ROLE OF THOUGHT EXPERIMENTS IN SOLVING CONCEPTUAL PHYSICS PROBLEMS

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ABSTRACT

ROLE OF THOUGHT EXPERIMENTS IN SOLVING CONCEPTUAL PHYSICS PROBLEMS

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The purpose of this study was to contribute to the science education literature by describing how thought experiments vary in terms of the nature, purpose of use and reasoning resources behind during the solution of conceptual physics problems. Three groups of participants were selected according to the level of participants' physics knowledge- low, medium, and high level groups- in order to capture the variation. Methodology of phenomenographic research was adapted for this study. Think aloud and retrospective questioning strategies were used throughout the individually conducted problem solving sessions. The analysis of data showed that thought experiments were frequently used cognitive tools for all level of participants while working on the problems. Four different thought experiment structures were observed which were categorized as limiting case, extreme case, simple case, and familiar case. It was also observed that participants conducted thought experiments for different purposes such as prediction, proof, and explanation. The reasoning resources running behind the thought experiment processes were classified in terms of observed facts, intuitive principles, and scientific concepts. The results of the analysis suggested that, thought experiments used as a creative reasoning instrument for theory formation or hypothesis testing by scientists can also be used by students during the inquiry processes as well as problem solving in instructional settings. It was also argued that, instructional practices can be developed according to the outcomes of thought experiments, which illuminate thinking processes of students and displays hidden or missing components of their reasoning.

Keywords: Thought Experiment, Imagistic Simulation, Problem Solving

ÖZ

KAVRAMSAL FİZİK PROBLEMLERİNİN ÇÖZÜMÜNDE DÜŞÜNCE DENEYLERİNİN ROLÜ

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Bu çalışmanın amacı; kavramsal fizik problemlerinin çözümü sırasında, düşünce deneylerinin doğaları, kullanım amaçları ve temelinde yatan muhakeme kaynakları açısından ne tür farklılıklar gösterdiğini tanımlayarak, fen eğitimi literatürüne katkı sağlamaktır. Dağılımı ortaya çıkarmak için, fizik bilgisi seviyelerine göre - düşük, orta ve yüksek seviye- üç katılımcı grubu seçilmiştir. Bu çalışmada fenomenografik araştırma metodu kullanılmıştır. Birebir gerçekleştirilen problem çözme oturumları boyunca sesli düşünme ve retrospektif sorgulama stratejileri kullanılmıştır. Veri analizi göstermiştir ki; düşünce deneyleri, problemlerin çözümü sırasında bütün katılımcılar tarafından sıklıkla kullanılan bilişsel araçlardır. Limit durum, uç örnek durum, basit durum ve benzer durum olmak üzere dört çeşit düşünce deneyi yapısı gözlemlenmiştir. Katılımcıların ayrıca düşünce deneylerini, tahmin yürütme, kanıt ortaya koyma ve açıklama getirme gibi farklı sebepler için kullandıkları gözlemlenmiştir. Düşünce deneylerinin arkasında yatan muhakeme kaynakları; gözleme dayalı olgular, sezgilere dayalı prensipler ve bilimsel kavramlar olarak sınıflandırılmıştır. Analiz sonuçları şunu önermektedir ki; bilim insanları tarafından teori geliştirmek ve hipotezleri test etmekte yaratıcı düşünme aracı olarak kullanılan düşünce deneyleri, öğrenciler tarafından da sorgulama süreçleri ve problem çözme aktiviteleri sırasında kullanılabilir. Öğrencilerin düşünme aşamalarına ışık tutan, muhakeme kaynaklarının gizli ve eksik kalmış parçalarını ortaya çıkaran düşünce deneylerinin, öğretim uygulamalarını geliştirmede kullanılabileceği savunulmuştur.

Anahtar Kelimeler: Düşünce Deneyleri, Imgesel Simulasyon, Problem Çözme

To My Parents

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TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF SYMBOLS

SYMBOL	
TE:	Thought Experiment
RE:	Real Experiment

CHAPTER 1

INTRODUCTION

In typical science classrooms, teachers use variety of instructional methods to help students learn the concepts better, gain the basic science process skills, and able to retrieve necessary knowledge from the memory to solve problems. On the other hand, researchers continue to understand the reasoning processes of scientists as well as students to develop new methods and techniques for the effectiveness of instructions.

In order to better understand and improve students' learning and reasoning some of the researchers initiated the inquiries about creative theory formation and informal reasoning processes of scientists. Investigation on this domain led researchers to focus on some specific cognitive tools such as analogical reasoning, mental model construction, and *thought experiments* (Clement, 2008; Nersessian, 2008). Literature on philosophy and history of science has been providing convincing arguments that thought experiments have a particular role in the development of scientific theories. Especially, the practices in the domain of physics often involve cognitive processes like 'mental simulations' or 'mental animations' (Botzer & Reiner, 2005). History of physics offers various examples in which physicists used active mental simulations to make articulations or generate predictions about a specific phenomenon -generally referred as thought experiments- to achieve scientific discoveries. Albert Einstein claimed to achieve his insight into the nature of space and time by means of thought experiments, like Michael Faraday's analysis of electromagnetic fields in terms of imaginary field lines (Botzer & Reiner, 2005).

Although, the origin of thought experiment is claimed to have its roots in earliest era of Greek thinking, the term, thought experiment, was first coined in the literature in the 19th century, by Danish physicist Hans Christian Örsted (Klassen 2006, Kühne 1995). Ernst Mach was the first to make systematic examination about the nature of thought experiment. Mach emphasizes the importance of thought experiment as a method for development of inquiry in science and for mental development as well (Gendler, 1994). Similarly, studies of famous philosophers such as Thomas Kuhn and Karl Popper have great impact on the appreciation of thought experiment as a way of scientific inquiry. In spite of the long history of thought experiments the definition and characteristics of thought experiment is still under discussion. Stöltzner (2006) defines three categories about the discussions that dominate the thought experiment literature: a) discussions about the epistemological status of thought experiment in terms of whether thought experiment s are just argument or have a status of generating a new theory or falsifying the old ones b) discussions about the statues of thought experiment either being a mere theory or being a real experiment and c) comparison of thought experiment with laboratory experiments in terms of their similarities and differences).

Although, researchers could not negotiate on a certain definition of thought experiment, they mainly emphasize several key processes attached to thought experiments such as reasoning, problem solving, hypothesis testing, and constructing imaginary scenarios (Brown, 2006; Gendler, 2004; Reiner & Gilbert, 2000b; Reiner,1998; Rescher, 2005). According to one of the most cited researchers in the literature of thought experiments, Reiner (1998), the most basic form of thought experiment includes five components; a) posing a problem (or a hypothesis) b) forming an imaginary world c) mentally designing and conducting an experiment d) producing experiment result by logic e) drawing a conclusion

In the history of physics, it is almost unavoidable not to encounter a thought experiment during the revolutionary phase of scientific developments. Most familiar examples can be found in the 17th century which is proposed by physicists like Galileo's free fall and Newton's cannonball. Then, in the 19th and 20th century, thought experiments contributed to the development of modern physics by creation of relativity and quantum mechanics. In contemporary physics, teaching of those concepts without mentioning thought experiments, such as Einstein's elevator, Maxwell's demon, Schrödinger's cat or Heisenberg's gamma-ray microscope, became almost unthinkable. It is obvious that, much of modern physics is founded not upon measurements but instead on thought experiments (Cohen, 2005). Einstein did not carry out experiments in a rapidly descending elevator, nor did Schrödinger actually put a cat into a radioactive box and Galileo also did not drop the rock from the top of Pizza tower. They conducted their experiments in their laboratory of mind. Popularity of thought experiments are not limited to the domain of physics, research conducted in science education literature about the practice of thought experiments in education in recent years.

1.1 Purpose of the Study and Research Questions

Extensive use of thought experiment, particularly in teaching of modern physics, triggered researchers' interest to study on the practice of thought experiment in science education. John Gilbert and Miriam Reiner are among the researchers to make considerable contributions to the literature of thought experiment in science education (Gilbert & Reiner 2000a, Gilbert & Reiner 2000b, Gilbert & Reiner 2004, Reiner & Burko 2003, Reiner 2006).

One of the earliest studies in the literature about thought experiment was conducted by Helm, Gilbert & Watts (1985), where they suggested that students spontaneously generate thought experiments during problem solving and thought experiment may play an effective role in conceptual change process. Likewise, Reiner & Gilbert (2000a) concluded that students frequently use thought experiments as a strategy for solving physics problems and imaginary world constructed during thought experiment process provide the necessary conditions for students to uncover their tacit knowledge. In order to explore cognitive processes involved in contextual learning, Reiner (2006) questioned the validity of naïve students' thought experiments. Results indicated that unlike expert physicists- who plan the use of thought experiment as an argumentative device-, naïve students generate thought experiments spontaneously. It is also concluded that; contextual problems trigger sensory memories and so provide access to implicit knowledge.

The purpose of this study is to describe the nature and the role of thought experimenting while solving conceptual problem for three different knowledge level groups in the domain of physics. These knowledge levels were defined as low, intermediate, and high according to the competencies of the participants in physics. The research question of this study is:

1. While solving physics problems, do the participants-from different level of physics knowledge- construct thought experiments? If so, how these experimentation vary in terms of:

a) The nature of thought experiment
b) The purpose of generating thought experiment
c) The resources used by the participants during performing the thought experiments.

1.2 Significance of the Study

Imageries, mental simulations or visualizations are the forms of cognitive processes triggered by perceptual representations in mind. This process in scientific thinking is generally associated with thought experiments. Thought experiments have been one of the key topics of interest in the literature of history and philosophy of science. The researchers in science education have also been inquiring about the possible implications of thought experiments for the community of science educators.

However, majority of the studies were constituted by examination of historical thought experiments. Stephens & Clement (to appear) pointed out the difficulties of evaluating the mental processes of scientists' during thought experimenting by searching historical data. It is obvious that real time evidences are needed to be able to analyze the mechanism of thought experiments in detail. Recent studies in the field of physics education have been concentrating on this issue by examining thought experiment process during problem solving sessions in classroom environments. However, due to being conducted in classroom environment, these studies lack details about individuals' thought processes. This necessitates individually conducted thought experiments. Another issue with the currents studies is that the role of imagery for experts lacks sufficient evidence because of two reasons. First, the number of studies with experts is very limited. Second, the expertise of the participants of some studies questionable because the expertise was not defined as a domain specific expertise. In order to gain a more complete picture, three levels of expertise groups- low level, intermediate level and high level- were used in this study. As Snyder (2000) observed, intermediate groups are very convenient groups in terms of providing a link between expert and novice groups.

Based on these arguments, this study intends to a) understand the process and nature of thought experiment in response to encountered physics problems b) find evidence about the purpose of generating thought experiments c) identify the reasoning resources used by individuals during the process of thought experimenting.

CHAPTER 2

LITERATURE REVIEW

Science education literature consists of huge volume of research on developing effective instructional methods. For this purpose, researchers continue their inquiries to understand the reasoning routes of students by monitoring their thought processes.

Reiner & Gilbert (2004) exemplified the aim of their study with ‘Plato’s cave’ example where inhabitants of the Plato’s cave learn about the outside world by observing the shadows casting on the wall. They claimed that like inhabitants’ figuring out the outside world by following the shadows, researchers try to learn the intrinsic mental world of students by the shades of their reasoning processes, so by their mental representations. Mental representations were considered to be a valuable informant about students’ mental worlds.

2.1 Mental Representations

In the literature of cognitive science, although there exists an immense body of research about vision, imagery and cognition, it is difficult to encounter a systematic definition or categorization of mental representations according to content and process. One of the detailed studies on mental representations embodied by Gilbert, Reiner & Nakhleh (2008) in their book ‘Visualization: Theory and Practice in Science Education’ which brought together a collection of comprehensive approaches from cognitive science, science education, and computer sciences to produce a coherent view. In the book, likeliness or simulation of a concept or object was defined as ‘representation’ and the making of meaning of representations was named as ‘visualization’ (Rapp &

Kurby, 2008). Visualization was categorized as external and internal representations where 'external representations' defined as the representations available in the environment in the form of pictures, diagrams, graphs, tables, etc, whereas, 'internal representations' defined as the representations not accessible in the setting but they were personal thoughts kept in mind which were gained from mental activities (Rapp & Kurby, 2008). Internal representations were related to the mental creation, storage and utilization of an image that often is the result of external representations (Gilbert, Reiner & Nakhleh, 2008). As a result, it may be suitable to define visualization briefly as the formation of an internal representation from an external representation.

Rapp & Kurby (2008) also categorized mental representations as 'amodal' and 'perceptual' according to how they are represented in the memory. Amodal view was associated with abstract reasoning that does not involve actual experience; whereas; perceptual view advocated that when we think of a concept we conduct 'mental simulations' which were rearrangements of our perceptual experiences in mind. Therefore, these representations could help us see the situation that we imagine unfolding like a movie. Gibson (1969), referring the studies of physicist Hermann von Helmholtz, proposed that perception absolutely depends on previous experiences. In his book, Principles of Perceptual Learning and Development, he also mentioned theories of Bruner and Piaget related to perception. He described Piagets' views as; perception engages in assimilation of sensory data to a schema and accommodation of the schema to the specific object.

Implications of perceptual representations in classroom environments can be seen during instructional activities like role playing, problem based learning, or hands on laboratory activities. When studies in science education are analyzed, it is obvious to see that engaging with perceptual experiences of students lead to performance benefits. Rapp & Kurby (2008) emphasized the effectiveness of amodal view as well as perceptual view in classroom activities, stating that “children demonstrate better understanding of the spatial relationships described in them after *acting* out story scenarios using toys, or even *just imagining* using the toys to act out the scenarios, than simply read and reread the stories (p 44)”.

In the literature, cognitive scientists seem to keep an eye on image and visualization concepts to develop learning process. Especially, developing the effectiveness of external representations as instructional tools, constitute huge part of the literature. On the other hand, researches on internal representations appear to catch considerably less attention. Moreover, there seem to be not a consensus on the definition of the terms referring to cognitive processes performed by internal representations; such terms like ‘scenario visualization’, ‘mental simulation’ , or ‘imagistic simulation’ are among the most popular ones.

The term ‘scenario visualization’ was proposed by the researcher Robert Arp (2008) and defined as a mental activity where visual images were selected, integrated, transformed and projected into visual scenarios for the purpose of solving problems in the environment. He emphasized that scenario visualization was a process but not just recalling an image from the memory. He also claimed that it was a non-routine and creative problem solving activity. Similar definition but a different term used by Hegarty (2004) which was ‘mental simulation’ where he explicated it as examining a mental image of a physical situation. He exemplified the act of mental simulation stating that many people including scientists consciously conducts mental simulations to solve reasoning problems. “Tesla reported that when he first designs a device, he would run it in his head for a few weeks to see which parts were most subject to wear (Hegarty 2004, p 281)”.

Likewise, 'imagistic simulation' process was defined by Clement (1994b) as a process where a schema assimilates the image of a particular system and produces expectations about its behavior in a subsequent image. He stated that most studies concerning the use of 'imagery' in thinking, just focus solely on images of objects rather than actions. He used dynamic imagery in conjunction with perceptual motor schemas where the subject generates an imagistic simulation of an event. In a more recent study in his book 'Creative Model Construction in Scientists and Students', John Clement (2008) examined creative theory formation sources in scientists-whom he also calls as experts. During this investigation of creative theory formation, he analyzed analogical reasoning, mental model construction, imagistic simulation, applying physical intuition and an advanced technique-as he claims- using 'thought experiments'. He considered imagistic simulation, analogy and model constructing as playing key role in thought experiments. Similarly, in the literature of science and science education, perceptual representations as mental simulations, mental model or logical argument constructions were incorporated with *thought experiments.*

In the literature, thought experiments (TE) were generally defined to be constructed on mental processes of 'seeing with the mind's eye'. Moreover, when the literature examined, it was obviously seen that thought experiments have played central role as cognitive tools heading key innovations throughout the history of science, especially physics and philosophy.

2.2 History of Thought Experiments

The origin of TE method claimed to have its roots in earliest era of Greek thinking. Irvine (1991) stated that it was the Presocratic Greeks to introduce the use of TEs in their reasoning about nature and, in doing so, who presented an efficient instrument for later development of sciences.

On different grounds, Imre Lakatos introduced a connection between the Greek thinking on TE and the modern philosophy of mathematics (Moue, Masavetas & Karayianni, 2006). Mathematic is in fact one of the resources of TEs (Cohen, 2005).

In spite of originating from Presocratic thinking thousand years ago, the term TE first coined in the literature in the 19th century, by Danish physicist Hans Christian Örsted, within the German Naturphilosophie (Klassen 2006, Kühne 1995). Contrary to popular belief that Ernst Mach was the first to propose TE (as Gedankenexperiment), in fact he was the first to make systematic examination about the nature of TE. Mach emphasized the importance of TE method for development of inquiry in science and for mental development as well (Gendler, 1994). He argued that TE can tap into our tacit knowledge stocks about the world, which were not organized under any theoretical framework. However, objections and negative attitude to TE came at the beginning of 20th century. Pierre Duhem, historian/physicist/philosopher, was disappointingly critical about TE. He claimed that TE was misleading and can never be a substitute for real experiments (Brown, 1986).

> "To invoke such a fictitious experiment is to offer an experiment to be done for an experiment: this is justifying a principle not by means of facts observed but by means of facts whose existence is predicted…., an act of bad faith. (Duhem, 1954 as cited by Brown, 1986)".

Intensive discussion in the literature about TE concept initiated by Thomas Kuhn's essay 'A Function for Thought Experiments' and Karl Popper's 'On the Use and Misuse of Imaginary Experiments, Especially in Quantum Theory' (Gendler,1994). After these resume of TE by Kuhn and Popper, large body of articles on TE appeared both in science and in philosophy journals. They concerned about use of scientific theories, scientific method or theory change. After that, TE gained great popularity in various fields of science.

A large body of research- dated after the mid 1980s- related to the significance, function and role of TE appeared, especially in the community of philosophy and physics. Still, being a new topic of concern, it is not surprising to encounter arguments in the literature about the definition and characteristics of TE.

Stöltzner (2006) defined three categories about the discussions that dominate the TE literature:

a. Argument between John Norton and Robert James Brown which is about epistemological dimension of TE.
b. Discussions about the statues of TE either being a theory or experiment
c. Debate on TEs whether they fail or succeed like laboratory experiments (real experiments)

2.3 Definition and Classification of Thought Experiments

One of the most striking discussions in the literature of TE was -about epistemological dimension of TE- between Brown's (1991) 'apriori TE' and Norton's (1991) 'TE as arguments'. While Brown (1986, 1991, 2006) situated his arguments in rationalist perspective- where logic has superiority over experience, Norton (1991) adapted empiricist perspective where knowledge about the world was claimed to be gained by experience. Norton (2004, 1991) advocated that TEs were ordinary arguments which were deductive or inductive inferences based on our experiences; classifying them as type I (as deductive arguments) and type II (as inductive inferences). On the other hand, Brown (1991) interpreted TEs as apriori which means to be based on pure reason with no empirical data. He categorized TEs as constructive, destructive and platonic.

While ‘constructive TEs’ provides positive support to a theory, ‘destructive TEs’ destroys the theory presenting its deficiencies. ‘Platonic TEs’ on the other hand, destroys the theory but concurrently creates new one. Distinction between Brown’s and Norton’s assertions is on the point of validity, whether TEs can provide new knowledge or only presents old knowledge in a new way. Norton (2004) insisted that knowledge deduced from TEs was not new. Rescher (2005) commented on this issue stating that:

> “By their very nature as such, TEs are carried on in the mind and not in nature: the study rather than the laboratory is their natural habitat. And thought, not nature is the prime source of input. No new observation/empirical information is provided by a TE: in this regard all it can offer us is a new way of conceptualizing and reinterpreting the old… (p, 32)”.

Taking a similar position like Brown, Karl Popper in his studies classified TEs according to their possible uses as:

a. critical use: TEs criticizing exciting theories
b. heuristic use: TEs leading to innovations
c. apologetic use: TEs used as arguments in a defensive or apologetic mood (Velestzas, Halkia & Skordoulis, 2007).

It is possible to infer that, Poppers’ critical and heuristic TEs correspond to Browns’ destructive and constructive TE types. Despite occupying the opposite ends of the spectrum with Norton, Brown also commented on possibility of mislead by TEs. Brown (2006) stated that, both TE and laboratory experiments can sometimes be misleading and so both necessitate being developed.

Gendler (1998) as well opposed to Norton’s (1991) claims defining TEs as mere arguments, advocating that TEs were vehicles for conceptual developments. According to his claim, by using TEs we can develop imaginary scenarios where we are able to separate irrelevant issues from relevant ones and make modifications in our conceptual systems. Also, with the help of TEs, we can make judgments about the case in our imaginary scenario.

Supporting Brown’s classifications, Gendler (2000, 2004) proposed that the aim of TEs is to prove or refute a theory by contemplating a simulated world in mind.

TE was interpreted in the literature in various ways. Some researchers explained it as a problem solving methodology (Hibler, 1992; Wilkes 1993), others defined it as a technique for conceptual development (Sefton, nd.; Reiner & Gilbert, 2000a). Wilkes (1993) proposed that during thought experimentation; we ask a ‘what if’ question, then contemplate a possible imaginary world in which that what if situation actually occurs and analysis results of the situation either supports or destroys our tested claim (as cited in Reiner & Gilbert, 2000a). Whereas, Irvine (1991) emphasized that TE do not claim to generate new information, but new knowledge can be developed by making arguments on previous data, and this property differentiates scientific TE from any instance of hypothetical or counterfactual reasoning.

Apart from those interpretations, Nersessian (1993) advocated that TEs have different aspects from logical arguments or other propositional reasoning types. She defined TEs as simulative model based reasoning “The original TE is the construction of a mental model by the scientist who imagines a sequence of events. She then uses a narrative form to describe the sequence in order to communicate the experiment to others (p.27)”. Mental models are instruments to help people reason about, comprehend and predict the characteristics of complex physical systems. In another sense, they can be described as projections of physical situations that they represent and their deduction process simulates the physical processes being reasoned about (Hegarty, 2004). Another interpretation of TE as model based reasoning proposed by Gilbert& Reiner & Gilbert (2000a), who defined TE as models in itself and as models of phenomena, stating that “It can be seen as a model of an event, a representation of all the elements of mentally executed experiment (p. 267)”.

On the other hand, Rescher (2005) commented on mental model definition of TEs and stated that; TEs were not mere exercises of mental model construction or imaginative design, but they were activities operating information by inquiry. Similarly, Kujundzic (1998) emphasized that TEs were mental activities that were different from simple thinking about an illustration. Supporting this explanation, Scott (n.d.) defined TE as a theory evaluation activity where we manipulate the material we store in our memory that is gained by experience.

According to the one of the most cited definitions; Sorenson (1992) described TEs as limiting cases of real experiments and claimed that TEs can achieve the aim of real experiments without actually executing them but instead mentally simulating them in mind (Özdemir, 2008; Reiner & Burko, 2003). "TE may be considered as an attempt to solve a problem using logical derivations, conceptual constructs and imagination to understand the behavior of objects or people, just like RE (physical experiments do) (p, 3 Reiner, 2006)".

2.4 Thought Experiments versus Real Experiments

Brown (2006) stated that to conduct a TE; we generally used background information just as we do for real laboratory based experiments (RE). Irvine (1991) explained the similarities between TE and RE as; assumptions of both RE and many of TE should be based on empirical observations, they should have independently isolated variables, they should be hypothesis tested and its results would have implications for the background theory. He mentioned the differences as; TE do not involve with physical environment unlike RE and high cost and lack of equipment can be a problem for RE but not for TE, RE depends on actual intervention in nature while TE depends on argument based upon hypothetical premises.

In a similar sense, Reiner & Gilbert (2000b) claimed that:

1. Difference between RE and TE as:

a. TEs are conducted mentally.
b. TEs require one mental experimenter, while RE generally require a group of scientists
c. The designer and the experimenter are the same person in TEs, but REs generally have separate designer and experimenters
d. 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
e. TEs being conducted in mind, they can not cause personal and social harm, on the other hand REs may have.

2. Similarities between RE and TE as:

a. Both TE and RE are about the construction, testing and application of a theory
b. Experiment results of both are shared with the scientific community
c. Both may have unpredicted additional consequences, which later considered being measure of their significance.

According to Havel (1999), much of the TEs were alternatives of REs where all TEs form the fact of the real world in our hypothesized conceivable world.

2.5 Benefits and Threats about Thought Experiments

Sorenson (1992) suggested three criteria to prefer TE to RE (as cited in Reiner & Gilbert, 2000b):

a. unimprovability criterion: implementation of RE gives no development in insight when compared to TE
b. unaffordability criterion: inconvenience of implementation of RE and probable high cost of RE

c. impossibility criterion: RE may not be truly conducted
d. Likewise, Rescher (2005) proposes some good reasons to choose TE instead RE stating that RE can be unaffordable, time consuming and impractical to use.

In his study 'Promises and Perils of Thought Experiments', Brown (2006) made comments on both the assurances and dangers of using TE. He stated that; TE may be more helpful in elucidating some cases than RE does. However, both TE and RE can sometimes be misleading and so both necessitate being developed. He gave microscope example in which he claimed those microscopes, that we use to make scientific observations, can even give misleading results. "The fact that many TE mislead is no reason to reject them in principle as a source of evidence. We simply have to learn how to use them, just as we must continue to learn more about microscopes. (p 73, Brown, 2006)".

Janis (1991) claimed that TE can also fail in the same way as RE fails. Reasons for TE to fail:

a. unexpected external factors can effect the experiment process
b. poorly designed experiment can give incorrect results; thought experimenter's inability to carry the experiment or his lack of knowledge
c. thought experimenter may reach incorrect conclusion
d. although gives correct results, it can fail to provide the intended answers

Similarly, Rescher (2005) stated that malfunction in performing TEs can stem from some reasons like deficiencies in information, errors in reasoning process or drawing wrong conclusions.

2.6 Basic Characteristics of Thought Experiments

Brown (2006) mentioned the difficulty of making a precise definition of TEs but claimed that we can define TEs when we meet them. Although, researchers could not negotiate on a certain definition of TE, it was obvious that they mainly emphasized key terms like reasoning process, problem solving or hypothesis testing and constructing an imaginary scenario while explaining the characteristics of TEs (Brown, 2006; Gendler, 2004; Reiner, 1998; Reiner & Gilbert, 2000a; Rescher, 2005). Kujundzic (1998) He sketched basic features of TE as:

a. "TEs are performed in the 'laboratory of the mind'
b. It is possible to manipulate conditions and circumstances, so TEs are certainly experiments.
c. They are empirical in a sense that they can help us infer empirical consequences.
d. TE may reduce to absurdity a set of assumptions and thereby refute a certain explanation or alleged law (p 239)".

Contrary to the idea that the aim of TEs was to either test our hypothesis or reveal assumptions in our thinking, Cohen (2005) advocated that; TEs intends to achieve both of those claims.

Reiner (1998) proposed five components for TE;

a. posing a problem (or a hypothesis)
b. forming an imaginary world
c. mentally designing and conducting an experiment
d. producing experiment result by logic
e. drawing a conclusion (as cited in Reiner & Gilbert, 2000b; Reiner&Burko, 2003; Reiner & Gilbert,2000a).

In a similar fashion with Reiner (1998), Brown (2006) defined properties of TEs as: "a) visualize a situation b) carry out an operation c) use background information d) see the result (p 63)".

Bunzl (1996) claimed that to conduct a TE; we first construct an experiment in our imaginary world, then run it and finally examine the findings generated from the experiment. Those results not suddenly flash in mind but they are based on our knowledge about nature (as cited in Klassen, 2006). In addition to different interpretations of TEs, literature on TE also constitutes debates about TEs in science education.

2.7 Thought Experiment in Science Education

In history of physics, it is obvious to find examples of TEs dating early times. Most familiar examples can be found in the 17th century which is proposed by physicists like Galileo and Newton (Details of some historical thought experiments presented in Appendix C). After that, in the 19th and 20th century TEs contributed the development of modern physics by creation of relativity and quantum mechanics. In contemporary physics, teaching of those concepts without mentioning TEs, such as Einstein's elevator, Maxwell's demon, Schrödinger's cat or Heisenberg's gamma-ray microscope, became almost unthinkable. It is evident that, much of modern physics is founded not upon measurements but instead on TEs (Cohen, 2005). Einstein did not carry out experiments in a rapidly descending elevator, nor did Schrödinger actually put a cat into a radioactive box and Galileo also did not drop the rock from the top of Pizza tower. They conducted their experiments in their laboratory of mind.

Extensive use of TE, particularly in teaching of modern physics, triggered researchers' interest to study on the practice of TE in science education. John Gilbert and Miriam Reiner are among the authors to make considerable contributions to the literature of TE in science education (Gilbert & Reiner 2000a, Gilbert & Reiner 2000b, Gilbert & Reiner 2004, Reiner & Burko 2003, Reiner 2006).

One of the earliest studies in the literature is related to use of TE in textbooks. To explore how TE are presented and used in textbooks, Helm, Gilbert & Watts (1985) analyzed physics textbooks intended for 13-14 years olds and older in higher education. In addition, relying on the data of their previous works, they commented on how teachers include TEs in their explanations and so what students comprehend these TEs. It is suggested that students spontaneously generate TEs during problem solving and TE have an effective role in conceptual change. Moreover, TEs are helpful for teachers to build bridges between students' previous experiences and new concepts to be learnt. The authors also mentioned that the TEs are indispensible part of teaching and they have superiority over REs in terms of practical issues. Teachers can monitor their student's way of thinking by asking students anticipate the results of experiments and when the experiment is actually performed, students would feel a conflict. So, using TE in this way of activity can be helpful in the area of conceptual change.

In accordance with the findings of Helm et al. (1985), Gilbert & Reiner (2000a) concluded that students frequently use TEs as a strategy for solving physics problems. The study was conducted with a group of students and teachers. Data collected according to TEs performed by subjects in collaborative problem solving sessions. The aim of the study was to investigate how students use TEs for learning. Results indicated that TEs employed three type of epistemological resources; visual imagery, conceptual-logical inference and bodily-motor experiences.

Imaginary world constructed during TE process was identified to help the students to retrieve tacit knowledge which they were unaware of. In addition, thought experimenter can manipulate objects in mind. The study suggested that learning environments should include modalities of sensory information, not just visual imagery but also force sensations.

In another study, Gilbert & Reiner (2000b) discussed potential application of TEs in class and analyzed textbooks in order to see how TEs realized. The data collected from three typical school and higher education level physics textbooks. Findings suggested that elements of TE combined with thought simulations and suggested potentials not realized in textbooks.

Presence of TEs in textbooks was also explored in a recent study by Velentzas, Halkia & Skordoulis (2007). The study constituted two parts; a) investigation of the appearance of TEs (on theory of relativity and quantum mechanics) in physics textbooks and books popularizing physics, b) examining the effect of TEs, presented in textbooks, in providing students get acquainted with contemporary physics topics. Fifteen popular physics books and ten physics textbooks were used for the first part of the analysis. For the second part, six 14 year old students, whose physics knowledge is limited to Newton's' laws in one dimension, were participated as subjects. Results of the investigation proved that textbook authors accept the indispensability of use of TEs to communicate modern physics concepts. Moreover, the success of narrative techniques in triggering students' motivation while presenting TEs was emphasized.

The question of how to use TEs effectively in class is investigated by Klassen (2006). He made a definition of pedagogical TE as "mental re-enactments of natural processes for the purpose of clarifying concepts in science or providing answers to students' questions about science". He analyzed several TEs for their narrative techniques and re-wrote a TE in a story format. He claimed that TEs re-written in story like format can encourage students' motivation and active engagement so creates effective classroom environment.

In order to explore cognitive processes involved in contextual learning, Reiner (2006) questioned the validity of naïve students' TEs and the use of sensory memory with associated schemata engaged in TE.

Results indicated that students' problem solving discussions were in the format of TE. According to the analysis, naïve students spontaneously generate TEs, unlike expert physicists who plan the use of TE as an argumentative device. Students rather use TEs as a sense making device of the context. Contextual problems trigger sensory memories and so provide access to implicit knowledge.

Gilbert & Reiner (2004) explored epistemological resources of knowledge on students doing REs. Data collected from four students aged 12-13 whose formal background in physics not included magnetism. Subjects were given magnetic toys and analysis based on their hands on experiments with the toys. Results showed that while solving the given problem situation, students generated and used thought experiments as well as performing physical experiments in an intertwined manner. This study asserted that students conduct TE interconnected during the process of performing physical experiments. Authors call this coupling as 'mutual projection' in which; images in the imaginary world are the illustrations of the objects in the physical world and those images are connected with the process in the physical world. This mutualism claimed to help us go beyond just 'seeing' the physical phenomena and transform to 'knowing' about it.

Özdemir (2008) studied how physics graduates used mental simulations- under the framework of TEs- while solving physics problems. Data collected through problem solving sessions with five physics graduates. According to the findings, Özdemir concluded that participants' inconfidence about their mental simulation and not considering it as a reasonable reasoning tool, made them avoid the use of mental simulations.

Upto that point, researchers mentioned the crucial role that TEs play in science learning. From a different aspect, Reiner & Burko (2003) suggested that erroneous TEs also contribute to conceptual refinement for both expert physicists and naïve physics learners. The analysis was based on TEs about stellar evolution and general theory of relativity proposed by Einstein, Landau, Eddington and Schwartzschield. Analysis of the study based on the previous work of Reiner (1998) where he proposes five components for TE; a) core assumptions, posing a problem (or a hypothesis) b) an imaginary world c) mentally designing and conducting an experiment d) producing experiment result by logic e) drawing a conclusion. Authors identified the stages where crucial errors are done as the first two stages about general assumptions and features of the imagined world. While expert physicist did mistake on these two stages, naïve students were inclined to make mistakes in all stages of the TE. Three factors leading to mistakes performing TEs are suggested as: intuition, incompleteness and irrelevancy; a) intuitive judgments and past experiences can dominate theoretical framework, b) incompleteness of the imaginary world of TE c) irrelevancy of assumptions to the features of imaginary world. As a result, authors claimed TEs to be more prone to errors than RE.

In most of his studies, John Clement explored role of imagery in expert reasoning (Clement, 1994b, 2003, 2006). Contrary to the idea that knowledge used by expert scientists is abstract, he claimed that their knowledge structures are concrete and self evaluated (Clement, 1994a). To investigate the role of TE in large classroom, Clement (2006) analyzed the student and teacher generated TEs in classroom activities. Results showed that using TEs as sense making strategy, students assessed the reliability of new knowledge. Clement concluded that: 1) imagery and mental simulations used in TEs 2) There were similarities between expert and student uses of TE's such as a) Both use TEs as pedagogical devices b) both modify their TEs when needed c) Both use strategies for refinement of imagery which are helpful for TEs.

Clement (2008) in his study about role of imagistic simulation in TE, concluded that TEs function as evaluative and predictive devices.

Lattery (2001) made students apply a historical TE in laboratory. Galileo's Lax of Cords reviewed and it was used as a basis for a research project to be applied in the laboratory. The data were collected from a group of three students. Results showed that students spontaneously run TE of extreme cases during studying on the project. They had the opportunity to generate hypothesis and test their claims. Lattery concluded that his type of activities could be beneficial for a wide range of learners.

Stinner & Metz (2004) examined and illustrated Galileos' and Einsteins' TEs. They recommend that TEs should be presented in story format but it would be insufficient. In addition, quantitative aspect of the TEs should be incorporated in a comprehensive format to students.

Clement (2008), in his study of 'Hidden world of nonformal expert reasoning', focused on nonformal creative reasoning resources of experts and proposed that reasoning and learning processes used by experts to achieve scientific understanding can also be beneficial to help students develop scientific perspective. He maintained that in the literature there is a considerable shortage of research concentrating on higher-order cognitive processing such as creative reasoning and hypothesis formation in experts. Experts were defined as the experienced problem solvers in his study. He also asserted that, traditional research centers on expert novice differences, but similarities where we can build education on are less considered. He claimed that those studies describe novices as experts with holes, however they may be considered as the one having prior knowledge that differs from experts'.

In his earlier study with freshmen science students –whom he calls as novices-, Clement (1989) aimed to identify misconceptions and reasoning difficulties that hinders learning. He observed that students overcome these difficulties and solve problems by forming analogies to similar situations or even by using thought experiments. The results of the study revealed that it was possible to identify natural forms of powerful creative reasoning resources of students that we recognize very little. According to the study about role of expertise in analogical problem solving; during representations of problems, novices and experts were identified to have some differences. While novices' interpretations were based mainly on surface features; like terms or particular objects used in the problem, experts' representations concentrate more on structural features; such as the relations among elements of the problem (Novick, 1991).

Rapp & Kurby (2008) claimed that; our mental representations were not complete as we expected but in fact they were fragmented. They claimed that; during problem solving, students reassemble partially retrieved partial representations stored in the memory. Moreover, piecemeal representations were not just for novices but also for experts, advantages of experts however lies in the fact that they have the practice to piece together important representational elements in their expertise.

Similar to the studies conducted on thought experiment literature, this study requires using a qualitative research method. The following section discusses the methodology of this study.

CHAPTER 3

METHODOLOGY

Generally, the aim of teaching science is to help students get close to the experts' level of understanding and reasoning about how the world works with small steps through the instructions. However, at any point of instruction, it is possible to observe that students develop a variety of conceptions and reasoning in a domain which may or may not be consistent with the ones developed by the experts. Orgill & Bodner (2007), referring to Ference Marton (1986), claimed that phenomenographic method may be useful for researchers to detect variations on the conceptualization of a particular concept in terms of revealing the necessary conditions to facilitate the transitions from one way of thinking to another.

In the publications of early 1980s, Swedish educational psychologist Ference Marton described phenomenography as a new approach which was designed to answer questions about thinking and learning by analyzing the variations about them (Akerlind, 2005; Orgill & Bodner, 2007). Gall & Borg (2003) claimed that it resembles the method Jean Piaget used in his investigations while monitoring developmental changes in ones' thinking and changes in thinking. The core objective of phenomenographic research is to capture the variation of a phenomenon under the investigation. This phenomenon can be a concept, a process, or reasoning. The purpose of this study is to capture the variation on the nature and use of thought experiments during problem solving. Therefore the most appropriate methodology for this study is to follow a phenomenographic approach.

3.1 Aims of Phenomenographic Research

Phenomenography was generally defined in the literature as a specific method developed for explaining the differences in experiences of people for a phenomenon (Akerlind, 2005; Gall, Gall & Borg, 2003; Orgill & Bodner, 2007). Any mental processes such as perceiving, conceptualizing, apprehending, and understanding, were all considered as 'experience'. The aim is to see the world from different peoples' perspective, identify multiple conceptions of people and to build a typology of them (Ashworth & Lucas, 1998). So, focus on the correctness or incorrectness of the conceptions is irrelevant according to this theoretical stance, the emphasis is just on diversity.

In other words, the main objective of phenomenographic research is to uncover variation in the experience or conceptualization of some aspect of the reality (Bruce, Buckingham, Hynd, McMahon & Roggnkamp, 2004). Nevertheless, phenomenographers especially emphasized that phenomenography makes assumptions about the nature of conceptions but not about the nature of reality (Orgill & Bodner, 2007). "Phenomenography is interested in studying how reality appears to people rather than the objective nature of the reality. It can be used to study any aspect of reality about which individuals have formed some conceptions (Gall et al, 2003, p10)". Phenomenographic research seems to serve this purpose as Ashworth & Lucas (1998) explained, by generating a typology based upon categories of descriptions emerging from different ways of understanding

> "Phenomenography develops a descriptive framework based on the two elements of meaning and structure. Meaning is represented in categories of description that regroup logically the views of the participants, simultaneously contrasting differences and clustering similarities. Structure is represented within each category and in an outcome space that indicates the relationships between the categories. The structural elements of each category and the outcome space are typically most useful for developing understanding of the phenomenon investigated (Bruce et al, 2004, p 146)".

This study is not a phenomenographic study; however, methodology of phenomenographic researches is used in this study.

3.2 Data collection Instrument

Similar to the most of the qualitative methodologies, phenomenographic research depends on language as way of reaching information about thought processes. The purpose of this study, in terms of collecting data, is to reach as much information as possible about the thought experiment process. Therefore, face to face problem solving sessions was used to set the essential conditions to observe the thought experimentation processes through participants' verbal reports. Think aloud protocols were used during the sessions. Think aloud during problem-solving means that the subject keeps on speaking out loud the thoughts passing through their minds as they go through the problem (Someren, Barnard & Sandberg, 1994). Ornek (2008) suggests using think aloud protocols during problem solving for a phenomenographic research because it provides researchers unique opportunities to monitor what was happening inside the participants' head while performing on the given problem. During the sessions, retrospective questioning strategy was also used to get details about a specific thought process or capture the thought processes not verbalized by the participants. Retrospective questioning is simply asking participants about what they were thinking at a particular instant of time of problem solving process after the problem is solved.

3.3 Participants

Sampling in a phenomenographic study aims at capturing the breadth of variation in perspectives (Bruce et al, 2004). Therefore, the participants of this study were selected purposefully to capture the variations on the nature and use of thought experiments. As Gall, Gall & Borg (2003) stated:

> "In purposeful sampling the goal is to select cases that are likely to be information rich with respect to the purpose of the study. Purposeful sampling is not designed to achieve population validity. The intent is to achieve in depth understanding of selected individuals, not to select a sample that will represent accurately a defined population (p 165)".

To capture the variation on thought experiments three groups of participants were selected according to the level of participants' physics knowledge (five for each group and fifteen in total). These groups were named as low level, medium level, and high level groups.

3.3.1 High Level Group (Expert Group)

The aim of gathering data from this group was to detect the nature and role of thought experiments for experts. The following criteria were set for the selection of high level physics group: a) being a graduate students majoring in physics and b) already passed the PhD qualification exam. Graduate students were preferred instead of professors because professors' expertises are for the very specific physics topics such as quantum mechanics or electromagnetic theory. However, the physics problems used in this study are high school level conceptual problems based on fundamental physics laws on classic mechanics. It is believed that graduate level students' expertise on this topic is higher than professors. PhD qualification exam was also set as a criterion because this exam provides further evidence about graduate students' competencies on basic concepts of physics.

A list of eight individuals satisfying the criteria were determined from graduate PhD students enrolled in Department of Physics at Middle East Technical University. Procedures, ethical issues and aim of the study were explained to the participants. List of the individuals were generated by the help of secretariat of the Physics Department. Each individual was contacted face to face and informed about the nature of the study (see Appendix A). While explaining the aim of the study, the researcher consciously avoided from using several terms such as thought experiments, mental imagery, or mental simulation; because these terms might lead them to use those processes during problem solving processes. Instead a general term, reasoning, was used during the explanation on the nature of the study. Five individuals out of eight who agreed to participate in the study were selected. Detailed information about high level participants was presented in Table 3.1

Table 3.1 Information about High Level Participants

Participant	*Gender*	*Age*	*School Type*			*Grade*
			Undergrad	MS	PhD	
H1	Male	27	METU	METU	METU	PhD candidate
H2	Male	30	METU	MIT*	METU	PhD candidate
H3	Male	29	METU	METU	METU	PhD candidate
H4	Male	29	METU	METU	METU	PhD candidate
H5	Male	28	METU	METU	METU	PhD candidate

* MIT: Massacusess Institute of Technology
'H' indicates high level participants

3.3.2 Medium Level Group (Intermediate Group)

The following criteria were set for the selection of medium level physics group: a) had been taking basic undergraduate physics courses at university level for at least four semesters b) had not yet taken any courses from physics education department. Similar sensitivities mentioned for the high level group were considered for this group also. Conceptual physics problems- highschool level- that does not necessitate mathematical calculations.

However, problems solved in undergraduate physics courses calls for doing advance mathematical calculations. Participants for this group were undergraduate physics education students who have more advance physics knowledge compared to highschool physics students, but are not expert physicist when compared to high level group. According to the curriculum of physics education department; during the initial four semesters, students take physics courses and physics education courses begin after the fifth semester. It was assumed that, an individual who had taken courses from physics education department would likely be familiar with the conceptual physics problems- designed for highschool level- and with probable reasoning resources of students that were used for this kind of problems. These assumptions could have the potential to lead the participants infer the purpose of the study and behave accordingly. One of the problems used in this study was adapted from Force Concept Inventory (FCI) Test which was developed by Hestenes, Wells & Swachamer (1992). It was probable for students taking courses from physics education department to solve problems in FCI test. These criteria necessitate the participants being undergraduate physics education students who had just completed fourth semester in the program.

A list of ten individuals satisfying the mentioned criteria were determined from undergraduate students enrolled in Department of Physics Education at Middle East Technical University. Procedures, ethical issues and aim of the study were explained to the participants. List of the individuals were generated by the help of advisor of the undergraduate physics education students completed the fourth semester. Each individual was contacted face to face and informed about the nature of the study (see Appendix A). Five individuals were selected who agreed to participate in the study. Detailed information about medium level participants was presented in Table 3.2

Table 3.2 Information about Medium Level Participants

Participant	*Gender*	*Age*	*School Type*		*Grade*
			Highschool	University	
M1	Female	21	Anatolian High School	Undergraduate at METU	Fifth semester
M2	Female	21	Anatolian Teacher Preparatory High School	Undergraduate at METU	Fifth semester
M3	Female	22	Anatolian Teacher Preparatory High School	Undergraduate at METU	Seventh semester (repeated the first and second semesters)
M4	Male	22	General High School	Undergraduate at METU	Fifth semester
M5	Male	21	Anatolian High School	Undergraduate at METU	Fifth semester

'M' indicates medium level participants

3.3.3 Low Level Group (Novice Group)

The aim of gathering data from low level of novice group is also to detect the role of thought experiment in solving physics problems. The criterion for selection of this group was that; low group participants were the individuals who had been taking physics courses for at least four years so that they had covered all basic -highschool level- physics units.

Similar sensitivities, mentioned for the high level and medium level groups, were considered for this group also. Five highschool students in twelfth grade were selected as participants. The students were selected from a highchool at Çankaya district, where the researcher has developed mutual confidence with physics teachers and students in advance, during previous studies.

List of the individuals were generated by the physics teachers. Procedures, ethical issues and aim of the study were explained to the participants. Five individuals were selected who declared interest in the study. Each individual was contacted face to face and informed about the nature of the study (see Appendix A).

The data were collected from the low and medium level group first to identify the possible indicators of thought experiment otherwise it would have been ambiguous to collect data from the high level group. Same procedures mentioned for other participants were applied to this group. Detailed information about low level participants was presented in Table 3.3.

Table 3.3 Information about Low Level Participants

Participant	*Gender*	*Age*	*School Type*	*Grade*
L1	Male	18	Anatolian High School	12
L2	Male	19	Anatolian High School	12
L3	Female	18	Anatolian High School	12
L4	Male	18	Anatolian High School	12
L5	Female	18	Anatolian High School	12

‘L’ indicates low level participants

3.4 Interview Questions

In the initial phase of the study, twenty potential problems were identified. Selection of these problems were based on according to the following criteria: the problems a) should be suitable for doing thought experimentation in mind b) should not necessitate advance algebraic calculations c) should be related to daily life situations d) should be interesting so that encourage participants to generate a solution. Based on the literature review, it was concluded that mechanics questions have more potential to trigger alternative conceptions of students than other topics in physics. Therefore, using mechanics problems as data collection instrument was a fruitful approach for this study.

One of the problems, sixth problem, was adapted form Force Concept Inventory test developed by Hallun & Hestenes (1992). Three problems, fifth, ninth and tenth, were developed by researcher of this study with mutual agreement with the theses advisor. Rest of the problems was adapted from the book of Lewis Epstein (1994) called 'Thinking Physics'. He names the book also as 'Gedanken Physics', where the term 'gedanken experiments' used in the literature as a synonym of *thought experiments*. Epstein described the aim of problems in his book as: "The most important problem in physics is *perception*, how to *conjure mental images,* how to separate nonessentials from essentials and get to the heart of the problem, how to ask yourself questions. Very often this question has little to do with calculations. Qualitative questions are the most vital questions in physics (p, i)".

Pilots of these potential problems were conducted with three participants from physics education department. Discussing the results and coming to a mutual agreement with the theses advisor, a list of ten problems were identified. List of the problems used as data collection instrument during problem solving sessions are provided in Appendix B.

3.5 Data Collection Procedure

Data collection procedure of this study was based on individually conducted face to face problem solving sessions accompanied by think aloud protocols and retrospective questioning methods. Same problems were asked to each participant in each group.

Each participant was met individually. At the beginning of the session, participant was given the informed consent forms (see Appendix A). Purpose of the study was discussed briefly and participant was informed about the confidentiality issues.

It was also reminded that his/her participation was voluntary and it was free to withdraw at any time during the study. It was explained that he/she would be given several problems to solve and he/she would be asked to think aloud during the problem solving session. Clarification of the meaning of think aloud method was done by providing participant the opportunity to practice it on a sample problem. Participant was also notified that various retrospective questions would be asked to him/her in order to obtain deep information about their thinking process. It was repeated that the aim was not to evaluate physics achievement but to see the inside of his/her mind. Session did not start until the participant felt herself/himself comfortable and ready. Recording equipment was tested and problem sheet was given to the participant. He/she was asked to read the first problem and think aloud while thinking the solution. Retrospective questions were asked until participant had nothing to add more. Same procedure was followed for the rest of the problems and for each participant. The main argument for this study was to identify the variation among three groups of participants, for this reason, data collection process was started with low level group and next continued with medium level group, then finalized with high level group. Each interview lasted about in an hour.

3.6 Trustworthiness

Parallel to internal validity, external validity, reliability and objectivity issues in quantitative studies, qualitative researchers interpreted and categorized trustworthiness in terms of credibility, transferability, dependability and conformability (Lincoln & Guba, 1985). They suggested several strategies for judging the trustworthiness of data collection and data analysis procedures (Creswell & Miller, 2000; Lincoln & Guba, 1985) such as peer debriefing, member check, thick description, prolonged engagement, and triangulation.

There are not special strategies suggested for phenomenographic studies; still, researchers emphasize that defensible interpretation of the outcomes is the aim of phenomenographic research more than the correct interpretation (Akerlind, 2005). Phenomenographers do not advocate that their research results represent truth but they are useful (Orgill & Bodner, 2007). The aim is to check if the results provide meaningful and useful knowledge to the intended audience. The general expectation for academic researches is that repeated measurements should come up with the same or similar results. Phenomenographers however advocate that, analyses for phenomenographic studies are not based on measurements but on discoveries (Orgill & Bodner, 2007). Marton (1994) compares this process to botanists that discover a new plant species on an island and claims that different researchers can form different categories while working on the same data individually. The important point is to describe the categories in a clear way so that all researchers can understand and use them. Fully detailing the steps and presenting the examples that illustrate these steps is a suggested method to clearly represent the interpretive steps of the analysis (Akerlind, 2005).

Considering the main concerns of phenomenographic research and analyzing the suggested trustworthiness strategies for qualitative studies; member check, thick description, prolonged engagement, and triangulation strategies were employed in this study for establishing the trustworthiness.

3.6.1 Member Check

Member check is considered as one of the most curial strategies for establishing the credibility of the study (Lincoln & Cuba, 1985; Lietsz, Langer & Furman, 2006). It is also named as respondent validation, where participants asked to review the results of the analysis collected from them in order to check the authenticity of the interpretations.

During and after the problem solving sessions, the researcher always checked with the participants on the consistency of the researcher's interpretations with their verbal reports. At the end of the analysis procedure, the researcher met with each of the participant and went over the results of the final analysis. During the meetings, the researchers checked with each of the participant whether the researcher's conclusion is consistent with the participants' intentions and the reasoning. When a participant declared her/his disagreement on a particular result, the researcher and the participant worked on it together and resolved the conflict.

3.6.2 Prolonged Engagement

It is suggested for researchers to engage in the research site for a prolonged period of time. That is; the researchers should develop a mutual trust with participants to create a comfortable environment gain access to participants (Creswell & Miller, 2000). Therefore, participants in this study were selected from individuals who had known the researcher for at least three months. The researcher spent three moths in a high school to establish rapport with the students, teachers and managers and participants of the low level group were selected among these students. The researcher of this study was the advisor of the first year university students in department of physics education (PHED). Medium level group of participants were selected among second year PHED students, who the researcher had known for one year since their first year in university. The high level group of participants was selected from PhD students in physics department. Researcher took physics courses with the participants when they were undergraduate students. Earlier to data collection process, researcher had already assured prolonged engagement with the participants of the study.

3.6.3 Thick Description

"The purpose of thick description is that it creates verisimilitude, statements that produce for readers the feeling that they have experienced, or could experience, the events being described in a study (p, 129; Creswell & Miller, 2000)". In order to provide further evidence on the credibility of the research, 'thick description' of the participants, data collection procedures, and analysis with sufficient details was provided in this study.

3.6.4 Triangulation

Common practice in qualitative studies to provide confirmatory evidence is to triangulate the data collection methods; by collecting data through multiple methods such as interviews, observations and additional materials. In this study, think aloud strategy and retrospective interview method were used. In addition to verbal reports of participants, their hand and body motions were observed and transcribed and coded. Moreover, ten physics problems were asked during problem solving sessions of interviews, where each context assessed by two problems to establish the credibility of the data.

3.7 Limitations and Delimitations of the Study

Fifteen participants were selected for this study in order to make deep analysis about thought experimentation process. The number of participants was delimited to fifteen only because of the feasibility concern of the researcher to complete the collection and analysis of data in a limited time interval allowed for the dissertation. Selection of participants was based on some established criteria and three levels of participant groups were formed.

Participant groups were not formed by using a measurement tool but they were formed according to participants' academic position. Therefore, the participants' competency level on physics is limited to their academic positions and does not reflect their individual competencies independent from their academic positions.

Another limitation of the study is related to the analysis of data. Gender difference was not on the focus of the study, therefore possible relations between gender and thought experimentation process was not considered during the analysis. Considering that the variation of gender among groups is not homogeneous, possible gender differences may limit the results of the study.

Difficulty level of the problems used in this study brings another limitation for the results. Same problems were used for all groups of participants for this study in order to be consistent during the analysis. However, the difficulty level of problems may change according to educational level of participants. This is considered as an issue because participants' thought experimentation process may change according to the difficulty of the problem situation. Finally, content of the problems which were used during the interviews were limited to conceptual problems covering mechanics concepts which should also be considered as a limitation because it is highly possible that the nature and use of thought experiments may change when the content and problem type is changed.

In this chapter, method of the study, strategies used to increase the trustworthiness, limitations and delimitations were mentioned. The following chapter is about analysis of data.

CHAPTER 4

ANALYSS OF DATA

Detailed analysis of data, collected through problem solving sessions, will be presented in this chapter. There are totally fifteen participants from three groups. The participants in the high level group were named as H1, H2, H3, H4 and H5; participants in medium level group were refereed as M1, M2, M3, M4, M5; and similarly low level group were named as L1, L2, L3, L4, L5. Providing the whole analysis for all participants would cover a huge volume of space; therefore, only some exemplary cases will be discussed in detail while presenting the analysis of data. Nevertheless, the results of analysis for each participant will be presented in figures or tables. During the analysis of data, direct quotations from participants' responses to the problems will be used throughout the analysis. Italic words in the quotations will be employed to signify the codes for related purposes. Problems used during the interview were attached in Appendix B, still in order to help readers follow the analysis easily a brief descriptions of the problems will be presented before the specific analysis. In order to provide a clearer analysis, this chapter is divided into four sections. Each section addresses particular analysis leading to generate a response for a specific research question. The first section focuses on thought experimentation processes of participants. The purpose of this section is to detect whether participants construct thought experiment during problem solving sessions and locate the thought experiment processes generated by the participants. Following sections are focused on the located thought experiments to capture the variations among thought experiments in terms of the nature of thought experiments, the purpose of using them, and the resources used during the thought experiment processes.

4.1 Locating Thought Experiments

As discussed in earlier chapters, there is not an agreement on the exact definition of thought experiment in the literature. Therefore it is necessary to provide an operational definition before passing into the detailed analysis.

The most explicit definition of thought experiments allowing an operational definition were proposed by Brown (2006) and Reiner (1998). Both proposed similar characteristics from which several steps of a thought experimentation process can be identified. These steps, demonstrated in Figure 4.1, were used to locate the thought experimentation processes during the analysis of data.

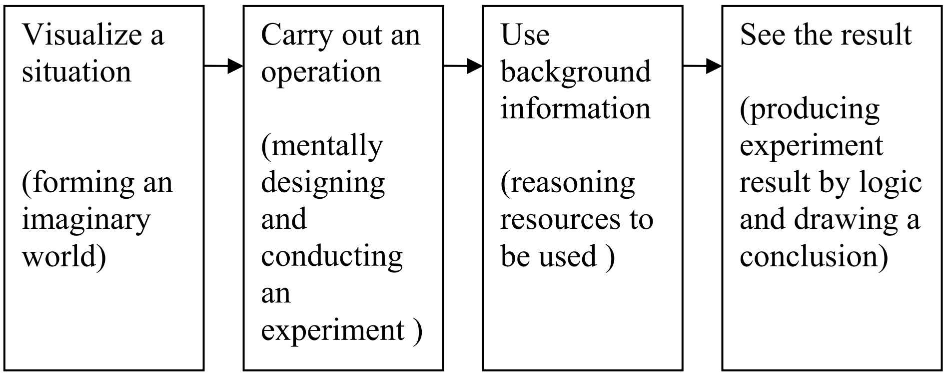

Figure 4.1 Thought experiment steps

Literature emphasizes animated imagery as an indispensible element of thought experimentation process. That is; running imagistic simulation of an event or in other words, experimenting in mind. It is not imagining solely an image but instead visualizing a situation or process of an action. Suggestions of Clement (2008) were used in this study as a reference for animated imagery indicators. Kinesthetic and dynamic imagery reports as well as body and hand motions were regarded as indicators of visualizing a situation or forming an imaginary world for thought experimentation.

In his study, Clement (2008) presented an extended code list but in order to suppress the fuzziness and perform more robust analysis; a list of most evident and representative imagery indicators, presented in Table 4.1, is used in this study.

Table 4.1 List of Imagery Indicators

Indicators	*Types of Indicators*	*Details*
Imagery	Imagery reports	subjects states that s/he is ‘imagining’, ‘seeing’, ‘feeling’, ‘suppose that’, ‘if’, ‘think that’
	Depictive motions	hand or body motions depicting object, force, location
Dynamic Imagery	Hand Motions	hand motions depicting a dynamic event, not a static picture
Kinesthetic imagery	Kinesthetic imagery reports	reports imagining physical actions or muscular effort
	Personal movement projection or Analogy	movement of entities in target situations as if they were moved by a person (analogy by others)
		using a personal analogy by referring to an analogous situation involving the body (personal analogy)

(adapted from Clement, 2008, p, 180)

In order to locate thought experiments, imagery indicators in the videotapes were scanned and located. Transcripts of videotaped interviews as well as images on videotapes themselves were analyzed simultaneously in order to crosscheck the gestures, hand and body motions with the inferences from the written document.

After the location of imagery indicators subsequent steps of thought experiments were analyzed. These analyses consist of searching whether the visualized situations were used to carry out an operation by using some background knowledge and coming up with a conclusion. The following two episodes were presented to demonstrate how the thought experiment processes were located.

Italic words in the episodes were used to represent imagery indicators, while the parentheses were devoted to the descriptions of bodily motions. Snapshots of photographs taken from the interview videos were also included to display the visual data.

4.1.1 Episode 1

Episode 1 was taken from the transcript of L2's response to the problem 3.

Problem 3: Suppose an open railroad car is moving on a straight road. It is raining heavily and an appreciable amount of rain falls into the car and accumulates there. Will the accumulated rain have an effect on the motion of the car? Will the rain have an effect on the motion of the car, if rain drops fall sideways (if rain drops fall at an angle, suppose making 45° angle with horizontal direction)?

> 'L2: I do not think that the rain will have an effect on the motion of the car. Because.. *Suppose that* the car is on an inclined road (he makes his hand inclined, as in the first photo of Figure 4.2). When the mass of the car increased, it will then move with a higher speed. But on a straight road, increasing mass will not affect the motion. On an inclined road, when cars' mass increases it goes down the hill more quickly. *Suppose we leave* an empty car or toy car down from the hill. Then *we filled* the same car with sand, and released it again, it will go down the hill with a higher speed (he again puts his hand in a position as if it is an inclined road, and shows the motion of the car from the top of incline to the bottom, as in the second and third photos of Figure 4.2).
> R: why?
> L2: It may be about … I mean, when we leave two objects, heavier one falls faster, because, gravity pulls the heavier one more. It is the same in our case. Because there is slope here, there is a *pull*. There is more pull, so more speed.
> R: What if it rains with an angle?
> L2: It will have no effect on that car because that car looks like a heavy car. But suppose that there is a plastic toy car. If rain falls from left side making an angle with the horizontal direction, then it can push the car to the left. If this car was a light car, and if it rains heavily, then rain can

push the car in its raining direction. But it should rain heavily; otherwise, it won't have an effect on the motion of the car.
R: What about the speed of the car? Will it change?
L2: Car will move with a changing speed, because rain drops will not touch the car regularly. Based on my daily life observations, when we are in a car for example, every drop touches different part of the car, they do not hit the same point with the same intensity'.

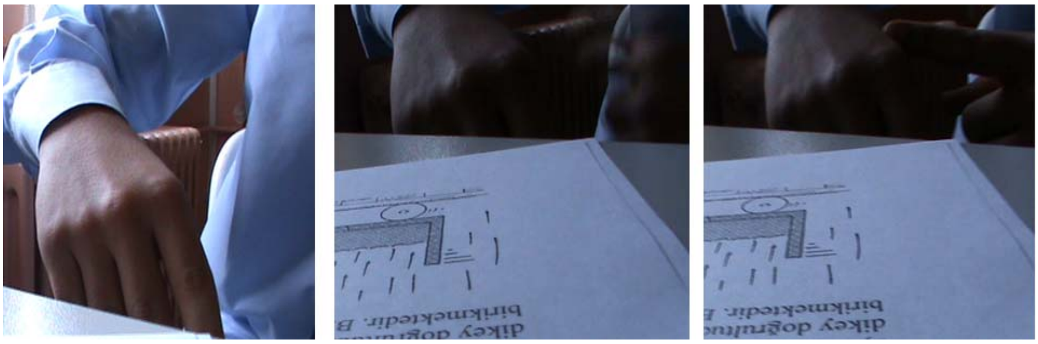

Figure 4.2 Displays of hand motions of L2 on problem 3

In episode 1, the word 'suppose that' was coded as imagery indicator. It was the sign that L2 was going to visualize a situation in his mind; he was forming an imaginary world. He visualized an inclined road and showed it by putting his arm in inclined position in air as shown in Figure 4.2. He proposed a hypothesis as; when the mass of the car increases, it will then move with a higher speed (if it is moving on an inclined road). Proposing the hypothesis, he started conducting his experiment in the laboratory of his mind. He imagined replacing the car in the original problem with a plastic toy car (toy car is proposed to represent a light car because he said he imagined the car given in the problem as a heavy car). First, he let the plastic car roll down the inclined road, and observed his motion and velocity. Then, he filled the toy car with sand and let it roll again. He observed the motion and velocity again (he showed the path of the car down the hill on his inclined arm, as shown in the second and third photographs in Figure 4.2). And he concluded that the car filled with sand will go down the hill with a higher speed.

He explained his conclusion with bottle example, with his intuitive knowledge. As a result all the steps of thought experiment process (visualizing a situation, conducting imaginary world, using resource and seeing the result) were completed. Table 4.2 summarizes the thought experiment steps and evidences from the episode 1.

Table 4.2 Summary of Episode 1

Thought Experiment Steps	*Evidence from Episode 1*
Visualize a situation	‘Suppose that the car is on an inclined road’
Carry out an operation	‘Suppose we leave an empty car or toy car down from the hill. Then we filled the same car with sand, and released it again’
Use background information	‘heavier one falls faster…Because gravity pulls the heavier one more’
See the result	‘It (car filled with sand) will go down the hill with a higher speed’

4.1.2 Episode 2

Episode 2 was taken from transcript of M4’s response to the problem 1.

Problem 1: There is a water hose whose one end is folded into a figure 6 and the other end is connected to the tap. When the tap turned on, which path will the water shooting out the folded end follow?

> ‘M4: It will follow path B. because we should apply *force* on the things if we want to change their direction… If force acts on the water at the moment it leaves the hose, then it will follow path C…. *Lets’ imagine a bullet*…Fired from the gun (he showed the flight of bullet by his hand, by drawing a straight-line path in air, as represented in Figure 4.3) bullet would already reach its target. It will reach its target before gravity acts on it. Because, flight time would be very short. In fact gravity should act on the bullet, but there would not be enough time for gravity to act, because bullet would already reach its target before feeling the affect of gravity.

> We can think this and hose problem similarly. Water will follow path B. If the water is shooting very slightly and slowly, then it will bend and follow path C. Even when it follows path B, it will soon bend like path C (he draws a parabolic path in air as shown in Figure 4.4)'.

Figure 4.3 Hand motion representing flight of bullet

Figure 4.4 Hand motion representing path of water

In episode 2, the word '*let's imagine'* was coded as imagery indicator. It was the sign that M4 was going to visualize a situation in his mind; he was forming an imaginary world. First he proposed a hypothesis that force should be applied to things in order to change their direction. Then, he started conducting his experiment in the laboratory of his mind by forming totally a different case than the original one given in the problem. The problem was about path of water shooting from a hose but he imagined path of a bullet fired from the gun (he showed it with his hand motions depicted in Figure 4.3). He observed the motion of the bullet by tracing his hand motions as the path of the bullet and reasoned that bullet will reach its target before gravity acts on it.

Then he turned back to original case, he traced the path of water in his mind (as shown in Figure 4.4). Then he concluded that water will follow path B. As a result all the steps of thought experiment process were completed. Table 4.3 summarizes thought experiments steps and evidences from episode 2.

Table 4.3 Summary of Episode 2

Thought Experiment Steps	*Evidence from Episode 2*
Visualize a situation	'Lets' imagine a bullet.'
Carry out an operation	'Fired from the gun (he showed the flight of bullet by his hand, by drawing a straight-line path in air) bullet would already reach its target'
Use background information	'We should apply force on the things if we want to change theirs direction'
See the result	'In fact gravity should act on the bullet but there would not be enough time for gravity to act, because bullet would already reach its target before feeling the affect of gravity'

Episode 1 and 2 were provided to exemplify the analysis procedure of thought experiments based on the data emerging from the problem solving sessions with the participants. The whole data set was analyzed by following the same procedure to locate the thought experiments. The results of the analysis were presented in Table 4.4.

Table 4.4 Frequency of Thought Experiments

Problem/ Participants	High Level Group (H)					Medium Level Group (M)					Low Level Group (L)				
	H1	H2	H3	H4	H5	M1	M2	M3	M4	M5	L1	L2	L3	L4	L5
P1								+	+		+				
P2		+							+				+		
P3	+			+	+	+		+	+	+		+*	+		+
P4	+		+				+*		+			+*			+
P5		+													
P6						+								+	
P7		+	+	+				+	+						
P8			+			+			+						+*
P9		+					+		+						+
P10						+								+	+

The asterisks (*) in the table specifies that participant conducted more than one thought experiments during the solution of the related problem.
'+' represents the type of reasoning resources used by each participant during each thought experiment process.
'H' indicates high level group, 'M' indicates medium level group, 'L' indicates low level group.
Capital letter 'P' represents the problems which is associated with related problem number.

The results show that all the participants conducted thought experiment at least once, during the sessions. In some cases, participants conducted more than one thought experiment for the same problem. It was also observed that thought experiments conducted for each problem at least by two participants. Total number of thought experiments did not vary so much among the groups (high, medium and low). In this section, the analyses were focused on how to define and locate thought experiments. In the following sections, the variations on thought experiments will be analyzed.

4.2 Nature of Thought Experiments

Kujundzic (1998) declared the basic characteristic of TE as constructing an imaginary scenario in mind and manipulating the conditions. Therefore, the imaginary scenarios were taken as foci while trying to understand the variation about the nature of thought experiments. The key question leading the analysis was how the participants' changed the problem situation while they were generating an imaginary scenario. A problem situation consists of variables (e.g., velocity, force, distance etc.) and objects (e.g., car, train, ball etc.). The analysis of data showed that the participants changed the problem situation in two different ways; by manipulating the variables of the problem situation (manipulation of variables) or by modifying the objects of the problem situation (modification of objects). A schema of the variation on the nature of thought experiments is presented in Figure 4.4. As the figure reveals there are two subcategories for manipulation of variables and modification of objects. In the following sections, the details about the each category will be presented.

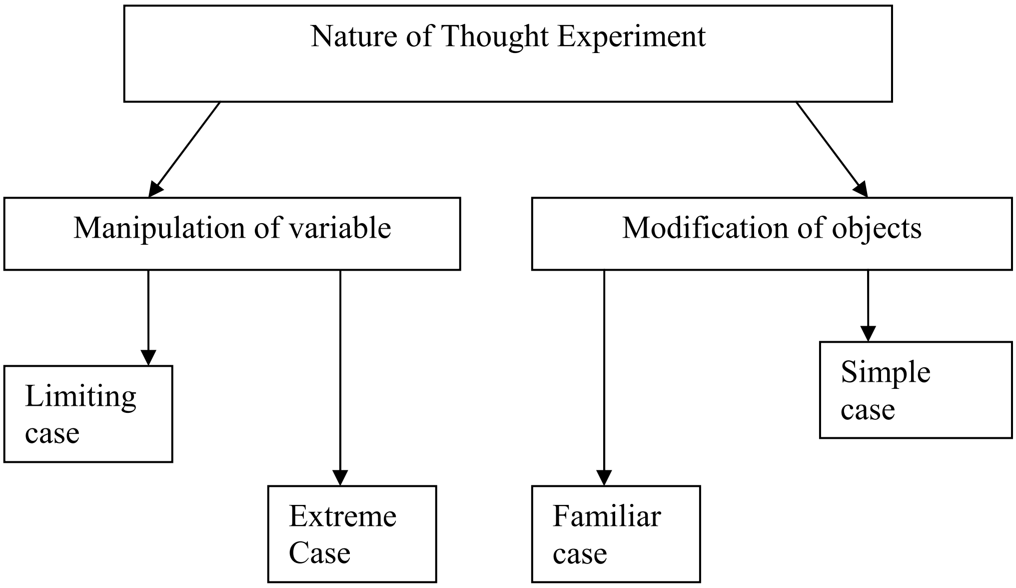

Figure 4.5 Nature of thought experiments

4.2.1 Manipulation of Variables

Purposefully manipulating the variables of the original problem situation but keeping the objects of the problem situation unchanged was coded as manipulation of variables. Manipulation of variables was observed in two different ways which were categorized as limiting case and extreme case.

4.2.1.1 Limiting Case

If at least one of the variables of the original problem situation was purposefully excluded or reduced to a certain degree by the participants during the thought experiment process it was categorized as a limiting case. The following episode extracted from the problem solving session with H2 exemplifies how the participants used limiting case during their thought experimentation process. In this episode, H2 was working on Problem 5.

Problem 5: There is a straight rod hanged from its center, holding two pans at each end. Two kilograms put to the right pan and three kilograms to the left. At that point, left pan is touching the table, right pan is hanging in an upper position. What do we expect to observe, if we take one kilogram from the left pan?

> 'H2: Nothing will happen because equilibrium position will not change.
> R: are you sure?
> H2: I am 99% percent sure but physicians should be flexible in thinking and should always keep some margin of error. Now, if we *consider ideal conditions*; that is lets imagine a *homogenous rod.* It has pans at both ends. *Pans are dimensionless* and *weightless* so does not produce net tork (he holds a pencil parallel to the horizontal direction, he holds the pencil as if it is hanged from the center. Then he draws in air two pans hanged at both ends). Suppose rod is in contact with nothing, pans do not touch it. Now, if we take one mass from left pan, hoooop… rod will make a turn and stand in vertical direction (he holds the pencil parallel to horizontal direction and then turns it 90° as if the pencil stands parallel to vertical direction) But in this question, nothing will happen at these conditions…Equilibrium position will not change'.

In this problem and during the interview, H2 mentioned the necessity of considering ideal conditions for solving physics problems. He preferred to limit the problem in ideal conditions by excluding some of the variables such as the weight of the pans and distribution of the mass of the road.

4.2.1.2 Extreme Case

If at least one of the variables of the original problem situation was maximized by the participants while they were generating a mental scenario during the thought experiment process it was categorized as extreme case. The following episode exemplifies how the participants used extreme case during their thought experimentation process. In this episode, M4 was working on Problem 3.

Problem 3: Suppose an open railroad car is moving on a straight road. It is raining heavily and an appreciable amount of rain falls into the car and accumulates there. Will the accumulated rain have an effect on the motion of the car? Will the rain have an effect on the motion of the car, if rain drops fall sideways (if rain drops fall at an angle, suppose making 45° angle with horizontal direction)?

> 'M4: It will affect…Let's imagine rain drops *as very huge* rain drops. *They are very heavy*. It rains. Huge rain drops fall making an angle with the horizontal direction. Rain drops will have components in horizontal and vertical direction. The vertical component of the rain drops would then push the car, make it move (he shows by his hand that rain drops will pushing the car). If the car is moving forward, rain drops will accelerate the car. If car is going backward, rain drops will decelerate the car'.

In this problem, M4 manipulated the mass of the rain drops. In order to observe the effect of rain drops better, he enlarged the rain drops to extreme dimensions. He then let the experiment run and concluded the result easily.

4.2.2 Modification of Objects

Purposefully changing the objects of the original problem situation but keeping the variables of the problem situation unchanged was coded as modification of objects. Modification of objects was also observed in two different ways which were categorized as simple case and familiar case.

4.2.2.1 Simple Case

When the participants changed the objects of the original problem situation in order to set easier conditions to generate an answer, it is coded as simple case. Episode taken from the transcripts of H3, during the session on problem 7, was presented to exemplify usage of simple case by the participants during thought experiment process.

Problem 7: There is a vehicle having a fan and sail system on it. The vehicle is staying at rest on a straight road. When the fan of the vehicle switched on, do we expect the vehicle to move?

> 'H3: The part with fan will behave like a plane and the part with sail will behave like a sailboat….This vehicle will not be able to move.
> R: why?
> H3: Suppose that we switched on the fan and then we *broke the vehicle into two parts*; one part having the fan on it, other part having the sail on it separately. Now, sail will move forward and fan will move backward independent from each other (he shows the parts moving in opposite directions). Otherwise this vehicle will not move.
> R: So you mean that this car will not move.
> H3: yes. But if we take into consideration its efficiency, if we think more complex.. This fan has a capacity of blowing air in a specific period of time. However all of the air molecules produced by the fan will not reach the sail, but escape. So vehicle will move backward a bit due to the force produced as a reaction to the force of air molecules blown by the fan in forward direction (he draws the forces on figure) '.

In order to reduce the problem to a more understandable and simple situation, H3 preferred to make some modifications in the problem by dividing the objects. He proposed to break the vehicle into two as fan and sail and considered their motions separately, so that he tried to explain the reason why the vehicle will fail to move.

4.2.2.2 Familiar Case

When the participants changed the objects of the original problem situation in order to set more common and recognizable conditions, it is coded as familiar case. Different from the simple case, during the use of familiar case, almost all the objects of the original problem situation is modified.

Episode taken from the transcripts of M4, during the problem 9, was presented to exemplify usage of familiar case.

Problem 9: There is a train wagon on an elliptically shaped road. Inside the wagon, there is a plastic ball standing at the center of the floor. After the wagon started to move around the elliptical road, the ball is released. What can be observed about the reaction of the ball at that time?

> M4: 'Ball will move in upright direction. Suppose that we are *inside the bus turning the curved road*. While it is turning the corner, what do we do? We lean towards outward direction (he makes his body as if leaning outward) we stick to the window. So, this ball will lean outward and will keep its position there as if it is stuck to the wall of the wagon'.

M4 preferred to imagine the problem by modifying the objects of the original problem to set a familiar case so that he could be able to experiment it easily. M4 first imagined a bus instead of the wagon and put himself inside the bus instead of the ball. But he did not change the variables of the original problem scenario. Both of them are about motion of an object/person in a vehicle moving on the curved road. He visualized a common and familiar situation instead of the one provided in the original problem.

It is possible to examine the brief summary of above cases in Table 4.5, which also helps to better distinguish the categories from each other.

Table 4.5 Table of Nature and Variables/ Objects

Nature	*Variable/Object in the original problem*	*Variable/Object in Thought Experiment*
Limiting case	Balanced rod-pans	Homogeneous rod-weightless pans
Extreme case	Rain drops	Huge rain drops
Simple case	Fan- sail system vehicle	Vehicle broken into two as vehicle having only a fan and vehicle having only a sail
Familiar case	Wagon moving in elliptical road	Bus moving on curved road

During the analysis chapter, only some exemplary cases were discussed in detail, Table 4.6 demonstrates the rest of the cases for each category and for each participant.

Table 4.6 Nature of Thought Experiments

Nature/ Participants		High Level Group (H)					Medium Level Group (M)					Low Level Group (L)				
		H1	H2	H3	H4	H5	M1	M2	M3	M4	M5	L1	L2	L3	L4	L5
Manipulation of variable	Extreme case				++	+				++						
	Limiting case		+++	+												
Modification of object	Familiar case	++		+			++ ++	++	++	++ ++ +		+	+	++	+	++
	Simple case		+	+				+	+		+		++ +		+	++ ++

'+' represents the type of nature of thought experiment generated by the participants.
'H' indicates high level group, 'M' indicates medium level group, 'L' indicates low level group.

During problem solving sessions, participants in high level group were very cautious about satisfying ideal conditions before solving the problem.. As seen in the table, in most cases, high level participants manipulated the variables to extreme points or ideal conditions. They also tend to manipulate the variables to simplify the conditions or they proposed familiar cases during their thought experimentation processes. On the other hand, low level and medium level participants were inclined to simplify the conditions or describe analog situations by proposing familiar cases. They do not seem accustomed to manipulation of variables during the thought experimentation process. .

In this section, it is observed that participants purposefully do some changes in variables or structure of the original problems during the thought experimentation processes. The next section aims to reveal why the participants used thought experiments while they were working on the problems.

4.3 Purpose of Generating Thought Experiments

Analysis about the purpose of generating thought experiments showed that participants conduct thought experiments either as a major tool to generate a prediction for the problem or as a supplementary tool. If the participants generated a prediction for the problem by using thought experiments then the purpose of using thought experiment was coded as ‘prediction’. On the other hand, if the participants used a thought experiment to check whether his/her prediction (generated without using thought experiments) was true or wrong then the purpose of using of thought experiment was coded as ‘proof’. The last category of ‘explanation’ was coded when the participants was used thought experiments to bring further explanation about her/his prediction.

A schema of the variation on the purpose of thought experiments is presented in Figure 4.6. In the following sections, the details about the each category will be presented.

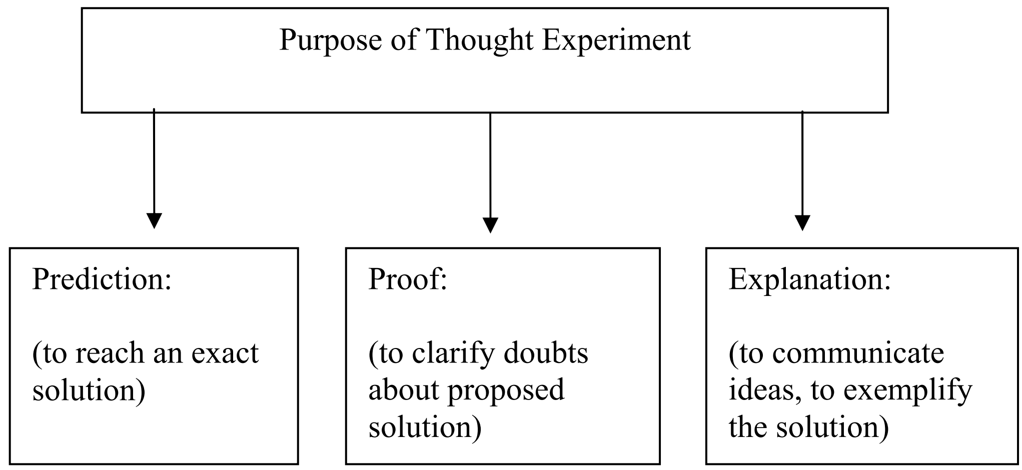

Figure 4.6 Purpose of thought experiments

4.3.1 Prediction

If the participants generated their solution for a problem based upon their thought experiment process then the use of thought experiment was coded as ‘prediction’. Reactions of participants’ like ‘that is it’, ‘I got it’, and ‘a-ha’ were considered as the indicator of prediction because they mean that participant reached a prediction at the end of the thought experiment process. The following episode extracted from the problem solving session with M3 exemplifies how the participants make predictions by using thought experiments. In this episode, M3 was working on Problem 7.

Problem 7: There is a vehicle having a fan and sail system on it. The vehicle is staying at rest on a straight road. When the fan of the vehicle switched on, do we expect the vehicle to move?

> ‘M3: I want to remove the fan from that system. I would like to imagine it without the fan. Now, (she is drawing a car with a sail) this car has only the sail. The wind will flow from here (showing right side). Sail will move forward (in the direction of the wind flow). (She returned to the original question) the same in here. With or without the fan, wind will flow from here and car will move. *So, that is it*. Car will move in either case.’

As obviously identified from the passage, M3 was conducting the thought experiment to generate a solution. She had no pre assumption beforehand. She run the experiment and reached the conclusion. Italic words in the passage (*so, that is it*) indicates that she concluded the solution by experimenting in thought.

4.3.2 Proof

If the participants have already generated a solution for a problem in another way like using a formula, a law or a concept and then performed the thought experiments to check the solution, the use of thought experiment was coded as ‘proof’. Words like ‘may’, ‘isn’t it’ and pauses that signify hesitations were coded as indicators of poof. The following episode exemplifies how the participants make proofs by using thought experiments. In this episode, M1 was working on Problem 3.

Problem 3: Suppose an open railroad car is moving on a straight road. It is raining heavily and an appreciable amount of rain falls into the car and accumulates there. Will the accumulated rain have an effect on the motion of the car?

> ‘M1: Rain drops filling the car can slow down the car because total mass would increase, *isn’t it…[PAUSE].. Lets imagine a stroller*. We are pushing it. When we put 5kg baby on the stroller, mass of the stroller will increase. Or suppose that two babies sitting in it. Speed of the stroller when there are two babies will be different than the speed of

the stroller when there is only one baby in it. We will fell difficulty in pushing it when there are two babies, we will push it slower. So, I think when the mass increases, speed will decrease'.

After reading the problem, M1 proposed a theory about the solution; she comprehended that there should be inverse proportion with mass and speed. However, she was not sure about her theory, she asked for acceptance. Then she paused for a few seconds. These reactions indicated that she has some hesitations about her answer and needs an experiment to justify herself. She decided to verify her theory by proposing a new case totally different from the original one. She imagined a stroller and babies, let the experiment run and proved her theory.

4.3.3 Explanation

If the participants have already generated a solution for a problem in another way like using a formula, a law or a concept and then performed the thought experiments to better communicate and exemplify their ideas, the purpose of using thought experiment was coded as 'explanation'. Words like 'for example', 'to illustrate', 'for instance' were coded as indicators of explanation. The following episode extracted from the problem solving session with L1 demonstrates how the participants used thought experiments to explain their predictions. In this episode, M3 was working on Problem 1.

Problem 1: There is a water hose whose one end is folded into a figure 6 and the other end is connected to the tap. When the tap turned on, which path will the water shooting out the folded end follow?

'M3: It will follow path C due to gravity. I am imagining it not as a hose but as an object on the table. *For example*, suppose that there is an object on the table. I give it motion. I pushed it (she shows an object rolling on the table). Then it rotated and felt to the ground from the edge of the table. During falling, it seems as if it will make a free fall (she shows the object falling from the table). Because of gravity. It is the same in the hose case. Water is shooting out of the end of the hose making a free fall, it will follow the path C. Suppose water is shooting like a torrential water flow, then it will follow path A. but in our case, I imagined it as a weak water flow. So it will follow path C. in our garden, I used to play with water.. When I opened the pipe slightly, water was shooting as C. like 'fışşt'.. was free falling. Path depends on speed of water.'

M3 proposed her answer immediately after reading the problem as: 'water will shoot out the hose following path C'. Then she generated the thought experiment in order to explain her solution for the problem. Table 4.7 represents a summary table for indicators and examples of indicators. The purpose of using thought experiments for all the cases are represented in Table 4.8

Table 4.7 Examples of Purpose Indicators

Purpose	*Indicators*	*Examples of participant responses*
Prediction	Words like 'that is it', 'I got it', and 'a-ha'	'With or without the fan, wind will flow from here and car will move. *So, that is it.* Car will move in either case' 'If he bounces the ball, it goes straight. *A-haaa. Yes*, he can catch the ball if goes straight'
Proof	Words like 'may', 'isn't it' and pauses that signify hesitations	'Rain drops filling the car can slow down the car because total mass would increase, *isn't it…[PAUSE].. Lets imagine a stroller*' 'Car *may* move.. lets imagine it not as a elliptical road but as a straight road..'.
Explanation	Words like 'for example', 'to illustrate', 'for instance'	'I am imagining it not as a hose but as an object on the table. *For example*, suppose that there is an object on the table' '*For instance*, if I throw an object out of the window of the car, it will always move in opposite direction of the car'

Table 4.8 Purpose of Thought Experiments

Purpose/ Participants	High Level Group (H)					Medium Level Group (M)					Low Level Group (L)				
	H1	H2	H3	H4	H5	M1	M2	M3	M4	M5	L1	L2	L3	L4	L5
Proof	+			+		++	++	+	++ ++	+					
Explanation		+++ +	+++	+	+	++		+	++		+	++	++	+	++ +
Prediction	+						+	+	+			++		+	++ +

'+' represents the type of reasoning resources used by each participant during each thought experiment process.
'H' indicates high level group, 'M' indicates medium level group, 'L' indicates low level group.

Table 4.8 displays the variation among participants in terms of the purpose of conducting thought experiments. As seen in the table, the most frequently observed purpose of using thought experiments is for 'explanation'. On the other hand, frequency of prediction is higher among low level group while frequency of proof is higher for medium level group. This variation indicates that medium level participants needed further evidence before providing their final answer and used thought experiments for a proof, but interestingly, low level participants were more confident about the accuracy of their solutions and prefer to use thought experiments in order to explain those solutions like the participants of high level group. Following table, Table 4.9, is presented to give more detail about the relation of purpose and nature of thought experiments conducted by the participants.

Table 4.9 Purpose versus Nature

Nature/Purpose		Prove	Explain	Prediction
Modification of Object	Familiar case	MMMMM MMMM H	LLLL H MM M	LLL M M H
	Simple case		LLLL L HH M	LLL M
Manipulation of variable	Extreme Case	M	HHH M	
	Limiting case	H	HHH	

Each capital letter in the table indicates a thought experiment process and shows the participants' group identity that performed the thought experiment (L for low, M for medium, and H for high level group). As the table indicates, both modification of the objects and manipulation of variables were used by all groups for the purpose of explanation of their ideas. This indicates that participants generally had predictions about the solutions of the problems before conducting thought experiments. Medium level group participants generally used familiar cases for self justification which means that they need analog cases to convince themselves for the accuracy of their solutions.

Low level group used just familiar and simple cases for the purposes of explanation and prediction. On the other hand high level participants preferred to manipulate the variables into extreme or limiting conditions in order to explain their ideas.

4.4 Resources Used During Thought Experimentation

In the previous sections, the mechanism of thought experiment and the purposes for conducting thought experiment were analyzed. This section discusses the resources used by the participants while conducting thought experiments. The area of reasoning resources is very comprehensive and diverse.

A huge volume of study has been conducted in this area in order to understand why students fail to reason like experts. Many different labels such as 'alternative conception' or 'intuitive knowledge' referring to stable and context generable ideas of students' and different interpretations such as 'phenomenological primitives' or 'naïve framework theory' were discussed in the literature (Brown, Clement & Zietsman, 1987; Chi & Slotta, 1993; diSessa, 1993; Vasniadou, 1994). The purpose of this section is to identify variation in reasoning resources of three groups of participants. Therefore, general terms and categorizations were used in this section and consciously avoided the detailed analysis about the nature of these resources to keep the track of the main course the study. The term, 'reasoning resources', was used to cover larger spectrum of reasoning elements. Three types of reasoning resources were identified from the analysis, which were named as; observed/experienced facts, intuitive principles, and scientific concepts. A schema depicting the variation of the reasoning resources used during the thought experiment process is presented in Figure 4.7. The following sections cover the details about each category.

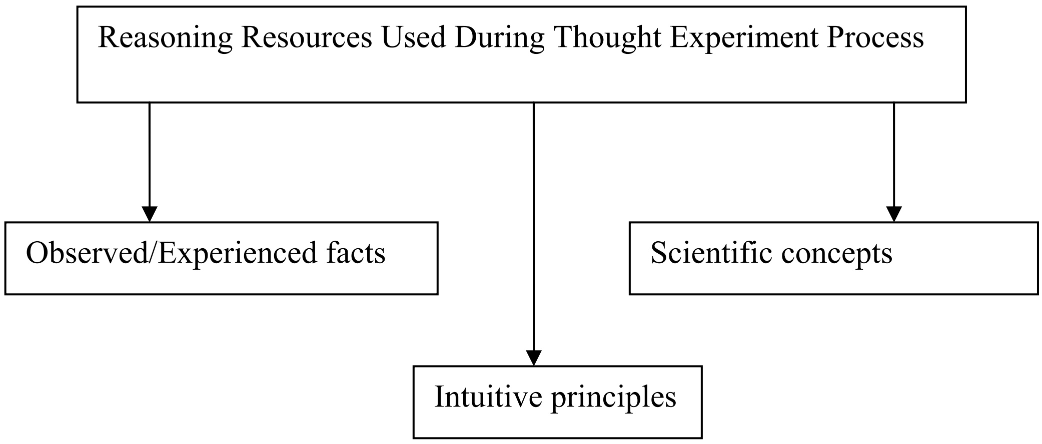

Figure 4.7 Reasoning resources

4.4.1 Observed/Experienced Facts

During thought experiment process, some of the participants were observed that they used some specific experiences or observations. Nevertheless, these observations or experiences were not generalized as a rule, but instead they can be defined as; remembered facts which were triggered by conceptual problems. Participants who were determined to reason with observed or experienced facts used thought experiments to form analog situations with their experiences and observations in order to reach a conclusion. The following passage, taken from the transcript of L5 where she was reasoning about the problem 9, is represented to exemplify how the participants reasoned by using observed/experienced fact through thought experiment process.

Problem 9: There is a train wagon on an elliptically shaped road. Inside the wagon, there is a plastic ball standing at the center of the floor. After the wagon started to move around the elliptical road, the ball is released. What can be observed about the reaction of the ball at that time?

> 'L5: While we are going on holidays… We are in a car moving on the curved road.. *While turning the curves, where do I lean*?.. hııım.. Or I am standing on a crowded bus moving on the road. I am trying to imagine which of my leg do I use to keep my balance.. While the bus turning right, I lean to the left. Okay, so in this case, while train is moving forward, ball will move in upright direction. This is an elliptical road so; it means train is like turning right (shows inward direction, towards the center of the ellipse) and ball will move opposite, upward direction'.

L5 had no pre assumption about the solution of the problem. She imagined a scenario and reached the result referring to a specific experience. She imagined a very common and daily occasion; traveling in a bus. She visualized the situation of bus's turn from a corner and at that moment she tried to remember the reaction of her body to the effect resulted from the motion of the bus.
Then she formed an analogy between the situation in the original problem and her experience, so that she concluded a solution about the motion of the ball. She did not mention or imply any scientific physics law or concept during this process; she did not reason using rule based intuitive knowledge either.

4.4.2 Intuitive Principles

During the data analysis, it was observed that participants frequently referred to their abstractions generated through everyday experiences or observations which were labeled as intuitive principles. These intuitions were in the form of generalizations. It differs from the category of observed/experienced facts in a way that while observed/experienced facts refer to a specific event, intuitive principles are independent from the specific events but in the form of general rules. To illustrate, 'heavier objects fall faster than the light objects' is one of the most common intuitively accepted principles that people use frequently. This principle is independent from the objects. Whether the object is an apple, a rock, or a feather is not important the principle is about its weight.

However, in the case of observed/experienced facts, the reasoning resource is a particular event with particular objects. For example, an argument of 'apple fall faster than the leaf' refers to an observed fact which only refers to an apple and a leaf. The following passage, taken from the transcript of L2 where she was reasoning about the problem 3, was presented to exemplify the use of intuitive principles.

Problem 3: Suppose an open railroad car is moving in a straight road. An appreciable amount of rain falls into the car and accumulates there. Will the accumulated rain have an effect on the motion of the car?

> 'L2: I do not think that the rain will have an effect on the motion of the car. Because.. *Suppose that* the car is on an inclined road. When the mass of the car increased, it will then move with a higher speed. But on a straight road, increasing mass will not affect the motion.
> On an inclined road, when cars' mass increases it goes down the hill more quickly. *Suppose we leave* an empty car or toy car down from the hill. Then *we filled* the same car with sand, and released it again, it will go down the hill with a higher speed
> R: why?
> L2: It may be about … I mean, when we leave two objects, heavier one falls faster, because, gravity pulls the heavier one more. It is the same in our case. Because there is slope here, there is a *pull*. There is more pull, so more speed'.

It was obvious that L2 based his solution to the intuitively developed principle 'heavier object falls faster'. He claimed that on an inclined road, massive car would move with a higher speed as in the case of free falling objects. He had a prediction that mass increase would not affect the motion of the car if it was moving on a straight road, but I it was moving down from an inclined road, mass increase will accelerate the car. He used thought experiment to explain his ideas.

4.4.3 Scientific Concepts

Another resource used by the participants during their thought experimentation process was coded as scientific concepts which refer to physical concepts, principles, laws, and theories like; Newton's laws, force, acceleration, conservation of momentum, etc. The aim of the study was not to analyze whether the participants solved the problems correct or not. Similarly, the participants correct or wrong use of scientific concepts was not analyzed either. The major course of the analysis in this section is to categorize what kind of resources the participants use independent from whether it is appropriately used or not. Therefore, the code of 'scientific concepts' does not necessarily mean that the participants used those concepts correctly and appropriately during their thought experimentation process. The following passage, taken from the transcript of H1 where he was reasoning about the problem 8, is presented to exemplify how the participants reasoned by using scientific concepts through thought experiment process.

Problem 8: There is an open railroad car is moving on a straight road. The car is full of water and there is a cork at the bottom of the car. Will the motion of water have an affect on the motion of the car, when the cork is opened?

> 'H1: No, *momentum* of the car will not change because they have the same velocity… If we consider air friction, water will flow backwards. Water will flow perpendicular to the horizontal direction. So it will not have an effect on the motion of the car. If we consider the *reference* point, as reference of the car. Suppose that we are inside the car. Car is moving with *constant velocity*. I am observing the motion of water from inside of the car. I will not be aware about the motion of the car there. Because the car is moving with constant velocity, so *Newton's laws* do not change. I will observe the water flowing perpendicular to the road '.

H1 used scientific concepts while answering the problem 8. He referred to momentum concept to explain that car motion of the flowing water will not have an affect on the motion of the car. In order to explain the motion of water, he constructed a thought experiment. He imagined himself inside the car and observed the flow of water from there. He claimed that water will be observed to flow perpendicular to the road due to constant velocity of the car and due to Newton's laws.

Table 4.10 displays the frequency of reasoning resources and types of resources used during thought experimentation process, for each participant in each group.

Table 4.10 Reasoning Resources

Resources/ Participant	High Level Group (H)					Medium Level Group (M)					Low Level Group (L)				
	H1	H2	H3	H4	H5	M1	M2	M3	M4	M5	L1	L2	L3	L4	L5
Intuitive principles						+++	+++	+	+++	+		++	+	+	++ +
Observed/ Experienced facts								+	+		+	++	+	+	++ +
Scientific concepts	++	++ ++	+ ++	++	+	+		+	+++						

'+' represents the type of reasoning resources used by each participant during each thought experiment process.
'H' indicates high level group, 'M' indicates medium level group, 'L' indicates low level group.

The table evidently presents that intuitive facts and observed facts were used by medium and low level groups, whereas, high level group used scientific facts as expected. They were expert physicists who internalized and accommodated scientific facts in their schemata. Low level group also used observed facts where they had no predictions about the solution of the problems. They referred to their experiences frequently. All participants in the low level group at least once needed to use observed facts. Participants of the medium group referred to both scientific and intuitive rules. It can be inferred that they have principles in their minds but intuitive and scientific rules seem to coexist in an intertwined way.

Table 4.11 displays the interaction of reasoning resources with the nature of thought experiments and purpose for conducting thought experiments.

Table 4.11 Interaction of Nature Purpose and Resource

Nature/Purpose		Prove	Explain	Prediction
Manipulation of variable	Extreme case	S_H	I_M S_M S_H S_H	
	Limiting case		S_H S_H S_H S_H	
Modification of object	Familiar case	I_M I_M I_M I_M I_M I_M S_M S_M S_H	I_L I_L I_M S_M S_M O_L O_L S_H	I_M S_H O_L O_L O_L O_M
	Simple case	I_M I_M	I_L I_L I_L I_L I_L S_H S_H	O_L O_L O_L O_M

The capital letters in the table indicates types of reasoning resources (I for intuitive principles; O for observed/experienced facts; and S for scientific concepts). Each subscripted capital letter in the table shows the participants' group identity that performed the thought experiment (L for low, M for medium, and H for high level).

Table 4.11 clearly explains that the participants who modified the objects constructed analog cases with observed/experienced facts in order to make predictions about the solution of the problem. During self justification, intuitive principles and scientific concepts were used. All types of resources were used for explanation purpose where intuitive principles and scientific concepts were frequent in all types of cases.

4.5 Summary of the Findings

The main purpose of this study was outlined in four research questions: 1) while solving physics problems, do the participants-from different level of physics knowledge- construct thought experiments? How these experimentations vary in terms of a) the nature of thought experiment; b) purpose of generating thought experiments; and c) the resources used by the participants while performing the thought experiments.

While solving physics problems, do the participants-from different level of physics knowledge- construct thought experiments?

It was concluded that all of the participants, at least once, generated thought experiments during problem solving session. Number of thought experiments did not vary so much among the participant groups; however, variations occurred in terms of the nature, purpose of use and reasoning resources behind during the solution of conceptual physics problems.

How do thought experiments vary in terms of nature?

The analysis of data showed that the participants changed the problem situation in two different ways while they were generating an imaginary scenario during thought experiments; by manipulating the variables of the problem situation (limiting case, extreme case) or by modifying the objects of the problem situation (simple case, familiar case). It was concluded that, high level participants manipulated the variables of the problem situations. They manipulated the variables either using limiting cases or extreme cases, while other participants tend to use simple and familiar cases. Low level group and also medium level group were constructed analog cases by modifying the objects of the problem in a way that ease the imagination of the problem situation. Medium level participants behaved like low level participants while making changes on the problem situation.

How do thought experiments vary in terms of purpose of generating thought experiments?

The results of analysis showed that participants conducted thought experiments either as a major tool to generate a prediction for the problem (coded as prediction) or as a supplementary tool for evaluating (coded as proof) and explaining his/her prediction which was generated without using thought experiment (coded as explanation). It was concluded that, medium level participants were the most hesitating participants. Highest frequency for the purpose of 'proof' was shown by medium level group. They needed self justifications in order to believe the accuracy of their predictions. Variation also observed in the relationships of how and why participants conducted thought experiments. As indicated in the analysis of the previous research question, both medium and low level groups manipulated the objects of the problem situation so that imagined familiar or simple analog cases. Although they used the same strategy, variation occurred in their purpose for doing it; familiar cases were used by medium level participants for proof, while low level group used familiar and simple cases for the purposes of explanation and prediction.

It can be inferred that low and medium level participants reason through analog cases, on the other hand high level participants use high order reasoning by manipulating the variables into extreme or limiting conditions in order to explain their ideas.

How do thought experiments vary in terms of the resources used by the participants during the thought experimentation process?

Three types of reasoning resources were identified from the analysis, which were named as; observed/experienced facts, intuitive principles, and scientific concepts. Variations observed among three groups. All of the low level participants at least once needed to use observed facts where they had no predictions about the solution of the problems so they frequently referred to their experiences. The medium level group refereed to both scientific principles and intuitive rules for the solution of the problems during thought experimenting process. All of the medium level participants confessed that their physics knowledge contradicts with their daily life experiences and they had difficulty in deciding which reasoning resource to use.

The results of the analysis were provided in four sections. Each section addressed particular analysis leading to generate a response for a specific research question. First of all thought experiments were located by identifying them in four steps. Then, these steps were analyzed separately in order to seek the answers for the specific questions. These steps and the results of the analysis were summarized in Figure 4.8.

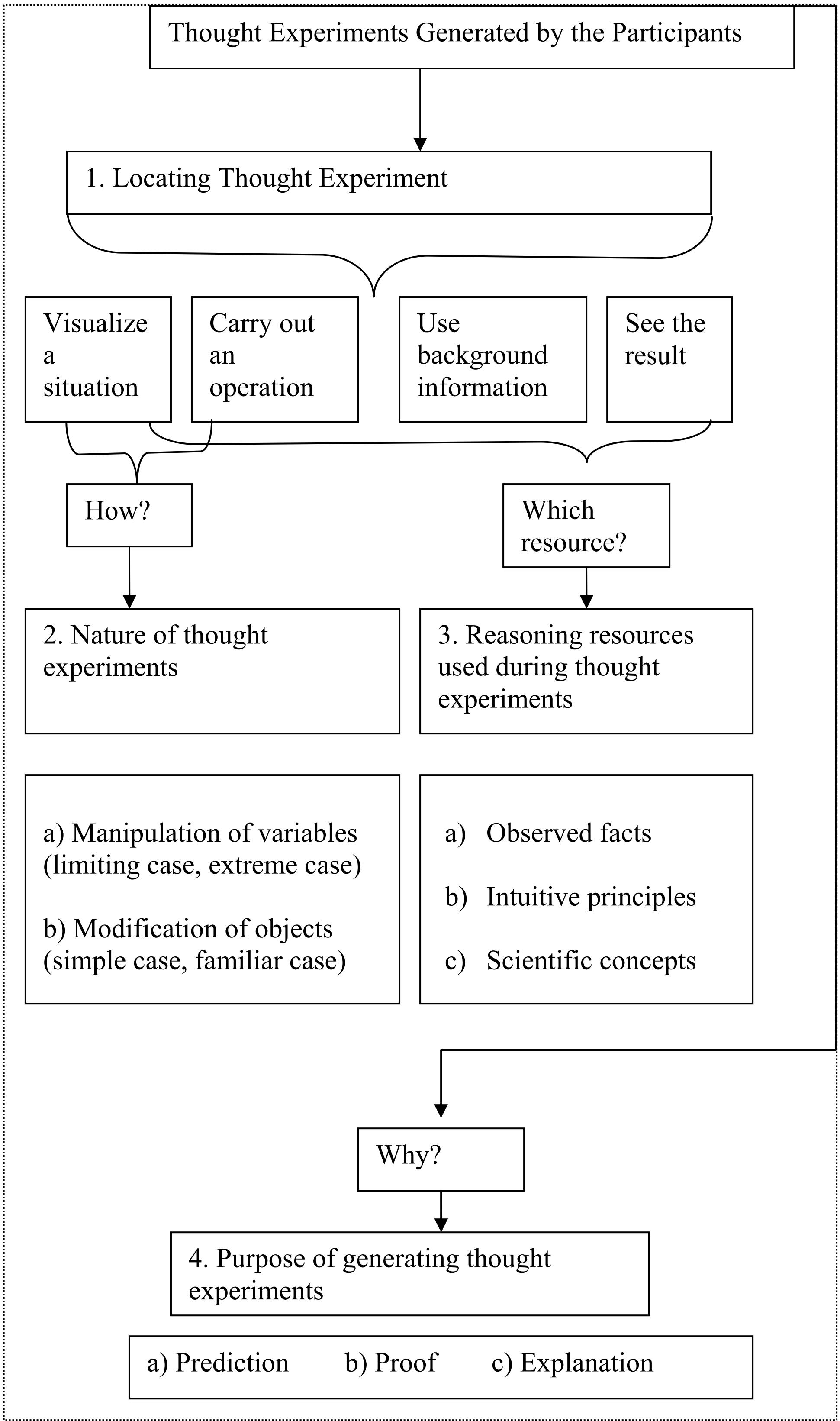

Figure 4.8 Analysis process

CHAPTER 5

DISSCUSSION AND IMPLICATION

Investigations on the role of imagery in science showed that imagery is an indispensible component of scientists' reasoning. Scientists perform experiments by manipulating imagery scenarios in their mind, which was named as thought experiment. However, the majority of the studies about thought experiments concentrated on the examination of historical thought experiments. This study was particularly motivated by the idea of making analysis on real time data. Individually conducted problem solving sessions were used in order to monitor the mechanism and to capture the variations on thought experiments. The purpose of this study was to contribute to the science education literature by describing how thought experiments vary in terms of the nature, purpose of use, and reasoning resources behind during the solution of conceptual physics problems.

The results of this study supported the arguments in the literature that thought experiment was a common cognitive tool for students as well as experts while they were working on problems (Clement 2006, 2008; Reiner1998, 2006). This study supported the arguments in a way that like scientists in history of physics, all participants- independent of their knowledge level- were capable in experimenting in thought. However, some variations were observed in the nature of thought experiments used by the participants. Two main categories of variations were defined as object modification and variable manipulation. Although both types of thought experiments reflect some creative elements, variable manipulation requires higher level reasoning processes because variables manipulated by participants are abstract concepts such as force, velocity, or mass.

On the other hand, modification of objects is limited to concrete reasoning because objects manipulated by participants are concrete in nature such as table, car, or human. This is probably why, low level participants' thought experimentation process was limited to modification of objects while the high level group performed both type of thought experiments effectively. Scientists in history of physics also performed their thought experiments through manipulation of variables as well as modification of objects. For example, Newton gradually increased the horizontal launch speed of cannonball to extreme conditions while he was performing his famous cannonball thought experiment. Likely, Galileo manipulated mass in his free fall thought experiment. Obviously, scientists performed higher level reasoning during their thought experimentation processes through the use of variable manipulations. Generally, the aim of teaching science is to help students get close to the experts' level of reasoning as well as understanding. Therefore, based upon object modifications, students should be informed about and helped to use variable manipulations while reasoning about physical phenomena. However, it does not mean that object modification is worthless. During the analysis of data, it was observed in both high level and low level participants' reasoning that object modification can be used very creatively and help participants make sense of the problem situation and generate a solution. Besides, object modification can be used as a scaffold during instructions to help students make sense of the new concepts. In fact, there is a method in the literature that fully describes the efficiency of using object modification, which is known as anchoring/bridging analogies. During the development and implementation of this method instructor locates some particular situations (anchors) that students familiar with and use them to help students understand the targeted concept. One of the most common examples in the literature is about action-reaction forces on the book lying at rest on a table (Clement, 1993).

In this example, teacher proposes a perfect thought experiment to help students understand the reaction force applied by the table through the use of bridging cases, where he/she modifies the object for each bridging case (book on the spring, book on the foam, book on the cardboard etc.). This is a creative example for modification of objects to help students understand a new concept. Another intention of this study is to understand participants' purpose of using thought experiments while they were working on problems. The results provided quite a detailed picture which was mostly consistent with the arguments in the literature of science education. The studies in the literature showed that while scientists use thought experiments to generate hypothesis or as an evaluating tool (Gendler 1998, 2000, 2004; Reiner & Gilbert 2000a), students use them as a sense making tool or predictive device (Reiner & Gilbert 2004; Stephens &Clement, to appear). Reiner (2006, 1998) advocated that unlike expert physicists, who plan the use of thought experiments as an argumentative device, naïve students' use thought experiments spontaneously. In a similar fashion, high level participants in this study generated thought experiments intentionally to explain and elaborate their predictions; however, low level participants generated them spontaneously. Both groups conducted thought experiments for the purpose of 'explanation', but the difference was in their intentions. Low level participants behaved more like communicating their thoughts by thought experiments, however high level participants behaved like exemplifying their thoughts.

In terms of reasoning resources running behind the thought experiments, three categories were emerged from the data, scientific concepts, intuitive principles, and observed/experienced facts. The aim was not to evaluate physics achievement of the participants, so the accuracy of the resources or problem solutions was not analyzed. As expected, scientific concepts were generally used by the high level group. On the other hand, intuitive principles, frequently used by medium and low level groups. Intuitive principles in fact have similar characteristics with 'phenomenological primitives' (p-prims) in the literature (di Sessa, 1993). Detailed analysis about the nature of these resources was consciously avoided to keep the track of the main course of the study. Details about intuitive principles can be traced from similar discussions in the literature, like p-prim literature that covers fragmented intuitive knowledge elements. The most striking result of the current study is the use of observed/experienced facts. Observed/experienced facts are also fragmented in nature but they are not generalized as a rule as in the case of intuitive principles.. In this sense, they are not as abstract as intuitive principles and they seem to be more primitive reasoning resource than intuitive principles. Considering that observed/ experienced facts were frequently used resources especially by the low level participants it deserves special attention for the future studies. In the literature, it was argued that thought experiments have power to trigger and elicit tacit knowledge of students (Reiner & Gilbert 2000a, 2004; Reiner, 2006; Scott; n.d.). It was argued that imaginary worlds of thought experimenters reflect the experiences of the physical world they live in. The results of the current study about reasoning resources confirmed this claim that thought experiments play a significant role in eliciting even the most primitive and hidden forms of intuitive knowledge. Teachers can benefit from this potential of thought experiments during classroom discussions. Tracing the thought experiments of students, teachers can get the opportunity to monitor students' reasoning and identify productive as well as unproductive ideas hold by the students. Based upon this information teachers can decide where and how the instruction should proceed. Various thought experiments proposed by students also links the learned concepts to different contextual situations which is highly relevant with the transfer of knowledge. For example, it was very interesting to witness that participants in this study imagined different situations during the solution of the problem 3, where it was asked if the rain drops accumulated in a car would have an effect on cars' motion. In order to answer this question, participant L2 imagined a plastic toy car filled with sand, while M1 imagined a stroller having a baby sitting on it, on the other hand M3 imagined train wagons loaded with cargo.

Discussions about the relevancy of the context used by these students with the concepts at hand can help students match the learned concepts with the relevant contexts.

The discussions provided so far shows that thought experiments have a potential of shading some lights on several issues of science education ranging from understanding students' tacit knowledge and reasoning to possible instructional practices for an effective learning environment. However, the number of empirical studies is quite limited in the literature of science education especially the literature in Turkey. Although this study intended to contribute this literature it has some inherent limitations and further studies are needed for some elaborations for every aspect of the results emerged from the analysis. For example, the structure of thought experiments may be elaborated further because this study is focused on solely about mechanical problems and these problems were quite easy for high level groups. It is highly possible to capture different forms of thought experiments when the content and the difficulty level of these problems were changed. Similarly, in this study, conceptual physics problems were used; however, different forms of problems like quantitative or ill defined may also reveal different forms of thought experiments. As a final remark, it has to be noted that the community of science educators have still long way on understanding the nature of thought experiments, but we also need to work on different ways of integrating thought experiments into instructional practices to help students get the most out of these practices.

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APPENDIX A

INFORMED CONSENT

GÖNÜLLÜ KATILIMCI FORMU

Değerli katılımcı,

Bu çalışma ODTÜ Eğitim Fakültesi, Orta Öğretim Fen ve Matematik Alanları Eğitimi bölümü doktora öğrencisi Şule Dönertaş tarafından yürütülmektedir. Çalışmanın amacı, farklı fizik bilgi düzeyindeki katılımcıların, fizik problemlerini çözerken ne tür düşünsel aktivite süreçlerinden geçtikleri ve sonuca ulaşmak için ne tür kaynaklar kullandıklarını incelemektir. Çalışmanın sonuçları fizik alanında uzmanlaşmış kişilerin, lise fizik öğrencilerinin ve fizik eğitim alanında öğrenim gören öğrenci ve öğretmenlerinin kendi düşünsel aktivitelerini gözden geçirmelerini ve diğer gruplardaki bireylerin ne tür benzer veya farklı aşamalar izleyerek problem çözdüklerini görmelerine katkı sağlamayı amaçlamaktadır.

Bu mülakat formunda, yukarda belirtilen amaca yönelik hazırlanmış on adet fizik soru bulunmaktadır. Soruları okuyup, aklınızdan geçen her düşünceyi sesli olarak ifade etmeniz beklenmektedir. Araştırmacı gerekli gördüğü yerlerde sorular sorarak, anlatmak istediğiniz ifadeleri netleştirmek üzere ek sorular yöneltebilir. Bu çalışmanın amacına ulaşabilmesi için, problemle çözümü esnasında düşündüğünüz her detayı ifade etmeniz önemlidir. Mülakat yaklaşık olarak bir saat sürmektedir. Mülakat video kameraya kaydedilecektir.

Bu çalışmaya katılım gönüllülük esasına dayanmaktadır. İstediğiniz zaman yarıda bırakıp çıkabilme hakkınız vardır. Katılımcıların sağladıkları bilgiler sadece araştırmacı tarafından incelenecektir ve sadece bilimsel amaçla kullanılacaktır. Elde edilecek bilgiler başka hiçbir amaç için kullanılmayacak ve başka kişi ve kurumlarla paylaşılmayacaktır. Araştırmacıya sormak istediğiniz ek bilgiler için iletişim adresini kullanabilirsiniz.

Çalışmaya sağladığınız katkı için şimdiden teşekkür ederiz.

Şule Dönertaş
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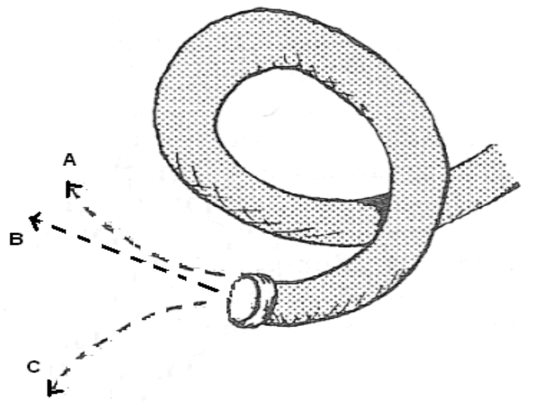
APPENDIX B

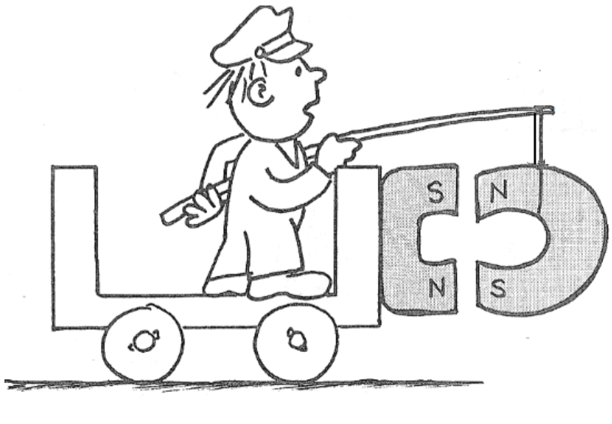
PHYSICS QUESTIONS USED FOR INTERVIEW

SORULAR

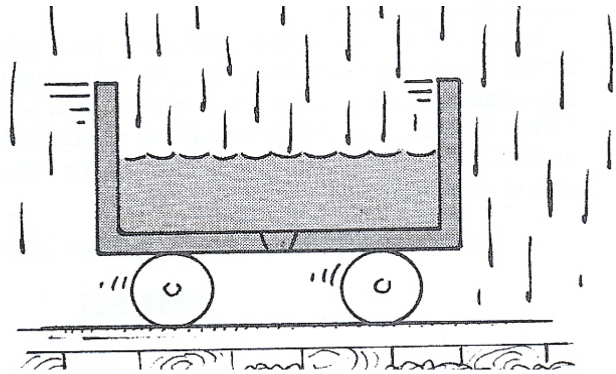
1) Bir ucu şekildeki gibi kıvrılmış olan hortumun, diğer ucu musluğa bağlıdır. Musluk açıldıktan sonra hortumun kıvrılmış ucundan çıkan suyun hangi yolu izlemesi beklenir? Neden?



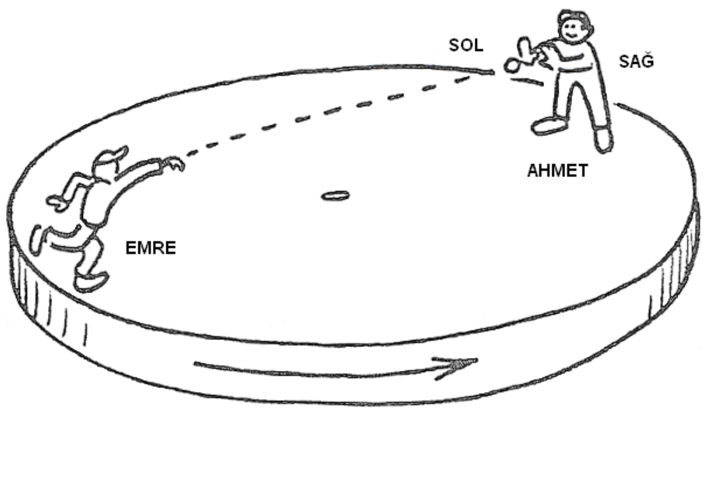
2) Şekilde gösterildiği gibi, demir bir arabanın ön tarafına bağlı duran bir U mıknatıs vardır. Bu mıknatısın karşısına ters kutuplu başka bir U mıknatıs asılırsa araba hareket eder mi? Neden?



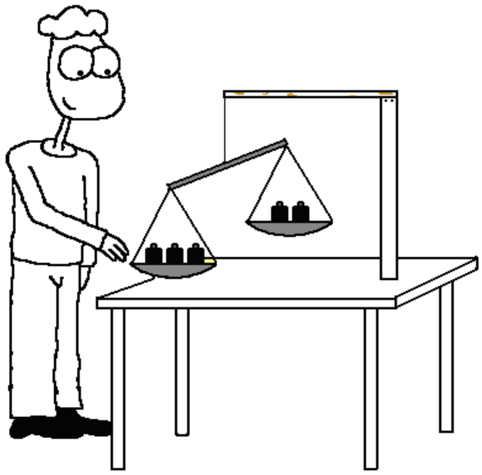
3) Sürtünmesiz düz bir yolda sabit hızla ilerleyen, şekildeki gibi üzeri açık bir araba vardır. Arabanın içine - dikey doğrultuda- yoğun miktarda yağmur yağmaktadır ve yağan yağmur arabanın içinde birikmektedir. Biriken yağmurun, arabanın hareketine bir etkisi var mıdır? Yağmurun açılı yağdığını düşünürsek (örneğin yatay düzlemle 45° lik açı yaparak yağarsa), arabanın hareketine bir etkisi olur mu?



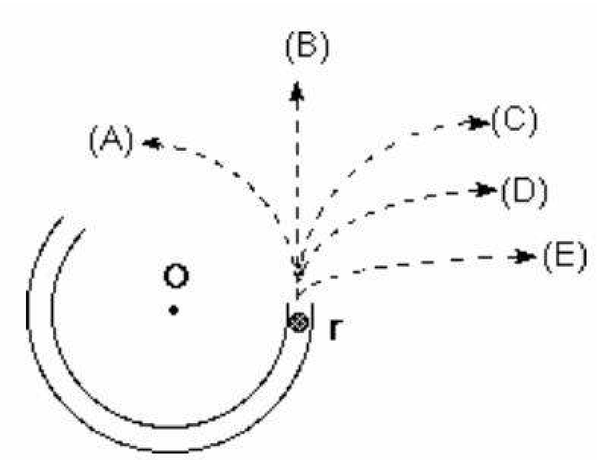
4) Emre ve Ahmet lunaparkta, kendi etrafında dönen bir platformun üstünde top oynamaktadır. Emre topu düz bir doğrultuda Ahmet'e doğru atmıştır. Ahmet topu tutabilmek için hangi yöne doğru uzanmalıdır?



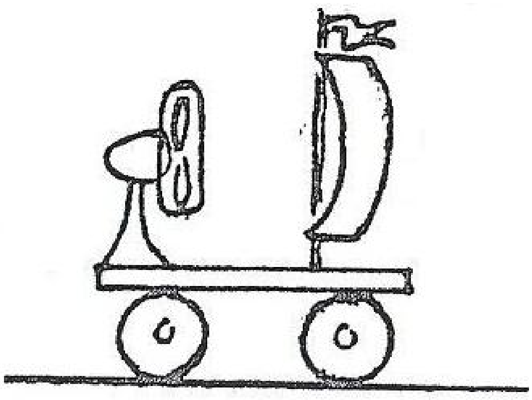
5) Düzgün bir çubuğun iki ucuna kutular bağlanmıştır ve tam orta noktasından bir masanın üzerine şekilde görüldüğü gibi asılmıştır. Kutulardan birine birer kilogramlık iki ağırlık, diğerine ise yine birer kilogramlık üç ağırlık eklenmiştir. Bu durumda şekilde gösterildiği gibi bir durum oluşmuştur. Tam bu anda, sol kutudaki üç ağırlıktan bir tanesini alırsak sistemde ne gibi bir değişiklik olmasını bekleriz?



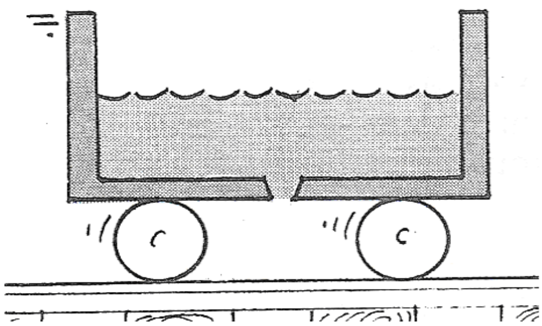
6) Şekilde masa üzerine yapıştırılmış olan yarım çember şeklinde bir tüp ve tüp içinde ilerleyen bir top gösterilmiştir. Top "r" ucunda tüpten çıkıp, sürtünmesiz masa üzerinde hareket ederken hangi yolu izler?



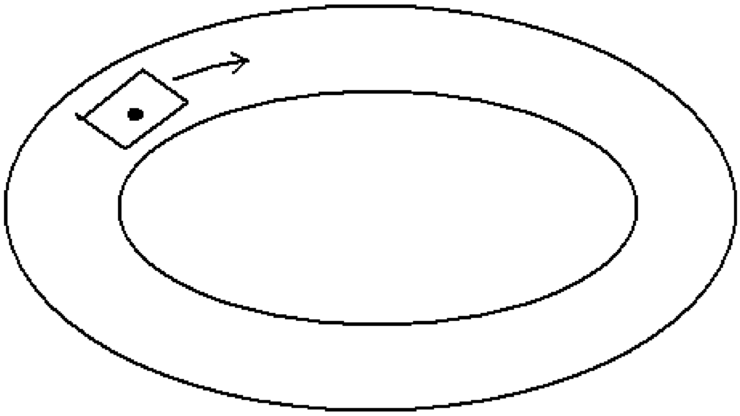
7) Şekilde gösterildiği gibi, düz bir yolda hareketsiz halde duran tekerlekli bir araç vardır. Aracın üzerinde bir vantilatör (fan), ve vantilatörün karşısında gemi yelkenlerine benzer bir yelken düzeneği bulunmaktadır. Vantilatör çalıştırıldığı zaman, aracın hareket etmesi beklenir mi? Nasıl bir etki gözlemlenebilir?



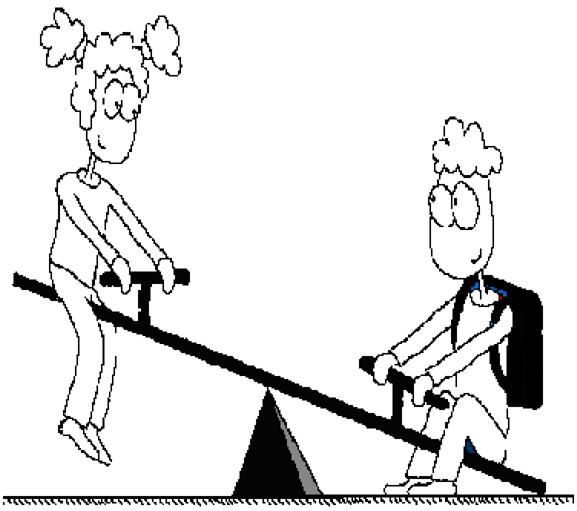
8) Sürtünmesiz düz bir yolda ilerleyen içi su dolu arabanın altına, şekildeki gibi bir delik açılmıştır. Arabanın içindeki su bu delikten boşalmaktadır. Boşalan suyun arabanın hareketi üzerinde bir etkisi var mıdır? Nasıl?



9) Şekilde gösterildiği gibi elips şeklinde bir tren yolu üzerinde, bir tren vagonu bulunmaktadır. Vagonun zemininin tam orta noktasında bir top vardır. Vagon belirtilen ok yönünde hareket etmeye başladıktan bir süre sonra top serbest bırakılırsa, bu andan itibaren topun durumuyla ilgili ne gözlemlenebilir?



10) Haluk, arkadaşı Özge ile birlikte şekilde görüldüğü gibi bir tahterevallinin üzerinde merkezden birbirlerine eşit mesafede oturmaktadırlar. Haluk ve Özge'nin ağırlıkları tam olarak birbirlerine eşittir. Fakat Haluk'un sırtındaki çantadan dolayı şekildeki gibi bir konumda bulunmaktadırlar. Haluk oturduğu yerini hiç değiştirmeden sırtındaki çantayı çıkararak bir kenara koyar ise tahterevallinin durumunda nasıl bir değişiklik olması beklenir?



APPENDIX C

THOUGHT EXPERIMENTS IN HISTORY OF PHYSICS

Schrödinger's Cat Thought Experiment

Schrödinger's cat is a thought experiment that was proposed by the Australian physicist Erwin Schrödinger in 1935. The experiment was related to quantum mechanics which aimed to describe a paradox about Copenhagen Interpretation. According to the Copenhagen interpretation, reality is indeterminate in a state of superposition. That is, Schrödinger aimed to undermine the uncertainty principle in quantum mechanics. Schrodinger showed that this interpretation was indefensible by his 'cat' TE.

> "He imagined a cat jailed in a closed box. He also imagined a capsule of cyanide placed in the box. If the capsule would be broken with a hammer, then it would kill the cat. This would be released by a detector triggered by an emission produced by the decay of one atom of a radioactive substance. The substance has a half-life such that, with equal probability, one atom may or may not decay in a one-hour period. The cat would be alive after one hour if no atom had decayed but dead if one had. The superposition of the eigenvalues for the two equal probabilities (decay, nondecay) would suggest, following the Copenhagen interpretation that the cat would be, in equal parts, dead and alive after one hour into the experiment. The absurdity of the physical consequence of this prediction, based on the theory cast doubt on the Copenhagen interpretation of it (Reiner & Gilbert, 2000b, p 269)".

That means; after a while the cat is simultaneously alive and dead, however, when the box was observed, the cat would be either alive or dead, not both alive and dead.

Figure A.1 Schrödinger's cat (adapted from Reiner & Gilbert, 2000b, p 270)

Maxwell's Demon Thought Experiment

James Clerk Maxwell proposed a thought experiment in 1867 in order to question the validity of second law of thermodynamics. According to this law; when two bodies having equal temperatures, isolated from the surrounding effects, were contacted with each other, heat from will not be observed between them because the entropy of closed system would never decrease.

> "The model associated with the theory depicted gas molecules as being billiard-ball-like objects, subject to Newton's laws, in rapid random movement. The temperature of the gas was the average kinetic energy of the molecules, which is calculated statistically. The problem was that this statistical treatment allowed the possibility that some molecules would move from a cold body to a hot body, which would defy the second law of thermodynamics. Maxwell pictured a hot gas and a cold gas contained in a box separated by a trap door. Although there was a distribution of molecular speeds within each box, the cold gas contained far fewer fast molecules than did the hot gas. The mythological demon was able to open the door between the two gases so that the few fast, and therefore 'hot', molecules in the cold chamber to escape into the hot chamber. As a consequence, the temperature of the cold gas decreased and that of the hot gas increased. The Maxwell's Demon TE thus justified the deviation from the universal law and hence permitted the drawing of conclusions from the molecular kinetic theory by statistical means (Reiner & Gilbert, 2000b, 269-270)".

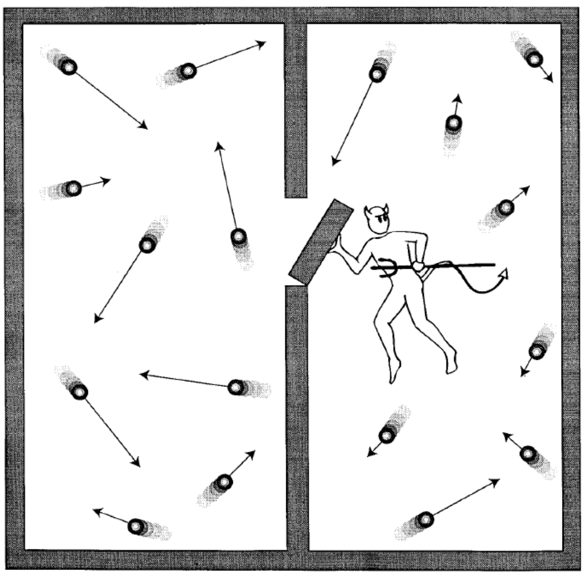


Figure A.2 Maxwell's demon (adapted from Reiner & Gilbert, 2000b, p 271)

Newton's Cannonball Thought Experiment

Sir Isaac Newton proposed his famous cannonball thought experiment in 1687, where he speculated that; the force which makes the satellites return around the planets and the force that pulls the apple toward the ground were the same, which is gravitational force.

> "Newton imagined a cannonball fired from a mountain top. The cannonball falls toward the earth each time. The more powder we put in, the farther it goes. We could conceivably carry this on to the limit when the cannonball falls all the way around the earth and comes back to where it started from. Once we see this possibility for a projectile, we then see that the moon is not suspended in the sky, but rather, is constantly falling to the earth in exactly the same way as the cannon ball (Brown, 1986, p 7)".

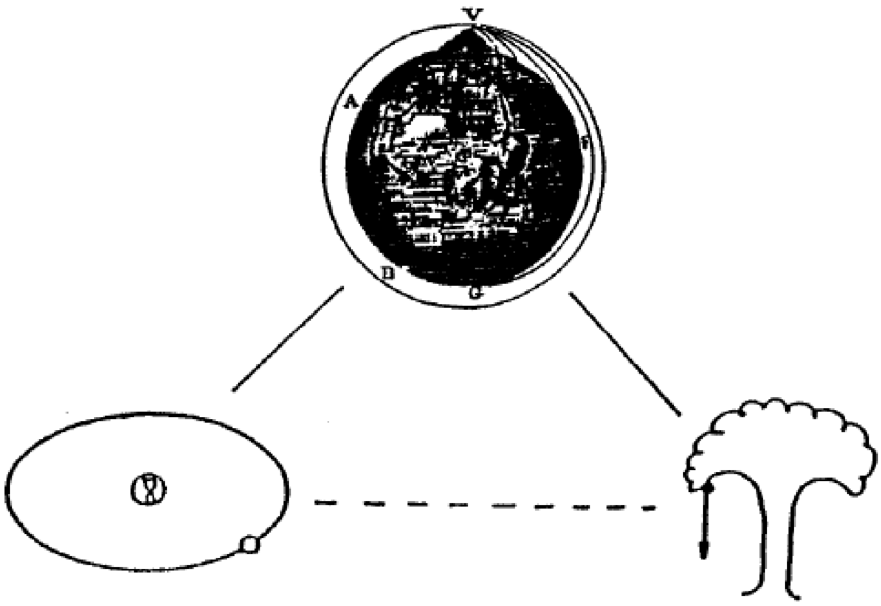


Figure A. 3 Newton's cannonball (adapted from Clement, 1998, p 1277)

Galileo's Free Fall Thought Experiment

Galileo's free fall TE aims to refute Aristotle's view that heavier things fall faster than lighter things. Galileo Galilei proposed a thought experiment and suggested that all objects fall at the same speed.

> "According to his thought experiment, he imagined two objects, W1 (light object) and W2 (heavy object) which have different masses. He suggested dropping them separately in free fall from the same point at the same moment. He claimed that, according to the Aristotle's view (heavier object moves with a higher average velocity than a lighter object) V2 would be greater than V1 and, W2 would arrive at the ground before W1. Then he repeated the experiment with the two objects tied. As the mass of the tied objects would be greater than the heavier object (W1+ W2 > W2), then it would be expected that velocity of tied objects would be greater than the velocity of heavy object (V(1+2) > V2). However, as light object, W1, would on its own, fall slower than heavy object, W2, then W1 would exercise a retarding (a parachuting) effect on W2 when the two were tied together. This would lead to velocity of tied objects would be smaller than velocity of heavy object (V(1+2) < V2). The two conclusions contradict each other, thus refuting the original theory and supporting the view that V1 = V2 (Gilbert & Reiner, 2000b, p 273-274)".

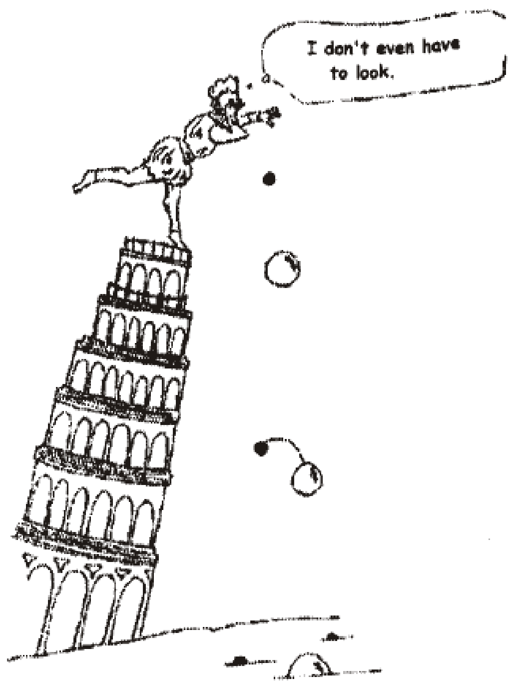


Figure A. 4 Galileo's free falling objects (adapted from Brown, 2006, p 65)

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PUBLICATIONS/ CONFERENCES

1. Dönertaş, Ş. & Yerdelen, S., 'Can Sixth Grade Science Textbook Reflect the Reform Made in Turkish Curriculum? Critical Analysis of School Science Textbook, IOSTE 2007, Tunisia.
2. Dönertaş, Ş., 'Multicultural Education: A Fragile Issue in Turkey', International Dialogue Through Education, MESCE 2008, Malta.
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