AN ANALYSIS OF THOUGHT EXPERIMENTS IN THE HISTORY OF PHYSICS AND A MODEL OF A TEACHING SEQUENCE

Jongwon Park°, Ikgyun Kim*, Sunggi Kwon•, Jinwoong Song▽

°Dept. of Physics Education, Chonnam National University, Kwangju, Korea
*Dept. of Science Education, Chungbuk National University, Cheongju, Korea
•Dept. of Science Education, Taegu National University of Education, Taegu, Korea
▽Division of Science Education, Taegu University, Kyungsan, Korea

ABSTRACT

In this study, the thinking processes and backgrounds of some typical thought experiments in the history of physics, including Galileo’s free falling, Leibniz’s vis viva, Newton’s bucket, and Schödinger’s cat, were analyzed. Based on this analysis, we constructed a *thinking process diagram* of a thought experiment, and illustrated three functions of thought experiment: (1) falsifying existing knowledge, (2) manifesting existing knowledge, and (3) inventing new knowledge. We further summarized five characteristics of thought experiments as follows: (1) thought experiments start from well-known and familiar existing knowledge, (2) no empirical data is required, (3) logical inference plays an important role in drawing the result, (4) ideal conditions are necessarily involved, and (5) thought experiments are frequently used for making clear or sharing the meanings of disputed knowledge. A model of a teaching sequence for thought experiments is suggested.

1. INTRODUCTION

Experimentation can be used to persuade us to accept the truth of a theory. However, as we know, we can not always obtain the necessary agreement between theory and experiment. Naylor [1] pointed out that, even though Glileo's experimental results had convinced him of the validity of his theory, he was dissatisfied with the relationship between his theory and his experiments. Therefore, Galileo [2], in his famous book, ‘Dialogues Concerning Two New Sciences’, introduced a thought experiment (TE) to convince the reader of the truth of his idealized world of theory by removing the gap between his theory and experiments. The fact that TEs have persuasive power implies that TEs can be used in the context of teaching and learning physics.

Many researchers have been concerned with TEs in the area of the philosophy of science, as well as in physics. Popper’s argument about the use and misuse of TEs in quantum theory [3], Kuhn’s discussion about the role of TEs providing crucial anomaly to an existing paradigm [4], Gooding’s comment of the similarity between TE and real experiment [5], and Nerssesian’s analysis of TEs in relationship with mental modeling [6] are among the cases. Brown [7], also, proposed a classificatory scheme of TEs, and Sorensen [8] brought broad discussions concerning TEs and extended scientific TEs to philosophical TEs.

Relating to science education, Matthews [9] stressed that TEs were a useful tool for improving students’ conceptual change, and Stinner [10] viewed TEs as mental devices that aided students to explicate physics concepts and recognize paradoxes. Reiner [11] applied TEs with computer simulations to collaborative learning in order to help students construct new scientific knowledge. Recently, Gilbert and Reiner [12] discussed the contribution of TEs to both conceptual change and investigative work activities, and criticized the use of TEs as ‘thought simulation’ in ordinary physics textbooks.

However, it is not yet fully understood that how TEs work or what the thinking processes of TEs really are [4], [13]. Moreover, TEs do not appear as part of the regular pedagogy of physics, even though they have played a distinctive role in scientific inquiry [14].

The main purpose of this study is to construct a basic general structure named “Thinking Process Diagram” showing how a TE proceeds. Based on this diagram, three functions and five chracteristics of TEs are discussed, and a model of a teaching sequence for TEs is suggested.

2. THINKING PROCESS DIAGRAM OF THOUGHT EXPERIMENTS

At first, Galileo’s free fall TE is analyzed according to the stages of conducting an experiment mentally. Of course, the historical context within which an actual TE is constructed and performed is extraordinary complex. In light of this, in this article, the process of Galileo’s TE is reconstructed.

2.1 Galileo’s Free Fall Thought Experiment

(1) *Background Knowledge*: Galileo’s free fall TE began from Aristotle’s account of free fall [2].

> “Simplicio: …he (Aristotle) supposes bodies of different weights to move in one and the same medium with different speeds which stand to one another in the same ratio as the weights.” (p. 61)

(2) *Relevant Observation*: The next important stage is the real observation of the falling bodies [2].

> “Sagredo: But, I, Simplicio, who have made the test can assure you that a cannon ball weighing one or two hundreds pounds, or even more, will not reach the ground by as much as a span ahead of a musket ball weighing only half a pound, ….”(p. 62)

(3) *Generating Logical Contradiction*: Galileo assumed two bodies (W_1 and W_2) tied together with a massless string to reveal that there is a logical contradiction in Aristotle’s account of free fall.

> “As $W_1+W_2>W_2$, then it would be expected that $V_{(1+2)}>V_2$. However, as W_1 would, on its own, fall slower than W_2, then W_1 would exercise a retarding effect on W_2 when the two were tied together. This would lead to $V_{(1+2)}<V_2$.” [12]

(4) *Rejecting Background Knowledge and Suggesting New Hypothesis:* Confronted with the logical contradiction, there can be alternative strategies to resolve the paradox. For instance, someone may think that the speed of two bodies tied together are determined by a degree of connectedness (C) such that the speed would be: $(C)(W_1+W_2)+(1-C)(W_1+W_2)/2$. That is, if the bodies are completely unified, C takes a value of zero, and if the bodies are completely disunified, C takes a value of zero [13]. However, Galileo boldly rejected Aristotle’s account of free fall, and suggested a new explanatory hypothesis that all materials descended with an equal speed because the mass of an object falling freely did not act on the motion of a falling body at all [2]:

> "Salviati: … One always feels the pressure upon his shoulders which prevents the motion of a load resting upon him, but if one descends just as rapidly as the load would fall how can it gravitate or press upon him? … during free and natural fall, the small stone does not press upon the larger and consequently does not increase its weight as it does when at rest." (p. 64)

(5) *Coordinating the New Hypothesis with the Real World*: Galileo also recognized that the new hypothesis did not exactly match with the real phenomena. To resolve this gap, Galileo introduced ideal conditions, such as, "If there is no air, …" [14]

> "Salviati: …when the larger has reached the ground, the other is short of it by two finger-breadths, …I found that the differences in speed were greater in those media which were more resistant, that is, less yielding. …Having observed this I came to the conclusion that in a medium totally devoid of resistance all bodies would fall with the same speed." (pp. 65-72)

2.2 Thinking Process Diagram and Some Instances of the Process of Thought Experiments

Similarly, the process of various TEs were analyzed, and based on this analysis, a "*Thinking Process Diagram*" of a TE is constructed (see Fig. 1).

According to Fig.1, there are 5 types of thinking processes, Type I: ABC_1, Type II: ABC_2(F), Type III: ABC_3D_1E(F), Type IV: ABC_3E(F), Type V: ABC_3D_2. Parenthesis in Types II, III, and IV indicates that the final stage, F, is not always shown in every type of TE. Examples of TEs involved in each type are listed in Table 1.

TABLE 1. Thinking Process of Various Thought Experiments

Thought Experiment	Process
Problem in an imagined experimental situation	ABC_1
Galileo's ball rolling on frictionless rail (law of inertia)	ABC_2(F)
Heisenberg's gamma ray microscope (uncertainty principle)	〃
Einstein's light bent by acceleration of elevator	〃
Galileo's free falling body	ABC_3D_1E(F)
Leibniz's vis viva	〃
Newton's bucket	ABC_3E(F)
Schrödinger's cat	ABC_3D_2
Galileo's well bored though the center of the Earth	〃

Because an example of Type III has already been analyzed for the case of Galileo's free fall, other types of thinking process are summarized, below:

Type I (ABC$_1$) : Problem in an imaginary situation

The process of solving some problems, having the aim of manifesting or confirming background knowledge by applying it to an imagined experimental situation, corresponds to the first type (ABC$_1$) of TE. For instance, Matthews [9] gave an example of Mach's TE: "… what happens when a stoppered bottle with a fly on its base is in equilibrium on a balance and then the fly take off?" (p. 99)

Numerous other examples of this type of problem can also be found in L.C. Epstein's "Thinking Physics"[15].

Physicists should always invent an imagined experimental situation before running a TE. However, in usual classroom learning, students do not design a TE, but only run one and, then draw conclusions. Similarly, when students usually solve problems in an imaginary world, they do not create the problem situation by themselves.

Type II (ABC$_2$(F)) : Galileo's ball rolling on the U-shaped rail

Background knowledge (A): pendulum swings up to a height equal to the starting point (the law of equal height in pendulum) → *Applyin*g (B): a ball rolls on the frictionless U-shaped rail → *Drawing new conclusion* (C$_2$): the ball continues in a uniform motion in a straight line forever unless force acts on a ball [13].

Type IV(ABC$_3$E(F)) : Newton's bucket [16]

Background knowledge (A): two bodies being at relative rest can be said to be at rest (Galileo's relativity), and observation* → *Applying* (B): water rotates inside the bucket hanging from the rope → *Contradiction* (C$_3$): the shape of the surface of the rotating water is different from the one of water at rest, even when rotating water is at rest relative to the rotating bucket → *Suggesting new hypothesis* (E): rotating motion is an absolute motion → *Applying* (F): when two globes connected with a cord revolve, the amount of absolute motion can be measured by the tension of the cord.

* Newton expressed that he observed water rotating inside the bucket as follows, "… as I have experienced, …"

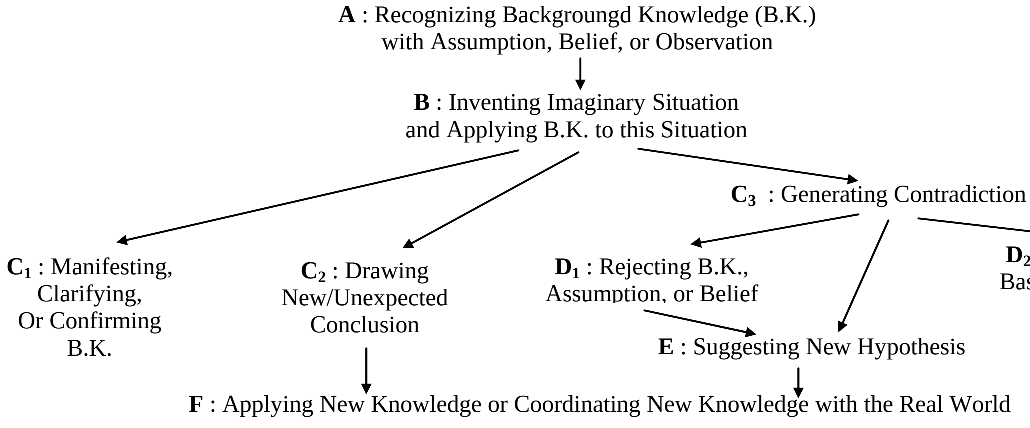

FIGURE 1. Thinking Process Diagram of Thought Experiment

Type V (ABC_3D_2) : Schrödinger’s cat [17]

Background knowledge (A): Copenhagen interpretation (quantum state is described as the suppression of eigen states) and metaphysical belief (law for the microscopic world can be applied to the macroscopic world) → *Applying* (B): a cat is penned up in a steel chamber, along with radioactive materials, Geiger counter, and flask of hydrocyanic acid → *Contradiction* (C_3): before opening the chamber, the cat is in a state of superposition of living cat and dead cat → *Drawing basic problem* (D_1): Is a state of superposition a physical reality or not? When a measurement is made, how does the quantum system change from a state of superposition to an eigen state? What defines a measurement?

2.3 Three Functions of Thought Experiments

According to the “*Thinking Process Diagram*” (Fig.1), the functions of a thought experiment can be easily deduced. The first type of TE assumes the role of the improving understanding of existing knowledge by manifesting, clarifying, or confirming existing knowledge. Therefore, the first function of a TE is ‘manifesting existing knowlege’. Stinner [10] pointed out that, in relation with learning physics, “(TEs) explicate concepts and aid students in understanding the world of physics in either anticipating or going beyond the ordinary textbook analytical solutions….”

The main function of a Type II TE is ‘inventing new knowledge.’ This function of a TE has been noted in literature, for instance, Winchester [13] claimed that, “They (TEs) seem to be crucially involved in the production of idealization, or of new concepts, ….”

Many thought exepriments which aim to destroy or at least present serious problems for existing knowledge are included in Type III, IV, and V. In these cases, the function of a TE is ‘falsifying existing knowledge’. Relating to this aspect, Kuhn [4] claimed that, “Galileo’s thought experiment brought the difficulty to the fore by confronting readers with the paradox implicit in their mode of thought. As a result, it helped them to modify their conceptual apparatus.” (p. 251)

It is worth noting that the function of ‘inventing new knowledge’ in Types III and IV is different from the function involved in Type II. In Type II, new knowledge is obtained directly as a result of conducting a TE, but in Types III and IV, the investigator should suggest or invent new knowledge to resolve the contradiction generated in the course of experimenting mentally. That is, Glileo’s new theory about free fall is not any kind of logical truth, but only a hypothetical explanation that should be tested by independent empirical experiment.

Another important thing to keep in mind is that these three functions of a TE are focused mainly on knowledge. This is the main difference with real experiments within which improving inquiry skills and manipulative techniques are two of the major functions. However, when physicists construct TE, they should create an imaginary situation in which technical and subtle difficulties are removed as much as possible and the process of executing the experiment is simple. So, when experimenting mentally, manipulative technical skills are not central. As a result, the physicist can focus his/her concern only on the logical process of applying knowledge. Nevertheless, an interesting point is that the effect of a TE is the same as a real experiment [4]:

> "… the effects of thought experimentation, even though it presents no new (empirical) data, are much closer to those of actual experimentation than has usually been supposed." (p. 242)

2.4 Five Characteristics of Thought Experiment

The first distinctive characteristic of a TE is that it starts from well-known and familiar existing knowledge. Related to this point, Kuhn [4] claimed that, "If a thought experiment is to be effective, it must … present a normal situation, that is, a situation which the man who analyzes the experiment feels well equipped by prior experience to handle." (p. 252)

The second interesting characteristic is that no empirical data is required in a TE. However, this does not mean that a TE is not related to the real world at all. Rather, in some cases, a TE should be supported by other empirical observations relevant to the issues of the TE. Here, an important point is that the outcome of a TE does not come from the reporting of new empirical data, but is deduced by logical reasoning. Therefore, one of the most interesting and curious aspects is that a TE postulating imaginary, even counterfactual, situations can be informative about the real world. Here, Kuhn [4] concluded that, "Though the imagined situation need not be even potentially realizable in nature, the conflict deduced from it must be one that nature itself could present." (p. 265)

Third, in a TE, logical inference plays an important role in drawing conclusions. Real experiments typically depend upon an actual manipulation in nature and upon instruments or methods of measurement. However, a TE fundamentally takes the form of an argument based on hypothetical premises. So, a TE can be said to be a semantic argument whose conclusions deal with the logical properties of theories. Because of this aspect, TEs are appropriate to develop higher-order thinking skills in the context of scientific inquiry. For instance, Matthews [8] quoted Mach's comment that, "experimenting in thought is important not only for the professional inquirer, but also for mental development as such."

As mentioned earlier, when designing a TE, to remove the technical or manipulative complexity of the TE, and to simplify its experimental context, ideal conditions are necessarily needed. This is the fourth characteristic of a TE. Here, it is worth noting that, as a TE starts from well-known background knowledge, the introduced ideal conditions or assumptions should not be the main issues in performing the TE, but should be simple enough for the investigator.

Finally, a TE is frequently used to make clear or share the meaning of disputed knowledge. One of the major skills of scientific inquiry is the ability to report, persuade, or discuss in classroom situation about the conclusions obtained through inquiry. Therefore, this final characteristic of a TE allows a TE to be used to improve students' communicative skill in the context of scientific inquiry.

PHASE	PURPOSE	STUDENT'S ACTIVITY
Exploration	To identify background knowledge (B.K.) To examine an imagined situation To recognize the purpose of the TE	By completing activities, such as observing demonstration, answering questions, or solving simple problems, to elicit students' understanding of B.K. By identifying ideal conditions or assumptions involed in an imagined situation
Running	To apply B.K. to an imagined situation To draw conclusions	By employing B.K. in the same ways students have employed it before By thinking logically, based on given premises in an imagined situation
Reflection	To check out logical processes To compare the conclusion with B.K. To give meaning to the conclusion, or to resolve the paradox	By disputing with others in class about the process completed, and the conclusions obtained in the second phase By discussing the meaning of the conclusion, or suggesting a new explanatory hypothesis
Application	To ascertain and to ensure student understanding	By applying conclusions or a new hypothesis to another situation By coordinating the conclusions or new hypothesis with the real world By observing a relevant demonstration or actual phenomena

FIGURE 2. A model of teaching sequence for conducting thought experiment

3. A MODEL OF A TEACHING SEQUENCE FOR PERFORMING THOUGHT EXPERIMENTS

When an designing activity worksheet to perform a TE, we need to discriminate between the constructing part and the running part of a TE. If the purpose of the inquiry activity is to improve students' creative thinking abilities, the constructing part will become a major part of the activity. However, if the activity aims to help students to think logically, to understand new knowledge, or to change their existing misconceptions, recognizing the context of the TE and running the TE will become the major parts of the activity.

Here, for the second aim of the activity, a sequential teaching model for a TE is suggested (Fig. 2).

4. FURTHER STUDIES

Physics educators have stressed the importance of real experiments in physics courses. Therefore, a great deal of research has been conducted on things, such as clarifying the nature of scientific inquiry, identifying inquiry skills involved in laboratory work, and evaluating the effectiveness of practical work. In the same way, further studies for the successful employment of TEs in physics learning are necessary. For instance, the teaching model suggested in this article has not yet been applied to actual classroom teaching, therefore, developing concrete worksheets based on this model, as well as inventing various strategies to encourage student activities, will be needed.

Further, the "*Thinking Process Diagram*" should be compared with the actual thinking processes of students when they perform TEs. A study investigating whether students' cognitive processes follow along the assumed path in the diagram or not will be very informative in order to understand students' cognitive processes of constructing knowledge.

Finally, as is noted in this article, some TEs begin with real observation and some end by coordinating the result of the TE with the real world. This means that a TE is closely related to real phenomena. Therefore, the unified use of TEs with real experiments can be a new more effective model for teaching of the physics.

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