and Burko (2003) analyzed several TEs related to stellar evolution and general relativity and described three cognitive processes that led scientists and students to erroneous conclusions. First, because thought experimenters lacked the previous experience to support their intuition, they used unproductive intuitions in designing a TE that led them to the wrong conclusions. Second, when the thought experimenters constructed their imaginary worlds, they set general assumptions that were incomplete (i.e., some crucial elements may be missing or faulty). Third, sometimes the thought experimenters used fragmented concepts, so the general assumptions and the features of the imaginary world were irrelevant.

Moreover, Reiner and Burko (2003) claimed that TEs are more susceptible to errors than laboratory experiments because, in TEs, it is very difficult to understand which system properties should not be compromised and which are merely complications.

> *Of course, also in laboratory experiments one can arrive at the wrong conclusions. However, when laboratory experiments are concerned, nature takes care of including all the relevant natural laws and effects, including effects which the physicist may think of as irrelevant. For example, when one actually builds the clock-in-the-box apparatus [TE of Einstein's light box] and tries to perform the laboratory experiment, all the effects will be included by the apparatus and its environment. The physicists may not notice that the gravitational red-shift effect is relevant, but the experiment itself cannot mistake about this. Therefore, there are more possibilities to err with TEs than with laboratory experiments* (Reiner & Burko, 2003, p. 381-383)

Rescher (2005) also found three factors that sometimes led TEs to fail. First, the lack of information needed to build TEs. Second, the mistakes in the reasoning process that leads to wrong conclusions. Third, mistakes in understanding the questions that would be targeted in doing TEs.

Brown (2006) illustrated the promise and perils of TEs and drawn two evident morals in TEs. First, "thought experiments can give us genuine knowledge. They can be extremely useful, both heuristically and pedagogically, in providing genuine insight" (p. 71). There are several examples, such as TE of Galileo's free-falling body involved two different objects actually succeeded in proving that all bodies fall at the same rate. This TE really gives us genuine knowledge. Second, "thought experiments can seriously mislead us" (p. 71). TEs do not always give us new knowledge, in some cases, they could be wrong and provide erroneous knowledge. Norton (2004) also argued that TEs often produce the wrong results even though they can provide useful results in the development of scientific theory. Reiner and Burko (2003) claimed that scientists generally make mistakes in constructing TEs at the stage of visualizing imaginary worlds and constructing hypotheses so that they produce error conclusions.

Others, such as Galili (2009), clarified the meaning of TEs by following relevant episodes of TEs throughout the history of science, claiming that TEs are logical devices that mediate between theory and experimentation with mental simulations. Galili (2009) emphasized that TEs are as special theoretical constructs for scientists not only for developing scientific theories but also for clarifying, and criticizing existing theories. After tracing Mach's paper, Arcangeli (2010) argued that imagination had a very crucial role in TEs. TEs are not simple "images of experiments," but complex processes involving imagination.

2.3.2. Studies on the role of thought experiments in science education

Ernst Mach was considered as the first to introduce the term of TEs into active use, particularly in education (Matthews, 1988; Galili, 2009). In his paper "On Thought Experiments" (1976), Mach stated that

> *I have seen this method [TEs] in operation both in the case of my own high school teacher, H. Phillipp, and also when visiting the school of F. Pisko, another admirable pedagogue. Not only the pupil but also the teacher gains immeasurably by this method: it is the best way to get to know one's pupils* (p. 142*).*

Besides being effectively used as a method for guessing which problems can be solved and which cannot, TEs are important for professional inquirers and also for mental development (Mach 1976).

Trying to understand the role of TEs in learning physics, Reiner (1988) analyzed the natural processes of students in constructing TEs in the context of computer-based simulations and proposed five stages of TEs: visualization, hypotheses, experiments, results, and conclusions. Reiner (1998) then suggested to physics teachers for using computer simulations when teaching TEs because it allows students to see physical processes and construct a deep understanding of physics concepts. Reiner and Gilbert (2000) investigated a series of TEs performed by teachers and students when they were working on problems. They claimed that both teachers and students solved problems using TEs as a logical tool that draws on three epistemological resources: conceptual-logical inferences, visual imagery, and bodily-motor experience. They then argued that new knowledge could be generated from TEs when the tacit knowledge as a result of the experiment is coupled with logical process:

> *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 in a TE, is unconsciously recruited to generate new knowledge* (Reiner & Gilbert, 2000, p. 502).

Georgiou (2005) investigated the role of intuition and imagistic simulation in the process of constructing TEs while students were solving physics problems collaboratively. The results showed that students usually abstracted the phenomenology of the physical world into intuition to be used to determine the phenomenology of the imaginary world, and therefore, intuition is an important link between physical experiments and TEs. Georgiou (2005) also claimed that imagistic simulation in TEs is an indispensable part because, without it, predictions will remain "only conjecture." Reiner (2006) analyzed the context of TEs in physics learning based on some relevant literature, claiming that there are three types of learning context problems (LCPs) that trigger TEs. First, technological LCPs─TEs emerged from interacting with construct a technological device. Second, empirical LCPs─TEs emerged out of real experiments that triggered the construction of spontaneous representations. Third, imaginary LCPs─TEs emerged from familiar past experiences and triggered implicit knowledge that has been organized in bodily schemata.

Clement (2009) analyzed think-aloud protocols from professors and graduate students in physics, mathematics, and computer science. The results showed that participants using TEs were almost similar to scientists; for example, both of them used TEs to confirm and discredit theories. In addition, the results showed that imagistic simulation plays a central role in TEs, and it can produce new knowledge using several sources, including implicit prior knowledge and spatial reasoning operations. After reviewed some studies related to the role of TEs in science instruction and applied their analysis in the classroom, Stephens & Clement (2012) argued that middle and high school students could run TEs produced by teachers, which indicates that students' TEs can be similar to experts in many ways. They wrote that TEs do not need to be built together because students can independently produce novel scenarios, make predictions, and evaluate their own scenarios during class discussions.

Kösem and Özdemir (2014) investigated the role of TEs through physics problem-solving activities. Results showed that there are three resources used by students during TEs processes: observed/experienced fact, intuitive principles, and scientific theory. Another interesting result showed that in some cases, the participants conducted more than one TE while other participants could not perform a TE. This indicates that doing TEs depends on the ability of individual participants. Ince et al. (2016) investigated the effect of TEs on students' logical problem-solving skills. Results showed that TEs helped students in understanding the law of physics and in modifying their ideas related to the physics concepts. Myhrehagen & Bungum (2016) reported the results from the project ReleQuant on how Norwegian physics students in upper secondary schools interpret the TEs. They claimed that the lack of knowledge about the purpose and the historical context of the TEs limited students' understanding of the physics content.

Asikainen and Hirvonen (2014a) explored physics teachers' understandings of a double-slit TE. Their study involved 9 pre-service teachers and 18 in-service teachers with different experiences in teaching modern physics in high school. The results showed that the experienced teachers who had been teaching modern physics at the upper secondary level were more capable of performing double-slit TE than pre-service or inexperienced teachers. They also said that most participants in their study failed to perform TEs because of misunderstandings and gaps that occurred with previous knowledge:

> *In our study, only a small minority of the participants (4 out of 27) were able to describe the basic assumptions of the thought experiment correctly. The remainder revealed misunderstandings and gaps in their previous knowledge, which probably hindered their thought experimenting* (p. 1828).

2.3.3. Studies on the use of thought experiments in science textbooks

Trying to understand how TEs are presented in the general physics textbooks, Gilbert and Reiner (2000) studied and focused on three popular physics textbooks. One of them, *Understanding Physics for Advanced Level* written by Jim Breithaupt, was intended for 16-18 year-olds in high schools in England and Wales. The other two, *Physics (2nd edition)* written by Hans

C. Ohanian and *Conceptual Physics (7th edition)* written by Paul G. Hewitt, are widely used in first-year university courses in the USA and elsewhere. The results showed that the popular physics textbooks often miss the opportunity to introduce TEs even though there are various reasonable opportunities to do so. Moreover, most of the TEs in those textbooks often transform into thought simulations. Gilbert & Reiner (2000) argued that the writers of these popular physics textbooks might not understand the actual potential of using TEs. In fact, TEs can be a fruitful approach to enhance students' cognitive engagement in the learning process.

Velentzas et al. (2007) specifically analyzed TEs on the theory of relativity and quantum mechanics in both physics textbooks and popular science books in Greece. There were 10 textbooks and 15 popular science books in their study. The physics textbooks that they analyzed were mostly from university books and only one from high school. The popular science books were addressed to the general public. The results showed that the authors of both physics textbooks and popular science books considered TEs as an essential tool in the presentation of the theory of relativity and quantum mechanics. The authors of both types of books also adjusted the language and the mathematical formalism of the TEs to be simpler.

Recently, Bancong and Song (2018) evaluated the TEs presented in Indonesian physics textbooks. They analyzed 30 high school physics textbooks from Grades 10 to 12 that are widely used by both teachers and students in Indonesia. Physics textbooks published by the Ministry of

Education were the main focus (BSE physics textbooks). However, the analysis also was carried out on several physics textbooks, which became available through government approval (Non-BSE physics textbooks). The results showed that physics textbooks published from 2009 to 2017 in Indonesia generally lack TEs, even though some popular TEs**,** such as Galileo's free-falling body, Galileo's relativity, Einstein's train, and Einstein's twin paradox were being presented at satisfactory levels. The dissatisfaction of TEs in physics textbooks may be because many authors of the Indonesian physics textbooks ignored or inadequately presented TEs. Some of TEs were introduced in the form of problem-solving, essays, and even project assignments resulting in the loss of background and experimental results

2.3.4. Studies on the use of thought experiments in science teaching

In the last twenty years, TEs have been used in the teaching of science in different ways, and some of the possibilities have been reported. In the following, I describe some of the implementations of TEs in teaching science: using computer simulations (Reiner, 1998), through historical approach (Velentzas and Halkia, 2011; 2013), and through written assignments (Lattery, 2001; Klassen, 2006; Asikainen & Hirvonen, 2014a).

Reiner (1998) analyzed the TEs that were designed and developed by 11th-grade students. A total of 12 students were given the task of designing periscopes with a wide visual field using a computer-based simulator. To solve the given task, the students worked in groups of three people. The results showed that TEs, when conducted in the context of computer-based simulation, are powerful tools for teaching science. She then argued that TEs are more easily constructed in a collaborative manner where the number of students' contributions can lead to a complete TE. Reiner (1998) then suggested to physics teachers for using computer simulations when teaching TEs because it allows students to see physical processes and construct a deep understanding of physics concepts.

Velentzas and Halkia (2011) reported positive results when they implemented Heisenberg’s historical TE of the microscope as a tool in teaching the “uncertainty principle” to high school students. In their study, 40 student participants were divided into 11 groups. The results showed that the use of TEs could help students to explain the principles of uncertainty concepts better and to be better able to obtain the uncertainty principle formula. Velentzas and Halkia (2013) also reported positive results when they implemented Einstein’s historical TE of the elevator and TE of the train for teaching the basics of relativity. They argued that the use of the history of TEs as a tool in teaching modern physics could help develop students’ syllogistic abilities and help them to imagine situations outside of everyday experience.

Lattery (2001) used a TE about Galileo’s law of chords as a basis for his students’ project in a physics course at the university. In their project assignments, students wrote a paper, prepared a poster, and made an oral presentation for their peers. Lattery (2001) argued that the use of a TE as a project assignment offered a positive learning experience for the students. Klassen (2006) also believed that by designing their own TEs, students are mentally involved in constructing concepts, and in turn, they will understand scientific concepts more deeply. He argued that TEs contain both arguments and narrative elements, and therefore, it is effective for teaching TEs in stories format. To test his assumptions, he wrote a story about Benjamin Franklin's life and experiments, and invited students to turn Franklin's experiments into TEs. Klassen (2006) then advised physics teachers to use a narrative technique and rewrite the TE in a story format when teaching TEs. The minimal story structure showed in Figure 2.4.

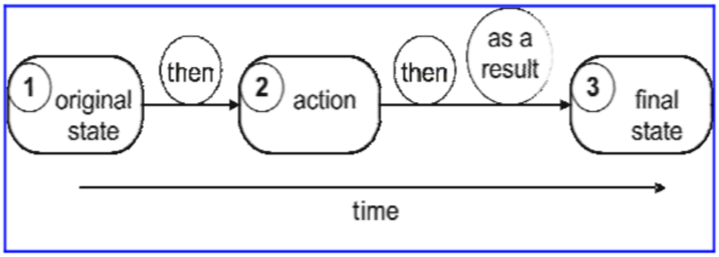


Figure 2.4. Minimal story sequence for teaching TEs (Klassen, 2006, p. 88)

Asikainen and Hirvonen (2014a) also using written assignments when explored physics teachers' understandings of a double-slit TE. In their study, the data collection was carried out using a paper-and-pencil test and interviews. The participants were asked to draw intensity distributions on the screen behind the slits using classical particles, light, and electrons. It was supposed that to form the intensity distributions, the participant would need to carry out the TE. The results showed that most participants in their study failed to perform TEs because there were misunderstandings and gaps with their previous knowledge.

In sum, a number of studies have been carried out in a variety of areas, such as in science (e.g., Brown, 1991; Norton, 1991; Galili, 2009), in science education (e.g., Reiner, 1998; Velentzas & Halkia, 2013; Asikainen & Hirvonen, 2014a), in science textbooks (e.g., Reiner & Gilbert, 2000; Velentzas et al., 2007; Bancong & Song, 2018) that have contributed to the TEs literature. However, recommendations to physics teachers on how to apply TEs in science teaching, and how to help students find effective thinking procedures in running TEs are still rare. Asikainen and Hirvonen (2014b) argued that so far, the researchers participating in this study are still small, and therefore recommendations on how to implement the TEs in teaching science are very necessary. In addition, there has been little research concerning the factors that influence students in constructing TEs, and also previous studies more focused on investigating the process of TE in students' individual activities rather than in groups.

Chapter 3. Methodology

3.1. Context

The main purpose of this study is to get as much information as possible about the processes and factors of collaborative TEs. 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, I 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 & Özdemir, 2014; Tortop, 2016) have adapted physics problems from Epstein's 1995 book entitled *Thinking Physics Is Gedanken Physics* when investigating the processes of students' TEs while solving physics problems. The term "Gedanken experiments" used in *Thinking Physics* as a synonym for TEs. 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, I 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 they would work according to the expected criteria. 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

Considering the geographical location of Indonesia, the participants in this study were selected on the island of Sulawesi. Sulawesi is considered as representative of Indonesian regarding the location in the middle of Indonesia, as shown in Figure 3.1. Sulawesi also has a diverse range of socio-economic and ethnic backgrounds. The population of the 2010 census in Sulawesi was 17,371,782 and was recorded as the island with the second largest population in Indonesia. The latest official estimate of the population in Sulawesi (for July 2019) is 19,573,800 (Badan Pusat Statistik [BPS], 2019). In addition, there are 114 native languages spoken in Sulawesi, all of which belong to the Malayo-Polynesian subgroup of the Austronesian language family (Lewis, 2009). Based on the census data in 2010, Sulawesi was noted to have a high linguistic diversity when compared to the most populous island of Java in Indonesia (BPS, 2019). The largest city on the island of Sulawesi is Makassar, which is located in the province of South Sulawesi.

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, South Sulawesi province, Indonesia. There were six master's students and six undergraduate students. In order to capture the variation of the collaborative TEs processes in-depth and 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. Detailed information about the participants is given in the following section.

Figure 3.1. The geographical location of research in Indonesia

3.2.1. Master's student group

The aim of gathering data from this group was to detect the role of TEs for experts. The criteria for selecting participants were (1) being a graduate student majoring in physics or physics education and (2) receiving their undergraduate education from a teacher-training university. Initially, Ph.D. students were to be chosen as participants in this group, but due to the difficulty of getting Ph.D. students who wanted to be participants voluntarily, then master's students were selected.

In this study, I chose a physics problem related to the fundamental physics laws on classical mechanics designed for high school students and 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 physics qualification exam was also set as a criterion because it provides further evidence of the competence of master's students on the basic concepts of physics higher than undergraduate students. Detailed information about participants in this group is presented in Table 3.1.

Table 3.1

Overview of participants in the master's student group

Code	Name	Gender	Age	School Type		Grade
				Undergraduate	Graduate	
H1	Nunu	Female	28	Unismuh	Unhas	Master's student
H2	Anis	Female	24	Unismuh	Unhas	Master's student
H3	Evi	Female	24	Unismuh	UNM	Master's student
H4	Fifi	Female	23	Unismuh	UNM	Master's student

'H' indicates master's student participants

3.2.2. Mixed student group

This group is a combination of master's students and undergraduate students. I expected that master's students have a deeper understanding of physical concepts than undergraduate students. Therefore, this group was set to observe the interaction that might occur between the master's student participants and undergraduate student participants in constructing collaborative TEs. Detailed information about mixed student participants is presented in Table 3.2

Table 3.2

Overview of participants in the mixed student group

Code	Name	Gender	Age	School Type		Grade
				Undergraduate	Graduate	
M1	Yusuf	Male	24	Unismuh	UNM	Master’s student
M2	Ahmad	Male	23	Unismuh	UNM	Master’s student
M3	Selvi	Female	21	Unismuh	-	Seventh semester
M4	Dewi	Female	20	Unismuh	-	Seventh semester

‘M’ indicates mixed student participants

3.2.3. Undergraduate student group

As mentioned earlier, the physics qualification exam was a criterion for selecting participants and, therefore, I assumed that master's students have a deeper understanding of physical concepts rather than undergraduate students. However, this context does not mean that undergraduate students have a poor understanding of physics or low cumulative GPAs. Rather, this group consists of undergraduate students who have not yet taken or passed the exam qualifications for graduation. 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. Detailed information about undergraduate student participants is presented in Table 3.3.

Table 3.3

Overview of participants in the undergraduate student group

Code	Name	Gender	Age	School Type		Grade
				Undergraduate	Graduate	
L1	Imma	Female	21	Unismuh	-	Seventh semester
L2	Rini	Female	21	Unismuh	-	Seventh semester
L3	Indah	Female	21	Unismuh	-	Seventh semester
L4	Adi	Male	21	Unismuh	-	Seventh semester

‘L’ indicates undergraduate student participants

3.3. Ethics

As this study involved human participants, the Institutional Review Board (IRB) of Seoul National University monitored all procedures, including recruitment of participants, consent forms for the participant, data collection, and analysis. This study received IRB approval (No. 1811/003-015). I orally explained all the possible ethical issues to the participants, and all the required documentation was provided to participants before commencing this study. Following guidelines for conducting an ethical study, I used codes for all participants in the data analysis and discussions.

3.4. Data collection

For the data collection, group observation and field notes were the primary methods for collecting the data. Some related literature has argued that TEs are cognitive tools for solving problem not only for the experts but also for students (Reiner, 1998; Stephens & Clement, 2006; Kösem & Ö zdemir, 2014). Therefore, small-group physics problem-solving activities were used to observe the processes and the factors that influence students in constructing collaborative TEs. The 12 participants were divided into three small groups. Audio and video of the three group activities were recorded as the source of data. The group observation was conducted in the physics meeting room and physics lab at the Unismuh University in Indonesia.

In addition, in order to ensure the validity of data, I also collected notes that were written and drawn freely by the students while solving the problems and observation notes of the researcher as the sources of data. The observation notes by the researcher included notes about the stage of collaborative TEs that was observed while students were solving physics problems. The observation notes by the researcher and students' notes were used to confirm the processes of TEs in the transcripts of the audio and video recordings. Thus, in this study, the data collected were audio and video recordings, students' notes, and observation notes by the researcher. Figure 3.2 shows a diagram that illustrates the process of data collection.

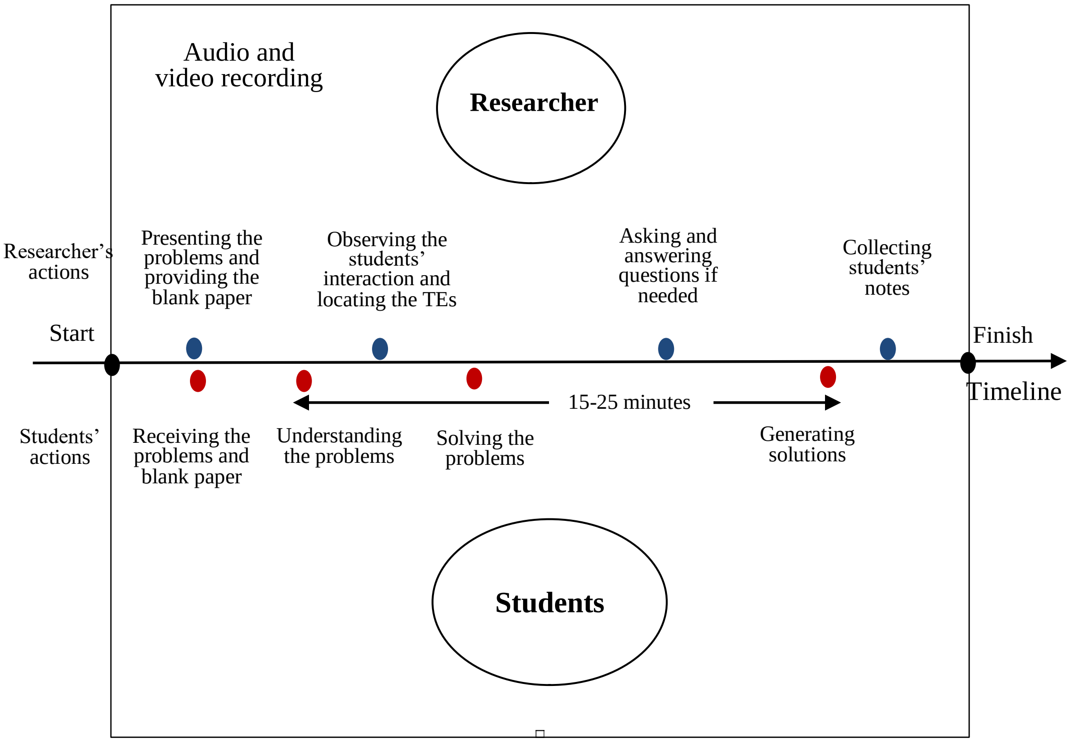


Figure 3.2. The process of data collection

First, I 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, I then carefully observed the activities and interactions that took place between students in each group, focusing particularly on identifying the processes and the factors that influenced students during constructing collaborative TEs. For each group, observation and recording were carried out five times, once for each of the five physics problems available. Observation and recording for physics problems 1, 2 and 3 were carried out on 15 January 2019, while for physics problems 4 and 5 on 1 February 2019. Figure 3.3 shows some notes written and drawn freely by the students while solving the problems.

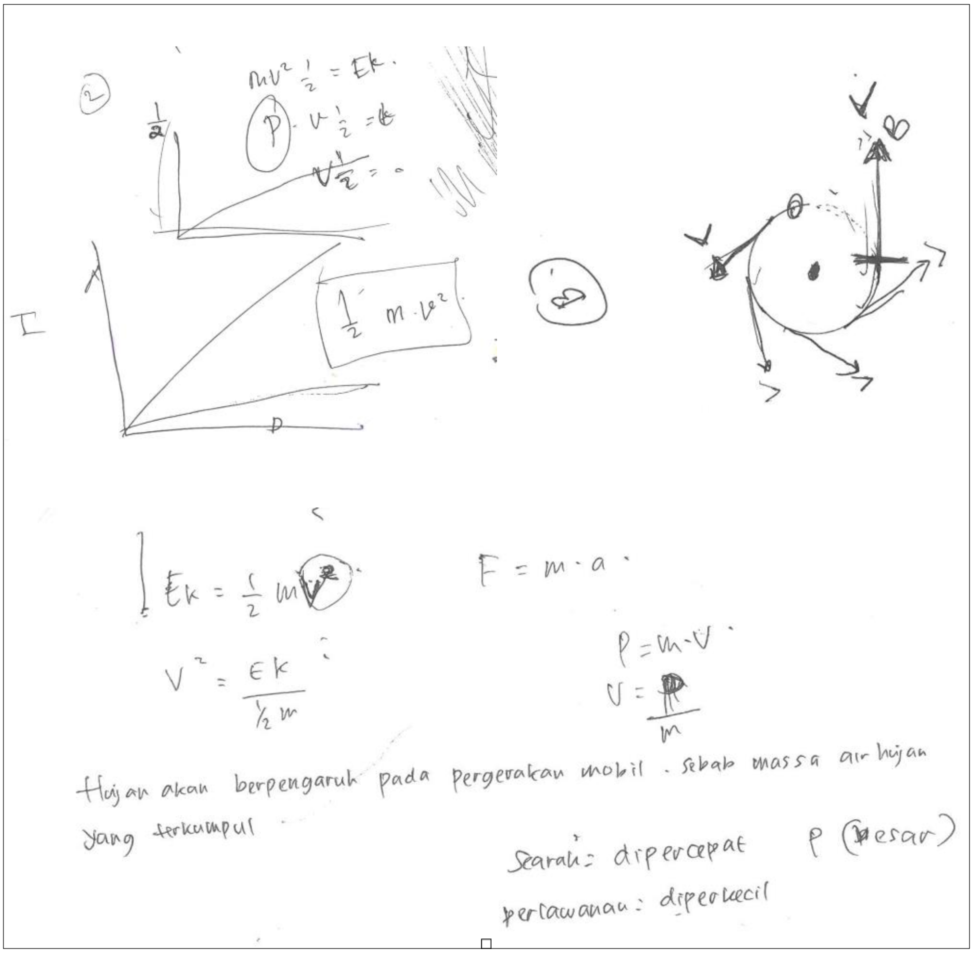


Figure 3.3. Examples of students’ notes

In this study, the researcher served as a participant-observer. Merriam and Tisdell (2016) argued that “using this method (observe as a participant), the researcher may have access to many people and a wide range of information, but the level of the information revealed is controlled by the group members being investigated” (p. 145). Adler and Adler (1998) refer to this method as a “peripheral membership role,” which is different from having an active membership role. Here the role of the researcher is to “observe and interact closely enough with members to establish an insider’s identity without participating in those activities constituting the core of group membership” (p. 85). By becoming a member of the group being studied, it is possible to gain access and obtain reliable information rather than just being a complete observer (Merriam & Tisdell, 2016).

Although the participation of the researcher can have effects, I tried to minimize intervention in order to minimize the encouragement of interactive discourse. I only engage in dialogue at particular instants, for example, asking them whether the problem is clear or unclear, responding to participant questions related to the problem given, and asking them about the conclusions they have drawn after solving the problem given, as shown in the example below. In addition, in order to understand students' thinking, I also used questions only at particular instants during physics problem-solving activities, asking them what they thought about something or why they thought something? As shown in the example below. Figure 3.4 shows the procedure for processing data in this study.

R	Well. Today I am collecting the research data on thought experiments, as I stated at a previous meeting. I will focus on investigating the processes and factors of collaborative thought experimentation when you are solving the problems. . . . Ok. Let's start from the first question [the researcher then reads the question]. Now, what do you think?
H4	Is the path a straight line?
H1	Is it pushed like this [while pushing the cellphone]?
R	Yes, the path is a straight line. Yes, it is pushed.
H1	If so [while thinking].
	[. . .]
H2	Yes, the trolley will be slower and will stop.
H1	That is right.
R	So, does the rainwater affect to the motion of the trolley?
H3	Yes, It has an effect on the trolley's speed.
R	So, the speed will change?
H1	Yes, by the time the speed became slower, and finally, it stops.
H2	The speed will change.
H4	Yes, the speed gets smaller and smaller because of the mass increases.
R	What mass is increasing?
H3	The car, eh, trolley.
H2	There is additional mass, the mass of rainwater.
H1	The total mass [the mass of trolley + rainwater collected]. Because the raindrops hit the trolley and were accumulated in the trolley [while pointing the trolley image on the given question].

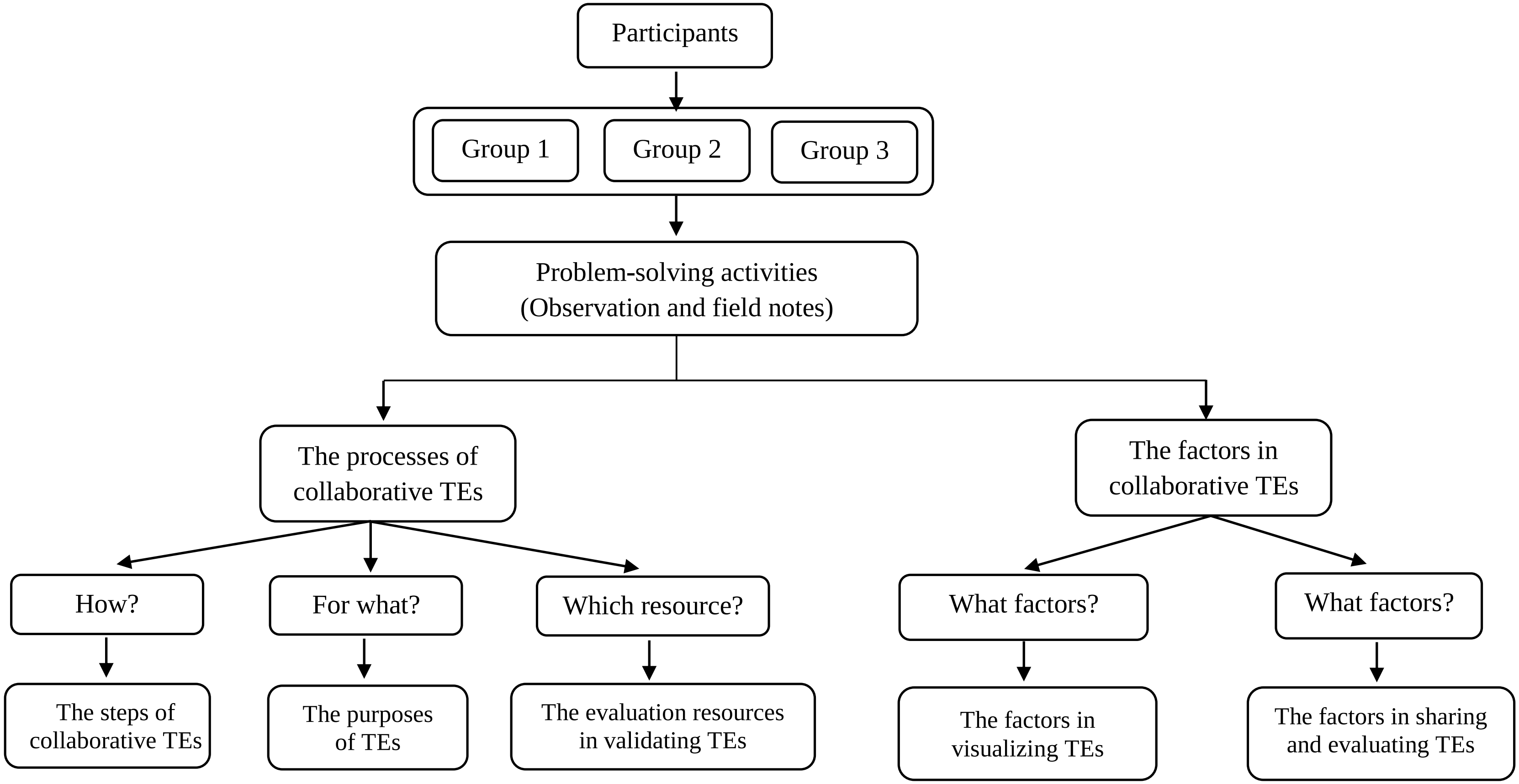


Figure 3.4. The data processing procedure

3.5. Data analysis

3.5.1. 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 TEs 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 I identified discourses that appeared to be a TE, I watched and listened to the video carefully several times. Third, the selected TEs episodes in the second step were cross-checked with observation notes and students' notes. The processes of TEs that have been written in the observation notes and the notes written and drawn freely by the students were used to confirm the TEs episodes in the transcripts of the audio and video recordings. In addition, I also checked carefully whether there were any missed TEs episodes from the second step by watching and listening to the video repeatedly.

Based on the literature review, I defined TE as a structured activity of visualizing an imaginary world in which experiments will be designed and generated in the head of an individual, and then the results of experiments are described. In this study, therefore, these three activities – visualizing the imaginary world, performing experiments, and describing the results – were used as an indicator of the TE. In order to identify the visualization of TE, the framework for "imagery-related observation indicators" provided by Clement et al. (2007) and Clement (2009) was used in this study. These indicators are presented in Table 3.4.

Table 3.4

List of imagery-related observation indicators

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

The following transcript excerpt is an example of how TE processes carried out by a student were detected.

R	OK. Let's start from the first question . . . Now, imagine the possible effect of the accumulating rainwater on the trolley's speed as shown in the figure. What do you think? [. . .]	1
H1	So, I think that there is no external force and no friction.	2
H4	Aaa, external force.	3
H2	What is the effect?	4
H1	It will move continuously [It will never stop moving].	5
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 [while pointing the trolley image on the given problem]. [2]I push this trolley forward to roll on a straight road and the rain falls down vertically and hits it, [3]so the mass of this trolley will increase, so there is an external force, which means that the trolley will automatically stop at a	6

	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

In the transcript excerpt above, the words “suppose that” (Line 6) were coded as an imagery reports indicator. This indicated that H2 started to visualize a TE. Besides using the imagery reports (suppose that), H2 also used hand motions indicators. 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. First, H2 imagined pushing the trolley forward to roll on a straight road. As the trolley rolls, rain falls down vertically and hits the trolley. H2 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). H2 then described the results of her TE that the mass of the trolley will increase and will stop at a certain time.

In this example, as can be seen, because H2 did structured activities that begin from visualizing imaginary worlds, performing the experiment, and then describing the results, H2 was considered to be doing TE. The following transcript excerpt is another example of TE and not TE, which I took from the Group 1 transcript excerpt when responding to Problem 2.

H2	Ooo, that means the scientist is in the box, and the box is moving.	1
H1	Yeah, but is the box moving? So, we could be turned around or knocked if we are walking.	2
H2	[1]Assume that the box is like this room [indicating the physics laboratory room at the Unismuh University as a place for collecting data] that is moving and we are inside. We are now moving but we are not aware if we are moving because we cannot look outside.	3
	[. . .]	
H4	Oo, yes, remember [2]when we were traveling by train and dropped something. When the track was straight and the train moved constantly, [3]it will fall down. won't it? It is similar to that.	4
	[. . .]	
H2	Yes, right [H2 agrees with H4].	5
H4	Yeah, what do you think, H3?	6
H3	For me, this [pointing at the spinning box].	7
H4	Ahh, [1]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. [2]If we drop a coin into a glass, [3]the coin will surely go into the glass, right? [1]If, for instance, we are on spinning, like a propeller, and [2]we try to drop a coin [into a glass], then [3]it will be more difficult to drop the coin right into the glass, right?	8
H3	Yes, the logic is like that.	9
H4	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.	10

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

As can be seen, during Group 1 solving Problem 2, H4 did a TE (Line 8). First, H4 visualized herself in a super-fast train that moves straight at a constant speed. She then performed an experiment in her mind by dropping a coin into the glass. By using her mind's eye, H4 saw that the coin she had dropped fell right inside the glass (as the result of the experiment). She then imagined for a different situation that when she was above the propeller (something moving around) and was dropping a coin. She then described the result of the experiment by saying that the coin she dropped was very difficult to get into the glass. Based on this example, it is clearly seen that H4 conducts the structured activities that begin from visualizing imaginary worlds, then conducting experiments, and describing the results. I refer to the activities carried out by H4 as the TEs.

However, there are some activities carried out by students while solving the problems that were categorized as not TEs. For example, as seen in the transcript excerpt above, H2 visualized an imaginary world (Line 3) by assuming that the box in which the scientist was located is like the physics laboratory room at the Unismuh University, where H2 and other students are in it. The box is moving, but they cannot feel if they are moving because they cannot see outside. In this activity, H2 was visualizing the imaginary world, but it was not followed by experiment activity. Therefore, the activity carried out by H2 is not a TE.

Furthermore, in line 4, H4 said that *when we were traveling by train that was moving at a constant speed on a straight road while dropping something, we will see that something dropped will fall down*. Even though H4 performed an experiment and described the results in this activity, this activity is not a TE because there is no activity of visualizing the imaginary world. The activity carried out by H4 was just a reminder of the activities that had been carried out in the past. Therefore, in this study, if students only did one or two activities that have been mentioned as TEs indicators, then it was categorized as not TEs.

3.5.2. Identifying the collaborative TEs

After locating the TEs, I then identified the collaborative TEs. As I said earlier that collaborative TE in this study is defined as activities where one or more individuals visualize imaginary worlds in which experiments will be designed and generated in their own mind laboratories and then shared them with group members to be run and evaluated as collective efforts to reach conclusions. Collaborative TE begins with one student generating experiments in mind then sharing them with the group members. The members of the group then run and evaluate the experiment, as suggested by its producer. In the processes of sharing and evaluating TEs, all students are engaged in discussion by asking and answering questions, supporting and clarifying arguments, providing equations, validating the results of TEs, and so on. In the evaluation TEs, both the process and the results will be checked. This process was done continuously until students reached a mutual understanding and found strong evidence to support their TEs. Therefore, a collaborative TE is the result of the collective thoughts of all group members in building a TE.

The following transcript excerpt is an example of how collaborative TE processes performed by the students were detected.

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 [while pointing the trolley image on the given problem]. [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 [3]the trolley will automatically stop at a certain time on the condition that the rainwater is being collected in the trolley.	1
	[. . .]	
H4	Ooo, it will stop, why?	2
H2	Yes . . . [4]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.	3
H1	Yes, I agree [H1 agrees with H2] . . .	4
	[. . .]	
H2	$Ek = 1/2mv^2$	5
H1	Because of the mass increase.	6
H3	Yes, the mass increases.	7
	[. . .]	
H1	[4]The speed is decreasing, right? Because initially the mass is small and the speed is higher, then the mass increases, so that means . . .	8
H3	So, [5]it has an effect.	9
H1	[5]Yes, it has an effect, the trolley will stop.	10
H4	[5]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.	11

1 = visualize imaginary world; 2 = perform experiment; 3 = describe the results
4 = evaluate experiment; 5 = draw conclusions

As can be seen, after H2 generated a TE (Line 1), she 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 polish and validate their TE. 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. 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 3), and H1 used conceptual-logical inference (Line 8). This process was done continuously until they reached a conclusion as a collective agreement (Lines 9-11). In short, because all of the students are actively involved in running, polishing, and validating the TE until they draw conclusions as a collective agreement, I referred to this TE as a collaborative TE.

For the reliability of the analysis in this study, member checking was done (Miles & Huberman, 1994; Miles et al., 2014). After the first period of data collection was completed, I and two other science education experts recursively categorized the TEs processes of 9 physics problem-solving activities. As mentioned earlier, the first period of data collection was carried out on January 15, 2019, with observation and recording 3 times for each group. As a first step, I identified and coded the TEs that appears in the transcript of audio and video recordings from each group during physics problem-solving activities. As a second step, I invited two science education researchers to separately identify the TEs in the transcripts of audio and video recordings. Before checking, I first explained to them the meaning of TEs, the examples of scientists' TEs, and the indicators of TEs used in this study. During the discussion, the discourses were further analyzed by watching the video together with transcripts of audio and video recordings, students' notes, and observation notes by the researcher for better reliability. We discussed the discourse until reaching an agreement of around 95% in classifying the steps of collaborative TEs. I also provided opportunities for students to check whether the interpretation was distorted or not in order to improve the reliability of data analysis. Furthermore, I analyzed independently for the rest of the data (6 physics problem-solving activities) that was obtained in the second period of data collection on February 1, 2019.

3.5.3. Coding for collaborative TEs steps

Coding is “deep reflection about and, thus, deep analysis and interpretation of the data’s meanings” (Miles et al., 2014, p. 79). Saldaña (2015), in his book entitled *The Coding Manual for Qualitative Researchers*, divides coding into two main stages: first cycle and second cycle. He argued that first cycle coding is a way to initially summarize segments of data while the second cycle coding is a way of grouping those data summaries into categories or themes.

In this study, the steps of collaborative TEs were analyzed using deductive coding. Miles et al. (2014) argued that deductive coding is a method that develops the "preliminary list" of codes before fieldwork, which was derived from the conceptual framework or key variables that the researcher brings to the study. According to Reiner (1998), there are five stages in conducting TEs: (a) construction of an imaginary world, (b) hypotheses, (c) experiments, (d) results, and (e) conclusions. Brown (2006) also argued that

TEs are carried out in a laboratory of the mind and have at least three steps: (a) visualize a situation, (b) carry out an experiment, and (c) describe the results. In this study, therefore, the steps of conducting TEs proposed by both Reiner (1998) and Brown (2006) were used as the conceptual framework in order to code the steps of collaborative TEs.

However, when analyzing more data, I found that there was a category of the TEs steps proposed by Reiner (1998) that was not solid. In addition, I also discovered a new category that I considered to be part of the TEs steps. As I moved further along in data analysis, I found a trend in the pattern of TEs steps that was slightly different from the literature review. As I get toward the end of my study, where nothing new had been discovered, I then focused on finding more evidence to support the last set of categories I found. As a result, five categories were grouped deductively as the steps of collaborative TEs: visualize imaginary worlds, performance experiments, describe the results, share and evaluate experiments, and draw conclusions. The following Table 3.5 is an example of how I coded the steps of collaborative TEs.

Table 3.5

Example coding for collaborative TEs steps

	Raw data from transcriptions	Codes	Categories
	[The part of the transcription of Group 1 on Problem1]		
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 [while [2]pointing the trolley image on the given problem]. [3]I push this trolley forward to roll on a straight road and the rain falls down vertically and hits it, so [4]the mass of this trolley will increase, so there is an external force, [5]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]visualization (imagery reports) [2]visualizatiom (hand motion) [3]experiment activity [4]experiment result	[1] visualizing imaginary worlds [2] performing experiments [3] describing the results [4] sharing and evaluating experiments [5] drawing conclusions
H4	Ooo, it will stop, why?	[5]experiment result	
H2	Yes, [6]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.	[6]evaluation	
H1	Yes, I agree [H1 agrees with H2] . . . [. . .]		
H2	$Ek = 1/2mv^2$		
H1	Because of the mass increase.		
H3	Yes, the mass increases. [. . .]		
H1	[7]The speed is decreasing, right? Because initially the mass is small and the speed is higher, then the mass increases, so that means . . .	[7]evaluation	
H3	So, [8]it has an effect.	[8]conclusion	
H1	[9]Yes, it has an effect, the trolley will stop.	[9]conclusion	
H4	[10]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.	[10]conclusion	

3.5.2. Coding for purposes and evaluation resources of TEs

After identifying, discussing, and determining the steps of collaborative TEs, the purposes and evaluation resources of TEs were then analyzed. Some related literature argued that scientists used TEs to confirm or to disconfirm some theories, postulates, or assumptions (Reiner & Gilbert, 2000; Gendler, 2004). TEs are logical devices in our mind for developing, clarifying, and critiquing the theoretical conceptions (Galili, 2009). Similarly, Stephens and Clement (2012) argued that TEs are activities that can be used to evaluate scientific concepts, models, and theories and even to predict aspects of a concrete system. Therefore, in this study, the purposes of students doing TEs were analyzed independently while considering the purposes of scientists' TEs, as explained by the researchers above.

First, I located the TEs that were conducted by the students in the transcripts of problem-solving activities. After that, I focused on identifying the purposes of students in doing TEs. The procedure to analyze the data started with first cycle coding to summarize segments of data in the initial transcriptions, as suggested by Saldaña (2015). I then grouped the codes in the first cycle coding that seemed to have the same categories. As I moved further in the analysis and found nothing new, I then focused on finding more evidence to support the last set of categories I found. As a result, three categories were grouped deductively as the students' purposes in conducting TEs: prediction, verification, and explanation. Table 3.6 shows how I analyzed the purposes of students doing TEs. The sentences in italics in the table indicate a TE.

The analysis of the evaluation resources used by students in validating the results of their TEs also used deductive coding. 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 TEs 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 evaluate their TEs was analyzed independently while considering the evaluation resources presented by researchers (Fournier, 1995; Schwandt, 1997; Reiner & Gilbert, 2000; Kösem & Özdemir, 2014). As a result, four core categories were grouped deductively as the sources of TEs evaluation: conceptual understanding, past-daily experience, logical reasoning, and conceptual-logical inference. Table 3.7 shows how I analyzed the evaluation resources used by students in validating their TEs. The sentences in italics in the table indicate a TE.

This analysis was also shared and discussed with two science education researchers who were invited independently. I invited them to separately identify the purposes and evaluation resources of TEs in the transcript of audio and video recordings that were obtained in the first period of data collection (9 physics problem-solving activities). We discussed and classified them until around 92% agreement level was reached. For the rest of the data (6 physics problem-solving activities in the second period of data collection), I analyzed them independently. I also provided opportunities for students to check whether the interpretation was distorted or not in order to improve the reliability of data analysis. In addition, the results of this study were presented at a conference, and the feedback received from academics was positive. Shenton (2004) argued that peer scrutiny of research, such as discussions with colleagues or presentations at a conference, is one way to increase the credibility of qualitative research.

Tabel 3.6

Example coding for purposes of TEs

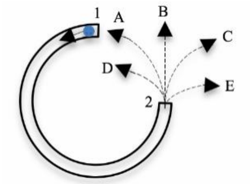
Raw data from transcriptions		Codes	Categories
[The part of the transcription of Group 2 on Problem 3]			
R	. . . Suppose that there is a semicircular channel that has been securely attached, in a horizontal plane. A ball enters the channel at 1 and exits at 2. So, which of the path representations would most nearly correspond to the path of the ball after exiting at point 2? 		to provide an explanation for hypotheses or assumptions
M1	[1]I think B.	[1]hypothesis	
M4	Yes, B.		
R	Why?		
M1	[2]Because of the vector of velocity . . . Based on experience when learning physics, [3]*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.*	[2]the reason why [3]TE	

Table 3.7

Example coding for evaluation resources of TEs

Raw data from transcriptions		Codes	Categories
[The part of the transcription of Group 1 on Problem 1]			
H2	*. . . suppose that I push this trolley while it is raining [while pointing the trolley image on the given problem]. 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, this means that the trolley will automatically stop at a certain time on the condition that the rainwater is being collected in the trolley*.		Conceptual understanding
	[. . .]		
H4	Ooo, it will stop, why?		
H2	Yes . . . Because [1]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.	[1]Newton's first law	
[The part of the transcription of Group 2 on Problem 3]			
M1	Because of the vector of velocity . . . Based on experience when learning physics, *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*.		
	[. . .]		
M1	Yes, [2]the direction of the velocity is always like that. Its direction is always perpendicular to radial acceleration. [3]It can move in a circular motion because there is force given, centripetal force, but, [4]the vector of its velocity is always pointing in the direction of motion. Like this	[2]The concept of centripetal force [3,4]The concept of circular motion	

3.5.3. Coding for factors

The coding procedure for factors also followed the same procedure for the purposes and evaluation resources of TEs. In order to encode the factors that trigger the emergence of collaborative TEs when students interact with each other in their groups to solve problems, first of all, I located the process of visualization in the transcripts of problem-solving activities. After that, I focused on identifying the situation in which students started visualizing a TE. As a result, five core categories were grouped deductively as the factors for the emergence of the collaborative TEs: conflicting ideas, similar ideas, guidance and support from more experienced people, inspiration by bodily knowledge, and inspiration by imaginary visual knowledge. Table 3.8 shows how I analyzed the factors that trigger the emergence of collaborative TEs when students interact with each other in their groups to solve problems. The sentences in italics in the table indicate a TE.

Furthermore, in order to encode the factors that influence students in the process of sharing and evaluating TEs, I first located the evaluation moment in the transcripts of problem-solving activities. Every moment of evaluation of TEs that was identified as long as students constructing their TEs were analyzed. After that, I focused on identifying the factors that influence students in the process of sharing and evaluate their TEs before drawing conclusions. As a result, four core categories were grouped deductively as the influencing factors in the process of sharing and evaluating

TEs: validity concerns, understandings, logical arguments, and conflicting evidence. Table 3.9 shows how I analyzed the factors that influence students in the process of sharing and evaluating TEs. The sentences in italics in the table indicate a TE.

Table 3.8

Example coding for factors in visualizing TEs

Raw data from transcriptions		Codes	Categories
[The part of the transcription of Group 2 on Problem 5]			
R	Now, we are going to the last question. So, what do you think is the solution to this problem?.		Inspiration by bodily knowledge
	[. . .]		
M1	Ok. In my opinion, the car would move on the condition that the hanging magnet has a greater magnetic force so that it could move the car. … Try to [1]remember when we were kids and playing with magnets. *Imagine if we are playing with magnets. If the magnets, usually put on the table, if one of the magnets is pulled in this way [M1 demonstrates as if putting one magnet closer to another magnet] then the other magnet will be attracted*. That is the analogy, that's what I think.	[1]Physical experience	
[The part of the transcription of Group 2 on Problem 3]			
M1	I think B.		
M4	Yes, B.		
R	Why?		
M1	Because of the vector of velocity . . . [2]Based on experience when learning physics, *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.*	[2]Knowledge gained from learning physics	

Table 3.9

Example coding for factors in sharing and evaluating TEs

Raw data from transcriptions		Codes	Categories
[The part of the transcription of Group 3 on Problem 3]			
L3	No, it's not like that. *Imagine if we hold the water hose and the hose line is curved, then the water coming out of the end of the hose will not bend too [following the curve of the hose] but will squirt upwards*. Try to imagine!		Understandings
L2	Yes, this is the same as the children's toy that is blown. The path [of the ball] will remain straight up even though the medium is curved.		
	[. . .]		
R	What is the name of that kid's toy that you blow into?		
L2	We do not remember. It is like a pipe which is blown and at its end, there is a small basket containing a ball. When it is blown, the ball will fly up.		
L3	[1]<u>Yes, it will fly up</u> [L3 supports L2's answer]. I also forget the name of the toy. But the thing is, the ball's direction will not curve.	[1]Supporting each other	
L1	Ooo, yaa, [2]<u>I understand now</u>. I think we blow it from the front [L1 starts to understand L2 and L3].	[2]Understanding the evidence presented	
L3	No, the shape of the toy is like a U.		
L2	Yes, like this [while demonstrating using his hand], but I forget the name.		

Chapter 4. Processes of Collaborative Thought Experiments

This chapter aims at investigating the processes of collaborative TEs during physics problem-solving activities. Before exploring their processes, I first explain the meaning of collaborative TEs based on the results of this study. The following questions were used to guide my data analysis and discussion.

1. What is the meaning of collaborative TEs?
2. What are the steps of collaborative TEs?
3. What are the students' purposes in conducting TEs?
4. How do students validate the results of TEs?

What I found in this chapter is that while solving physics problems, students construct, share, and evaluate their TEs. This indicates that TEs can be designed and constructed in a collaborative context, even though the TEs are mostly individual in nature. I referred to collaborative TEs 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. In the process of constructing collaborative TEs, the students carried out five activities: visualize imaginary worlds, perform experiments, describe the results, share and evaluate experiments, and draw conclusions. I referred to these activities as the steps of collaborative TEs. The TEs steps obtained in this study are slightly different from the TEs steps proposed by Reiner (1998) and Brown (2006). I also found the purposes of students conducting TEs while solving physics problems: prediction, verification, and explanation. In addition, in the process of evaluating TEs, four evaluation resources were then identified: conceptual understanding, past-daily experience, logical reasoning, and conceptual-logical inference.

Based on these results, I would recommend that collaborative TEs be introduced to both current and future physics teachers as a useful tool for teaching physics at school for several reasons. First, because TEs can produce both correct and incorrect results in the development of a scientific theory (Reiner & 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 reliable conclusions. Second, with collaborative TEs, students who have difficulties will be helped by other students in constructing TEs. Third, collaborative TEs can improve social interactions and support diversity. In collaborative TEs, students must work together in a group with different backgrounds, experiences, cultures, and knowledge. When students spend time together to work, they will learn how to relate to each other. In addition, through collaborative TEs, students clarify each other's ideas, views, and opinions through discussion forums before making conclusions. Therefore, collaborative TEs might nurture students' critical thinking skills.

4.1. The meaning of collaborative TEs

4.1.1. TEs as a tool for problem-solving

Based on data analysis, while solving physics problems, all students performed a TE at least once. 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. As seen in Table 4.1, the number of TEs performed by students does not vary much between groups. The number of TEs performed by Group 1 (master's student group) is eight, while Group 2 (mixed-student group) and Group 3 (undergraduate student group) performed them seven and nine times, respectively.

Table 4.1

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

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 4.1 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 real experiments, 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.

The following is an example of TE that occurs while students were solving a problem. The transcript excerpt 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 Figure 4.1.

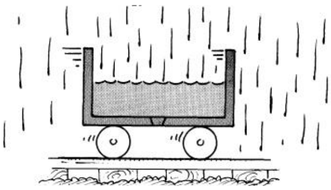


Figure 4.1. Illustration of Problem 1

R	OK. Let's start from the first question . . . Now, imagine the possible effect of the accumulating rainwater on the trolley’s speed as shown in the figure [Figure 4.1]. 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 [while pointing the trolley image on the given problem]. 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

As can be seen in the transcript above, before H2 started to do a TE, the students first actively involved themselves in understanding the problem. At the beginning of the 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. Besides using the imagery reports (suppose that), H2 also used hand motions indicators. As expected, she visualized pushing the trolley and showed that by putting one of her hands on the trolley image on the given problem. After the visualization step, H2 then performed an experiment in her mind. 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). H2 then described the results of her TE that the mass of the trolley will increase and will stop at a certain time. This activity shows that H2 did a TE by conducting the structured activities, starting from visualizing the imaginary world, performing an experiment, and then describing the results.

While solving Problem 1, Group 2 also carried out a TE, which was different from Group 1 TE, even though both TEs were used to prove that rainwater affected the trolley's speed. The following is a TE of Group 2, which I took from the Group 2 transcript excerpt when responding to Problem 1.

R . . . OK. We start from the first question [the researcher reads the problem]. In your opinion, is there any effect of rainwater on the trolley's speed? 1
[. . .]

M3 So, how is this? [while pointing to the problem given] 2

M2 In my opinion, the speed of the trolley will be affected. Try to remember when we were children; we often played with toy cars. Now, imagine if the 3 toy car is launched on an inclined plane. If I roll this trolley, consider a toy car [pointing to the trolley image on the given problem], then it will slide down, right? But the speed is low if, if compared to this car filled with, for example, stones. So, a toy car that filled with stones will slide faster than those that is not filled, right?

As can be seen, the words “imagine if” (Line 3) were coded as an indicator of visualization. This indicated that M2 began to visualize a TE. Besides using the imagery reports (imagine if), M2 also used hand motions indicators. As expected, he visualized launching a toy car on an inclined plane. After the visualization step, M2 then performed an experiment in his mind. First, he imagined launching a toy car on an inclined plane. As the toy car moved down, he then observed its motion and velocity in his mind's eye. M2 then filled the toy car with stones and relaunched it while observing its motion and velocity. After performing an experiment, M2 then described the results that the toy car that filled with stones would slide faster than those not filled with stones. Because H2 did the structured activities, which start from visualizing imaginary worlds, then performing experiments, and describing the results, H2 was considered to be doing a TE.

4.1.2. Collaborative TEs as social construction of knowledge

TEs are personal and tacit processes of experimentation that scientists perform within their own imagery in formulating new theories or refuting existing theories. For instance, Einstein designed, run, and evaluated his own TE of magnet and conductor in developing the theory of relativity (Einstein, 1905). However, by viewing learning as a social process, this study sought to examine whether TEs can be shared and communicated in group learning.

The data analysis shows that while solving physics problems, students not only created TEs but also shared and evaluated their TEs in group work. This indicates that TEs can be designed and constructed in a collaborative setting even though the TEs are individual activities by scientists. When students are given the opportunity to work together to solve meaningful problems, they perform TEs and share them with their group members to be polished and validated as a collective effort to achieve mutual understanding. The following is an example of collaborative TE that was taken from the transcript of a problem-solving session in Group 1 working on Problem 1 (see Figure 4.1).

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 [while pointing the trolley image on the given problem]. 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. [. . .]	1
H4	Ooo, it will stop, why?	2
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.	3
H1	Yes, I agree [H1 agrees with H2] . . .	4
H3	Stop? [H3 asks H2]	5
H2	Yeah. It will stop. Over time, surely.	6

[. . .]

H1 Wait, the question here is will the accumulated rain affect the motion of the trolley? 7

H2 It will affect it. If, for example, the mass increases, the speed decreases . . . That is the effect. 8

[. . .]

H4 Wait, if forces, not, kinetic energy [while writing a formula] 9

H2 $Ek = 1/2mv^2$ 10

H1 Because of the mass increase. 11

H3 Yes, the mass increases. 12

[. . .]

H1 The speed is decreasing, right? Because initially the mass is small and the speed is higher, then the mass increases, so that means . . . 13

H3 So, it has an effect. 14

H1 Yes, it has an effect, the trolley will stop. 15

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. 16

H2 Yes, the trolley will become slower and will stop. 17

H1 That is right. 18

As can be seen in the transcript above, while solving Problem 1, H2 conducted a TE (Line 1). The words "suppose that" were coded as an indicator of visualization, which indicated that H2 started to visualize a TE. After generated a TE, H2 then shared her TE to group members so that it could be run and evaluated together. 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 2-13). 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 3), and H1 used conceptual-logical inference (Line 13). This process was done continuously until they reached a conclusion as a collective agreement (Lines 14-18). In short, because all of the students are actively involved in running, polishing, and validating the TE until they draw conclusions as a collective agreement, I referred to this TE as a collaborative TE.

Figure 4.2 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 an experiment in mind and 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 sharing 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 a mutual understanding and found strong evidence to support their TE.

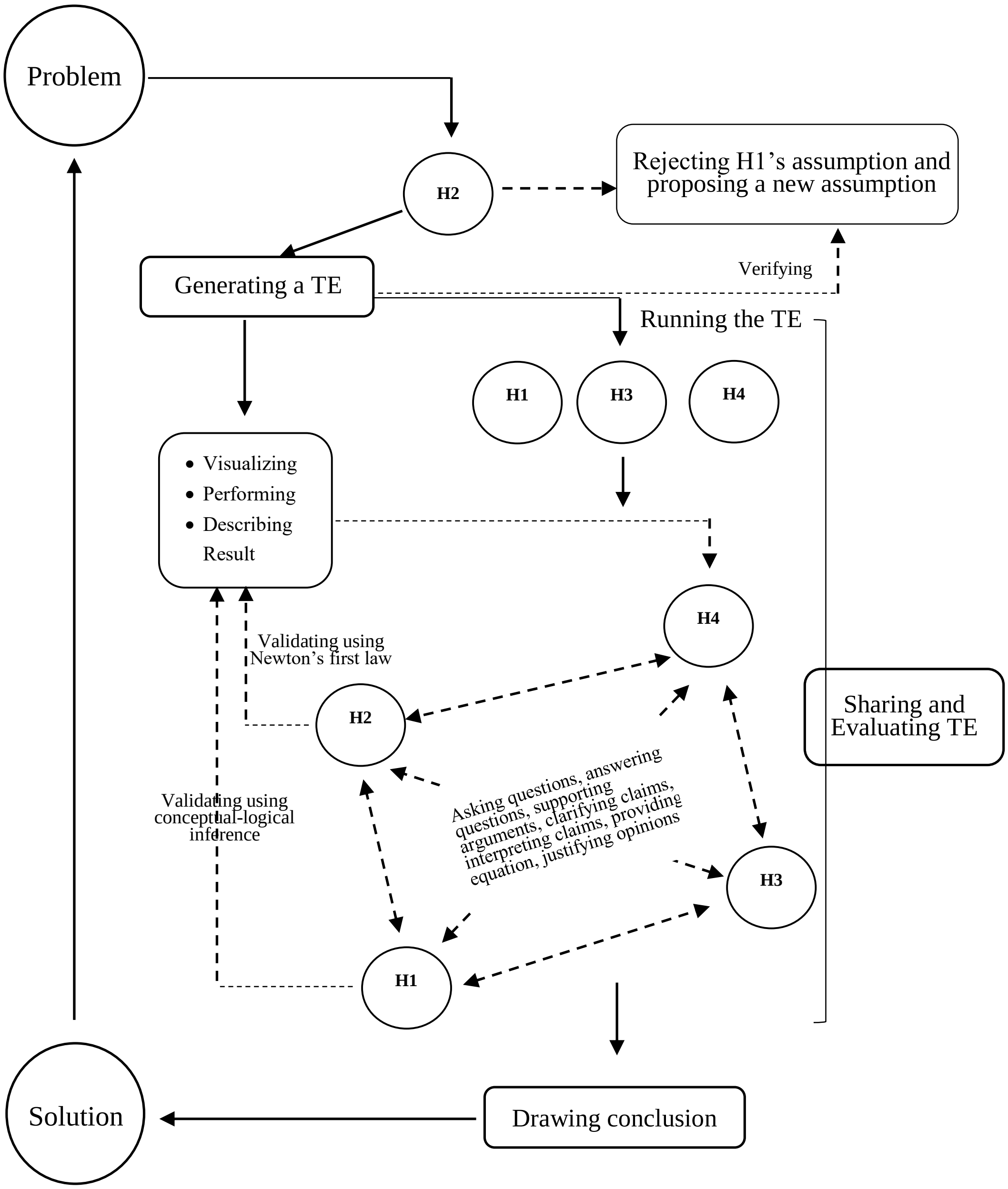


Figure 4.2. Illustration of collaborative TE by Group 1 on Problem 1

While solving physics problems, students also have the possibility of doing more than one TE, as shown in Table 4.1. This is because the TE that has been produced by a student is shared with group members to be run and evaluated together. In the evaluation TE, both the process and the results will be checked. In fact, when they failed to provide evidence of the resulting TE, they did not hesitate to redesign a new TE. Students do this evaluation activity continuously until they get strong evidence to support the truth of their TE. Another reason why students did more than one TE while solving physics problems is to support the TE that being evaluated so that they get strong evidence to support their argument. The transcript piece below is an example that shows three TEs that occur when students were solving the problem. The transcript was taken from the transcript of a problem-solving session in Group 1 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.

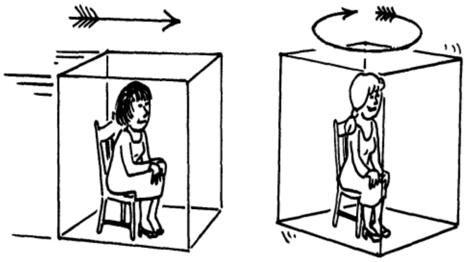


Figure 4.3. Illustration of Problem 2

R Now. We are moving to the second problem [the researcher then reads the question]. So, which scientist can feel that she is moving? Is the scientist in the box moving straight or the one in the spinning box? 1

[. . .]

H2 For example, like this case, I try to imagine [while holding her forehead], maybe this case is similar, when I am in a car that moves straight ahead then I drop a pen into a glass, so we will see that the pen will move downward. 2

H4 But how will someone outside the car see the situation? 3

H2 People who are outside the car will view this differently. 4

H1 But there is gravity there. This situation will be different if there is no gravity. Maybe what H4 means is an apparent motion. 5

H2 What does it mean? [apparent motion] 6

H1 When we are in the car, you can see the trees beside the road as if they are moving, in fact, it is us who are moving. It is called an apparent motion. 7

H2 So here [pointing at the question]: Which one feels that she is moving? 8

[. . .]

H1 Ok. Suppose that, if I were in the box that is moving straight ahead, then I drop a coin or a pen, and there is no gravity, then if I move forward, the pen I drop will be left behind. 9

H4 Yes, that will happen if there is no gravity. How if the gravity exists? The coins will go into the glass, right? 10

P [All participants are silent while thinking]. 11

H1 As long as the speed [of the box] is constant 12

H4 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. 13

H2 So, I think the scientist in the spinning box will feel if she is moving because if we drop the pen. 14

H3 Yes, the pen will fall randomly [it will not fall straight down]. 15

[. . .]

H4 Ahh, 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 16 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?

H3 Yes, the logic is like that. 17

H4 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. 18

H2 Yes, I think so. 19

R How about you, H1? 20

H1 Yeah, I agree with them (while smiling). 21

As seen in the transcript above, while solving Problem 2, Group 1 conducted 3 TEs (Lines 2, 9, and 16). The words “try to imagine” (Line 2) were coded as an indicator of visualization, which indicated that H2 started to visualized a TE. As expected, she visualized herself in the car that moves straight ahead. She then performed an experiment in her mind and described the results (Line 2). By using her mind's eye, H2 saw that the pen she dropped while the car moved straight ahead would enter exactly into the glass. H2 then shared her TE with the group members so that it could be run and evaluated together.

However, in the process of sharing and evaluating TE, H2 did not have evidence to support the assertion that the pen she dropped in the car would fall downward. When H1 refuted it by arguing that there is gravity there (Line 5), H2 did not have the appropriate answer to refute H1. Therefore, they did not continue their TE to its conclusion. They then returned to the physics problem given and tried other ways to solve the problem (Line 8).

After refuting H2's TE, H1 then carried out another TE by assuming that there is no gravity in the box (Line 9). The TE being built by H1 was used to predict the answers to the problems they face. The words "suppose that" were coded as an indicator of visualization, which indicated that H1 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 9). By using her mind's eye, H1 saw that the pen she dropped while the box moved straight ahead would not fall down but will be left behind. H1 then shared her TE with the group members so that it could be run and evaluated together.

During the evaluation process, H4 agreed with the results of H1'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 like H2's TE. H1 then responded by saying that the coin will fall down if there is gravity in the box with the condition of the box moving at a constant speed. After students discussed for a while, H4 then did another TE by visualizing herself in a super-fast train that moves straight at a constant speed (Line 16). She then performed TE and saw with her mind's eye that the coin she had dropped fell right inside the glass. She then imagined that when she was above the propeller (something moving around) and was dropping a coin, the coin she dropped was very difficult to get into the glass. H4 then shared her TE to be run and evaluated by other students until they reached the conclusion that the scientist who is completely isolated inside a smoothly moving box that travels a straight-line will not feel that she is moving (Lines 17-21). This activity showed that the students constructed a collaborative 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 and then shared them with group members to be run and evaluated together as collective efforts to reach conclusions.**

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. Thus, TEs are a tool for both personal and social construction of knowledge.

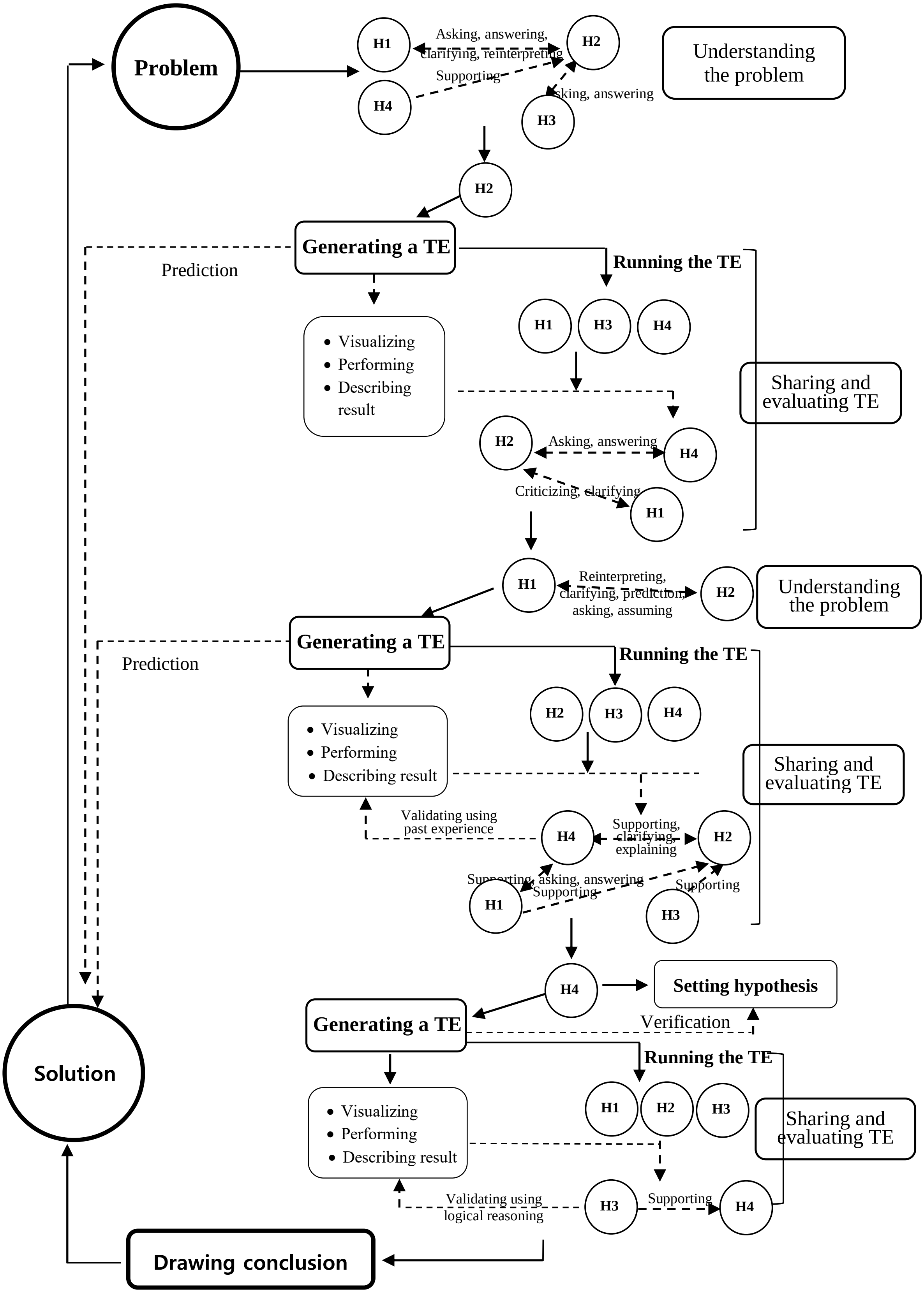


Figure 4.4. Illustration of collaborative TE by Group 1 on Problem 2

4.2. The steps of collaborative TEs

Based on what I defined as collaborative TEs, I then analyzed their steps. At the beginning of the data analysis, I used the steps of TEs proposed by Reiner (1998) and Brown (2006) to encode my data. However, when analyzing more data, I found there was a category of the TEs steps proposed by Reiner (1998) that was not solid. In addition, I also discovered a new category that I considered to be part of the TEs steps. As I moved further along in data analysis, I found a trend in the pattern of TEs steps that was slightly different from the literature review. As a result, five categories were grouped deductively as the steps of collaborative TEs: visualizing imaginary worlds, performing experiments, describing the results, sharing and evaluating experiments, and drawing conclusions. 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.

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 [while pointing the trolley image on the given problem]. 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 reports 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 pushing the trolley and showed that by putting her hand on the trolley image on the given question (see Table 4.2). Another example can be seen when Group 2 responded to Problem 5, as shown in the transcript excerpt below. The problem was asking about magnetic cars: "imagine a U-shaped magnet fixed in front of car as shown in Figure 4.5. Will hanging another U-shaped magnet facing it at opposite pole make the car move? Why or why not?"

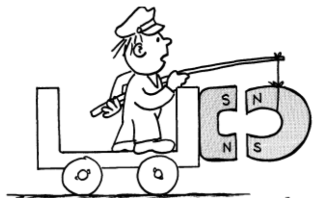


Figure 4.5. Illustration of Problem 5

M1 Ok. In my opinion, the car would move on the condition that the hanging magnet has a greater magnetic force so that it could move the car. … Try to remember when we were kids and playing with magnets. Imagine if we are playing with magnets. If the magnets, usually put on the table, if one of the magnets is pulled in this way [M1 demonstrates as if putting one magnet closer to another magnet] then the other magnet will be attracted. That is the analogy, that's what I think

The words "imagine if" were coded as an imagery indicator, which indicates that M1 started to visualize a TE. Visualizing a TE is not only marked by students saying words (imagine if, suppose that, feeling and so on) but also through hand motions (describing objects, locations, force, and dynamic events) and analogy (using a personal analogy by referring to an analogous situation involving the body forces).

In the transcript excerpt above, M1 showed an example of an analogy indicator where he moved his left hand (as a representation of a magnet) because it was pulled by another magnet that was represented by his right hand. The following are examples of imagery indicators of hand motions and analogy that appeared in this study.

Figure 4.6. Examples of imagery indicators of hand motions

Figure 4.7. Examples of imagery indicators of analogy

4.2.2. Performing experiments

After the visualization step, students begin to perform 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. Both types of experiments are, therefore, very similar:

> *We might be tempted to say the same about thought experiments, given that they are so similar to real experiments. In both we set things up, let them run, then we see what happens, and we finish by drawing a few morals* (Brown, 2013, p. 53).

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. Here, the important point is that the results of a TE do not come from the reporting of new empirical data, but are deduced by reasoning. 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 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, which means that the trolley will automatically stop at a certain time on the condition that the rainwater is being collected in the trolley." 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 trolley or because of the accumulation of mass from the collected rainwater. These factors will make the trolley stop at a certain time.

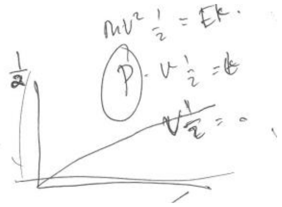
After performed the TE, H2 then believed that the trolley she pushes through the rain would stop over time. This belief was obtained after carrying out the process or mental model activity herself. This kind of belief or knowledge seems to be tacit knowledge. Sternberg (1999) and Nonaka and Takeuchi (1995) argued that tacit knowledge is a personal knowledge of mental models that individuals follow in certain situations. Therefore, I think that the results of TEs are only 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 scientific theory or experience or logical reasoning, it will become a new knowledge that can be applied to the real world:

> *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 in a TE, is unconsciously recruited to generate new knowledge* (Reiner & Gilbert, 2000, p. 502).

4.2.4. Sharing and evaluating experiments

As can be seen in the script earlier when Group 1 was responding to Problem 1, there is a process of sharing and evaluating the results of the experiment generated by H2. After declaring the result of her TE, H2 then shared with all members of the group. The members then ran this H2's TE and tried to evaluate its processes and results. The following was the interview script from Group 1 when they were evaluating their TE.

H4	Ooo, it will stop, why?	1
H2	Yes . . . <u>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</u>.	2
H1	Yes, I agree [H1 agrees with H2]	3
	[. . .]	
H4	Wait, if forces, not, kinetic energy [while writing a formula].	4



H2	$Ek = ½ mv^2$	5
H1	Because of the mass increase.	6
H3	Yes, the mass increases.	7
	[. . .]	
H1	The speed is decreasing, right? Because initially the mass is small and the speed is higher, then the mass increases, so that means . . .	8
H3	So, it has an effect.	9

As can be seen, there is a process of evaluating the results of TE generated by H2 (Line 2). H2 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 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 (Line 8). By using the kinetic energy equation written by H4, $Ek = ½\, mv^2$, 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, its speed then will decrease. This is the process of evaluating a TE, where students tried to support their constructing claims using various evaluation sources to support the claims that they were constructing. In the upcoming section, the evaluation resources used by students in evaluating the TEs will be presented in detail.

H3 and H4 were also involved in the process of sharing and evaluating TE. They engaged in the discussion by asking a question, listening, and supporting the claims. For example, H4 was engaged in evaluating the TE by providing kinetic energy equations (Line 4). H1 then used this kinetic energy equation as the basis for evaluating TE using conceptual-logical inference. Previously, H3 supported H1's arguments by saying, "yes, the mass increases" (Line 7). Therefore, in collaborative TEs, all group members contribute in constructing new knowledge either by asking and answering questions, supporting claims, validating results of TE, and so on. This process was done continuously in order to evaluate the tacit knowledge obtained from performing the TE until they reached a conclusion.

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 a negotiation of meaning. The new knowledge that has been gained by a thought experimenter going through a series of image manipulations and then shared and 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. 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 4.2 shows a summary of the episode when Group 1 was responding to Problem 1.

Table 4.2

Summary of the steps of the collaborative TE by Group 1 on Problem 1

Step of collaborative TE	**Evidence from the episode**
Visualizing imaginary worlds	• "Suppose that" • Hand motion 
Performing experiments	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.
Describing results	So the mass of this trolley will increase . . . Which means that the trolley will automatically stop at a certain time.
Sharing and evaluating experiments	• 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 . . .
Drawing conclusions	• So, it has an effect. • 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.

Figure 4.8 shows an illustration of the collaborative TEs steps that occurred in this study when students were working on physics problems. As can be seen, tacit knowledge, as a result of the performance of TEs, needs to be validated. The activities of sharing and evaluating TEs with other students will enable this tacit knowledge to be more reliable than it would be when just being evaluated personally. Through the group evaluation, students sometimes modify and refine their previous TEs if it is not valid according to the rules that they set together. If the tacit knowledge as a result of a TEs is coupled with conceptual understanding, past-daily experience, logical reasoning, or conceptual-logical inference, it will become new knowledge. This new knowledge is then used by students in understanding real-world situations.

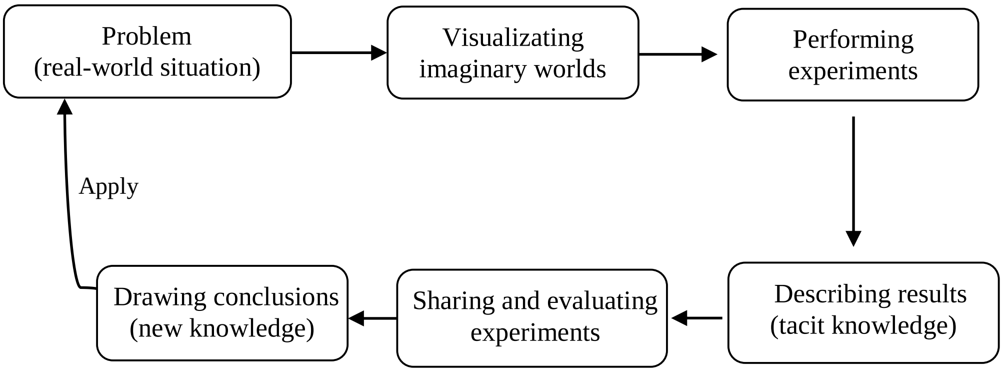


Figure 4.8. General steps of collaborative TEs that occurs when students are working on problems

4.3. Purposes of students' TEs

This section explains students' purposes in conducting TEs while solving physics problems. After identifying, discussing, and determining the steps of collaborative TEs, the purposes of students' TEs were then analyzed. As seen in Table 4.1, students can do more than one TEs when solving a physics problem. In other words, in a collaborative TE, it is allowed for students to do more than one TEs when solving a problem. Therefore, the purposes of students' TEs were analyzed by looking at the three activities or three steps of collaborative TEs: visualizing imaginary worlds, performing experiments, and describing results. These three activities are activities of a TE carried out by an individual.

Based on the data analysis, the purposes of students conducting TEs can be categorized into three types: prediction, verification, and explanation. If students make a prediction to solve a problem using a TE, then the purpose of TEs is coded as "prediction." On the other hand, if students use a TE to check whether their hypothesis or assumption is true or false, then the purpose of TEs is coded as "verification." For the last category, when students use a TE to provide further explanations about their hypothesis or assumption, then the purpose of TEs is coded as "explanation."

Table 4.3 shows the distribution of the purposes of using TEs for students in solving physics problems. As can be seen, Group 1, whose members were all master's students, tended to carry out TEs to be used to provide more explanation for their hypotheses or general assumptions that they have submitted earlier as the solution to the problems they face. When the problem was given, Group 1 members did not directly design and run the TE but instead submitted hypotheses or assumptions first. Their hypotheses were based on their prior knowledge or experiences. Similarly, Group 2, whose members were a combination of master's students and undergraduate students, tended to do TEs to be used to provide more explanation for their hypotheses or assumptions, or to prove whether the hypotheses or assumptions being submitted are true or false. Their hypotheses were also based on their prior knowledge or experiences.

On the other hand, Group 3, whose members were all undergraduate students, tended to carry out TEs to be used to predict the solution to the problems given. When the problem was given, Group 3 members directly visualized an imaginary world and then designed and ran the TE to predict the solution to the problem. They did not have a hypothesis or general assumption about the solution to the problems. In this study, there were nine TEs that occurred during Group 3 working on five different physics problems, and seven of them were used by Group 3 to predict the solutions to the problems given. There was only one TE carried out by group 3 for each of them to prove and provide more explanation for their hypotheses or assumptions being submitted as the solution to the problem given. In the following section, details about the purposes of students doing TE while solving physics problems are presented.

Table 4.3

Distribution of the students' purposes in conducting TEs

Purposes	**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	
Prediction		**									*	**	**	*	*	9
Verification		*			*	*	**					*				6
Explanation	*		*	*	*			*	**	*					*	9

4.3.1. Prediction

During the data analysis, there are some incidences that the students performed TEs to predict the solution to the problems given. For this purpose, students do not have a hypothesis or assumption about the solution to the problems. When the problem was given, students directly visualized an imaginary world and then designed and ran a TE to predict the solution to the problem given. There were some typical reactions used by the students when they used TEs as predictions, such as "aha," "that is it," "I think the logic like this," or "maybe this case is similar to this." The following is an example where a student used a TE to predict the solution to a given problem. The transcript was taken from Group 3 of the problem-solving session while responding to Problem 2 (see Figure 4.3).

R	. . . The question is which scientist can feel if she is moving? Is the scientist in the straight-moving box or the one in the spinning box? [. . .]	1
L4	Aha, the situation is like on a ship. Imagine when we are inside a ship. At that time, we do not know whether we are moving or not because we cannot see outside. If I drop something, let's say gravity exists there, then the something I drop will fall straight down, not left behind.	2
L3	Aa, yeah, we will not realize that we are moving.	3
L1	Yes, it is similar when we are inside a car moving forward very fast, we usually do not realize that we are moving.	4

As can be seen in the transcript above, L4 was conducting a TE to predict the solution to the problem given. When the problem was given by the researcher (Line 1), L4 did not have pre-assumptions, nor did he try to find other ways to produce predictions of solutions to the given problem. He directly visualized an imaginary world, and then designed and ran a TE and achieved the results. In his TE, L4 imagined himself inside a ship that resembled a box. He then performed a TE that if he were on a ship moving at a constant speed while dropping an object, the object would still fall down perpendicular (Line 2). The results of this TE would be used as a solution to the problems they faced: the scientist who is in a box that moves straight ahead will not feel that she is moving. Therefore, this example shows that students perform TEs to be used to predict the solution to the problems.

4.3.2. Verification

Based on the data analysis, there are some pieces of evidence that students conducted TEs to prove their general assumptions or hypotheses that they have submitted earlier as a solution to the problem. Their hypotheses were based on their prior knowledge or experiences. They designed and ran a TE to be used to prove whether the hypothesis or assumption being submitted was true or false. There were some typical reactions uttered students in this TEs' purpose, such as "maybe," "isn't it?" “won’t we?” or "right?" The following is an example in which the student used a TE to prove the assumption being proposed. This transcript piece was taken when Group 1 was responding to Problem 2.

H4	When we are in a steady position, and we drop a coin into a glass, the coin will surely go into the glass. If we are moving forward with constant speed, the coin will also go into the glass.	1
H2	Yes, right [H2 agrees with H4].	2
H4	Yeah, what do you think, H3?	3
H3	For me, this [pointing at the spinning box].	4
H4	Eh, 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?	5
H3	Yes, the logic is like that.	6
H4	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.	7

As seen in the transcript above, H4 performed a TE (Line 5) to prove the assumption or hypothesis that the coin dropped while moving forward with constant speed will definitely enter the glass (Line 1). This situation is the same when people who are unmoving and put coins into a glass. In other words, H4 hypothesizes that a scientist who is completely isolated inside a smoothly moving box that travels a straight-line will not feel that she is moving. In the traveling box, if the scientist drops a coin, then it will go straight into the glass. This is different from the spinning box, where the scientist will find it difficult to put coins into a glass (Line 7).

After building the hypothesis as a solution to the problem at hand (Line 1), H4 performed a TE by visualizing herself in a super-fast train that moves straight at a constant speed (Line 5). She then designed and ran a TE and saw with her mind's eye that the coin she had dropped fell right inside the glass. She then imagined that when she was above the propeller (something moving around) and was dropping a coin, the coin she dropped was very difficult to get into the glass. Therefore, this example shows that students perform TEs to be used to verify the hypothesis that they submitted as a solution to the problems.

4.3.3. Explanation

The last purpose of students in conducting TEs while solving physics problems is to provide an explanation for their hypothesis. Similar to the purpose of verification, when a problem was given, students did not directly design and run a TE but instead submitted a hypothesis first. Their hypothesis was based on their prior knowledge or experiences. There were some typical reactions uttered by students in this TEs' purpose, such as "for example," "for instance," "to illustrate." The following is an example where students used a TE to give more explanations of their hypothesis. The piece of the transcript was taken when Group 2 was responding to Problem 3, which asked the path of ball after it exits at 2, as shown in Figure 4.9.

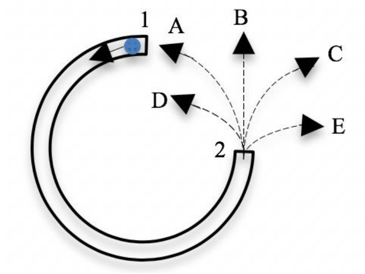


Figure 4.9. Illustration of Problem 3

R	. . . So, which is the path of the ball after exiting at point 2?	1
M1	I think B.	2
M4	Yes, B.	3
R	Why?	4
M1	Because of the vector of velocity . . . Based on experience when learning physics, 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. That is what in my mind, how about you?	5

[This photo shows M1 was doing a TE while solving a physics problem]

As seen in the transcript above, after the researcher reading the problem (Line 1), M1 immediately provided a solution to the problem without trying to do TE first. He chose B in response to the problem given because it is the direction of the velocity vector (Line 2-5). M1 then gave an explanation of his answer using a TE. The words “for example" used by M1 before starting to design and run a TE is considered as an indicator of explanation (Line 5).

Therefore, based on the evidence presented above, it can be concluded that TEs are used by students in solving physics problems for three purposes. First, students use TEs as a tool to predict solutions to the problems. Second, students use TEs as a tool to check whether the hypothesis or assumption submitted is true or false. Third, students use TEs as a tool to provide further explanation about the hypothesis or assumption as the temporary answer to the problem at hand. The illustration of the purposes of students conducting TEs while solving physics problems is shown in Figure 4.10.

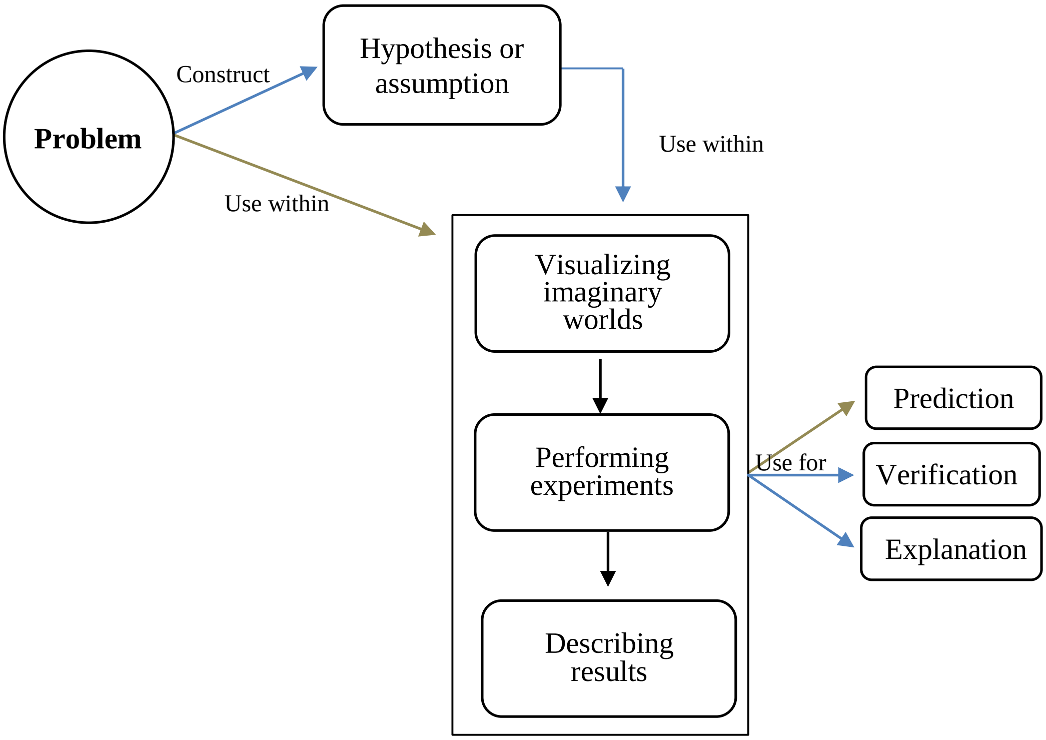


Figure 4.10. The purposes of students in conducting TEs

4.4. Sources of TEs evaluation

This section explains the evaluation resources used by students in validating the results of TEs. In a collaborative TE, after student generated a TE, s/he then shared it with group members to be run and evaluated together. This evaluation activity was carried out continuously until the students get strong evidence to support their TE. In fact, when they failed to provide evidence of their TE, they did not hesitate to redesign the new TE. Therefore, it is important to capture what kind of resources are used by students in validating their TEs. The sources of TEs evaluation were analyzed in the sharing and evaluating steps of collaborative TEs.

Based on the data analysis, four sources of TEs evaluation were identified. Firstly, students used conceptual understanding that refers to physics concepts, equations, and laws such as Newton's law. Secondly, students used their experience, such as watching movies, playing ball, and traveling by motorcycle. Thirdly, students used logical reasoning in the form of personal assumptions or perceptions. Lastly, students used conceptual-logical inference that combines laws, principles, or concepts of physics with logical manipulation. An overview of the variation of evaluation resources used by students in validating their TEs is presented in Table 4.4.

As can be seen, all groups used the four sources of TEs evaluation in validating their 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 3 was detected using logical reasoning and past-daily experience 6 and 5 times, respectively. In other words, 85% of TEs evaluation resources used by Group 3 were logical reasoning and past-daily experience. Group 2, whose members were a combination of master's students and undergraduate students, also tended to evaluate their TEs using their experience but not with logical reasoning. 50% of the TEs evaluation resources used by Group 2 were past-daily experience.

In contrast, Group 1, whose members were all master's students, did not tend to use the experience to evaluate their TEs. But they looked for scientific concepts or physics laws first and then combined them with logic. Group 1 was detected using conceptual-logical inference and logical reasoning 4 and 3 times, respectively. In other words, 70% of the sources of TEs evaluation used by Group 1 were conceptual-logical inference and logical reasoning.

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 and then proceeded with other evaluation resources. 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. The following section will discuss each category of the evaluation resources in detail.

Table 4.4

Evaluation resources used by students in validating their TEs

Type of validation	Group/Problem (P)															Total
	Group 1					Group 2					Group 3					
	P1	P2	P3	P 4	P 5	P1	P 2	P3	P 4	P 5	P1	P 2	P3	P4	P 5	
Conceptual understanding	*							*		*				*		4
Past-daily experience		*			*		**	*	**		*	*	*	*	*	12
Logical reasoning		*		*	*	*				*		*	*	*	***	11
Conceptual-logical inference	*		*	**					*					*		6

4.4.1. 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 a transcript from Group 1 while responding to Problem 1 (see Figure 4.1).

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 [while pointing the trolley image on the given problem]. 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, this means that the trolley will automatically stop at a certain time on the condition that the rainwater is being collected in the trolley.

[. . .]

H4 Ooo, it will stop, why?

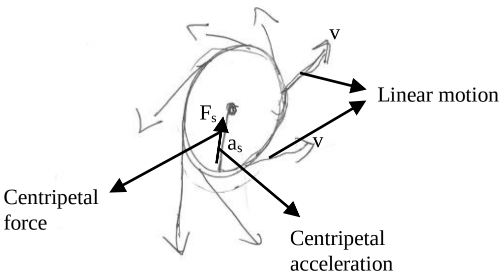
H2 Yes . . . <u>Because if there is no external force action, it will continue to move. But if, for example, there is an external force, it will stop at a certain time</u>.

As seen in the transcript excerpt above, H2's TE posited that the trolley would come to a stop at a certain time. H2 then validated this result 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. In her TE, H2 believed that the trolley she pushed while it rained would stop because there was an external force on it. The external force might be in the form of either the interaction between the rainwater and the wall and floor of trolley or because of the accumulation of mass caused by the collected rainwater.

Because of the external force that works on the trolley, it will not move continuously but will stop at a certain time.

The following is another example that was taken from the transcripts of the problem-solving session with Group 2 when they were responding to Problem 3 (see Figure 4.9). 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 conceptual understanding, as shown below.

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



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 (the description is added). These two pieces of evidence show conceptual understanding being used as a source for evaluating the tacit knowledge produced from TE performance.

4.4.2. Past-daily experience

During the evaluation of TEs, some students used their experience when evaluating the results of the TEs that they ran. 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 past experience when evaluating the results of TEs. The transcript was from Group 3 when responding to Problem 5 (see Figure 4.5).

L2 In my opinion, the car will move. Imagine that there is a magnet here (Magnet A) and in front of it there is also a magnet (Magnet B). Hence, if I am in the car and put the magnet that is hung (Magnet B) closer, then the magnet in the car (Magnet A) will move in any direction from the magnet in front of it . . .

L3 Will they pull each other?

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

As seen in the transcript above, L2 evaluated the results of the TE using her past experience. She assumed that the car on which the magnet was hung would move in the direction of the magnet being hung. This 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. The experience of watching cartoons is used by L2 in evaluating the TE she ran.

There was another example in Group 2 when they 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. M1 performed 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 members of the group. After discussing it for a while, M1 evaluated the results of the TE, as shown below.

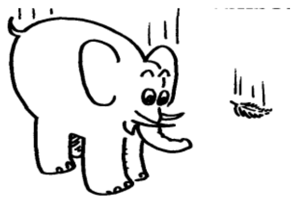


Figure 4.11. Illustration of Problem 4

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

Based on the transcript excerpt above, it is clear that M1 used his daily experience to evaluate the results of the TE that he carried out. He used his experience when riding a motorcycle and riding behind small cars and trucks. From this experience, M1 believed that if he dropped a plane 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, the air currents around the plane were more chaotic than those around the chicken feathers. This indicates that the airplane has a greater air resistance force than the chicken feathers. These two pieces of evidence show past-daily experience being used as a source for evaluating the tacit knowledge produced from TE performance.

4.4.3. Logical reasoning

Another resource used by the students during the evaluation of TEs was coded as logical reasoning. 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 TE, which I took from the Group 3 transcript excerpt when responding to Problem 5 (see Figure 4.5).

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 don't 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 (see the above section on past-daily experience). Then she brought another magnet, which was hanging, to the car. She then sensed that the car would move closer to the hanging magnet wherever the magnet was. L2 then evaluated the results of the TE by using her experience when watching cartoons.

However, during the process of negotiation of meaning, L3 was also involved in evaluating the TE. She then rejected the L2's argument 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 argued that maybe the hanging magnet would be attracted to the car because the rope and the stick were not strong enough to pull the car. If, according to L3, the hanging magnet was tied to a truck or an object heavier than a car, then the car might move. 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. The logic built by L3 was not based on a theory, a principle, or a law of physics. It was only a personal assumption or perception, but it was enough to convince thought experimenters to support or reject the tacit knowledge they evaluated. This example shows logical reasoning to be a source of evaluation used by students in evaluating the results of TEs.

4.4.4. Conceptual-logical inference

The last source of evaluation used by the students during the evaluation of TEs is conceptual-logical inference. This is different from conceptual understanding, which also emphasizes the use of logic. It is also different from logical reasoning, which uses the elements of theory, principle, or law.

The conceptual-logical inference 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 use conceptual-logical inference in evaluating the results of their TE. This example was taken from Group 1 when responding to Problem 1 (see Figure 4.1).

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

As seen in the transcript above, H1 used conceptual-logical inference in evaluating the result of their TE. 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, the trolley speed should decrease and the trolley would even eventually stop. Here, H1 used logic along with the kinetic energy equation.

The section below is another example of the use of conceptual-logical inference in evaluating the results of a TE. The transcript excerpt below is taken from Group 1 when was responding to Problem 4 (see Figure 4.11). In the process of solving the problem, H2 performed a TE by imagining herself dropping a ball and a sheet of paper instead of elephants and chicken feathers. After H2 performed the TE, the other group members ran it and began to evaluate it.

H1	Force zigma $(\sum F) = 0$
H2	This means that if $F_w - F_u = 0$ then $F_w = F_u$. Are there any other influential forces?
H3	This is influenced by mass, right? $F_w = mg$.
H2	Oh yeah, correct! This means *mg*. If for example, here the mass [paper] is 10 multiplied by 9.8 = 98. If the mass [ball] is 20, let’s say, it means the highest *Fu* is?
H3, H4	Elephant.

As seen in the transcript section above, the members of Group 1 tried to analyze the forces acting on an object falling from a certain height. H1 used Newton's first law about the resultant force acting on an object equal to 0 ($\sum F = 0$). H2 then analyzed the forces on the object dropped and obtained gravity (F_w), which was downward, in the same direction of the motion of the object, and the friction force of air (F_u), which was in the opposite direction of motion of the object. After obtaining the two forces, H2 asked the group members whether there were other possible influential forces? The group members then agreed that there were only two forces that affected the object that was falling down.

H3 then said that this gravity was influenced by mass ($F = mg$). H2 supported H3's argument and then performed logic games using the equation. He said if this paper (substituted for a chicken feather) had a mass of 10, then it would have a gravity of 98. If the mass of this ball (substituted for an elephant) was 20 then it would have a greater gravity than the paper. This means that objects that have a greater mass when dropped will have a larger air resistance force as well. That is the logic Group 1 built based on Newton's first law and the gravity equation of the object. The use of conceptual-logical inference led Group 1 members to believe that an elephant dropped from a certain height would experience greater air resistance than a chicken feather. These examples show conceptual-logical inference being a source that students use in evaluating the tacit knowledge they produce from performing TEs.

4.5. Summary and discussion

I believe that the power of TEs can be exploited if the communicative processes in their construction are made possible. TEs are a personal and tacit process of experimentation with personal imagery that scientists use in formulating a new theory or refuting an existing theory. For instance, Einstein designed, ran, and evaluated his own TEs in developing the theory of relativity. However, by looking at learning as a social process in which meaning is built and continuously negotiated in a public forum (e.g., Vygotsky, 1978; Lave & Wenger, 1991; Hennessy, 1993), this study sought to examine whether TEs can be shared and communicated in the group learning. Four research questions were outlined to guide me in data analysis and discussions. From the four research questions, I finally gave a definition of collaborative TEs and explained how it could occur.

What is the meaning of collaborative TEs?

This study has shown that while solving physics problems, students construct, share, and evaluate their TEs. This indicates that TEs can be designed and constructed in a collaborative manner even though the TEs are mostly individual in nature. I referred to collaborative TEs as 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 with group members to be run and evaluated together as collective efforts to reach conclusions.

In the process of sharing and evaluating TEs, there is an activity of negotiation of meaning as the main characteristics of collaborative activities. Each individual or member of the groups in this study are engaged in discussion by asking and answering questions, supporting and clarifying arguments, providing equations, validating the results of TE, and so on. Wenger (1998) argued that the negotiation of meaning involves the interaction of participation and reification in the act of processing the claim. As a participation, students contributed to the negotiation of meaning by being a member of the social community and described their social experience of living the world in their practice. Meanwhile, in reification, students produced claims based on their experiences, and they were continuously fixed in their form until the final process of negotiation of meaning: an agreement with all group members. This agreement is the step towards the final processes of collaborative TEs: conclusion. 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.

The results of this study support argument in the literature that TEs are a cognitive tool that both experts and students can use to work on problems (Reiner, 1998; Stephens & Clement, 2006; Kösem & Özdemir, 2014). Although TEs are individual activities by scientists, TEs can also be constructed in a collaborative setting. When students are given the opportunity to work together to solve meaningful problems, they perform TEs and share them with their group members to be polished and validated as a collective effort to achieve mutual understanding. 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. Thus, TEs are a tool for both the personal and social construction of knowledge.

What are the steps of collaborative TEs?

It is concluded that there are five steps of collaborative TEs that occur during physics problem-solving activities. Visualization is the first step that aims to construct a common understanding of representation with the objects and events in the imaginary world. The words, such as “imagine if,” “suppose that,” “seeing,” “think that,” and “if” are coded as visualization’s indicators. Visualizing a TE is not only marked by students saying words, but also through hand motions (describing objects, locations, force, and dynamic events) and analogy (using a personal analogy by referring to an analogous situation involving the body forces).

After the visualization step, students begin to perform experiments in the mind. In the performing TEs, students seem to do real experiments in the real world. However, the performance of TEs can only be observed by using the mind’s eye. The next step of collaborative TEs is students describe the results of their TEs. Although in both real and thought experiments, we can design objects and related variables, then let them run while observing the results, there is no empirical data obtained in TEs. The results of TEs are only in the form of tacit knowledge, which is a belief or personal knowledge that thought experimenter holds after carrying out the TEs. However, when this tacit knowledge is then evaluated using either conceptual understanding, past-daily experience, logical reasoning, or conceptual-logical inference, it will become a new knowledge that can be applied to the real world.

After declaring the results, the students then shared their TEs with all members of the group to be run and evaluated together. In the process of evaluating TEs, students engaged in discussion by giving questions, listening, supporting and clarifying claims, validating the results of TE, and so on. This process was done continuously in order to evaluate the tacit knowledge obtained from performing the TEs until they reached a conclusion as the final process of collaborative TEs. This is an agreement or a decision made after considering all the information through a negotiation of meaning. The new knowledge that has been gained by students going through the performance of TEs and then evaluated by group members is located in this step.

Although I agree with Reiner (1998) that TEs are more easily constructed in a collaborative manner in which the number of students' contributions can lead to the complexity of TEs, some of the Reiner's TEs steps do not match with my results. Reiner (1988) had analyzed the processes of students in constructing TEs while they were working on the problem in collaborative setting and proposed five steps of TEs: visualization, hypothesis, experiment, results, and conclusions. In my study, I did not see students propose hypothesis after the visualization step. When the problem was given, the students visualized the imaginary world, and directly designed and ran experiments without setting hypotheses first. In this case, students performed TEs to predict the solution to the given problem. There were also students who proposed a hypothesis first and then visualized the imaginary world as the first step in constructing TEs. In this case, students designed and ran TEs to determine whether the hypothesis is true or false or to give more explanation of their hypothesis, and therefore, I think that proposing hypothesis is not an integral part of the TEs steps.

In addition, after students described the results of TEs, they did not immediately draw conclusions as proposed by Reiner (1998) but they shared with group members to be run and evaluated together. During sharing and evaluating TEs, students were involved in the process of negotiation of meaning which is the hallmark of collaborative activity (Bruffee, 1995; Dillenbourg, 1999; Chiu, 2000). Therefore, based on this study, there are five activities carried out by students in constructing TEs in the collaborative setting: visualizing imaginary worlds, performing experiments, describing results, sharing and evaluating experiments, and drawing conclusions. I refer to these activities as the steps of collaborative TEs.

What are the students' purposes in conducting TEs?

Based on the data analysis, the purpose of students conducting TEs while solving physics problems can be categorized into three types: prediction, verification, and explanation. In prediction, students do not have a hypothesis or assumption about the solution to the problem. When the researcher gave a problem, students directly visualized an imaginary world, and then designed and ran a TE to predict the solution to the problem. There are some typical reactions used by students when they use TEs as prediction, such as "aha," "that it is," "I think the logic is like this," or "maybe this case is similar to this."

In verification, students first proposed a hypothesis or an assumption, and then designed and ran a TE to determine whether the hypothesis or assumption is true or false. Their hypotheses were based on their prior knowledge or experiences. There are some typical reactions uttered students in this TEs' purpose, such as "maybe," "isn't it?" "won't we?" or "right?".

The last purpose of students in conducting TEs while solving physics problems is to provide an explanation for their hypothesis. Similar to the purpose of verification, when a problem was given, students did not directly design and run a TE but instead submitted a hypothesis first. Their hypothesis was based on their prior knowledge or experiences. The words, such as "for example," "for instance," "to illustrate," were commonly used by students in this TEs' purpose.

Based on data analysis, Group 1, whose members were all master's students, tends to carry out TEs to be used to provide more explanation for their hypotheses or assumptions that they have submitted earlier as the solution to the problems. When the problem was given, Group 1 members did not directly design and run the TEs but instead submitted hypotheses or assumptions first. Similar to Group 2, whose members were a combination of master's students and undergraduate students, tended to do TEs to be used to provide more explanation for their hypotheses or assumptions, or to prove whether the hypotheses or assumptions being submitted are true or false. Their hypotheses were based on their prior knowledge or experiences. On the other hand, Group 3, whose members were all undergraduate students, tended to carry out TEs to be used to predict the solution to the problems given. When the problem was given, they did not have pre-assumptions, nor did try to find other ways to produce predictions of solutions to the given problem. They directly visualized an imaginary world and then designed and ran the TEs and achieved the results. The results of the TEs would be used as a solution to the problems they faced.

How do students validate the results of TEs?

This study has shown that the students evaluate the results of TEs using four sources. Firstly, some students used conceptual understanding that refers to physics concepts, physics equations, and laws such as Newton's law. Secondly, some students used their specific experience. Past and daily experiences such as watching movies, playing ball, and traveling by motorcycle or train are examples used by the students when evaluating their TEs. Thirdly, students used logical reasoning in the form of personal assumptions or perceptions. Although this source is only a personal assumption or perception, it is enough to convince thought experimenters to support or reject the tacit knowledge they evaluated. Lastly, students used conceptual-logical inference that combines laws, principles, or concepts of physics with logical manipulation. This is different from scientific theory, which also emphasizes the use of logic. It is also different from logical reasoning, which uses the elements of theory, principle, or law.

Based on data analysis, past-daily experience and logical reasoning were the most frequently used by students in validating their TEs. Group 3, whose members were all undergraduate students, tended to evaluate their TEs by first connecting with their experience or using logical reasoning. 85% of TEs evaluation resources used by Group 3 are logical reasoning and past-daily experience. Group 2, whose members were a combination of master's students and undergraduate students, also tended to evaluate their TEs using their experience but not with logical reasoning. 50% of the TEs evaluation resources used by Group 2 are past-daily experience. In contrast, Group 1, whose members were all master's students, did not tend to use the experience to evaluate their TEs. But they looked for scientific concepts or physics laws first and then combined them with logic. 70% of the sources of TEs evaluation used by Group 1 are conceptual-logical inference and logical reasoning.

There is some evidence that students evaluate not only the results but also the processes of the 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 they failed to provide evidence of the resulting tacit knowledge, they did not hesitate 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 TEs, both the process and the results will be checked. Figure 4.12 illustrates the processes of new knowledge obtained through collaborative TEs during physics problem-solving activities.

Based on the results of this chapter, I would recommend that collaborative TEs be introduced to both current and future physics teachers as a useful tool for teaching science at school for several reasons. First, because TEs can produce both correct and incorrect results in the development of a scientific theory (Reiner & 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 reliable conclusions. Second, with collaborative TEs, students who have difficulties will be helped by other students in constructing TEs. Third, collaborative TEs can also improve social interactions and support diversity. In collaborative TEs, students must work together in a group with different backgrounds, experiences, cultures, and knowledge. When students spend time together to work, they will learn how to relate to each other. They also make friendships by getting to know each other, thereby increasing morale and group performance. Fourth, through collaborative TEs, students clarify each other's ideas, views, and opinions through discussion forums before making conclusions. Therefore, collaborative TEs might nurture students' critical thinking skills. Fifth, collaborative TEs can also bring students closer to scientific argumentation through the interpretation and evaluation of the ideas and views with each other. Over the past decade, scientific argumentation has received serious attention from science educators around the world as core competencies in schools (e.g., Erduran et al., 2015; Lazarou et al., 2017).

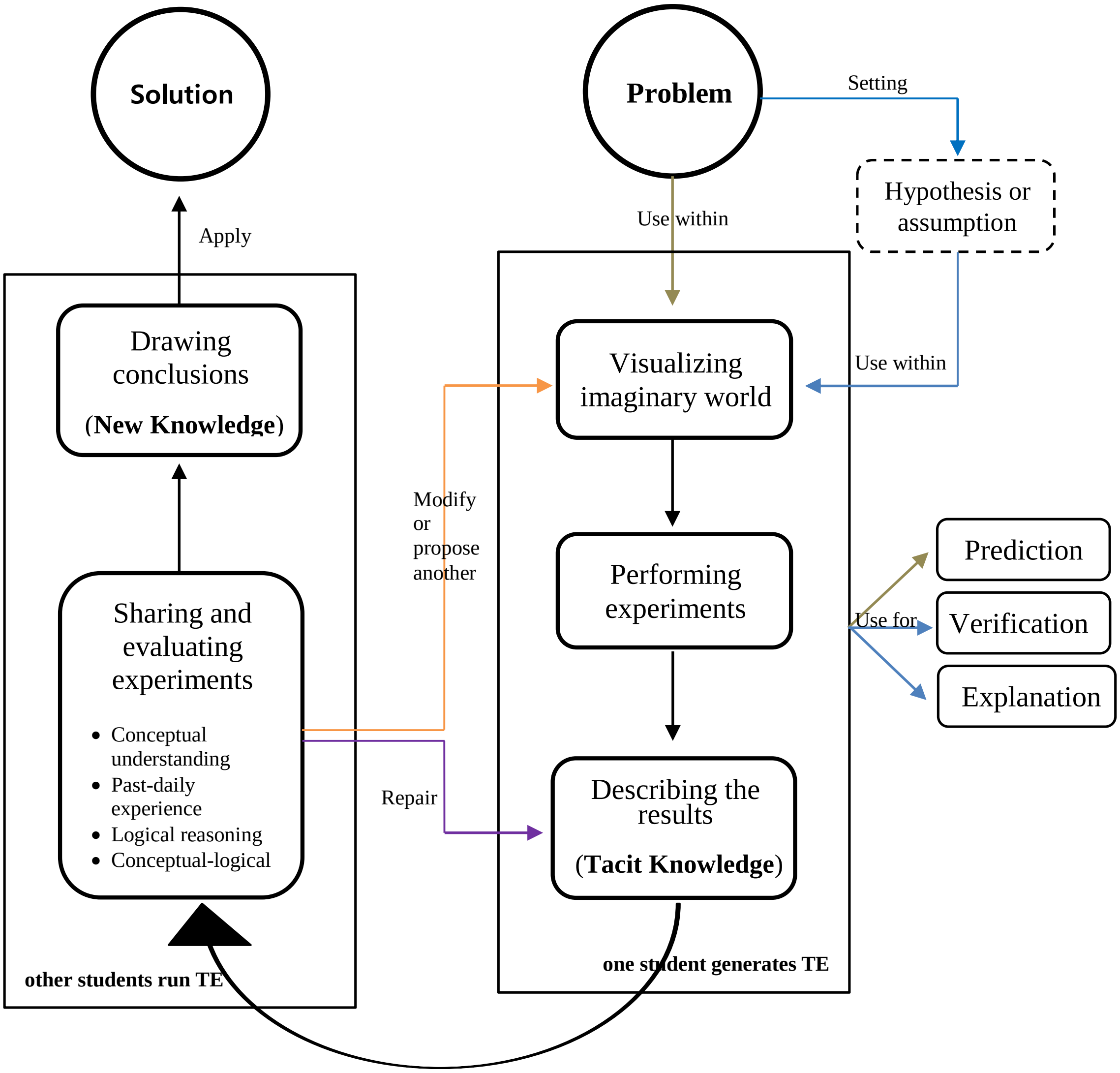


Figure 4.12. The processes of new knowledge obtained through collaborative TEs during physics problem-solving activities.

Chapter 5. Factors Influencing Collaborative Thought Experiments

This chapter aims at identifying the factors that influence students when constructing collaborative TEs. This is intended to provide answers to questions: What can be done to support students in running TEs, particularly in collaborative learning? And why are some students more successful in doing TEs than others? Therefore, I think that understanding the factors that influence students in constructing collaborative TEs can give us not only a clear understanding of how students do TEs in detail but also can generate information about how to help students to improve their TEs. To achieve these goals, the following questions were used to guide my data analysis and discussion.

1. What factors influence students in visualizing TEs?
2. What factors influence students in sharing and evaluating TEs?

What I found in this chapter is that there are five factors that can encourage students to visualize TEs as the first step of collaborative TEs. First, conflicting ideas between students in understanding the problems. Second, the similarity of ideas in building hypotheses or assumptions. Third, the guidance and support of more experienced students (in this case, master's students and undergraduate students). Fourth, students' bodily knowledge, which refers to students' physical experience that may be similar to the physics problems with which they faced. Last, students' imaginary visual knowledge, which refers to individual abilities of imagistic simulation, such as the manipulation of imaginary objects and imagined situations.

I also found four factors that influence students in the process of sharing and evaluating TEs: validating of concerns, understandings, logical arguments, and conflicting evidence. The absence of evidence to validate the results of a TE during the evaluation process leads to the failure of the TE. Likewise, a misunderstanding between students in understanding the evidence presented by others or the argument being built illogically can lead to the failure of a TE. Also, when the evidence obtained through life experience contradicts with other evidence presented by others, students will try to maintain their beliefs to reach conclusions.

Some researchers (e.g., Stephens & Clement, 2012) argued that TEs do not need to be built together because students can independently produce novel scenarios, make predictions, and evaluate their own scenarios during class discussions. However, this study has shown that students performed TEs not only because they were inspired by their own imaginary visual knowledge or bodily knowledge but also because of interaction between students in a group. In addition, this study showed that TEs could arise when master's students provide support and guidance for undergraduate students. In order to teach TEs at school, therefore, I think that mentorship by a teacher or a more experienced person in the design and conduct of TEs is essential not only to encourage students to perform TEs but also to improve the quality of students' TEs.

5.1. Factors in visualizing TEs

This section describes the factors that trigger students to visualize TEs while solving physics problems. In order to identify the factors that trigger the emergence of TEs, first of all, I located the visualization steps of collaborative TEs. After that, I focused on identifying the factors that triggered students to visualize the TEs. Gendler (2004) stated that TEs could not occur without visualization. Similarly, Gooding (1992) argued that TEs in physics do work because of the visualization process that directs thought experimenters to embodied inferences. The Oxford Dictionary of English provides two definitions of the word “visualization” as “(1) Representation of objects, situations, or information as a chart or other image; (2) The formation of a mental image of something” (Stevenson, 2010, p. 1986). From this definition, visualization can be categorized into two types: visualization as external representation and internal representation. As an external representation, visualization refers to representations that are usually used for learning, such as graphics, diagrams, models, and simulations. Conversely, as an internal representation, visualization is used to describe internal mental construction, that is, mental models, which are considered to be in the mind's eye and used in mental imaging. In this study, the term visualization used is the second definition of the Oxford Dictionary of English.

Based on data analysis, there are five factors that trigger the emergence of TEs when students interact with each other in their groups to solve problems. The five factors are categorized as conflicting ideas, similar ideas, guidance, and support from more experienced people, inspiration by bodily knowledge, and inspiration by imaginary visual knowledge. The list of the factors that trigger the emergence of collaborative TEs are presented in Table 5.1.

As can be seen, students performed TEs not only because they were inspired by their own imaginary visual knowledge or bodily knowledge but also because of interaction between students in a group. The similarity of ideas, conflicting ideas, and inspiration by bodily knowledge are the main factors that trigger the emergence of collaborative TEs. Group 1, whose members were all master's students, tended to do TEs because of the differences of ideas in understanding the problems given or because of the similarity of ideas in developing hypotheses, and not because they were inspired by imaginary visual knowledge or bodily knowledge. Conversely, Group 2 tended to do TEs because they were inspired by their bodily knowledge that refers to students' physical experiences that may be similar to the physics problems with which they faced. The following section discusses each category of the factors in detail.

Table 5.1

List of factors that trigger the emergence of TEs

Factors	**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	
Conflicting ideas	*	**											*	*		5
Similarity of ideas		*	*		*				*		*	*	*			7
Guidance and support							**									2
Inspiration by bodily knowledge					*	*		*		*		*			*	6
Inspiration by imaginary visual knowledge				*					*			*			*	4

5.1.1. Conflicting ideas

During the data analysis, there was some evidence that led me to believe that TEs emerged due to differences in opinion between group members in understanding the problems. These differences encouraged group members to broaden their perspectives so that they could try to build a TE to prove their ideas, and simultaneously refute the ideas of their fellow group members. The following transcript is an example of a TE arising because of differences of opinion among the students. The transcript was taken from the Group 1 problem-solving session transcript while working on Problem 1, asking the effect of the accumulating rain on the speed of the trolley.

R	OK. Let's start from the first question . . . Now, imagine the possible effect of the accumulating rainwater on the trolley's speed as shown in the figure [Figure 4.1]. 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	9

> trolley while it is raining [while pointing the trolley image on the given problem]. 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 this episode, 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 with the group members so that it could be run and evaluated together.

However, before H2 started to visualize a TE, the students first actively involved themselves in understanding the problem. At the beginning of the 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, using the words “suppose that” in order to prove her assumption and simultaneously refute H1’s and H4’s assumptions.

This discourse demonstrates that the conflicting ideas in understanding a problem can encourage students to broaden their perspectives so that they are compelled to perform a TE in order to support their ideas, and simultaneously reject the ideas of their opponents. In physics, there are several examples of TEs that are similar to the case above, where they are used by scientists to refute opposing ideas and simultaneously produce new ideas. Brown (1991) called this kind of TE as platonic TE. Galileo’s free-falling body TE is an example that refuted Aristotle’s view that heavier objects fall faster, and simultaneously established the new idea that all objects fall at the same speed. Thus, the conflict of ideas in understanding problems is one of the factors that can trigger the emergence of collaborative TEs.

5.1.2. Similar ideas

Collaborative TEs can also arise when two or more students who have similar ideas are actively involved in constructing assumptions. There were a few moments in this study where two or more students jointly constructed assumptions, and then one of them carried out a TE to support their assumption. The following is an example where a collaborative TE arises under these conditions. The transcript is taken from Group 1’s work on Problem 5, asking about the magnetic car.

R Now we are going to the last question, Problem 5. . . . [The researcher reads the problem] So, do you think the car would move or not? 1
[. . .]

H2 Is the car initially at rest? 2

H1 Yes, the car is at rest, then someone brought the magnet closer to it. 3

H2 I think that if the model is like this picture [while pointing the picture on the given problem] then the car will move. 4

H1 Yes, I think so. 5

H2 Except the hanging magnet has the same magnetic force as the one in the car. 6

H1 Because it could be that the hanging magnet will be pulled by the magnet in the car. 7

H2 So, maybe it depends on how strong the magnetic force is. If these two magnets have the same magnetic force, the car will not move, right? 8

H1 Yes, maybe. 9

H2 Yes, for example, try to imagine, if you [H1] are in the car with a magnet fixed in front of it, then you hold another magnet like in the picture from the given problem [H2 uses hand to demonstrate]. If the model is like that, then the car will not move, instead it may be a hanging magnet will move towards the car, right? 10

H1 Yes, because there is additional mass in the magnet fixed to the car 11

H2 Yes, because the force here [pointing the hanging magnet] is smaller . . . 12

H3 What force do you mean? 13

H1 I think his intention [indicating H2] is the magnitude of the magnetic force on the hanging magnet. So when the hanging magnet is brought close to the magnet in the car, the car will not move because of the masses of the car and 14 person attached to it. So, we think that the hanging magnet cannot make the car move.

H2 Yes, I think it is logical if the situation is like it is in the picture [pointing to the problem given].

At the beginning of the discourse, it is clearly seen that H1 and H2 jointly built the assumptions used as the basis for solving the problem at hand (Lines 2-9). They responded to and supported each other. To further strengthen their ideas that the car would not move, H2 did a TE (Line 10) using the words “try to imagine” and “if” (as an indicator of visualization). In her experiment, H2 imagined that if H1 brought a U-shaped magnet closer to another U-shaped magnet attached to the car (assuming the car would move), then perhaps the magnet held by H1 would be attracted to the magnet in the car. Thus, according to H2, the car will not move. The results of this TE were supported directly by H1, who suggested that the magnet in the car has extra force (the extra mass of the car and the person) that the hanging U-shaped magnet does not have. Therefore, H1 and H2 suggest that the hanging U-shaped magnet does not have a force strong enough to make the car move because the magnets have the same magnetic force (Line 7-8) and the U-shaped magnet on the car has extra force (Lines 11, 12, and 14).

Unlike the previous conditions (conflict of ideas), this collaborative TE arises when the students have similar ideas. The similarity of ideas encouraged students to do a TE to further support their assumptions. This corresponds to the function of TEs as cognitive tools used by scientists in developing and supporting their theories (Gendler, 2004; Galili, 2009). Thus, it can be said that the similarity of ideas in building an assumption or hypothesis is one of the factors that can trigger the emergence of collaborative TEs.

5.1.3. Guidance and support from more experienced people

Another condition that can encourage the emergence of collaborative TEs while students are interacting in small groups to solve physics problems is the guidance and support from more experienced people. In this study, one group consisted of some participants who were master's students and some who were undergraduate students, and it was noticeable that undergraduate students were able to perform TEs because of the support and guidance from the master's students. This support can be in the form of positive responses and also emotional support, such as facial expressions and hand gestures. The following is an example where an undergraduate student did a TE because she got support and guidance from master's students. The transcript was taken from Group 2's response to Problem 2, asking about the scientists in the box.

R	We continue on to Problem 2 . . . Now, which scientist can detect her motion? [. . .]	1
M1	In my opinion, the scientist who feels that she is moving is the scientist in the smoothly spinning box . . . Meanwhile, the scientist in the box moving in a straight line will not feel that she is moving. I think it is the same if we are on a ship. How about you guys [pointing to undergraduate students]	2

M3 Maybe this one [pointing the spinning box]. 3

M4 Yes, maybe the spinning one because if we are on the airplane. 4

M1 The spinning box, why? 5

M4 Because if we are on an airplane . . . 6

[These photos show the situation right before M4 did visualization as the first step in a collaborative TE. M4 seems to feel embarrassed to start doing a visualization of TE. Shortly before M4 started to visualize the TE, M4 and M3 laughed several times, glanced at each other, and M4 lowered her face to the table. M4 took about 1 minute to start visualizing the TE when asked by M1].

M1 Yes, what happens if we are on an airplane? Do not be shy, just speak up. 7

M4 That is the same thing as you [M1] said when we are on a ship. 8

M1 Yes, can you imagine that we are on a ship? 9

M4 Yes, I try to replace a ship with airplane so that it is easy. Try to imagine that we are on an airplane that moves in a straight line and at a constant speed without any friction. If I drop a coin into a glass, that coin will go into the glass, right? 10

M2 Yes, I think it's the same if we are on a plane with this one [pointing at the box moving in a straight line]. 11

M1 Yes, I think so too. 12

M4 Ahh… then if, for example, when we are on a roller coaster. If we are on a roller coaster and try to drop a coin into a glass, then it is difficult, so, we will keep feeling like we are moving, won't we? 13

M2 Roller coaster? 14

M1 Carnival swings, maybe. 15

M4 Something that moves like this [while spinning her hand], right? When we are on it, can you feel that you are moving? 16

M1 Yes, sure. 17

M2 Yes, we can feel it. 18

At the beginning of the discourse, M1 responded to the problem given by saying that the scientist who is pushed forward will not feel that she is moving because the situation is the same as that of people on a ship (Line 2). M1 then asked M3's and M4's opinions, and they also agreed that the scientist in the box who was pushed forward did not feel that she was moving. However, to prove this claim, the two undergraduate students felt ashamed about explaining their opinions. Several times they laughed before starting to do a TE, and M4 even lowered her face to the table (Line 6). In this condition, M1, as a master's student, tried to encourage and support M4 to express her opinion (Line 7). M4 then did a TE using the ideas expressed earlier by M1 (people on a ship), but she replaced the imaginary ship with an imaginary airplane (Lines 8-10).

The results of M4's TE were then responded to positively by M1 and M2 (Lines 11-12). With this support, M4 then continued to do TE for different situations in order to describe the situation that occurs for a scientist who is in a rotating box (Line 13). Afterward, the participants began to run, evaluate, and fix their TE until they reached a mutual agreement (Lines 14-18). It is clearly seen in the transcript above, M4 carries out TE using the words "right?" (Line 10) and "won't we?" (Line 13) which indicated that she feels not too sure of her TE. I think that she uses these words to request responses from M1 and M2. Therefore, this discourse demonstrates that the guidance and support of experienced people is an important factor that can encourage the emergence of collaborative TEs.

5.1.4. Inspired by bodily knowledge

Collaborative TEs can also arise when students interact in a group to solve physics problems because they are inspired by their bodily knowledge. According to Reiner and Gilbert (2000), “bodily knowledge rises from physical experiences, such as riding bikes or playing basketball and provides us with tacit knowledge about the dynamics of objects and motor performance” (p. 490). The knowledge embodied in perceptual-motor intuition is often used not only by students but also by experts when they are solving a problem (Clement, 1998), and it can be reflected in their motor and kinesthetic actions (Reiner & Gilbert, 2000). For example, students may push their bodies reflexively forward when imagining being in a car speeding forward that brakes suddenly.

During the data analysis, there was some evidence that students begin visualizing a TE because they are inspired by their physical experiences that are similar to the physics problems they are faced with. Their experiences trigger the visualization of an imaginary world where a TE can be done. The following is an example of a student visualizing a TE because it was inspired by his bodily knowledge. The following transcript was taken from the problem-solving session when Group 2 was responding to Problem 5, asking about the magnetic car.

R Now, we are going to the last question. So, what do you think is the solution to this problem? 1

[. . .]

M1 Ok. In my opinion, the car would move on the condition that the hanging magnet has a greater magnetic force so that it could move the car. … Try to remember when we were kids and playing with magnets. Imagine if we are playing with magnets. If the magnets, usually put on the table, if one of the magnets is pulled in this way [M1 demonstrates as if putting one magnet closer to another magnet] then the other magnet will be attracted. That is the analogy, that's what I think . . . 2

M2 Wait, I think the distance between the two magnets must also be considered. Because if it is too close, they will stick together . . . 3

As can be seen, M1 started visualizing a TE because he had experience as a child playing with magnets (Line 2). M1's physical experience of playing with magnets encouraged him to perform a TE in order to solve the problems he was facing. The words "imagine if" are coded as an imagery indicator, which indicates that M1 started to visualize a TE (Line 2). While performing the TE, M1 demonstrated using both hands as if bringing the first magnet closer to the second magnet, with the second magnet being attracted to the first magnet. After that, M1 shared his TE to be run and evaluated together by members of the group. This demonstrates that bodily knowledge can be an important factor that can encourage the emergence of collaborative TEs.

5.1.5. Inspired by imaginary visual knowledge

The last factor that can encourage the emergence of collaborative TEs is students' imaginary visual knowledge. Unlike bodily knowledge, this knowledge is not inspired by physical experience but instead refers to individual abilities in imagistic simulation, such as manipulation of imaginary objects and imagined situations (Reiner & Gilbert, 2000).

The data analysis showed evidence that students began visualizing TEs because they were inspired by their own imaginary visual knowledge. In general, students who are in this state perform a TE to predict the answer to the problem given. When the researcher finished reading the problem, students immediately visualized the imaginary world by manipulating imagined objects and situations. The transcript below was taken when Group 3 was responding to Problem 2 is an example of this.

R	. . . The question is which scientist can feel if she is moving? Is the scientist in the straight-moving box or the one in the spinning box?	1
	[. . .]	
L4	Aha, the situation is like on a ship. Imagine when we are inside a ship. At that time, we do not know whether we are moving or not because we cannot see outside. If I drop something, let's say gravity exists there, then the something I drop will fall straight down, not left behind.	2
L3	Aa, yeah, we will not realize that we are moving.	3
L1	Yes, it is similar when we are inside a car moving forward very fast, we usually do not realize that we are moving.	4

After students discussed the problem for a while, L4 had an idea for solving the problem and said, "Aha" (Line 2). He then created an imaginary world by manipulating the object (in the problem given, the object is a box, while in L4's TE, the object is a ship). L4 then constructs a situation where he is inside a ship, and the ship has no windows, so outside the ship cannot be seen. With this situation, L4 then did an experiment, dropping an object into floor and seeing that the object would still fall down perpendicular. Afterward, L4 shared his TE with the group members to be run and evaluated together.

As can be seen in the transcript above, L4 was conducting a TE to predict the solution to the problem given. When the problem was given (Line 1), L4 did not have pre-assumptions, nor did he try to find other ways to produce predictions of solutions to the given problem. He did the TE not because he was inspired by his experience or because there were different or similar ideas in the group but because he was inspired by his imaginary visual abilities. He first manipulated imaginary objects and conditions to start doing a TE. This demonstrates that imaginary visual knowledge is an important factor that can encourage the emergence of collaborative TEs.

5.2. Factors in sharing and evaluating TEs

By viewing collaborative TEs as an activity to socially construct knowledge where students carry out experiments in their minds and then share them with group members, evaluating the processes and the results of TEs become crucial. In the processes of evaluating TEs, all students are engaged in discussion by asking and answering questions, supporting and clarifying arguments, providing equations, validating the results of TEs, and so on. This process was done continuously until they get strong evidence to support the truth of the tacit knowledge they have obtained. In fact, when they failed to provide evidence of the resulting tacit knowledge, they did not hesitate to redesign their TEs. Therefore, I think that sharing and evaluating TE is a crucial step in constructing collaborative TEs.

In order to identify the factors that influence students in the process of sharing and evaluating TEs, I first located the evaluation moment in the transcripts of problem-solving activities. Every moment of evaluation of TEs that was identified as long as students constructing their TEs were analyzed. After that, I focused on identifying the factors that influence students in the process of sharing and evaluate their TEs before drawing conclusions as a collective effort. As a result, there are four factors that influence students in the process of sharing and evaluating TEs. These factors are categorized as validity concerns, understandings, logical arguments, and conflicting evidence. In the following section, these four factors are explained one by one with examples.

5.2.1. Validity concerns

I think that the main challenge in the process of sharing and evaluating a TE is concerns about the validity of the TE. As mentioned before, the results of the TE are in the form of tacit knowledge. Such tacit knowledge, when properly validated, it will become reliable new knowledge: As Reiner and Gilbert (2000) wrote, “Such tacit knowledge, when coupled with logical processes [validity tool] in a TE, is unconsciously recruited to generate new knowledge" (p. 502). The lack of information to validate the tacit knowledge is the main issue in sharing and evaluating TEs. In this case, when students run and share their TE but do not provide reasonable evidence to support their TE, the other students will find it difficult to accept. Moreover, it will be worse when other students also do not have the knowledge or experience to support it.

In this study, when this situation happened, the other students rejected the TE and tried to find other ways to solve the problem given. For example, when Group 1 was solving Problem 2, H2 carried out a TE but could not provide evidence to validate the results of her TE, so the group did not accept the conclusion of her TE. This made other students perform another TE in order to solve the problem. The following is a transcript from Group 1 responding to Problem 2, asking about the scientists in the box.

H2	For example . . . I try to imagine [while holding her forehead], maybe this case is similar, when I am in a car that moves straight ahead then I drop a pen into a glass, we will see that the pen will move downward.	1

H4	But how will someone outside the car see the situation?	2
H2	People who are outside the car will view this differently.	3

H1	But there is gravity there. This situation will be different if there is no gravity. Maybe what H4 means is an apparent motion.	4
H2	What does it mean? [apparent motion]	5
H1	When we are in the car, you can see the trees beside the road as if they are moving, in fact, it is us who are moving. It is called an apparent motion.	6
H2	So here [pointing at the question]: Which one feels that she is moving?	7

As seen in the transcript above, the words “try to imagine” (Line 1) were coded as an indicator of visualization, which indicated that H2 started to visualized a TE. As expected, she visualized herself in a car that moves straight ahead. She then performed an experiment in her mind and described the results (Line 1). By using her mind's eye, H2 saw that the pen she dropped while the car moved straight ahead would enter exactly into the glass. H2 then shared her TE with the group members so that it could be run and evaluated together.

Yet, in the process of evaluating the TE, H2 did not have evidence to support the assertion that the pen she dropped in the car would fall downward. When H1 refuted it by arguing that there is gravity there (Line 4), H2 did not have the appropriate answer to refute H1. Therefore, they did not continue their TE to its conclusion. They then returned to the physics problem given and tried other ways to solve the problem (Line 7).

In this example, the absence of evidence to validate the results of the TE during the evaluation process causes the TE to fail. A collaborative TE will not occur if students do not provide evidence to validate the truth of the tacit knowledge obtained through performing the TE. Collaborative TEs will occur easily if students are rich in the experience, knowledge, or logic necessary to validate their TE.

5.2.2. Understandings

Mutual understandings among group members in the process of sharing and evaluating TEs is also the factor in constructing collaborative TEs. In our data, when the students failed to understand the evidence presented by others, they isolated themselves in the discussion. For instance, when L3 (one of the members of Group 3) performed a TE to predict the solution to Problem 3, which asked about the path of the ball after it exists at 2. The results of L3's TE indicated that the water coming out of the end of the hose would still spur vertically and perpendicularly even though the hose path is curved. L3 then shared her TE with the members of the group for evaluation. During the evaluation process, L1 did not take part, keeping quiet and listening to the other students who were busy evaluating the TE. The following is a piece of the transcript that shows that because L1 misunderstood the argument provided by L2 and L3, she was not active in the process of evaluating the TE.

R	What is the name of that kid's toy that you blow into?	1
L2	We do not remember. It is like a pipe which is blown and at its end, there is a small basket containing a ball. When it is blown, the ball will fly up.	2
L3	Yes, it will fly up [L3 supports L2’s answer]. I also forget the name of the toy. But the thing is, the ball’s direction will not curve.	3

L1	Ooo, yaa, I understand now. I think we blow it from the front [L1 starts to understand L2 and L3].	4
L3	No, the shape of the toy is like a U.	5
L2	Yes, like this [while demonstrating using his hand], but I forget the name.	6

As can be seen, L2 validated the results of the TE from her experience of playing with a *bola tiup*, a classic children's toy in Indonesia that is like a U-shaped pipe where the short end has a small basket containing a ball (Line 2). L3 also supported the arguments built by L2, although she also forgot the name of the toy (Line 3). However, L1 did not take part in this evaluation until she understood the meaning of L2's and L3's arguments. After L1 understood the evidence offered by L2 and L3, she also began to be involved in the process of evaluating the TE (Line 4). This demonstrates that mutual understanding is an influential factor in the process of sharing and evaluating TEs. This is in line with a study conducted by Asikainen and Hirvonen (2014a), who investigated teachers' understanding of a double-slit TE. Most participants in their study failed to perform TEs because of misunderstandings and gaps that occurred with previous knowledge.

> *In our study, only a small minority of the participants (4 out of 27) were able to describe the basic assumptions of the thought experiment correctly. The remainder revealed misunderstandings and gaps in their previous knowledge, which probably hindered their thought experimenting* (Asikainen & Hirvonen, 2014, p.1828).

5.2.3. Logical argument

Another factor that is closely related to sharing and evaluating TEs is the logic of the arguments made by the students. During the evaluation of a TE, students are actively involved in constructing arguments to support or reject the tacit knowledge as the results of the TE. Therefore, the logic of the arguments built by students is crucial in evaluating that tacit knowledge. If the argument is considered illogical, they will be hampered in the process of evaluating a TE. If the argument is based on the experience of the students but is not logical, the students will then be hampered or even stopped in the process of evaluating the TE and will not reach a conclusion.

The following transcript is an example of students being hampered in the process of evaluating a TE because the arguments they developed were not logical. The transcript is from Group 1 responding to Problem 5. While solving the problem, H2 performed a TE by imagining herself being in the car while holding a hanging magnet, as given in Problem 5. Using her mind's eye, H2 saw that the magnet she held was attracted towards the magnet on the car. H2 then shared her TE with the other group members to be run and evaluated together.

H2	Wait, when we were children we usually played magnets with something, let's say with nails. Imagine that we move the magnet closer to the nails, then the nails will move toward the magnet.	1
H1	So, do you think the magnet doesn't move?	2

H2 No, because we are holding it, while the nail is free, there is nothing restraining it. 3

[. . .]

H2 So, if the case is like that, then the car cannot move. Conversely, the hanging magnet will move. Hmm, but wait, but if the nail is held and the magnet is not, the magnet might be attracted. 4

H1 Yes, possible. But you said the nails will move. 5

H2 [shy laugh] I am a little confused. Let's try to look back at the question. 6

As can be seen, H2 tried to support the results of TE with her experience when playing with a magnet and nails. H2 argued that when the magnet being held is brought closer to a nail, then the nail will be attracted to the magnet (Lines 1-3). Therefore, H2 claimed that the hanging magnet would be attracted to the car as the answer to the problem given. However, H2 quickly realized that the argument she built was illogical because if the nail was held and directed at the magnet, the magnet would move (Line 4). As such, the argument built by H2 was considered illogical and automatically rejected. The students then returned to the problem given and tried to find other ways to solve the problem (Line 6). This demonstrates that the logical argument is an influential factor in the process of sharing and evaluating TEs.

5.2.4. Conflicting evidence

Another factor that influences students in the process of sharing and evaluating TEs is conflicting evidence. When the evidence obtained through life experience contradicts with other evidence presented by others, some students will try to maintain their evidence to reach conclusions. They can accept the arguments that are contrary to their beliefs, but still feel agnostic about their validity. During the data analysis, there is evidence that students ignore and reject the contradictory evidence presented by others because it is different from what they believed. The following transcript section taken when group 3 was responding to problem 5 is an example of this case.

L2	In my opinion, the car will move. Imagine that there is a magnet here (Magnet A) and in front of it there is also a magnet (Magnet B). Hence, if I am in the car and put the magnet that is hung (Magnet B) closer, then the magnet in the car (Magnet A) will move in any direction from the magnet in front of it . . .	1
L3	Will they pull each other?	2
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.	3
	[. . .]	
L3	So what do you think the car will move?	4
L2	Yeah, it will.	5
	[. . .]	
L1	For me, it will not move. I think that the accumulation mass of the magnet on the car is greater than the hanging magnet. It will affect as well.	6
L2	I still disagree with you (L1) because the magnets remain in front of the car and will attract each other. Therefore, when the hanging magnet is brought close to the car, I think that the car will also move wherever the hanging magnet moves like the video I have seen . . .	7
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].	8
L4	But still, there is a possibility, though very little, that the car will move.	9
	[. . .]	

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 don't think it's logical that the car will move.	10
L4	Yes, I think so.	11
	[. . .]	
R	So, what is the conclusion?	12
P	All participants laugh.	13
L1, L3, L4	The car will not move.	14
L2	I think the car will move like in the video I have seen.	15

As seen in the transcript above, L2 visualized a TE by imagining herself being on a magnet-mounted car in front of her (Line 1). L2 sensed that if she brought another magnet, which was hanging, to the car, then the car would move closer to the hanging magnet wherever the magnet was. L2 evaluated the results of the TE using her experience of watching cartoons (Line 3). 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. The experience of watching cartoons is used by L2 in evaluating the TE she ran.

During the evaluation of TE, L1 tried to refute the result of TE because L1 claimed that the magnet in the car has extra force (the extra mass of the car and the person) while the hanging magnet does not have (Line 6). Therefore, according to L1, the car will not move. However, L2 still maintains her argument that the car will move based on her experience when watching a video (Line 7). L3 was also involved in evaluating of the TE. She then rejected the L2's argument 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 argued that maybe the hanging magnet would be attracted to the car because the rope and the stick were not strong enough to pull the car (Line 8). She assumed that if the two magnets were tied together on a rope, then they might be pulling each other (Line 10). However, L2 still believed that the car would move like the video she had seen before (Line 15). The video watched by L2 was similar to the problem given, so she had a high firmness in her beliefs. This demonstrates that conflicting evidence is an influential factor in the process of sharing and evaluating TEs.

5.3. Summary and discussion

By viewing collaborative TEs as an activity to socially construct knowledge where students carry out experiments in their minds and then share them with group members to be run and evaluated together as a collective effort to reach a conclusion, this chapter aims to investigate the factors that influence students in constructing collaborative TEs. Understanding these factors not only gives us a clear description of how students perform TEs in detail but also can generate information about how to help students to improve their TEs. To achieve the intended goals, there were two research questions that are used to guide me in analyzing the data and discussion.

What factors influence students in visualizing TEs?

It can be concluded that there are five factors that encourage students to visualize TEs as the initial step of collaborative TEs. First, conflicting ideas between students in understanding a problem can encourage them to broaden their perspectives so that they are compelled to do TEs in order to support their assumptions, and simultaneously to refute the assumptions of their fellow group members. Second, the similarity of ideas in building an assumption or hypothesis also can encourage students to do TEs to further support their assumptions. Third, the guidance and support of more experienced students can also encourage less experienced students to visualize TEs so that the collaborative TEs can occur (in this case, master's students and undergraduate students). Fourth, students' bodily knowledge is also considered an important factor that can encourage the emergence of collaborative TEs, in that students' physical experience that may be similar to the physics problems with which they faced. Last, students' imaginary visual knowledge, which refers to individual abilities of imagistic simulation, such as the manipulation of imaginary objects and imagined situations, can also encourage the emergence of collaborative TEs.

What factors influence students in sharing and evaluating TEs?

It can be concluded that there are four factors that influence students in the process of sharing and evaluating TEs: validating of concerns, understandings, logical arguments, and conflicting evidence. The absence of evidence to validate the results of a TE during the evaluation process leads to the failure of the TE because it can cause students to not be able to arrive at a conclusion for the TE. Likewise, a misunderstanding between students in understanding the evidence presented by others or the argument being built being illogical can lead to the failure of a TE. Students establish an argument based on their experience, but if it is considered illogical, then students will be hampered or even stopped in the process of evaluating a TE and may not reach a conclusion. Also, when the evidence obtained through life experience contradicts with other evidence presented by others, the students will try to maintain their beliefs to reach conclusions. They can accept the arguments that are contrary to their beliefs, but still feel agnostic about their validity.

Stephens and Clement (2012) argued that TEs do not need to be built together because students can independently produce novel scenarios, make predictions, and evaluate their own scenarios during class discussions. However, this study has shown that students performed TEs not only because they were inspired by their own imaginary visual knowledge or bodily knowledge but also because of interaction between students in a group. Conflicting ideas between students in understanding a problem will encourage them to broaden their perspectives, leading them to perform TEs in order to support their ideas and to refute the ideas of their fellow group members. Likewise, sharing similar ideas can lead to students responding to and supporting each other and performing TEs in order to further support their assumptions. This is in accordance with the function of TEs as an imagination tool for scientists not only to refute a theory by disclosing a conflict between the existing concepts and nature (Kuhn, 1977) but also to develop and support a hypothesis (Gendler, 2004; Galili, 2009). In addition, this study also showed that TEs could arise when master's students provide support and guidance for undergraduate students. In order to teach TEs at school, therefore, I think that mentorship by a teacher or a more experienced person in the designing and implementing TEs is essential not only to encourage students to perform TEs but also to improve the quality of students' TEs.

Finally, I hope that this study will help physics educators to improve their students' TE abilities by better understanding the factors that influence students in constructing collaborative TEs during physics problem-solving activities. I would highly recommend that future physics teachers be introduced to and familiarized with TEs as useful tools for teaching physics at school. It is because TEs as a tool of the imagination for investigating the nature of science (Brown, 2006; Sorensen, 2016) have great potential to be used in encouraging and developing students' creative thinking. Hadzigeorgiou (2016) argued that "although one can imagine without being creative, one cannot be creative without being imaginative" (p. 4).

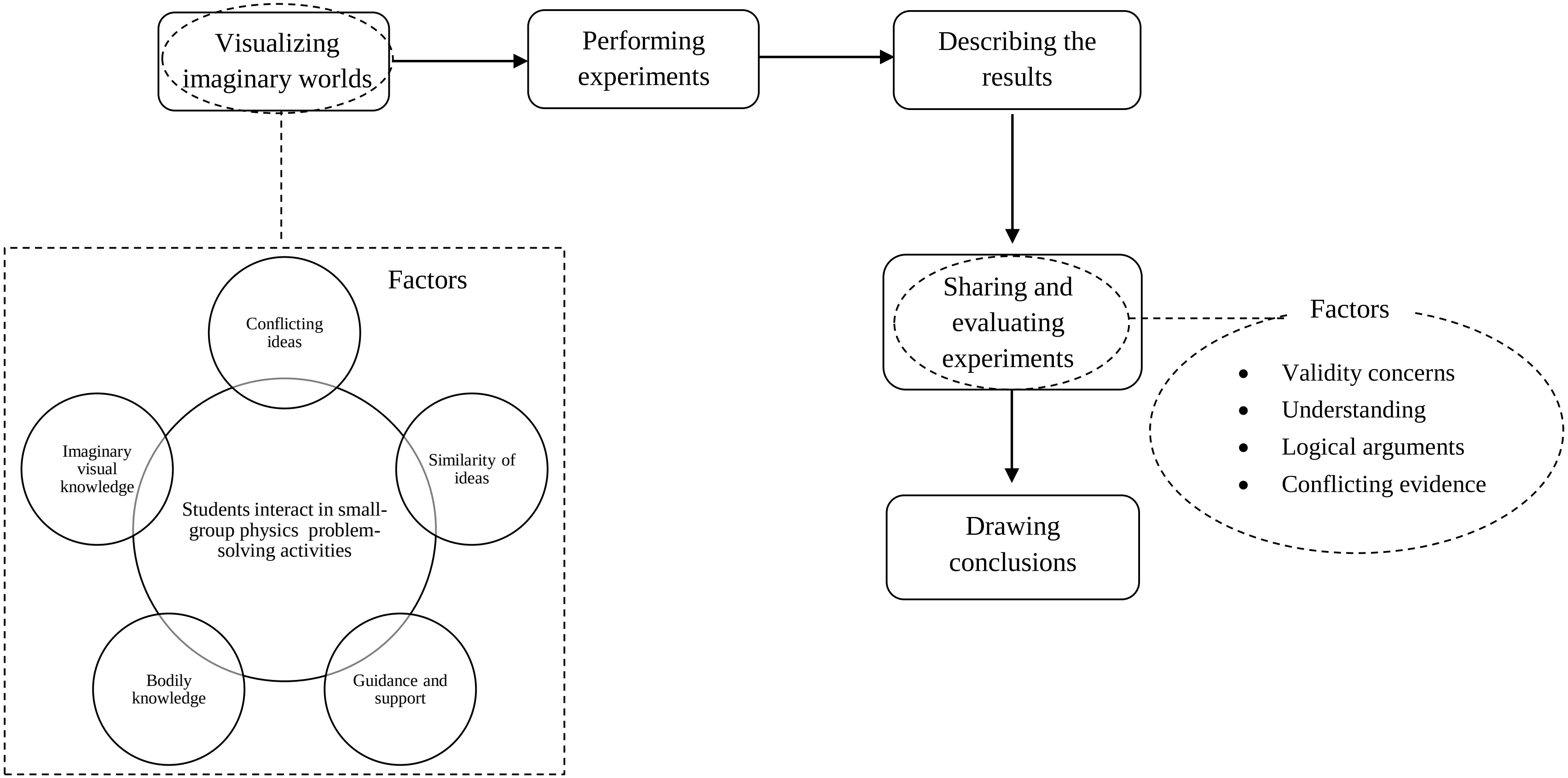


Figure 5.1. Factors influencing collaborative TEs

Chapter 6. Conclusions and Implications

6.1. Summary and conclusions

Several studies in science education have shown that most science teachers and students have difficulties in designing and doing TEs (e.g., Reiner & Burko, 2003; Asikainen & Hirvonen, 2014a, Kösem & Özdemir, 2014). Even when students visualize the imaginary world appropriately, design and run experiments in their heads structurally, they may still draw erroneous conclusions from the TEs (Reiner & 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.

In particular, there is limited study on TEs in relation to collaborative learning. Previous studies have focused more on the TEs' processes at the individual level rather than in groups (e.g., Georgiou, 2005; Clement, 2009; Asikainen & Hirvonen, 2014a; Bademci & Sari, 2014; Kösem & Özdemir, 2014). Although Reiner (1998) argued that TEs are more easily constructed in a collaborative manner, how TEs are constructed collaboratively are not clearly explained either by Reiner (1988) or subsequent studies. In addition, the steps of TEs proposed by Reiner (1988)—visualization, hypothesis, experiment, results, and conclusions—did not reflect the existence of collaborative activities. Brown (2006) also proposed three steps of TEs: (a) visualize a situation, (b) carry out an operation, and (c) describe the result. Both Reiner (1998) and Brown (2006) focused on TEs steps of an individual perspective while ignoring aspects of the group. Therefore, the purposes of this study were to explore how students are involved in the process of constructing TEs in group learning, how students share and negotiate meaning during constructing TEs, how students validate the knowledge generated from TEs, and what factors influence students in constructing TEs in group learning.

There were 12 voluntary participants in this study, six master's students, and six undergraduate students in three universities in Makassar, Indonesia. The participants were divided into three groups, so that each group consisted of four students. The physics problem-solving activities were used to set the necessary environments for observing the processes and factors that influenced students when constructing collaborative TEs. Audio and video of the three group activities were recorded as the source of data. The group observation was conducted in the physics meeting room and physics lab at the Unismuh University in Indonesia. In order to ensure the validity of data, the notes that were written and drawn freely by the students while solving the problems and researcher' observation notes were also collected as the sources of data. Thus, the data collected in this study were audio and video recordings, students' notes, and observation notes by the researcher.

The results show that while solving physics problems, students construct, share, and evaluate their TEs. This indicates that TEs can be designed and constructed in a collaborative manner even though the TEs are mostly individual in nature. In the process of sharing and evaluating TEs, there is an activity of negotiation of meaning as the main characteristics of collaborative activities. Each individual or member of the groups in this study are engaged in discussion by asking and answering questions, supporting and clarifying arguments, validating the results of TEs, and so on. Wenger (1998) argued that the negotiation of meaning involves the interaction of participation and reification in the act of processing the claim. As participation, students contributed to the negotiation of meaning by being a member of the social community and described their social experience of living the world in their practice. Meanwhile, in reification, students produced claims based on their experiences, and they were continuously fixed in their form until the final process of negotiation of meaning: an agreement with all group members. This agreement is the step towards the final processes of collaborative TEs: conclusion.

Figure 6.1 shows the processes and factors of collaborative TEs while students were solving physics problems. As can be seen, collaborative TEs begin with one student generating a TE then sharing it with the group members. The members of the group then run the TE as suggested by its producer. After the group members run it, they begin to evaluate not only the processes but also the results. In fact, when students failed to provide evidence of their TE, they did not hesitate to redesign or proposed a new TE. The new TE was then shared again with the group members to be run and evaluated together. This evaluation process was done continuously until the students reached conclusions as a collective effort. Therefore, I refer to collaborative TEs as 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. 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 by asking and answering questions, supporting arguments, clarifying claims, validating the results of TEs and so on, collaborative TEs are considered as a process of socially constructing knowledge.

Although I agree with Reiner (1998) that TEs are more easily constructed in a collaborative manner in which the number of students' contributions can lead to the complexity of TEs, some of the TEs steps proposed by Reiner do not match with my results. Reiner (1988) had analyzed students' activities in constructing TEs when they were working on the problems in collaborative settings and proposed five steps of TEs: visualization, hypothesis, experiment, results, and conclusions. In my study, I did not see students proposing hypotheses after the visualization stage. When the problem was given, the students visualized the imaginary world, and directly performed experiments without setting hypotheses. Although in this study there were some students who proposed hypotheses first and then visualized the imaginary world as the first step in constructing TEs, they did TEs to determine whether their hypothesis was true or false, or to provided more explanation about their hypothesis, and therefore, proposing hypothesis is not an integral part of the TEs steps. In addition, after students described the results of TEs, they did not immediately draw conclusions as proposed by Reiner (1998) but they shared with group members to be run and evaluated together. During sharing and evaluating TEs, students were involved in the process of negotiation of meaning which is the hallmark of collaborative activity (Bruffee, 1995; Dillenbourg, 1999; Chiu, 2000). Therefore, based on this study, I propose five activities or steps carried out by students in constructing TEs in collaborative settings: visualizing imaginary worlds, performing experiments, describing the results, sharing and evaluating experiments, and drawing conclusions.

There are five factors that can encourage students to visualize TEs as the initial step in constructing collaborative TEs, as shown in Figure 6.1: conflicting ideas, similarity of ideas, guidance and support from more experienced people, inspiration by bodily knowledge, and inspiration by imaginary visual knowledge. Stephens and Clement (2012) claimed that TEs do not need to be built together because students can independently produce novel scenarios, make predictions, and evaluate their own scenarios during class discussions. However, this study has shown that students performed TEs not only because they were inspired by their own imaginary visual knowledge or bodily knowledge but also because of interaction between students in a group. Conflicting ideas between students in understanding a problem encourage them to broaden their perspectives, leading them to perform TEs in order to support their ideas and simultaneously refute the ideas of their fellow group members. Likewise, sharing similar ideas can lead to students responding to and supporting each other, and performing TEs in order to further support their assumptions. This is in accordance with the function of TEs as an imagination tool for scientists not only to refute theories by disclosing a conflict between the existing concepts and nature (Kuhn, 1977) but also to develop and support existing theories (Gendler, 2004; Galili, 2009). In addition, this study also showed that TEs could arise when master's students provide support and guidance for undergraduate students. Thus, I believe that placing students into a group is a most effective way not only to encourage students to perform TEs but also to minimize TEs errors because, in group learning, students will use each other's resources and skills (e.g., experience, knowledge, and logic) in validating their TEs so that they come to the correct conclusion.

There are three purposes of students in conducting TEs when they were working on the problems: prediction, verification, and explanation. In prediction, students do not have a hypothesis or general assumption about the solution to the problem. When a problem was given, students directly visualized an imaginary world, and then designed and ran a TE to predict the solution to the problem. In verification, students first proposed a hypothesis or an assumption, and then designed and ran a TE to determine whether the hypothesis or assumption was true or false. Similar to the verification, in explanation, students did not directly design and conduct a TE but instead submitted a hypothesis first. They then performed a TE as a tool to provide further explanation about the hypothesis as the temporary answer to the problem at hand.

The study has also shown that the students validate the results of TEs using four evaluation resources, as shown in Figure 6.1. Firstly, some students used conceptual understanding that refers to physics concepts, physics equations, and laws such as Newton's law. Secondly, some students used their specific experience. Past and daily experiences such as watching movies, playing ball, and traveling by motorcycle or train are examples used by the students when evaluating their TEs. Thirdly, students used logical reasoning in the form of personal assumptions or perceptions. Although this source is only a personal assumption or perception, it was enough to convince thought experimenters to support or reject the tacit knowledge they evaluated. Lastly, students used conceptual-logical inference that combines laws, principles, or concepts of physics with logical manipulation.

In addition, there is some evidence that students evaluate not only the results but also the processes of the 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 they failed to provide evidence of the resulting tacit knowledge, they did not hesitate to redesign a new TE. However, when the results of TEs were invalid, the students corrected the results without trying to redesign new TEs. Therefore, in the evaluation TEs, both the process and the results can be checked.

Figure 6.1 also shows four factors that influence students in the process of sharing and evaluating TEs that can cause students not to be able to arrive at a conclusion for the TE or to draw wrong conclusions: validating of concerns, understandings, logical arguments, and conflicting evidence. The absence of evidence to validate the results of a TE during the evaluation process leads to the failure of the TE. Likewise, a misunderstanding between students in understanding the evidence presented by others or the argument being built illogically can lead to the failure of a TE. Students establish an argument based on their experience, but if it is considered illogical, then students will be hampered or even stopped in the process of evaluating a TE and may not reach a conclusion. Also, when the evidence obtained through life experience contradicts with other evidence presented by others, students will try to maintain their beliefs to reach conclusions. They can accept the arguments that are contrary to their beliefs, but still feel agnostic about their validity.

In summary, even though TEs are mostly constructed by an individual scientist, the TEs can also be designed and constructed in a collaborative manner. 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. There are three purposes of students in conducting TEs: to predict the solution to the problem given, to verify whether the hypothesis or assumption being submitted is true or false, and to provide more explanation for their hypothesis. In order to validate the results of TEs, the students using four evaluation resources: conceptual understanding, past-daily experience, logical reasoning, and conceptual-logical inference. There are five factors that encourage students to visualize TEs: conflicting ideas, similarity of ideas, guidance and support from more experienced people, inspiration by bodily knowledge, and inspiration by imaginary visual knowledge. In addition, there are four factors that influence students in the process of sharing and evaluating TEs: validating of concerns, understandings, logical arguments, and conflicting evidence.

Based on this study, therefore, I would recommend that collaborative TEs be introduced to both current and future physics teachers as a useful tool for teaching TEs at school for several reasons. First, because TEs can produce both correct and incorrect results in the development of a scientific theory (Reiner & 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 reliable conclusions. Second, because TEs are mental model activities that are carried out mostly in the minds of individuals (Nersessian, 1992; Gilbert & Reiner, 2000), some students have difficulty in constructing TEs independently (Kösem & Ö zdemir, 2014). With collaborative TEs, students who have difficulties will be helped by other students. Third, collaborative TEs can also improve social interactions and support diversity. In collaborative TEs, students must work together in a group with different backgrounds, experiences, cultures, and knowledge. When students spend time together to work, they will learn how to relate to each other. They also make friendships by getting to know each other, thereby increasing morale and group performance. Fourth, collaborative TEs can also bring students closer to scientific argumentation through the interpretation and evaluation of the ideas and views with each other. Over the past decade, scientific argumentation has received serious attention from science educators around the world as a core competency in schools (e.g., Erduran et al., 2015; Lazarou et al., 2017). Fifth, through collaborative TEs, students clarify each other's ideas, views, and opinions through discussion forums before making conclusions. Therefore, collaborative TEs might nurture students' critical thinking and creative thinking skills. Vygotsky (2004) emphasized the fact that imagination based on prior knowledge and experience has implications for the development of creative thinking. It is a higher mental ability that involves a thought process that is directed consciously and is the basis of all creative activities, both in art and science:

> *In everyday life, fantasy or imagination refer to what is not actually true, what does not correspond to reality, and what, thus, could not have any serious practical significance. But in actuality, imagination, as the basis of all creative activity, is an important component of absolutely all aspects of cultural life, enabling artistic, scientific, and technical creation alike* (Vygotsky, 2004, p. 9).

There are various possibilities for including TEs in subject matter related to physics, such as mechanics, thermodynamics, and relativity (Asikainen & Hirvonen 2014b; Velentzas & 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 and take them into account in teacher guidance. In this way, future physics teachers would get a strong basis for using collaborative TEs as part of their physics teaching.

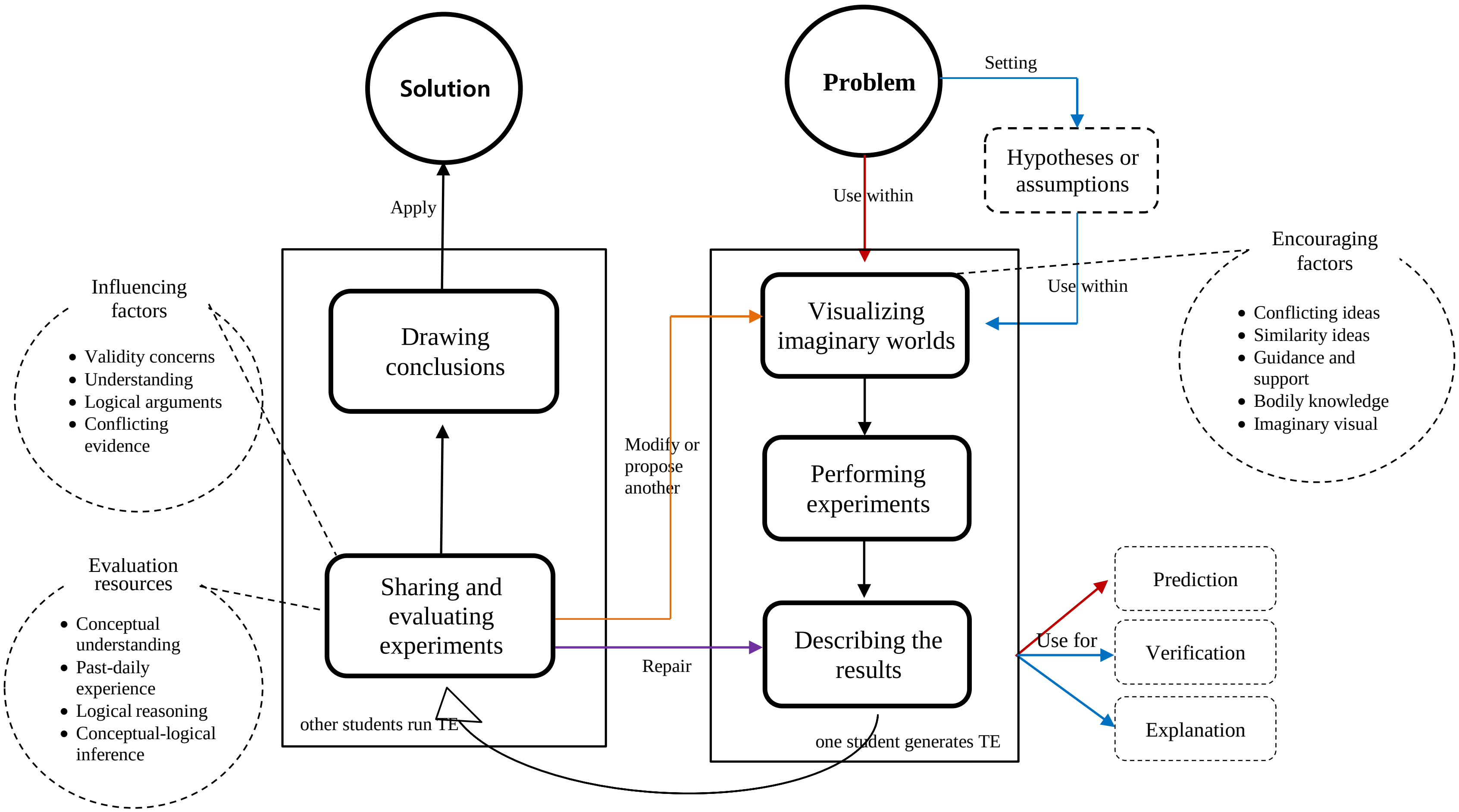


Figure 6.1. The Processes of and factors in collaborative TEs during physics problem-solving activities

6.2. Implications

The findings of this study have various pedagogical implications for physics classes. First, the results of the study have shown that while solving physics problems, students construct, share, and evaluate their TEs. This indicates that TEs can be designed and constructed in a collaborative way even though the TEs are a personal and tacit process of experimentation with personal imagery that scientists use in formulating a new theory or refuting an existing theory. Some studies have shown that most students have difficulty in constructing TEs independently (e.g., Reiner & Burko, 2003; Asikainen & Hirvonen, 2014a, Kösem & Özdemir, 2014) because TEs are mental model activities that are carried out mostly in the minds of individuals (Nersessian, 1992; Gilbert & Reiner, 2000). Several studies 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 (Norton, 2004; Brown, 2006). One way of overcoming this difficulty and helping students to construct TEs is with collaborative TEs. In collaborative TEs, students who have difficulties will be helped by other students in constructing TEs. I have observed in this study that some students have felt difficulties in starting and designing TEs can sometimes be more active in the evaluation of the TEs. Therefore, with collaborative TEs, all students are actively involved in constructing the TEs.

Second, this study has shown that students performed TEs not only because they were inspired by their own imaginary visual knowledge or bodily knowledge but also because of the interaction between students in a group. The similarity of ideas is the most influential factor in encouraging students to do TEs. Sharing similar ideas between students can lead to students responding to and supporting each other, and performing TEs in order to further support their assumptions. Likewise, conflicting ideas between students in understanding a problem would encourage them to broaden their perspectives, leading them to perform TEs in order to support their ideas and simultaneously refute the ideas of their fellow group members. This gives us implications about how to support the interaction and discourse between students in their groups. Therefore, I think that giving more interaction between students can give them more opportunities to do TEs.

Third, this study also showed that TEs could arise when master's students provide support and guidance for undergraduate students. This support can be in the form of positive responses and also emotional support, such as facial expressions and hand gestures. In order to teach TEs at school, therefore, I think that mentorship by a teacher or a more experienced person in the designing and conducting TEs is essential not only to encourage students to perform TEs but also to improve the quality of students' TEs.

Fourth, this study has shown that the students evaluated the results of TEs using four evaluation resources: conceptual understanding, past-daily experience, logical reasoning, and conceptual-logical inference. During the

TEs evaluation, students are involved in the process of negotiation of meaning. They do this evaluation activity continuously until they get strong evidence to support the truth of their TEs. In fact, when they failed to provide evidence of the resulting TEs, they did not hesitate to redesign a new TE. Therefore, it is necessary to not only encourage students to participate actively but also enhance the understanding of TEs evaluation resources.

6.3. Limitations and future directions

This study has explored the processes of and the factors in collaborative TEs. However, there were some limitations in this study, and recommendations for further study are suggested as follows.

First, this study has shown that students designed and ran TEs when solving physics problems. However, the problems in this study were on solely about mechanical problems, and these problems were quite easy for the master's student group. I think that it is possible to capture the different processes of TEs when the content and difficulty level of the problems are changed. Also, the form of the problem used in this study is only a conceptual physics problem. The different forms of problems, however, such as well-structure problems or ill structure problems, may also reveal different processes of TEs. Therefore, further study is needed to explore the processes of TEs for different contents, form, and difficulty of the physics problems.

Second, this study also showed that TEs could arise not only because of the cognitive factors (students' bodily knowledge or students' imaginary visual knowledge) but also because of affective factors (e.g., supporting of master's students to undergraduate students). However, this study did not examine in detail the forms of emotional imagination supports among students in a group that encourage them to perform TEs. Therefore, further study is needed to investigate the features of students' affective, especially the features of emotional imagination that might encourage the emergence of TEs while students are solving physics problems in their groups.

Third, the results of this study were only from small numbers of students who are difficult to say represent the experiences of all students. Therefore, further study is needed to support these results by implementing collaborative TE in real classes. 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 and refined.

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국문 초록

협력적 사고실험의 과정과 요인 탐색
- 물리학 문제해결 활동을 중심으로 -

Hartono Bancong B

과학교육과 물리 전공

사범대학

서울대학교

사고실험은 과학자들이 새로운 이론을 형성하거나 기존 이론을 반박할 때 그들 마음 속에서 수행하는 개인적이고 암묵적인 실험의 과정이다. 하지만 학습을 사회적 과정으로 보는 관점에서, 본 연구는 사고실험이 협력적 방식으로 구성될 수 있는지 알아보고자 한다. 특히 본 연구는 협력적 학습 상황에서 학생들이 어떻게 사고실험을 구성하는지 탐색하고 이 과정에서 학생들에게 영향을 미친 요인들을 밝히고자 하였다.

본 연구는 인도네시아 마카사(Makassar) 지역 소재 세 개의 대학에 재학 중인 12 명의 연구 참여자(6 명의 석사 과정생과 6 명의 학부생)를 대상으로 수행되었다. 연구 참여자는 네 명씩, 세 그룹으로 나뉘어 물리 문제해결 활동에 참여하였으며, 이 활동에서 학생들이 협력적 사고실험을 구성하는 과정과 이 과정에서 학생들에게 영향을 준 요인들을 관찰하였다. 마카사 지역 내 대학교의 물리학 실험실과 회의실에서 진행된 세 그룹의 물리 문제해결 활동은 모두 비디오카메라로 녹화, 녹음 되었으며 이를 분석 자료로 활용하였다. 자료 분석의 타당성 확보를 위해 학생들이 물리 문제해결 과정에서 자유롭게 작성한 노트와 연구자의 관찰 노트를 함께 분석하였다.

연구 결과, 학생들은 물리 문제해결 과정에서 그들만의 사고실험을 구성하고 이를 공유하고 서로 평가하는 것으로 나타났다. 이는 사고실험이 본질적으로는 개인적인 속성을 가졌지만 협력적인 방식으로 설계되고 구성될 수 있다는 것을 보여준다. 이러한 관찰 결과를 바탕으로, 협력적 사고실험(collaborative thought experiments)은 하나 혹은 그 이상의 개인의 마음 실험실에서 설계되고 구성된 가상의 세계를 시각화하여 이를 그룹 구성원들과 공유하고 함께 평가하여 결론에 이르는 협력적 활동으로 정의될 수 있다. 협력적 사고실험을 구성하는 과정에서 학생들은 '가상 세계의 시각화', '실험 수행', '결과 서술', '실험의 공유와 평가' 그리고 '결론 도출' 등 다섯 가지 활동을 수행하였으며 본 연구에서는 이를 협력적 사고실험의 단계로 보았다.

학생들이 사고실험을 하는 목적은 '예측', '검증', '설명' 세 가지였다. 예측을 목적으로 하는 사고실험에서 학생들은 문제가 주어졌을 때 바로 가상 세계를 시각화 하였으며 해결 방안을 예측하기 위한 사고실험을 설계하고 전개하였다. 검증을 목적으로 하는 사고실험에서 학생들은 먼저 가설을 제안하였으며, 제안된 가설의 진위여부를 결정하기 위해 사고실험을 설계하고 진행하였다. 설명을 목적으로 하는 사고실험에서 학생들은 자신들이 세운 가설에 관한 추가적인 설명을 제공하기 위한 도구로서 사고실험을 설계하고 이를 전개하였다.

또한 연구는 학생들이 네 가지의 평가 자원(evaluation resources)을 활용하여 자신들의 사고실험 결과를 입증하려 한다는 것을 밝혔다. 첫번째로 어떤 학생들은 물리 개념, 물리 식, 물리 법칙 같은 '개념 이해'를 사용하였다. 두번째로 영화에서 본 것, 어릴 적 장난감, 기차나 오토바이 여행처럼 학생의 '과거나 일상 경험'이 그들의 사고실험을 평가할 때 자원으로 활용되었다. 세번째로 학생들은 개인적 가정이나 인식을 형성하면서 '논리적 추론'을 사용하였다. 이 평가 자원은 개인적 가정이나 인식에 불과하나 다른 학생에 의해서 제안된 사고실험의 암묵적 지식을 거절하거나 지지하기에 충분하였다. 마지막으로 학생들은 논리적 조작과 함께 물리 법칙, 원리 또는 개념을 결합한 '개념적-논리적 추론'을 사용하였다.

이 연구는 협력적 사고실험의 첫번째 단계인 가상 세계의 시각화를 촉진할 수 있는 다섯 가지 요인-'상충되는 아이디어', '아이디어의 유사성', '보다 경험 많은 학생으로부터의 지도와 지원', '학생의 몸지식(bodily knowledge)'-을 밝혔다. 이는 사고실험이 학생의 개인적 지식(몸지식과 상상적 시각 지식)뿐 아니라 그룹 내에서 학생들 간의 상호작용으로 인해서도 촉진될 수 있다는 것을 보여주었다. 주어진 문제 이해에 있어서 구성원간 상충되는 아이디어는 학생들의 인식을 넓혀주고, 자신의 아이디어를 지지함과 동시에 상대방의 아이디어를 반박하기 위한 사고실험을 수행하도록 이끌었다. 마찬가지로, 비슷한 아이디어의 공유는 학생들이 서로를 지원하고 그들의 가정을 좀 더 지지하기 위한 사고실험을 수행하도록 만들었다. 또한 석사 과정생의 학부생을 위한 지원과 지도가 있을 때 사고실험이 유발될 수 있음을 알 수 있었다.

뿐만 아니라, 사고실험의 공유와 평가 과정에서 학생들에게 영향을 미치는 것으로 간주되는 네 가지 요인을 찾았다. 이는 '우려에 대한 검증', '이해', '논리적 논쟁' 그리고 '상충되는 증거'이다. 평가의 과정에서 사고실험의 결과를 입증할 수 있는 증거의 부재, 제시된 증거에 대한 서로 다른 이해, 비논리적인 논쟁은 사고실험의 실패를 가져오는 것으로 나타났다. 또한 일상 경험을 통해 획득한 증거가 다른 학생들이 제시한 증거와 상충될 때, 학생들은 결론에 도달하기 위해 자신의 신념을 유지하려고 노력하는 모습을 보였다.

이 연구를 바탕으로 현재 학교에서 물리를 가르치고 있는 그리고 앞으로 물리를 가르칠 교사들에게 협력적 사고실험을 교수학습의 유용한 도구로서 제안할 수 있을 것이다. 첫째, 협력적 사고실험에서 동료 간 상호작용은 사고실험이 신뢰할만한 결론에 도달할 수 있도록 과정과 결과 모두를 바로잡을 수 있게 해주는 큰 잠재력을 가지고 있다. 둘째, 사고실험의 구성에서 어려움을 겪는 학생은 협력적 사고실험을 통해서 다른 동료들의 도움을 받을 수 있다. 셋째, 협력적 사고실험은 사회적 상호작용을 향상시키고 다양성을 지지할 수 있다. 넷째, 협력적 사고실험은 아이디어의 해석과 다른 사람의 생각과 관점의 평가를 통하여 과학적 논변 활동을 학생들이 경험하도록 할 수 있다. 마지막으로 협력적 사고실험에서 학생들은 결론에 도달하기 전 의견을

종합적으로 토론하는 과정을 거침으로써 서로의 아이디어와 관점 그리고 의견을 더욱 명확하게 할 수 있다. 따라서 협력적 사고실험은 학생들의 비판적 사고력과 창의적 사고력을 키울 수 있을 것이다.

핵심어: 협력적, 요인, 물리 교사, 문제해결, 과정, 사고실험

학번: 2016-39911

Appendix A
IRB Letter of Approval

심의결과 통보서

수신

책임연구자	이름: Hartono Bancong B	소속: Department of Physics Education, Seoul National Un	직위: 박사과정
지원기관	해당없음		

과제정보

승인번호	IRB No. 1811/003-015		
연구과제명	물리 문제 해결 활동에서 나타나는 협력적 사고실험 과정		
연구종류	학술 연구, 학위 논문 연구, 관찰연구, 면담(FGI 포함)		
심의종류	재심의		
심의일자	2018-11-26		
심의대상	연구계획서(재심의), 재심의 답변서		
심의결과	승인		
승인일자	2018-11-26	승인유효기간	2019-11-25
정기보고주기	12개월		
심의의견	1. 심의결과 제출하신 연구계획에 대해 승인합니다. 2. 연구자께서는 승인된 문서를 사용하여 연구를 진행하시기 바라며, 만일 연구진행 과정에서 계획상에 변경사항 (연구자 변경, 연구내용 변경 등)이 발생할 경우 본 위원회에 변경신청을 하여 승인 받은 후 연구를 진행하여 주십시오. 3. 유효기간 내 연구가 끝났을 경우 종료 보고서를 제출하여야 하며, 승인유효기간 이후에도 연구를 계속하고자 할 경우, 2019-10-26까지 지속심의를 받도록 하여 주십시오.		
검토의견	계획서 검토 의견 동의서 검토 의견 기타 검토 의견		

2018년 11월 26일

서울대학교 생명윤리위원회 위원장

본 위원회가 승인한 연구를 수행하는 연구자들은 다음의 사항을 준수해야 합니다.

1. 반드시 계획서에 따라 연구를 수행해야 합니다.

2. 위원회의 승인을 받은 연구참여자 동의서를 사용해야 합니다.
3. 모국어가 한국어가 아닌 연구참여자에게는 승인된 동의서를 연구참여자의 모국어로 번역하여 사용해야 하며 번역본은 인증 및 위원회의 승인을 거쳐야 합니다.
4. 연구참여자 보호를 위해 불가피한 경우를 제외하고는 연구 진행중의 변경에 대해서는 위원회의 사전 승인을 받아야 합니다. 연구참여자의 보호를 위해 취해진 응급상황에서의 변경에 대해서는 즉각 위원회에 보고해야 합니다.
5. 위원회에서 승인 받은 계획서에 따라 등록된 연구참여자의 사망, 입원, 심각한 질병에 대하여는 위원회에 서면으로 보고해야 합니다.
6. 임상시험 또는 연구참여자의 안전에 대해 유해한 영향을 미칠 수 있는 새로운 정보는 즉각 위원회에 보고해야 합니다.
7. 위원회의 요구가 있을 때에는 연구의 진행과 관련된 사항에 관하여 위원회에 보고해야 합니다.
8. 연구참여자 모집광고는 사용 전에 위원회로부터 승인을 받아야 합니다.
9. 강제 혹은 부당한 영향력이 없는 상태에서 충분한 설명에 근거하여 연구참여자로부터 동의를 받아야 하며, 잠재적인 연구참여자에 대해서 연구 참여 여부를 숙려할 수 있도록 충분한 기회를 제공해야 합니다.

Appendix B
Consent Forms

IRB No. 1811/003-015 유효기간: 2019년 11월 25일

SEOUL NATIONAL UNIVERSITY

Consent to Take Part in a Research

Title of Research	: The Natural Processes of Collaborative Thought Experiments During Physics Problem-Solving Activities.
Investigator's Name	: Hartono Bancong B, Ph.D. Student, Principal Investigator. Jinwoong Song, Professor, Research Advisor.
Research Entity	: Seoul National University

This consent form may contain some information which is difficult to understand. If there is any information unclear, please contact and ask Hartono Bancong B. The contact numbers are written in the end of this consent form.

1. Why are we conducting this research?

The goal of this study is to create a framework of collaborative TEs. The researcher will investigate the students' activities in constructing collaborative TEs (the phases of collaborative TEs, the reasoning used, and the influencing factors) during physics problem-solving activities. The researcher will explain this research before asking you to participate.

2. How many people participate?

There are at least 12 pre-service physics teachers will participate in this research. The participants will be organized into three different groups. Each group consists of 4 participants.

3. Do I have to participate?

You may choose not to participate. There will be nothing harmful for choosing not to participate.

4. What am I going to be doing in this study?

If you agree to participate in this study, during about 8 weeks, the researcher will give you 4 physics problems to be solved with your group members. Group discussions will take approximately 20-30 minutes for each physics problem. During the group discussion, The researcher will video and audio record using two stationary cameras (one at the front focused on students and one at the back focused on the researcher). For each group of participants, observation and recording will be carried out four times according to the number of physics problem available (4 problems). The number of participants in each group consists of 4 participants. After that, during about 4 weeks, you will be interviewed individually. In the interview, you will be asked about your thinking at a particular instant time that is not expressed during problem-solving activities. The interview will be conducted in the physics meeting room or physics lab as much as one time with a duration of about one hour. The contents of the interview will be recorded on the personal mobile

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phone of the researcher and will be used as research data. However, your personal information will be anonymously protected.

5. How long will this research take place?

The research is planned to take about 12 weeks. However, it depends on the data obtained, this research may finish earlier than expected. During this period, you will participate in 4 group discussions and 1 interview.

6. Can I stop while I am participating?

Yes, you can leave at any time without any disadvantages during your participation. If you want to stop participating in the study, please tell your researcher immediately. If you quit, the collected data is immediately discarded and excluded from the analysis.

7. Are there any side effects?

Except for the embarrassment of seeing yourself on videotape segments shown during the discussions and interview, there are no potentially harmful risks related to participating in this study.

8. Do participants benefit from participating in this study?

There is no direct benefit from your participation in this study. However, science education can contribute to a better understanding of practical ways of influencing the lives of learners.

9. Are there any disadvantages if I choose not to participate?

If you feel uncomfortable with participating in the study, you may not choose to participate. There are no disadvantages for choosing not to participate.

10. Is the confidentiality of all personal information obtained from the study guaranteed?

Yes, there is a guarantee of the confidentiality of all personal information obtained from this study. Personal information manager is Hartono Bancong B of Seoul National University (010-2163-9154). The personal information that will be collected in this study are full name, age, gender, phone number, and email address. The researcher will collect your email addresses as a way to contact you during the research activities. As a consideration, your phone numbers will also be collected due to the internet instability in Indonesia. The researcher will send a message via telephone to you a day before data collection activities begin to remind the time and place. As long as the researcher is in Indonesia, the researcher will contact you by phone. However, if the researcher has returned to Korea and there is something that needs further information, the researcher will contact you via email. Your phone numbers and e-mail addresses will be discarded 3 months after the research is published in the journal. Your names will be assigned with an ID (anonymity) randomly in the process of transferring and coding the data. The collected data (audio-recorded file and video-recorded file) will be saved in external memory and stored in the laboratory of EPIC (Education of Physics in Context), department of physics education, building 13-315, where the research director is located. Data will be kept secure on a password protected personal server. All the data will be coded without identifying the participants. The consent form will be retained for 3 years after the end of the study in accordance with the relevant laws and regulations, and the research data will be retained for 5 years after the end of the study and will be disposed in 2024 (5 years later). We will do our best to ensure the confidentiality of all personal information obtained through this study. The collected data will not be used except for academic purposes (writing thesis, publishing papers or conferences). However, if the law requires it, your personal information may be provided. In addition, monitor personnel, inspectors, and bioethics committees can directly access the research results to verify the reliability of the procedures and data of the study within the scope of the relevant regulations without violating the confidentiality of personal information of research participants. By signing this agreement, you are deemed to have accepted voluntarily.

11. Will I receive any present for participation in this study?

A small souvenir of around 20,000 won will be presented to you in appreciation of your research participation.

12. If I have questions about the study, whom should I contact?

If you have any questions about this research or if you have problems during this research, you can contact the research director.

Name: Hartono Bancong B Phone: 010-2163-9154 Email: hartono88@snu.ac.kr

If you have any questions about your rights as a research participant, please contact the Bioethics Committee of Seoul National University.

Seoul National University Bioethics Committee (SNUIRB) Phone: 02-880-5153

IRB No. 1811/003-015 유효기간: 2019년 11월 25일

Consent Form for Research Participant

Title of Research : The Natural Processes of Collaborative Thought Experiments During Physics Problem-Solving Activities.

Investigator's name : Hartono Bancong B, Ph.D. Student, Principal Investigator.
Jinwoong Song, Professor, Research Advisor

1. I have read this consent form and discussed it with the researcher.
2. I have heard the risks and benefits of this research, and all my questions were answered by the researcher.
3. I voluntarily agree to participate in this study.
4. By participating in this study, I give permission to use the information obtained from this study to the extent permitted by current legislation and Bioethics Committee Regulations.
5. I agree to confirm my confidential personal information if the researcher or authorized representative conducts research or results management and if only the National Institution prescribed by law and Bioethics Committee of Seoul National University approves it.
6. I can withdraw my participation in this study at any time, and I know that this decision will not affect me in any way.
7. Upon signing and returning this consent form to the researcher, I will receive a copy of the signed consent form for my records.
8. By participating in this study, I give permission to be recorded.
   I agree ( ) I disagree ( )
9. I know that my (name, age, gender, phone number, and email address) is being collected and allow it to be used for this research.
   I agree ( ) I disagree ( )

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Participants	Signature	Date
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Researcher	Signature	Date
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Research Director	Signature	Date

SEOUL NATIONAL UNIVERSITY

Pernyataan Persetujuan untuk Berpartisipasi dalam Penelitian

Judul Penelitian	: The Natural Processes of Collaborative Thought Experiments During Physics Problem-Solving Activities (Proses Alami dari Thought Eksperiments Secara Kolaboratif selama Aktivitas Pemecahan Masalah Fisika)
Nama Investigator	: Hartono Bancong B, Mahasiswa S3, Peneliti utama Jinwoong Song, Professor, Pembimbing
Institusi Penelitian	: Seoul National University

Pernyataan persetujuan ini mungkin berisi beberapa informasi yang sulit untuk dimengerti. Jika ada informasi yang belum jelas, silakan hubungi dan tanyakan kepada Hartono Bancong B. Nomor kontak ditulis di lembar akhir form ini.

1. Mengapa kami melakukan penelitian ini?

Tujuan dari penelitian ini adalah untuk menciptakan framework dari kolaboratif TEs. Peneliti akan menyelidiki kegiatan siswa dalam membangun TE secara kolaboratif (langkah-langkah kolaboratif TEs, penalaran yang digunakan, dan faktor yang mempengaruhi) selama kegiatan pemecahan masalah fisika. Peneliti akan menjelaskan penelitian ini sebelum meminta Anda untuk berpartisipasi.

2. Berapa banyak partisipan?

Setidaknya ada 12 calon guru fisika akan berpartisipasi dalam penelitian ini. Para partisipan akan diatur ke dalam tiga kelompok yang berbeda. Setiap kelompok terdiri dari 4 peserta.

3. Apakah saya harus berpartisipasi?

Anda boleh memilih untuk tidak berpartisipasi. Tidak akan ada yang berbahaya jika memilih untuk tidak berpartisipasi.

4. Apa yang akan saya lakukan dalam penelitian ini?

Jika Anda setuju untuk berpartisipasi dalam penelitian ini, selama sekitar 8 minggu, peneliti akan memberi Anda 4 masalah fisika untuk dipecahkan bersama anggota kelompok Anda. Diskusi kelompok akan memakan waktu sekitar 20-30 menit untuk setiap masalah fisika. Selama diskusi kelompok, peneliti akan merekam (video dan audio) menggunakan dua kamera stasioner (satu di depan difokuskan pada siswa dan satu di belakang difokuskan pada peneliti). Untuk setiap kelompok peserta, observasi dan perekaman akan dilakukan empat kali sesuai dengan jumlah masalah fisika yang tersedia (4 masalah). Jumlah peserta dalam penelitian ini adalah 12 peserta, dan mereka akan diorganisir ke dalam tiga kelompok yang berbeda. Setiap kelompok terdiri dari 4 peserta. Setelah itu, selama sekitar 4 minggu, Anda akan diwawancarai secara individu. Dalam wawancara, Anda akan ditanya tentang pemikiran Anda pada waktu tertentu yang tidak diungkapkan selama kegiatan pemecahan masalah. Wawancara akan dilakukan di ruang pertemuan fisika atau lab fisika sebanyak satu kali dengan durasi sekitar satu jam. Isi wawancara akan direkam pada ponsel pribadi peneliti dan akan digunakan sebagai data penelitian. Namun, informasi pribadi Anda akan dilindungi secara anonym.

5. Berapa lama penelitian ini akan dilaksanakan?

Penelitian ini direncanakan berlangsung sekitar 12 minggu. Namun, itu tergantung pada data yang diperoleh, penelitian ini mungkin saja selesai lebih awal dari yang direncanakan. Selama periode ini, Anda akan berpartisipasi sebanyak 4 kali diskusi kelompok dan 1 kali wawancara.

6. Bisakah saya berhenti saat saya sedang berpartisipasi?

Iya, Anda dapat berhenti kapan saja tanpa ada kerugian yang ditimbulkan dari partisipasi Anda sebelumnya. Jika Anda ingin berhenti berpartisipasi dalam penelitian ini, tolong segera beri tahu peneliti. Jika Anda berhenti, data yang dikumpulkan segera dibuang dan dikeluarkan dari analisis.

7. Apakah terdapat efek samping dari penelitian ini?

Kecuali perasaan gugup atau malu saat pengambilan video di kelas selama diskusi dan wawancara, tidak ada yang berpotensi berbahaya untuk menjadi partisipan dalam penelitian ini.

8. Apakah partisipan akan mendapatkan manfaat jika berpartisipasi dalam penelitian ini?

Tidak ada manfaat secara langsung dari partisipasi Anda dalam penelitian ini. Namun, pendidikan sains dapat berkontribusi pada pemahaman yang lebih baik tentang cara-cara praktis untuk memengaruhi kehidupan para pembelajaran.

9. Apakah ada kerugian jika saya memilih untuk tidak berpartisipasi?

Jika kamu merasa tidak nyaman dengan berpartisipasi dalam penelitian ini, kamu boleh memilih untuk tidak berpartisipasi. Tidak ada kerugian yang akan ditimbulkan jika memilih untuk tidak berpartisipasi.

10. Apakah ada jaminan kerahasiaan semua informasi pribadi yang diperoleh dari penelitian ini?

Iya, ada jaminan kerahasiaan semua informasi pribadi yang diperoleh dari penelitian ini. Manajer dari informasi pribadi adalah Hartono Bancong B dari Seoul National University (010-2163-9154). Informasi pribadi yang akan dikumpulkan dalam penelitian ini adalah nama lengkap, usia, jenis kelamin, nomor telepon, dan alamat email. Peneliti akan mengumpul alamat emailmu agar dapat menghubungimu selama penelitian berjalan. Sebagai pertimbangan, nomor teleponmu juga akan dikumpul karena internet tidak stabil di Indonesia. Peneliti akan mengirimkan pesan/sms sehari sebelum aktvitas pengumpulan data dimulai untuk mengingatkan waktu dan tempat. Selama peneliti di Indonesia, dia akan menghubungimu lewat telepon. Tetapi jika peneliti telah kembali ke Korea dan terdapat sesuatu yang ingin ditanyakan maka dia akan menghubungimu lewat email. Nomor telepon dan alamat emailmu akan dibuang setelah 3 bulan penelitian ini terpublish di jurnal. Namamu akan diberi ID (anonimitas) secara acak dalam proses transfer dan pengkodean data. Data yang dikumpulkan (file rekaman audio dan video) akan disimpan dalam memori eksternal dan disimpan di laboratorium EPIC (Education of Physics in Context), Departemen Pendidikan Fisika, gedung 13-315, di mana direktur penelitian bertugas. Data akan disimpan dengan aman di server pribadi yang dilindungi kata sandi. Semua data akan diberi kode tanpa mengidentifikasimu. Pernyataan persetujuan akan disimpan selama 3 tahun setelah penelitian selesai sesuai dengan hukum dan peraturan yang berlaku, dan data penelitian akan disimpan selama 5 tahun setelah penelitian selesai dan akan dibuang pada tahun 2024 (5 tahun kemudian). Kami akan memastikan untuk merahasiakan semua informasi pribadi yang diperoleh melalui penelitian ini. Data yang dikumpulkan tidak akan digunakan kecuali untuk tujuan akademis (tesis, jurnal atau konferensi). Namun, jika undang-undang mewajibkannya, informasi pribadi Anda mungkin diberikan. Selain itu, petugas monitor, inspektur, dan komite bioetika dapat secara langsung mengakses hasil penelitian untuk memverifikasi keandalan prosedur dan data penelitian sesuai dengan peraturan yang relevan tanpa melanggar kerahasiaan informasi pribadi peserta penelitian. Dengan menandatangani perjanjian ini, Anda dianggap telah menerima tanpa ada paksaan.

11. Akankah saya menerima hadiah jika berpartisipasi?

Sebuah souvenir kecil seharga 20.000 won akan diberikan kepada Anda sebagai penghargaan atas partisipasi Anda.

12. Jika saya memiliki pertanyaan terkait penelitian ini, siapa yang harus saya hubungi?

Jika anda memiliki pertanyaan atau sesuatu yang belum jelas tentang penelitian ini, mohon menghubungi direktur peneliti

Nama: Hartono Bancong B Phone: 010-2163-9154 Email: hartono88@snu.ac.kr

If you have any questions about your rights as a research participant at any time, please contact the Bioethics Committee at the University of Seoul. Jika Anda memiliki pertanyaan tentang hak Anda sebagai partisipan, silakan hubungi Komite Bioetika Seoul National University.

Seoul National University Bioethics Committee (SNUIRB) Phone: 02-880-5153

IRB No. 1811/003-015　　유효기간: 2019년 11월 25일

Pernyataan Persetujuan untuk Partisipan

Judul Penelitian : The Natural Processes of Collaborative Thought Experiments During Physics Problem-Solving Activities (Proses Alami dari Thought Eksperiments Secara Kolaboratif selama Aktivitas Pemecahan Masalah Fisika)

Nama Investigator : Hartono Bancong B, Mahasiswa S3, Peneliti utama
Jinwoong Song, Professor, Pembimbing

1. Saya telah membaca pernyataan persetujuan ini dan telah mendiskusikannya dengan peneliti.
2. Saya telah mendengar resiko dan manfaat dari penelitian ini, dan semua pertanyaan saya telah dijawab oleh peneliti.
3. Saya secara suka rela setuju untuk berpartisipasi dalam penelitian ini.
4. Dengan berpartisipasi dalam penelitan ini, saya memberikan izin untuk menggunakan informasi yang diperoleh dari penelitian ini sejauh diizinkan oleh undang-undang dan Peraturan Komite Bioetika.
5. Saya setuju untuk mengkonfirmasi kerahasiaan informasi pribadi saya jika peneliti atau perwakilan lembaga penelitian resmi atau manajemen dan hanya jika Lembaga Nasional yang ditentukan oleh hukum dan Komite Bioetika dari Seoul National University menyetujuinya.
6. Saya dapat berhenti berpartisipasi dalam penelitian ini kapan saja, dan saya tahu bahwa keputusan ini tidak akan mempengaruhi saya dengan cara apa pun.
7. Setelah menandatangani dan mengembalikan pernyataan persetujuan ini kepada peneliti, saya akan menerima salinan formulir persetujuan yang ditandatangani untuk arsip saya.
8. Dengan berpartisipasi dalam penelitian ini, saya memberi izin untuk direkam.
   Saya setuju ( ) Saya tidak setuju ( ).
9. Saya tahu bahwa (nama, usia, jenis kelamin, nomor telepon, dan alamat email) saya dikumpulkan dan dimungkinkan untuk digunakan untuk penelitian ini.
   Saya setuju ( )　saya tidak setuju ( )

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Partisipan	Tanda tangan	Tanggal
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Peneliti	Tanda tangan	Tanggal
-------------------	--------------------	--------------------------
Direktur Peneliti	Tanda tangan	Tanggal

IRB No. 1811/003-015　　유효기간: 2019년 11월 25일

Recruitment of Research Participant

Title of Research : The Natural Processes of Collaborative Thought Experiments During Physics Problem-Solving Activities.

Investigator's name : Hartono Bancong B, Ph.D. Student, Principal Investigator.
Jinwoong Song, Professor, Research Advisor

The main purpose of this study is to create a framework of collaborative TEs through the investigation of students' activities in constructing collaborative TEs (the phases of collaborative TEs, the reasoning used, and the influencing factors) during physics problem-solving activities.

If you agree to participate in this study, during about 8 weeks, the researcher will give you 4 physics problems to be solved with your group members. Group discussions will take approximately 20-30 minutes for each physics problem. During the group discussion, The researcher will video and audio record using two stationary cameras (one at the front focused on students and one at the back focused on the researcher). For each group of participants, observation and recording will be carried out four times according to the number of physics problem available (4 problems). The number of participants in this study is 12 participants, and they will be organized into three different groups. Each group consists of 4 participants. After that, during about 4 weeks, you will be interviewed individually. In the interview, you will be asked about your thinking at a particular instant time that is not expressed during problem-solving activities. The interview will be conducted in the physics meeting room or physics lab as much as one time with a duration of about one hour. The contents of the interview will be recorded on the personal mobile phone of the researcher and will be used as research data. However, your personal information will be anonymously protected.

Participants who are willing to participate in this study should disclose their intention to participate to the researcher. You will be fully informed of the details and procedures of the research plan, and you can read the research manually and tell us whether or not you will participate in this study. If you want to participate, you will then complete a written consent form. A small souvenir of around KRW 20,000 will be presented for your gratitude.

Furthermore, if you want to stop in this study, you can go anytime without any loss. If you feel uncomfortable in answering any question during the interview, you may choose to pass the question with no penalty. Or if you become excessively anxious during the observations or the interview, you can inform to the researcher, and the researcher will stop the data collection, and there will be no negative impact as a result of your stopping participation. We will do our best to ensure the confidentiality of your personal information in this research.

Thank you very much for your participation.

Research Director: Hartono Bancong B (010-2163-9154, hartono88@snu.ac.kr)

IRB No. 1811/003-015 유효기간: 2019년 11월 25일

Rekrutmen Peserta Penelitian

Judul Penelitian : The Natural Processes of Collaborative Thought Experiments During Physics Problem-Solving Activities (Proses Alami dari Thought Eksperiments Secara Kolaboratif selama Aktivitas Pemecahan Masalah Fisika)

Nama Investigator : Hartono Bancong B, Mahasiswa S3, Peneliti utama
Jinwoong Song, Professor, Pembimbing

Tujuan utama dari penelitian ini adalah untuk menciptakan framework dari kolaboratif TEs melalui penyelidikan kegiatan siswa dalam membangun TEs secara kolaboratif (langkah-langkah kolaboratif TEs, penalaran yang digunakan, dan faktor yang mempengaruhi) selama aktivitas pemecahan masalah fisika.

Jika Anda setuju untuk berpartisipasi dalam penelitian ini, selama sekitar 8 minggu, peneliti akan memberi Anda 4 masalah fisika untuk dipecahkan bersama anggota kelompok Anda. Diskusi kelompok akan memakan waktu sekitar 20-30 menit untuk setiap masalah fisika. Selama diskusi kelompok, peneliti akan merekam (video dan audio) menggunakan dua kamera stasioner (satu di depan difokuskan pada siswa dan satu di belakang difokuskan pada peneliti). Untuk setiap kelompok peserta, observasi dan perekaman akan dilakukan empat kali sesuai dengan jumlah masalah fisika yang tersedia (4 masalah). Jumlah peserta dalam penelitian ini adalah 12 peserta, dan mereka akan diorganisir ke dalam tiga kelompok yang berbeda. Setiap kelompok terdiri dari 4 peserta. Setelah itu, selama sekitar 4 minggu, Anda akan diwawancarai secara individu. Dalam wawancara, Anda akan ditanya tentang pemikiran Anda pada waktu tertentu yang tidak diungkapkan selama kegiatan pemecahan masalah. Wawancara akan dilakukan di ruang pertemuan fisika atau lab fisika sebanyak satu kali dengan durasi sekitar satu jam. Isi wawancara akan direkam pada ponsel pribadi peneliti dan akan digunakan sebagai data penelitian. Namun, informasi pribadi Anda akan dilindungi secara anonim.

Peserta yang bersedia berpartisipasi dalam penelitian ini harus mengungkapkan niatnya untuk berpartisipasi kepada peneliti. Anda akan diberitahu sepenuhnya tentang rincian dan prosedur dari rencana penelitian ini, dan Anda dapat membacanya secara manual dan beri tahu kepada kami apakah Anda ingin berpartisipasi atau tidak dalam penelitian ini. Jika Anda ingin berpartisipasi, Anda kemudian akan melengkapi formulir persetujuan secara tertulis. Sebuah souvenir kecil seharga 20.000 won akan diberikan sebagai rasa terima kasih atas partisipasi Anda.

Selanjutnya, jika Anda ingin berhenti dalam penelitian ini, Anda akan dipersilahkan tanpa ada paksaaan. Jika Anda merasa tidak nyaman dalam menjawab pertanyaan apa pun selama wawancara, Anda dapat memilih untuk meneruskan ke pertanyaan selanjutnya tanpa hukuman. Atau jika Anda merasa cemas selama observasi atau wawancara, Anda dapat menginformasikan kepada peneliti, dan peneliti akan menghentikan pengumpulan data, dan tidak akan ada dampak negatif sebagai akibat dari Anda berhenti berpartisipasi. Kami akan melakukan yang terbaik untuk memastikan kerahasiaan informasi pribadi Anda dalam penelitian ini.

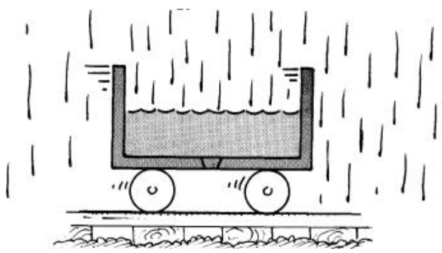
Terima kasih banyak atas partisipasi Anda.

Direktur Peneliti: Hartono Bancong B (010-2163-9154, hartono88@snu.ac.kr)

Appendix C
Physics Problems

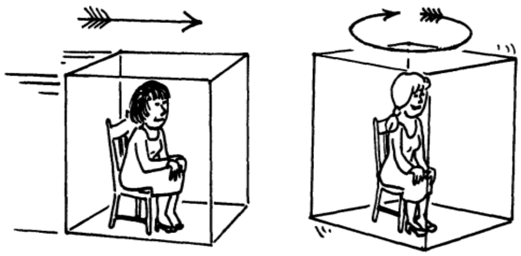
1. Troli meluncur ditengah hujan

Anggaplah kamu sedang mendorong sebuah troli sehingga dia meluncur pada jalan yang lurus. Kemudian, hujan turun secara vertikal sehingga sebagian air hujan jatuh ke dalam troli dan terkumpul di sana. Apakah air hujan yang tertimbun pada troli akan berpengaruh terhadap pergerakan troli?



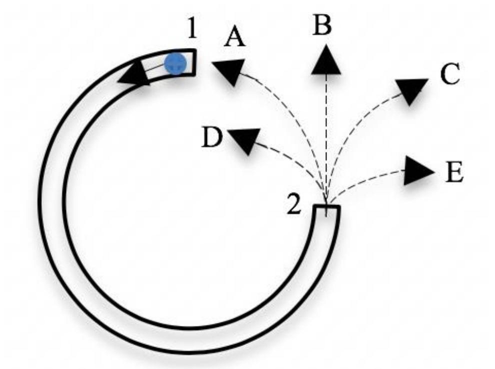
2. Ilmuwan di dalam kotak

Bayangkan seorang ilmuwan yang terisolasi di dalam kotak sedang bergerak lurus tanpa gesekan melalui ruang angkasa. Ilmuwan lainnya yang juga terisolasi di dalam kotak sedang berputar tanpa gesekan di ruang angkasa. Kira-kira, ilmuwan yang manakah yang bisa mendeteksi jika mereka sedang bergerak?



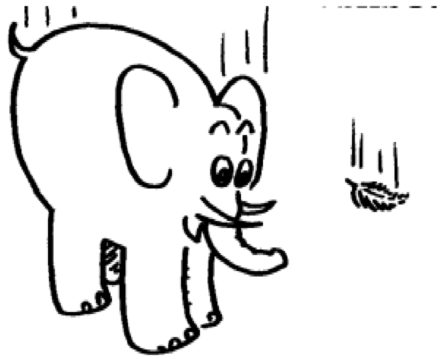
3. Bola keluar dari pipa

Misalkan ada saluran setengah lingkaran yang telah terpasang dengan aman dalam bidang horizontal. Bola memasuki saluran di titik 1 dan keluar di titik 2. Manakah dari representasi jalur berikut yang paling sesuai dengan jalur bola setelah keluar di titik 2 dan bergerak tanpa gesekan?



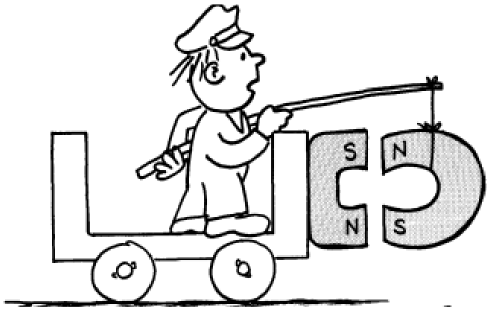
4. Gajah dan bulu ayam

Misalkan gajah dan bulu ayam jatuh dari pohon yang tinggi. Yang manakah yang mengalami gaya hambatan udara yang paling besar ketika jatuh ke tanah?



5. Mobil magnet

Bayangkan sebuah magnet berbentuk U terpasang di depan sebuah mobil besi seperti yang ditunjukkan pada gambar. Apakah dengan menggantungkan magnet berbentuk U lainnya menghadap ke kutub yang berlawanan membuat mobil bergerak? Jika iya atau tidak, mengapa?



Appendix D
Example of Transcription

Group 1 on Problem 1

R	Ok. Let's start from the first question [the researcher then reads the question]. Now, imagine the possible effect of the accumulating rainwater on the trolley's speed as shown in the figure. What do you think?
H4	Is the path a straight line?
H1	Is it pushed like this [while pushing the cellphone]?
R	Yes, the path is a straight line. Yes, it is pushed.
H1	If so [while thinking].
P	[All participants are silent while thinking].
H1	So, I think that there is no external force and no friction.
H4	Aaa, external force.
H2	What is the effect?
H1	It will move continuously [It will never stop moving].
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 [while pointing the trolley image on the given problem]. 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.

[H2 visualized pushing the trolley and showing it by putting her hand on the trolley image on the given question]

P [All participants are silent while thinking].

H3 Is the rainwater collected in the trolley?

H1 Yes, the condition is like that.

H4 Ooo, it will stop, why?

H2 Yes, the trolley will stop. 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.

H1 Yes, I agree [H1 agrees with H2]. If the condition is like that, trolley will stop.

H3 Stop? [H3 asks H2]

H2 Yeah. It will stop. Over time, surely.

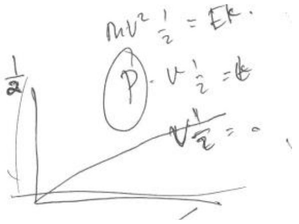
H4 If the trolley is filled with water? [while pointing to the trolley image on the given question]

H1 Wait, the question here is will the accumulated rain affect the motion of the trolley?

H2 It will affect it. If, for example, the mass increases, the speed decreases, maybe, I think, that is the effect.

P [All participants are silent while thinking].

H4 Wait, if forces, not, kinetic energy [while writing a formula]



H2 Ek = 1/2mv2

H1 Because of the mass increase

H3 Yes, the mass increases

H2 For example, if the mass increases, the kinetic energy increases. It is the same as momentum [H2 writes momentum formula]. Meaning that momentum is same. Eh, the momentum is getting bigger because the masses are getting bigger, but there is . . . [While looking at H1]

H1 The speed is decreasing, right? Because initially the mass is small and the speed is higher, then the mass increases, so that means . . .

H3 So, it has an effect

H1 Yes, it has an effect, the trolley will stop

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.

H2 Yes, the trolley will become slower and will stop.

H1 That is right.

R So, does the rainwater affect to the motion of the trolley?

H3 Yes, It has an effect on trolley' speed.

R So, the speed will change?

H1 Yes, by the time the speed became slower, and finally, it stops.

H2 The speed will change

H4 Yes, the speed gets smaller and smaller because of the mass increases

R What mass is increasing?

H3 The car, eh, trolley.

H2 There is additional mass, the mass of rainwater.

H1 The total mass [the mass of trolley + rainwater collected]. Because the raindrops hit the trolley and were accumulated in the trolley [while pointing the trolley image on the given question]

R OK.

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